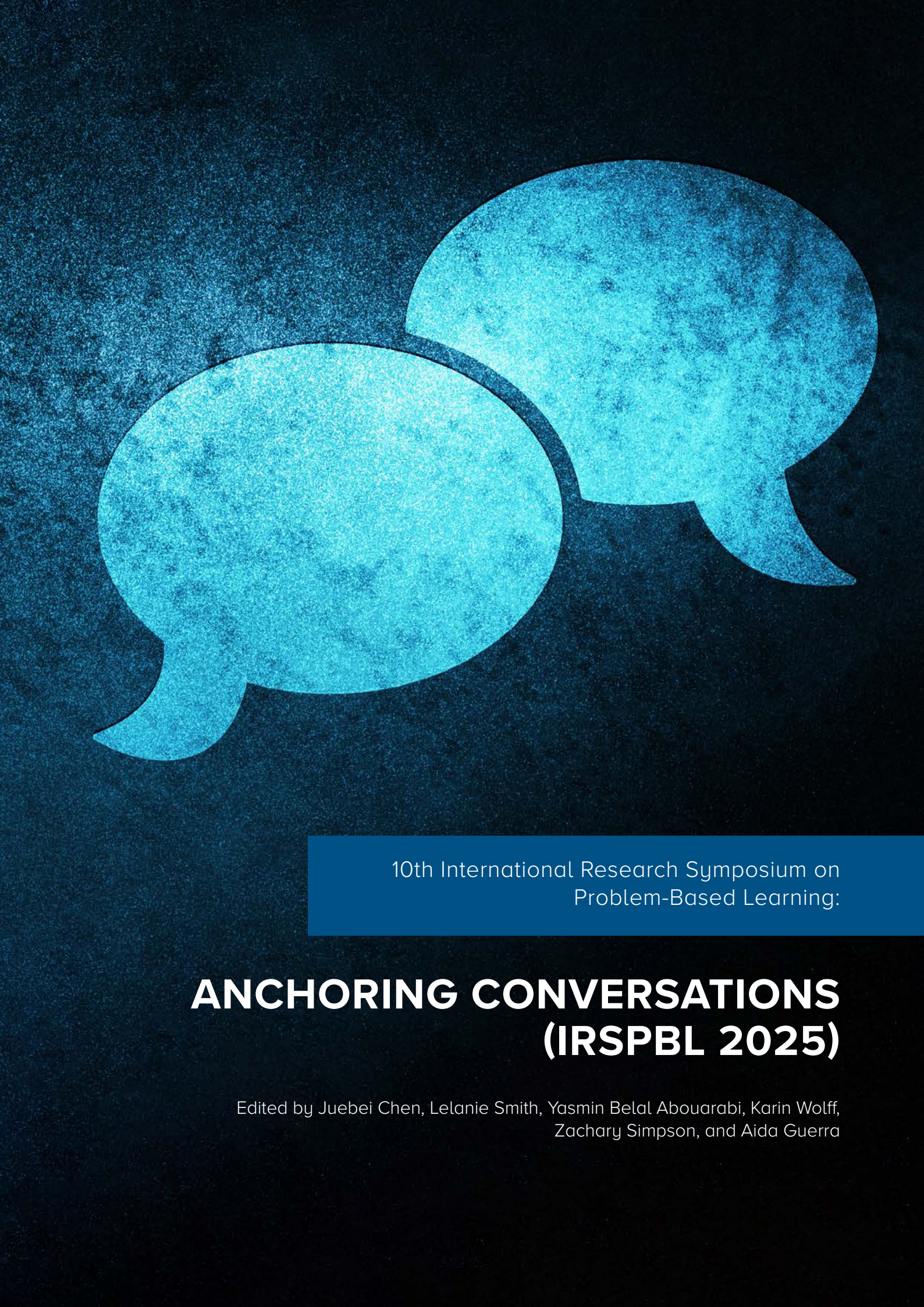

10th International Research Symposium on Problem-Based Learning:

ANCHORING CONVERSATIONS (IRSPBL 2025)

Edited by Juebei Chen, Lelanie Smith, Yasmin Belal Abouarabi, Karin Wolff, Zachary Simpson, and Aida Guerra

Foreword

Editors: Juebei Chen, Lelanie Smith, Yasmin Belal Abouarabi, Karin Wolff, Zachary Simpson and Aida Guerra

Engineering students are entering a profession defined by rapid change, transformation, and innovation. As graduates, they will navigate volatile, uncertain, complex, and ambiguous environments, striving to deliver sustainable solutions through their professional practices. Historically, engineering education has focused primarily on cultivating deep foundational knowledge in engineering sciences and technical expertise. However, this is no longer sufficient. While these foundations remain essential, today's engineers must also develop a broader set of cognitive skills - such as complex problem-solving, systems thinking, and creativity - alongside social skills like communication and teamwork, and emotional competencies including self-efficacy, empathy, and conflict management. International organizations and policy makers, including the World Economic Forum (WEF) and the Organisation for Economic Co-operation and Development (OECD), consistently highlight the evolving nature of professions, the socio-technological transitions underway, and the shifting demands of the labor market. Despite this, many engineering education institutions struggle to adapt their frameworks and practices to adequately prepare graduates for the realities of the modern workplace. Institutional transformation begins with awareness and dialogue.

Anchoring Conversations: Connection, Collaboration, and Co-Creation for the Future is the theme of the joint conference comprising the 10th International Research Symposium on Problem-Based Learning (IRSPBL 2025), the 7th South African Society for Engineering Education (SASEE), and the 5th SoTL in the South. This event is convened by the University of Pretoria and the Aalborg Centre for Problem-Based Learning in Engineering Science and Sustainability under the auspices of UNESCO, in collaboration with eight South African universities, two societies (SASEE and SoTL in the South), and Future Nation Schools. This conference invites dialogue and reflection on critical questions: To what extent is education transforming to meet the skill demands of fast-paced socio-technological transitions? How are institutions supporting students through various educational transitions and pathways, from K–12 to higher education and into the labor market? What knowledge, skills, competencies, and attributes must graduates possess not only to perform but to thrive in both work and life? What forms of agency and what kinds of change agents are needed to drive meaningful and sustainable institutional transformation?

These questions will spark conversations among researchers, educators, practitioners, and leaders across educational levels (K–12 and higher education), career stages (early, mid, and late), sectors (public and private, employers and industry partners), countries and regions (Global North–South, East–West).

They will be discussed during the conference, hosted by University of Pretoria and Future Nations Africa, on 17–21 November 2025. The IRSPBL 2025, 7th SASEE, and 5th SoTL in the South, have collected 103 contributions from 29 different countries[AG1.1][AG1.2], all of which will be presented during the conference and have been compiled in this book.

The contributions cover multiple relevant topics related to conference themes, namely Pedagogical Innovations and Competency Development in PBL, Institutional Implementation and Research Perspectives in STEM Education, Technology, AI, and Digital Learning in STEM Education, Sustainability, Professional Practice, and Global Transformation, Emotions, Well-being, Collaboration, and Social Responsibility, and K12 & Vocational Education. This book represents some of the newest results from research on PBL and best practices to inspire researchers and practitioners to transform their practice and their institutions.

We would like to acknowledge members of local and international committees: **Prof. Xiangyun Du, Dr. Sizwe Errol Nxasana, Dr. Lykke Bertel, Dr. Inês Direito, Dr. Anita Campbell, Dr. Teresa Hattingh, Ms. Bonolo Mokoka, Mrs. Jeanette Arboe, Mrs Renee Le Roux** and **Dr. Dr Curwyn Mapaling**, for their expertise, insightful suggestions and support during the process leading to this book.

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ANCHORING CONVERSATIONS

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Pedagogical Innovations and Competency Development in PBL

Developing and piloting a Q-study on pedagogical challenges in problem- and project-based learning for first-year engineering students

Niels Erik Ruan Lyngdorf
UCPBL, AAU, Denmark, nel@plan.aau.dk

Bettina Dahl
UCPBL, AAU, Denmark, bdahls@plan.aau.dk

Dan Jiang
UCPBL, AAU, Denmark, dji@plan.aau.dk

Abstract

Research highlights the benefits of Problem- and Project-Based Learning (PBL) for engineering education, but students face challenges with some of its pedagogical features. This pilot study uses Q-methodology to explore first-year engineering (FYE) students' learning challenges in a PBL environment. Based on literature, feedback from PBL experts, the University Student Counselling and Well-being unit, and students, 39 Q-statements was developed regarding different pedagogical challenges of students in PBL. Rather than simply identifying challenges, this study aims to identify the most predominant ones. Q-methodology is appropriate because participants rank statements in relation to each other, instead of rating individual statements. Our Q sorting question therefore asks FYE students to rank pedagogical features of PBL from most to least significant in terms of perceived challenge in relation to learning. To pilot the Q, we consulted two experts in PBL and Q-methodology and subsequently let 5 FYE students do the sorting activity. The results of this pilot are informative in themselves in further developing the tool. In the long term, this study is anticipated to provide knowledge about how students struggle with PBL which will help universities become aware of and remedy the situation.

Keywords: Problem based learning; Q-study; First-year engineering students; Pedagogical challenges

1 Introduction

1.1 Problem- and project-based learning for engineering students

Research in a variety of study programmes over the world has shown that problem-based learning (PBL) is a successful educational strategy (Du et al., 2009). At the university in which the study took place, PBL is usually understood as both problem-based and project-based learning, even though technically, PBL, only indicates 'problem'. PBL has been defined in various ways and implemented in different forms. One of the widely used definitions of PBL is "an instructional learner-centred approach that empowers learners to conduct research, integrates theory and practice, and applies knowledge and skills to develop a viable solution to a defined problem" (Savery, 2015, p.7). Project-based learning, on the other hand, describes students working in teams to solve a problem within a set timeline, resulting in end products (e.g. reports, designs, etc.) (Helle et al., 2006). Aalborg University (AAU) in Denmark has merged the characteristics of both problem- and project-based learning, and its curricula and teaching has been structured around the principles of PBL since its start in 1974 with six basic principles as guidelines (Askehave et al., 2015):

1. The problem as point of departure
2. Projects organized in groups
3. The project is supported by courses
4. Collaboration – Groups, supervisor, external partners
5. Exemplarity
6. Student responsibility for learning

A characteristic of PBL is that, ideally, the learning take outset in an ill-structured authentic problem which is contextualized. Students work collaboratively and are responsible for their own learning process. Hence, fostering student motivation by offering students ownership and multiple sources of learner agency are key elements of the PBL model (Jiang et al., 2023; Lyngdorf, Du & Lundberg, 2023). Such traits in the learner requires meta cognitive competencies, such as critical self-reflection, self-regulation, goal setting etc. (Bandura, 2006, 2008), which are less developed competencies among young learners (Knowles, 1978). Thus,

the transition to a PBL university, like AAU, in itself requires transformative changes in student identity and strategies which can be challenging for some. Furthermore, specific features of PBL, such as the strong emphasis on sociocultural learning processes, application, and transfer of knowledge for exemplarity and self-responsibility, might favour certain types of students over others. Therefore, AAU offers a mandatory 5 ECTS credit (1/6 of a semester) PBL course at the first semester bachelor for the students at the two engineering faculties. Despite the well-described advantages of PBL, Chen et al. (2021) document a concerning increase in challenges with students that are less prepared for student life in university or lack competencies in relation to academic achievement and a change in how students regard group work. This inspired us to find out more about these specific challenges for engineering students at AAU. Also, a subsequent literature review (Jiang et al., 2023) explored the multiple challenges that engineering students encountered when working in intercultural teams. By looking into the references in these studies, we learned how existing studies have identified and described specific challenges related to PBL environments. These studies provided us with inspirations and initial backgrounds to develop our Q statements. However, since these studies include many different types of challenges analysed in a non-holistic way, our study is also different since we focus on the pedagogical challenges only, and we also focus specifically on FYE students. We are also assuming that challenges may change over the years, and it is essential to learn more about the new FYE students' challenges to help retention and avoid drop-out. We are therefore not only interested in knowing what challenges are experienced, but also which are the most or least challenging from a student perspective. Therefore, it is necessary to apply a methodology that can approach this while at the same time offering a systematic and holistic approach with a specific focus on core PBL pedagogy elements.

1.2 Research Aim

While the principles and main features of the PBL-model at AAU University have remained virtually unchanged for a long time, the world around it has not. Therefore, we are interested in developing a tool that can uncover what pedagogical features of PBL challenge the new generations of FYE students. Some research (O'Brien & Reale, 2021) has found that introducing PBL in the first year of education can cause challenges and even lead to higher attrition rates due to the different expectations to students compared to what they are used to in lower levels of education. PBL provides students with more autonomy and freedom but also requires individuals to actively enact their agency. The transition to PBL pedagogics at university thus also requires students to transform their student role and rethink how to become a successful student (Brinkworth et al., 2009; Hagan & Macdonald, 2000). To understand the possible challenges in this transformation, we find Q-methodology to be relevant and valuable. This paper will present the work of developing a Q-study to study the above-described topic. In this sense, this study aims to address the following research question:

How can a Q-study be designed to study what pedagogical challenges FYE students experience in a PBL environment?

2 Methodology

2.1 Q Methodology

Methodologically, Q is used to study subjective opinions, values or beliefs (Watts & Stenner, 2012). It enables researchers to identify and describe the shared viewpoints that exist on a topic revealing areas of consensus and disagreement across these views (Brown, 2019). It combines the characteristics of quantitative and qualitative studies, using factor analysis to organize data from sorting activities and incorporating written reflections as post-sorting activities (Watts & Stenner, 2012).

Constructing a tool for data collection in Q-methodology can be regarded as a unique piece of work and contribution in itself since it can be shared and refined in a research community, which could lead to more studies and ultimately generalization of findings across studies. For example, it could be interesting to

compare how K-12 students experience PBL pedagogy and whether or not they are challenged by the same pedagogical elements as FYE students. Thus, this paper will present how we undertook the concourse development and Q-set construction (Lundberg et al., 2020) for studying FYE students' pedagogical challenges with the PBL model. We wish to emphasise that we focus on pedagogical challenges that are directly linked to PBL and therefore not challenges relating to other elements of student life such as feeling homesick, economic stress, etc. We have a system view of PBL (Kolmos, 2017) in the sense that we do not only focus on the projects, which directly applies PBL, but the education programme as a whole, including lectures which typically do not involve a lot of PBL in themselves, but they serve as support for the project.

2.2 Concourse development

To pilot Q, we followed the procedure of Tancredi et al. (2023), which includes the following steps: 1) concourse development; 2) construct the Q sample; 3) data collection (piloting) and 4) elaborate revisions.

Step 1: Concourse development

The concourse development includes the prework leading to the creation of a set of statements that participants will later rank to create their Q-sorts. The task here is to cover all existing knowledge in relation to the research question through various methods and formulate them into statements that research participants can sort. For this purpose, we inquired different sources as described in the following four steps, a-d:

a: Expert Insights. We sought input from local experts, namely the members of the research group of the authors, UNESCO Centre for PBL at AAU. At AAU, all FYE students have a first-semester course in PBL of 5 ECTS. The teachers of this course are all members of this research group as well as active PBL researchers. On 8 February 2024, authors Lyngdorf and Dahl gave a 10-minute presentation to this research group, followed by a 20-minute discussion with 10 research group members. We discussed our vision for the research and requested participants to write down suggestions to statements based on their experience as both teachers and researchers of PBL. In addition to the actual statements, it was also recommended to us that the term PBL should not in itself be used in the sorting question or in the statements as students may not always have a clear understanding of what PBL actually is, but they know when something is not working for them in this teaching environment. In total, this gave 8 statements.

b. Literature Review. We searched relevant literature to be better informed about student challenges in PBL. Here, the work by Chen et al. (2021) and Jiang et al. (2023) became central and inspired to the formulation of 26 statements. Other literature was also used (e.g., Bundgaard et al., 2021) for single statements.

c. Students' opinions. Author Dahl asked her students taking a 5 ECTS course in Mathematics Education to formulate statements on 18 March 2024. The class consisted of 13 students who were a mix of in-service and preservice mathematics teacher students for upper secondary level. The students were chosen as the authors assumed that, firstly, the students' particular interest in educational research would make it possible for them to come up with relevant statements from a pedagogical angle. Secondly, the students were experienced PBL-learners coming from either 4th or 6th semester of a Bachelor Programme in Mathematics, and for the in-service students taking the same class, they had graduated from AAU some years ago, hence they were considered able to also perceive their PBL education, and potential struggles, in a new light. Thirdly, even though the students were not engineering students, they are at the same faculty as the engineering students, hence experiencing a similar PBL model. During this process, it also became clear why it is a good idea to not mention "PBL" too specifically in the Q statements as the students here first thought that they were asked what they remember from their first semester course in PBL. Thus, many students, sadly, confuse PBL as the overall principles and structure of the education at AAU with a first semester course, also named "PBL". In total, this produced 15 statements.

d. Interview with staff: We arranged a meeting with the University Student Counselling and Well-being Unit to learn what kind of PBL related challenges students approach them with. Here author Lyngdorf interviewed

two experienced counselling staff that prior to the meeting had looked into data on types of challenges and frequency. They also helped by going through the already formulated statements to validate their relevance. Both the Mathematics education students and the Student Counselling and Well-being Unit emphasized that the group formation phase caused stress and worry. The student led group formation phase is a central part of PBL in most cases, but this can also be challenging for students. We have no explanation as to why this was not seen in any of the studies reported in the literature review other than, in our understanding, there is very little research done about group formation in PBL. In total, this validated 31 statements but did not produce new ones. 16 out of the 31 were identified as particularly relevant to the study as these reflected experiences that they encountered more frequently.

Step 2. Q-sample construction

The inputs were collected into a large excel-file, initially consisting of a collection of the 49 suggested statements from various sources described above. These were discussed and each of the three authors "voted" on the ones that were considered most suitable and checked for redundancy. This was done to ensure inter-reliability. Some of the statements were subsequently rephrased. For example, this challenge from Chen et al. (2021): "*Difficulties for new members in integrating into friend-knowing teams*" were phrased into the statement "*Creating an inclusive environment for all team members*" to make it more understandable for participants. We ended up with 36 statements (see Table 1).

Step 3: Data collection (piloting)

We did a piloting Q-sorting session on 25 November 2024 with five students from the first semester of the bachelor programme: Surveying planning and land management. We asked a project group to volunteer, offering them a free lunch, for piloting the q-statements which in total took one hour. This was done by authors Lyngdorf and Dahl. The piloting was a semi-structured session with room for participants to comment on the research design. Using Q as a group task is not what is usually done in Q, where participants sit individually and fill out the grid. However, since this was a pilot, and we assumed that having this as a group task, we would be able to hear how the students discussed the statements. In cases of doubts about how to interpret the statements, their thoughts would be open, and we were also able to discuss with the group and get various opinions about how a statement could be misunderstood. However, this method suffers from a weakness as some statements asked the participants to, e.g., make a decision about building trust among group members, which can be hard to agree on, if the group had trust-issues. Ergo, some of these statements might have had a much different place in the grid, had students filled out the grid by themselves. In any case, this was a pilot, which main purpose was to check the clarity and relevance of the statements.

Alongside the Q statements, we also needed the Q sorting question. This is the overall question used by the students to rank the Q Statements. The Q sorting question is the following: *Based on your own experience, which of the following statements describe the most significant challenges in your study at Aalborg University*? The students then rank the statements in order of significance in a sorting grid ranging from less significant to most significant. In Figure 1 below, it is shown how the students sorted the statements.

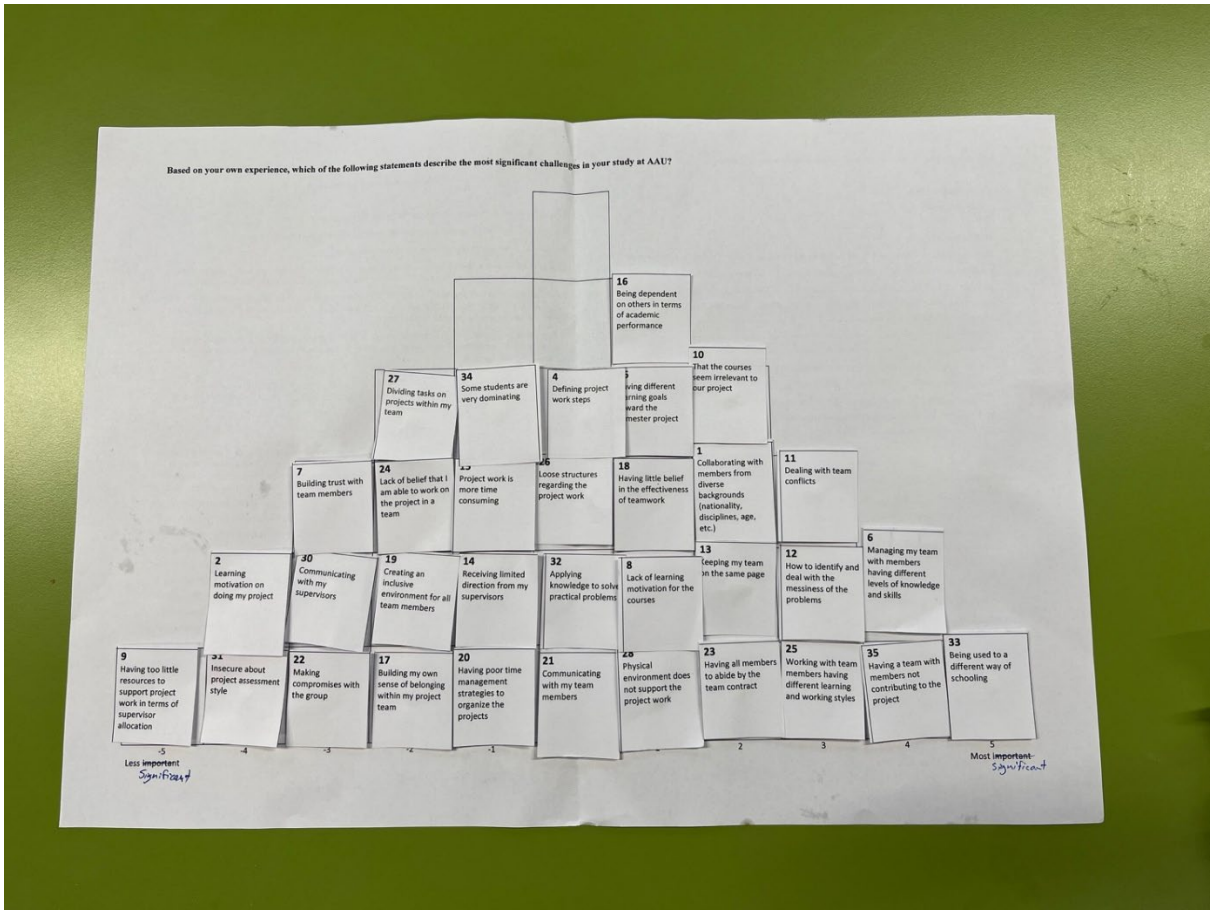

Figure 1: Student group's distribution of the Q statements

3 Results

3.1 The Q Statements

This section reports our Step 4 of Q piloting, as a result of the process described above, and the final Q set is presented in Table 1. Based on the piloting, several of the statements were adjusted to ensure better legibility and relevance to local practices. The results are shown in Table 1. As can be seen here, some statements were overlapping as several sources mentioned these. Also, two were from ourselves, for instance about the role of the physical group room, which some students have, others work in large office spaces. As examples, the statement "*How to identify and deal with the messiness of the problems"* was changed to *"How to identify and deal with the complexity of the problems".* In terms of relevance to local contexts, we found that three statements relating to group formation statements, e.g. *"Group formation is driven by social and not academic dynamics"* were not relevant, since our piloting participants were assigned in groups randomly by the study administration. As a result, which can be seen on Figure 1, these three statements were not placed on the grid. This points to the importance of adapting the Q-set to the local context and practices, which can differ even at the micro-level. As should be, PBL at AAU is not a one size fits all but rather implemented and adapted in a discipline and context specific way. Therefore, context responsiveness is important to consider, when using the tool across different contexts. In our piloting session we found that statement no. 3, 5, 29, are highly context dependent. The piloting also led to the formulation of three additional statements. These are *"Working in smaller teams isolates me from the rest of the course participants"; "Uneven motivation*

among team members"; "Loss of ownership feeling of the project when working in teams". These perspectives emerged through discussions with the group about missing statements.

Unlike in the design of a questionnaire, which is theory-driven, the process described above is rather a data-driven sampling task (Watts & Stenner, 2005) with the aim of generating a set of statements describing the most common pedagogically challenging elements of PBL. A Q set is typically around 40 statements as this is enough to capture diverse perspectives. Our concourse process resulted in 39 statements, which falls within the accepted range (Watts & Stenner, 2012).

*Table 1. The Q-set. The origin of a statement is indicated as follows: L: Literature, R: Researchers/Experts, S: Mathematics Education students, U: Student Counselling and Well-being unit, X: Piloting results, * = Context sensitive statements,* ***In bold = changed/new statements***

No.	Original statement + reference for literature	Source	Final statement
1	Collaborating with members from diverse backgrounds (nationality, disciplines, age, etc.) (Jiang et al., 2023)	LSU	**Collaborating with members from diverse backgrounds**
2	Learning motivation on doing my project (Lyngdorf, Du & Lundberg, 2023)	LU	Learning motivation on doing my project
3	Students not being included during group formation (Bundgaard et al., 2021)	L	Students not being included during group formation*
4	Defining project work steps (Chen et al., 2021; Savery, 2015)	L	Defining project work steps
5	Group formation is driven by social and not academic dynamics	SU	Group formation is driven by social and not academic dynamics*
6	Managing my team with members having different levels of knowledge and skills	S	Managing my team with members having different levels of knowledge and skills
7	Building trust with team members (Jiang et al., 2023)	SRLU	Building trust with team members
8	Lack of learning motivation for the courses (Lyngdorf, Du & Lundberg, 2023)	LS	Lack of learning motivation for the courses
9	Having too little resources to support project work in terms of supervisor allocation	R	Having too little resources to support project work in terms of supervisor allocation
10	That the courses seem irrelevant to our project	R(S)	That the courses seem irrelevant to our project
11	Dealing with team conflicts (Jiang et al., 2023)	LU	Dealing with team conflicts
12	How to identify and deal with the messiness of the problems (Chen et al., 2023; Savery, 2015)	L	**How to identify and deal with the complexity of the problems**
13	Keeping my team on the same page	U	Keeping my team on the same page
14	Receiving limited direction from my supervisors	R	**Receiving broad or ambiguous supervision to encourage independent problem-solving.**

15	Project work is more time consuming (Chen et al., 2021)	LU	**Project work demands a significant amount of time**
16	Being dependent on others in terms of academic performance	S(R)	Being dependent on others in terms of academic performance
17	Building my own sense of belonging within my project team (Jiang et al., 2023)	RLU	Building my own sense of belonging within my project team
18	Having little belief in the effectiveness of teamwork	U	Having little belief in the effectiveness of teamwork
19	Creating an inclusive environment for all team members (Jiang et al., 2023)	LSU	Creating an inclusive environment for all team members
20	Having poor time management strategies to organize the projects	S	Having poor time management strategies to organize the projects
21	Communicating with my team members	U	Communicating with my team members
22	Making compromises with the group	S	Making compromises with the group
23	Having all members to abide by the team contract	RU	Having all members to abide by the team contract
24	Lack of belief that I am able to work on the project in a team	SU	Lack of belief that I am able to work on the project in a team
25	Working with team members having different learning and working styles (Jiang et al., 2023)	LS	Working with team members having different learning and working styles
26	Loose structures regarding the project work	(S)	Loose structures regarding the project work
27	Dividing tasks on projects within my team (Du et al., 2009)	L	Dividing tasks on projects within my team
28	Physical environment does not support the project work	R	Physical environment does not support the project work
29	Lack of facilitation of group formation (Bundgaard et al., 2021)	LSU	Lack of facilitation of group formation*
30	Communicating with my supervisors (Du et al., 2009)	L	Communicating with my supervisors
31	Insecure about project assessment style (Chen et al., 2021)	LR	**Insecure about project group exam style**
32	Applying knowledge to solve practical problems	U	Applying knowledge to solve practical problems
33	Being used to a different way of schooling	R	Being used to a different way of schooling
34	Some students are very dominating	S	Some students are very dominating
35	Having a team with members not contributing to the project	LRS	Having a team with members not contributing to the project
36	Having different learning goals toward the semester project (Lyngdorf et al., 2023)	L	Having different learning goals toward the semester project

Newly added statements			
37		X	**Working in project teams isolate me from the rest of the course participants**
38		X	**Uneven motivation among team members**
39		X	**Loss of ownership feeling of the project when working in teams**

3.2 Some conclusions based on the piloting

Since this was a pilot of our Q design, done as a group sorting, and not an individual sorting, we did not do any statistics on it. In addition, this would also have required more Q sortings.

Even though we cannot do statistics on how they sorted the statement, we found it interesting to discuss which six statements (2 times 3) the student group had placed at the two extreme ends of the grid. The ones placed as “least significant”, ergo pedagogical challenges that caused the least concerns were the following: "Having too little resources to support project work in terms of supervisor allocation”, “Learning motivation on doing my project”, and “Insecure about project assessment style”. It appears that they had adequate supervisor resources, are motivated to do their project, and are not insecure about the exam format in PBL. The two first statements are heavily influenced by not only the semester design and university allocation of resources, but the actual project the students are doing and the specific supervisor. The three statements the students indicated as “most significant” were the following: “Being used to a different way of schooling”, “Having a team with members not contributing to the project”, and “Managing my team with members having different levels of knowledge and skills”. It is unsurprising that students need to get used to a PBL learning environment, but that it is the “most significant” is still surprising, given the quite positive statements in the opposite end. One may speculate that the group may have had a hard start but nevertheless managed to formulate a project everyone was happy with. Perhaps with help from a supervisor. To what extent the two other statements are related, hence some students may not contribute due to lack of knowledge, is uncertain, but it could also be a general experience. These findings are mostly speculative since a Q sorting should be done individually and with enough sortings to achieve saturation. Furthermore, this piloting led to several reflections for us and in the end changes in several statements as described in this paper.

We expect the outcome of this study to contribute to develop PBL practices locally but also give recommendations and inspiration beyond. Learning is not supposed to be without challenges or difficulties, but students must not be left struggling without direction. The art is to scaffold learning at a balance where students are challenged but not lost and overwhelmed. This balance has been a central focus of educational research. Vygotsky (1978) developed the concept of the Z*one of Proximal Learning*, describing the limits of what a learner is capable of individually and what is achievable with a more knowledgeable peer. Similarly, Bjork and Bjork (2011) introduced the notion of *desirable difficulties* in learning reflecting that learning might not be intuitive and that making learning processes harder in the short term might lead to deeper understanding and retention over time. These difficulties can be regarded as desirable because they force the learner to engage more with material and processes. Having such research in mind, it will be of interest to explore what kind of challenges students perceive as unsurmountable and therefore destructive for learning at a given time of their studies in a PBL environment and what we as educators can do to better scaffold and support students in these aspects. A Q study might not be able to give all the answers to this but combined with qualitative methodology, such as individual and group interviews, and observations during a semester, we hope to find enough evidence to get a better understanding of students struggles with PBL pedagogy. In the end, this could create awareness among educators about specific PBL pedagogy related challenges, e.g. in FYE, where we need to design stronger scaffolding and student support in PBL

environments. This might also necessitate professional development among educators in certain areas of PBL pedagogy that shows to be especially challenging if not scaffolded sufficiently.

4 Next steps and Summary

The final Q statements will be used for approximately 50 first-year students in Energy and Engineering Science programme in the autumn semester of 2025. 50 participants are sufficient to ensure a diverse sample and achieve saturation, meaning that no new perspectives would emerge from additional participants. The Q study methodology also involves a more open inquiry step, where students can describe challenges that were not included in the statements.

The process outlined in this paper involved various experts such as students, and academic and technical staff as well as building on previous research. We are anticipating that by learning more about, which are the most prevailing PBL pedagogical challenges for FYE students, remedies can be made. We expect that the result of the development of the Q study will both inspire others to try this particular methodology but also that discussing it with colleagues would help us further validate the study. Finally, we expect that the results of the study will contribute with essential information to be used in improving PBL practices and in addition be inspirational for other institutions that have implemented PBL or are considering doing so.

We wish to thank the students, colleagues and academic staff at AAU who took the time to help us develop the Q statements.

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The Complementary Nature of Computational Thinking and Critical Making in a Project-based Learning (PjBL) course on Design for Manufacture (DfM)

Francesco Ciriello*, Tabbi Wilberforce Awotwe, Jicheng Gong,
Samuel Piper, Charlotte Palmer, Ana Rubio Denniss
King's College London, United Kingdom, *francesco.ciriello@kcl.ac.uk

Abstract

In Engineering Project-based Learning (PjBL), learners often develop a physical prototype of a product, which provides an authentic context for the learning and experiential feedback on the design process. We often struggle as educators, however, to support learners in the analysis of the feasibility, viability and sustainability of the product when brought to production. This may be caused by the everchanging nature of supply chains and consumer demand, high capital costs associated to high production volumes, and the technical skills shortage within research-focused universities when considering how to scale commercial products for wide consumption.

In developing a new PjBL course at King's College London, we study how learners develop competencies for integrated problem solving associated to design for manufacture (DfM). Acknowledging the steep learning curve required to support open-ended projects, we have intentionally pushed the boundaries of how the design process is supported by computational thinking techniques, including automated quoting engines and embodied carbon estimators, generative design techniques, geometric design advice, AI-assisted digital product passport generation, manufacturing simulation and automated operation and toolpath planning. We study how these teaching innovations compound to shape the ability of a student to critically change the geometry of a component in response to multi-variate performance metrics. To this end, we compare the geometric features of more than 60 CAD models submitted by learners in the second week of the course, compared to the final product submitted after 12 weeks at the end of the course. We link this analysis to a thematic analysis of short reports that highlight key trade-offs for cost, sustainability and other performance metrics.

This methodology allows us to evaluate our cohort's decision-making process in selecting projects, computational techniques, and manufacturing strategies. The analysis reveals a strong yet nuanced relationship between the adoption and application of computational redesign tools and the quality and manufacturability of product designs. It also allows us to categorise various cognitive responses to the application of computational techniques in relation to DfM and relate these to outcomes.

Keywords: project-based learning, engineering design, manufacturing, computational thinking, critical making

Submission Category: Research Paper

Conference Community: IRSPBL

1. Introduction

In 2024, we introduced a new PjBL course at King's Engineering to develop our students' capability to manufacture physical projects and commercialise them into products. The course was framed around the principles of *computational design for manufacture* – the practice of redesigning an engineering component using computational techniques to improve its manufacturability and its commercial viability for high-production volumes.

DfM principles have been articulated in industry since the 1960s and further formulated into researched practices via seminal work that stemmed out of Amherst in the 1980s (Boothroyd 1996, Kuo & Zhang 1995). These principles became quickly embedded into design software, initially in the form of inspection and design advice tools. Many commercial software tools now connect DfM principles with computational design techniques, whereby a designer can define performance objectives for a component, *e.g.* to minimise mass for a prescribed structural load case, and the design tools can optimise its shape while considering the geometrical constraints of the manufacturing process, *e.g.* manufacturing-aware topology optimisation or generative design.

These tools enable the application of the four cornerstones of *computational thinking* (Seymour 1980): (i) the *abstraction* of the design into critical operation scenarios, (ii) the *decomposition* of its geometry into primitive features critical to assembly and function, (iii) the identification of geometric *patterns* that drive manufacturability and costs, and (iv) the *algorithmic* exploration of the design space in which a computer-aided design (CAD) model is setup for optimisation.

Critical making is an emerging topic that connects DfM to *critical thinking* pedagogical practices (Ratto 2009, Custer 2023). It involves reflective discourse that is contiguous with the experience of physical making. In our course, critical making was enacted via forming mixed study groups of academics, technician and students who regularly met to review each other's designs.

In this work, we evaluate the project journeys and outcomes of this course via these two lenses of computational thinking and critical making. We set out to study the cognitive reaction of learners during their epistemological development of critical making skills. The originality of this work lies in connecting this changing cognition to the evolution of the component geometry, and how this is shaped by computational and DfM principles.

In this practice paper, we present our learning design (§2), teaching setup, including innovations (§3), evaluation methodology (§4), analysis of results (§5) and conclude in §6.

2. Learning Design using Storytelling – the Character Arch of the Designer & the Tensions of Computational Design, Manufacturing & Commercialisation

Learners were tasked with redesigning a single-material component for manufacture over 12 weeks. They could select the component based on their interests and were required to use at least one form of computational design technique to redesign it for manufacture, for which they were trained on generative design (via a mandatory workshop), topology optimisation and field-driven computational latticing (via an optional workshop). They were also required to detail its manufacturing strategy for a high production volume (100,000 units per year) by designing the component, tooling and toolpath program required to make the part, while analysing the trade-offs between cost, performance and sustainability metrics. If they lacked agency to select the component, they could select a component for a bicycle (*e.g.* crank, pedal or fork), for which we provided a starting CAD model.

The course was intentionally designed with a plot, centred around the designer and his ability to overcome the project challenge. The designer would initially use computational techniques to improve the performance of an existing component. This would immediately create a tension between the geometry generated by optimisation algorithms and the manufacturability of the part. The remaining arch of the course would involve the continuous redesign of the component and its manufacturing strategy as the learner would develop skills related to DfM and receive physical feedback from making activities.

Learning was scaffolded with a series of experiential CAD and CAM workshops and manufacturing sessions on plastic and mould design, multi-axis milling and turning, additive manufacture, design for sustainability and sheet metal design. The projects were reviewed at four stages, with reviews targeting the component (week 3), tooling (week 5), toolpath program (week 7) and final product (week 9), respectively. We collected CAD models for evaluation in week 2 and for the final submission in week 12.

3. Teaching Innovations in Support of Rapid Design Space Exploration

A key instructional challenge laid in the open-endedness of projects relative to the technical skills requirements imposed by completely detailing a manufacturing strategy. We worked hard to weave computational thinking and critical making techniques to accelerate design iterations and link them to multi-criteria performance, including automated quoting engines and embodied carbon estimators, generative design techniques, geometric design advice, AI-assisted digital product passport generation, manufacturing simulation and automated operation and toolpath planning. While investigating the role of each innovation is out of scope of this treatment, we were keen to understand how these innovations compounded to change the cognition of learners relative to the manufacturability and viability of their projects.

4. Methodology

To this end, we structured an evaluation framework alongside the course design to address the following **research questions:**

- **RQ1.** how did learners leverage computational thinking to redesign their components?
- **RQ2.** how did learners enact critical making reviews to redesign their components and what impact does this have on the geometry of the CAD model?
- **RQ3.** how did learners inform their redesigns from investigating additional trade-offs, such as sustainability, cost, and feasibility for commercial production scale?

Evaluation was conducted in two ways, via: (i) the ethnographic participation of the teaching team in design reviews 4x2hr, (ii) a 2hr focus group with the teaching team, in which the team reviewed CAD models from weeks 2 and 12 and deduced tags for the thematic analysis (see §5) and (iii) asynchronous review of portfolio submissions to enhance the data set for RQ3. The teaching team was composed of subject-matter experts in design and manufacturing (namely the authors), including three members of academic staff and three manufacturing technicians. Sixty-four learners were enrolled in the course from the third-year cohorts of the General (67%) & Electronic (30%) Engineering Programs and from the Robotics MSc (3%), who each submitted an individual design portfolio and participated in the design reviews.

5. Thematic Analysis of CAD Models & Reports via Subject-Matter Expert Review

Herein, we analyse student project submissions, composed of CAD models and portfolios, to study how learners engaged with computational tools and critical making practices in redesigning components for manufacturability.

5.1 Component Selection and Rescoping

Learners exhibited diverse preferences in component selection, with 31% (20/64) opting for a bicycle component—the default choice provided by the teaching team—while 27% (17/64) selected consumer products such as golf clubs, carabiners, and pill bottles. A further 31% (20/64) chose mechanical components embedded within larger assemblies, such as wheel rims, piston rods, or robotic brackets.

Notably, 33% (21/64) of students altered their component selection between weeks 2 and 12. While it is difficult to directly correlate these changes to intended learning outcomes, this shift suggests that some students reassessed the suitability of computational techniques for their initial selections. However, students who persevered with their original component choice achieved higher average portfolio marks (71.7%) compared to those who changed their selection (59.7%), indicating that continuity in project focus may have contributed to stronger design outcomes.

5.2 Adoption and Cognitive Reactions to Computational Tools

The thematic analysis revealed varied cognitive responses to computational methods as students developed critical making skills:

- some students rejected computational techniques outright and opted to change their project scope;
- others dismissed computationally generated design outcomes and manually redesigned their components;
- a subset of learners used computational outcomes as a guide for manual redesign;
- and some fully integrated computational methods into their redesign process.

Computational tool adoption increased over the duration of the course. While 53% (34/64) of students initially applied some form of computational design technique—predominantly generative design—this figure rose to 66% (42/64) by the end of the module, with a broader range of computational strategies employed.

5.3 Impact of Computational Approaches on Redesign Quality

To evaluate the relationship between redesign approaches and project outcomes, students' portfolio submissions were categorised into four performance bands: poor (<40), average (40–60), good (60–75), and great (>75).

- **Great redesigns (22%, 14/64):** Among the highest-performing projects, 93% (13/14) incorporated computational techniques. Nine students primarily utilised generative design with minimal manual modifications, while three traced computational outcomes to simplify designs while retaining structural performance. One outlier rejected computational methods entirely, achieving high performance through fully manual redesign.

- **Good redesigns (47%, 30/64):** Computational tool adoption declined slightly, with 63% (19/30) employing these techniques. Fewer students modified computationally generated geometries manually.
- **Average and Poor redesigns (31%, 20/64):** Computational tool adoption dropped further, with only 40% (8/20) applying any computational methods, and none attempting to refine generated geometries.

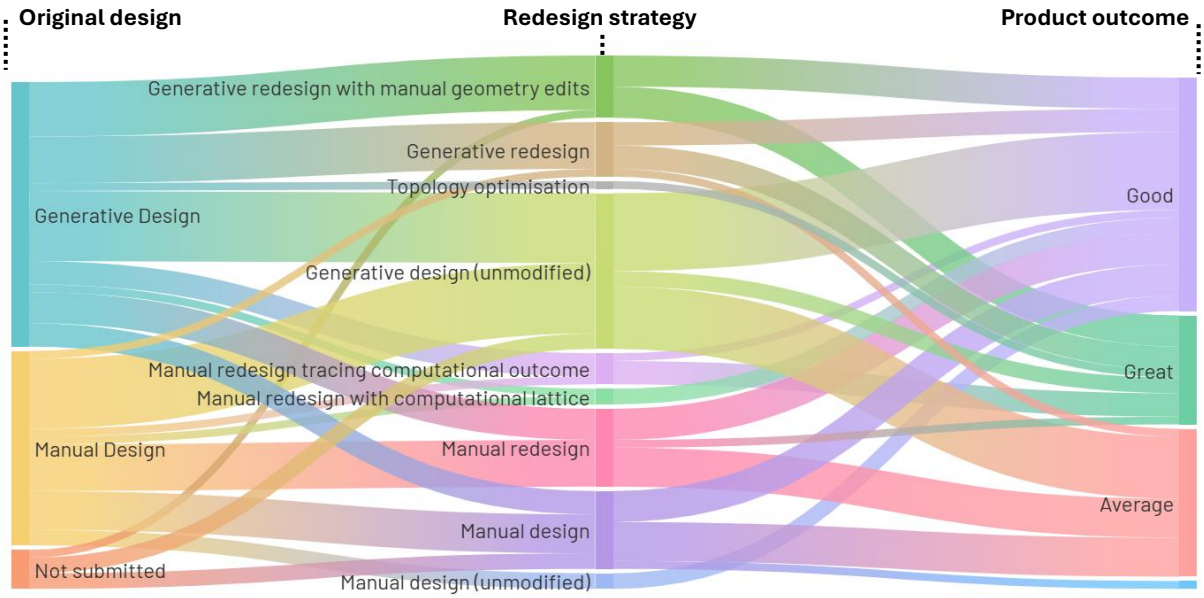

Figure 1: *shows a Sankey Diagram resulting from tags from the thematic analysis. It tracks how learners redesigned their original component, which had been generatively or manually designed, and how these were related to the quality of the final portfolio.*

5.4 Evolution of Manufacturing Strategies

The diversity of manufacturing strategies considered by students increased throughout the course. Initially, nine distinct strategies were explored, expanding to fourteen by the final submission (Figure 2a). A small subset (6%, 4/64) demonstrated self-directed learning by selecting manufacturing techniques not covered in formal instruction, indicating a level of independent inquiry.

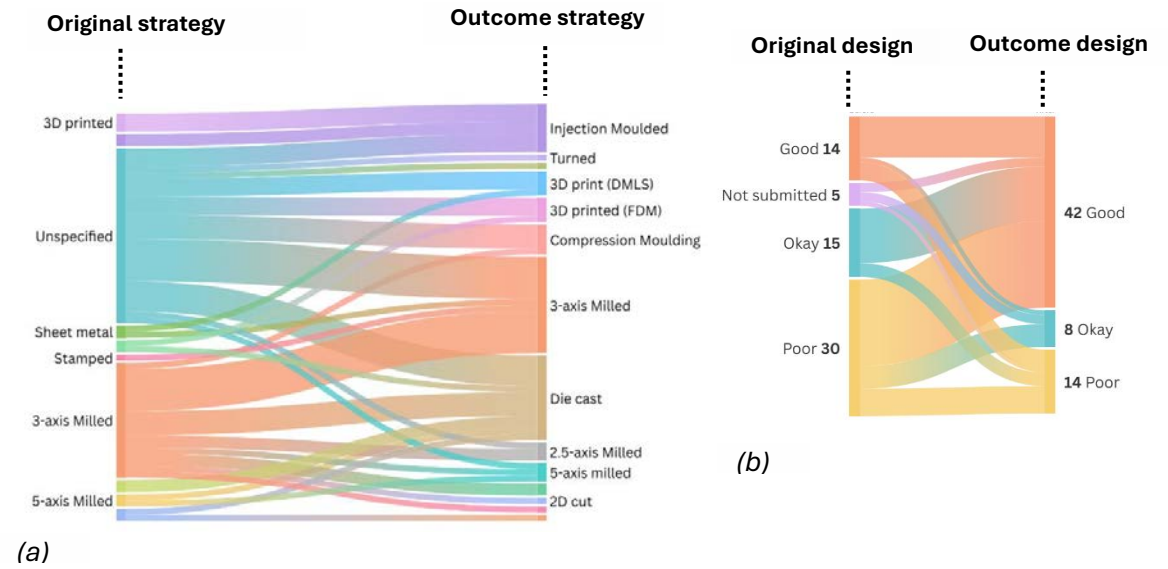

Figure 2: *shows Alluvial Diagrams that tracks how learners (a) re-selected their manufacturing strategy for the project, and (b) increased the manufacturability of their design.*

5.5 Design for Manufacturability and Sustainability

A substantial proportion (43/64, 67%) of students improved the manufacturability of their components, with many simplifying geometric complexities to enhance production feasibility (Figure 2b). However, a significant portion (8/64, 12.5%) worsened manufacturability, mostly due to a change in manufacturing strategy without adapting the geometry to suit.

While most learners engaged with design advice tools to align material selection and manufacturing strategies with embodied carbon considerations, there was no clear correlation between the use of computational redesign techniques and the ability to apply design for sustainability principles. This suggests that while computational tools facilitated manufacturability improvements, their integration into broader sustainability-driven decision-making remains an area for further pedagogical exploration.

6. Discussion

The integration of computational thinking and critical making in this course reveals a profound shift in how engineering students approach complex design challenges. Computational tools, such as generative design and topology optimisation, acted not merely as aids but as **enabling frameworks**, supporting students in exploring design spaces with unprecedented speed and depth while retaining the essential human elements of creativity and judgment. This duality is crucial: computational thinking, as Papert (1980) envisioned, amplifies cognitive capabilities but does not replace the need for deep domain expertise and intuitive problem-solving. The most successful student redesigns were those that combined algorithmic exploration with manual refinement, reflecting a sophisticated understanding of how to leverage computational outputs within the constraints of manufacturability. This hybrid approach is not just a practical strategy but a central **pedagogical intervention**, as it mirrors

industry practices where engineers must balance the creative potential of automation with the realities of production (Boothroyd, 1996).

Critical making, operationalised through collaborative reviews involving academics, technicians, and peers, emerged as a powerful mechanism for fostering adaptive problem-solving and epistemological flexibility. Students who engaged deeply with these reviews demonstrated resilience and a willingness to rescope their projects in response to new insights, even when initial choices proved unfeasible. This adaptive behaviour, while sometimes associated with lower marks, signals an important developmental stage in engineering education: the ability to reassess and pivot in light of new information. The variability in how students engaged with feedback highlights an opportunity to further structure reflective practices, particularly for those less confident in interpreting computational suggestions or articulating design rationales. This aligns with Ratto's (2009) argument that critical making bridges abstract problem-solving with tangible outcomes, grounding computational exploration in real-world constraints.

The evolution of manufacturing strategies over the 12-week period illustrates a growing awareness among students of the trade-offs inherent in production-scale design. However, the weak correlation between computational redesign and sustainability decisions points to a significant gap in current engineering education. While 67% of students improved manufacturability, sustainability considerations often took a backseat to immediate performance goals, such as structural integrity or cost reduction. This disconnect suggests that sustainability must be explicitly embedded into the design process, potentially through targeted prompts or tools that visualise environmental impacts alongside technical metrics. Similarly, the commercialization requirement, namely designing for 100,000 units annually, was frequently overshadowed by prototyping concerns, indicating a need for stronger connections to industry realities, such as supplier constraints or scalability simulations.

This study is not without limitations. The single-institution context may limit the generalisability of the findings, and the reliance on expert-led thematic analysis introduces potential bias. Future work could incorporate student self-reports to provide additional perspectives on the learning experience. While the narrative framework of the "designer's journey" offered a compelling structure for the course, its impact on learning outcomes was not quantitatively assessed. Exploring student perceptions of this storytelling approach could yield further insights into its efficacy as a pedagogical device.

Ultimately, this study demonstrates that the synergy between computational thinking and critical making can foster adaptive, industry-ready problem-solving skills. By refining how these elements are integrated, particularly in addressing sustainability and commercial viability, educators can better prepare students to navigate the multifaceted challenges of modern engineering design.

7. Conclusion

This study highlights the interplay between computational thinking and critical making in a project-based learning (PjBL) course on Design for Manufacture (DfM). Our analysis reveals that students who effectively leveraged computational tools achieved higher-quality redesigns, though manual refinement remained a key strategy for optimisation. While computational methods improved manufacturability and design outcomes, their adoption varied, with some learners rejecting or selectively integrating them. The increasing diversity of manufacturing strategies suggests a growing understanding of production trade-offs, yet the link between computational redesign and sustainability decision-making remains inconclusive. These findings underscore the importance of integrating computational tools with reflective design practices to enhance problem-solving skills in engineering education. Future work will explore targeted interventions to strengthen sustainability

considerations and refine the balance between automation and designer agency in engineering design curricula.

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Heatmapping Key Competencies STEM Students Present in PBL Environments

Euan D Lindsay
Aalborg University, Denmark, edl@plan.aau.dk

Giajenthiran Velmurugan
Aalborg University, Denmark, vel@plan.aau.dk

Stine Ejsing-Duun

Aalborg University, Denmark, sed@plan.aau.dk

Antonia B Scholkmann

Aalborg University, Denmark, ansc@ikl.aau.dk

Abstract

Aalborg University (AAU) uses Problem Based Learning (PBL) in which students develop professional competencies by engaging with authentic problems. All Engineering master students at AAU have had a PBL Competency profile as a compulsory exercise. The profiles are structured around the AAU PBL Competency Framework. This framework is comprised of 48 individual competencies, grouped into four categories; meta-reflective, problem-oriented, interpersonal, and structural. Students are free to choose which of these competencies they incorporate in their profile.

A total of 1095 PBL Competency profiles were reviewed across more than 50 STEM study programs, and each was evaluated for the presence or absence of each of the 48 competencies in the PBL competency framework. This study explores the relative prevalence of each competency within the profiles submitted by students, and the balance across the different categories. Further, it investigates the extent to which students made these competencies explicit, and evidence the competence.

The study reveals that the competencies are not equally represented in the competency profiles, with a subset of seven competencies comprising 40% of all reported competencies. The study further reveals that the students generally do not provide evidence to support their claims of competence.

Keywords: Active Learning, PBL, STEM, Key Competencies

1 Introduction

All degree programs at the Faculty of Engineering and Science (ENG) and The Technical Faculty of IT and Design (TECH) have included a PBL Competence Profile workshop in their 8th semester. At this workshop students engage in an active reflection process over which PBL competences they have developed and wish to communicate while searching for employment and/or internships (Velmurugan & Friedrichsen, 2023). These competences are captured in a PBL competency profile, which the students submit for feedback.

To assist students in their reflective process they are provided with the AAU PBL competency framework (Holgaard et al, 2020). This framework is a catalogue of different PBL competences divided in four areas: problem-oriented, interpersonal, structural, and metareflective competences (figure 1). Each of these areas have 12 competences embedded in them, and the students are encouraged to include competences from all areas in their profile. Students are also provided written guidance for preparing their competency profiles (Holgaard & Kolmos, 2021). Students are encouraged to consider the categories of competency in developing their profiles but are not formally required to present a profile that is balanced across the four categories. On average, students include between eight and nine of these competencies in their profile.

Analysing what competences students claim and how they do so may provide valuable insights for teachers and curriculum development: Knowing what competences students claim the most provides us with an improved understanding of their self-awareness and potentials for growth. On the other hand, knowing what they do not claim provides us with insights that may help suggest adjustments to the use of the AAU Competence Framework and the teaching itself. We are particularly interested in the relative prevalence of the different competencies (and competency categories), particularly whether there are any competencies that are universally reported, and if there are any that are universally overlooked by the students.

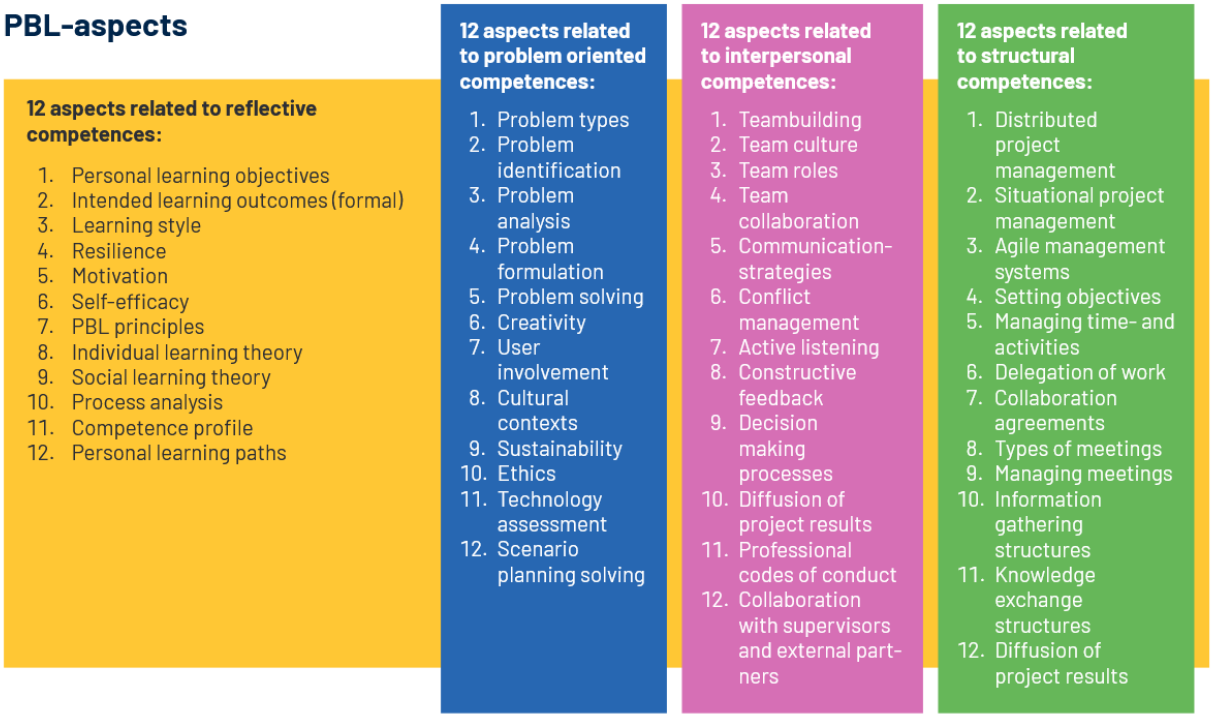

Figure 1: The PBL competency framework (Holgaard et al, 2020)

2 Theoretical underpinnings

Questions of which competences are being fostered through PBL have been discussed intensely over the years, and research for some time was focussed on demonstrating the advantages of PBL over more traditional lecture-based forms of learning (Albanese & Mitchell, 1993; Colliver, 2000;Dochy et al., 2003). This strand of research has highlighted the added value of PBL for competence development beyond mere knowledge acquisition. Subsequent studies have broken those down to communicative competences, problem-solving and teamwork, social and independent working competences (Cohen-Schotanus et al., 2008; Prince et al., 2005; Schmidt et al., 2006), however only for the domain of medical educations, and only for so-called case-based PBL, which is not the approach integrated into AAU's project-based PBL model (Kolmos et al., 2019). Moreover, recent years have shown a shift away from comparative and effectiveness-related studies and a heightened interest in understanding the interplay of PBL implementations and processes of competence development in specific domains, contexts and geographical areas with (Scholkmann, Boelt, et al., 2023; Yew & Goh, 2016).

With a more focussed view for the present study, a literature review within the engineering education context suggested that the most prevalent competences emphasized in the literature when describing PBL competences were teamwork, communication, problem-solving, navigating ambiguity, and self-directed learning (Boelt, Kolmos & Holgaard, 2022). In the review the PBL competences were clustered into four dimensions with distinct orientations towards problems, interpersonal relations, structural and managerial aspects, and meta-cognitive abilities (Boelt, Kolmos & Holgaard, 2022). These findings were used as a direct underpinning to our study, as the four dimensions are represented in the AAU Competence Framework (see Figure 1).

However, the present study must also be seen in the broader context of efforts to systematize PBL competences in frameworks and models. Here, concepts such as constructive alignment (Biggs, 1996); and theory and research on metacognitive and reflective skills development in open, active and problem based learning environments. Constructive alignment alerts us to the fact that learning outcomes – both knowledge and competence – are dependent on both the learning opportunities provided to the students and the modes of assessing these outcomes, as they signal the relevance and value of certain learning activities (Biggs & Tang, 2011; Brabrand & Dahl, 2009). Theory and research on learning in open, active and problem based learning environments has highlighted the intricate interplay between the elements of the PBL scenario, the learning processes unfolding and the resulting manifestations of competences. For example, it has been argued that a carefully crafted phase of problem-analysis and problem-formulation will enhance students' competencies to engage with complexity and uncertainty (Thomassen & Stentoft, 2020). Research on students' development of meta-cognitive competences – i.e., competences to analyse, reflect and design their learning processes – has shown that also in the Aalborg PBL model these competences not necessarily are acquired automatically (Scholkmann, Tretow-Fish, et al., 2023), but instead adjustment of educational practices will be needed to foster them (Holgaard et al., 2023). Students working with our competence framework can be seen as such an adjusted practice, and through this lens the present study enriches research on PBL competences with a facilitated approach that also focusses on reflective competences.

Previous studies on PBL competence development and comparison frequently have relied on self-reported competence gains, which have been shown to be limited in their robustness and validity (Khaled et al., 2014). Alternative measure such as essay-based, scenario-based and mixed method approaches have therefore been explored and recommended in recent years (Davis et al., 2023; Routhe et al., 2023; Scholkmann et al., 2018). By applying at methodology that combines self-report in form of reflective texts with a scaled coding, the present study expands PBL competence research in this direction.

3 Method

The dataset for this analysis is 1095 PBL competency profiles submitted in the Spring 2024 semester. Each of these profiles were evaluated by a marker, and the presence of each competency was rated on a four point scale, depending on whether the competence was explicit and evidenced (Table 1):

Table 1: Evaluation rubric for competencies

Rating	Implying
Absent (0):	This competency is not addressed in the assignment.
Implicit (1):	This competency is addressed in the assignment but is not explicitly named.
Asserted (2):	This competency is explicitly addressed and named within the assignment, but is only asserted, and is not supported by an example of previous experience.
Evidenced (3):	This competency is explicitly addressed within the assignment and is supported by an example from previous experience.

The resulting dataset has scores for each of the 48 competencies for each of the 1095 participants.

The key limitation of this study is that the competency profiles are ultimately self-reported data, and the choice of competencies to include is ultimately made by the students according to their own priorities. Students make decisions about which competences to include in their profiles, which are space limited to two pages. As such it is possible that students have also developed other competencies that were omitted from the profile in favour of competences that were seen to be more important, or were more preferred, or had better examples to include within the narrative. While this limitation may affect the ability to draw

conclusions regarding an individual student, the size of the dataset allows for conclusions to be draw in the aggregate.

A further potential limitation is the phrasing of competences within the AAU competence framework that has been interpreted differently by students and markers. Also, some students did not explicitly use the labels from the AAU Competence Framework when writing their competences profiles, therefore increasing the reliance on the interpretation of the marker in this analysis.

4 Finding one: Claims are clustered in a small subset of competencies

Across the 1095 PBL competency profiles there were a total of 9,444 instances in which a competency was evaluated as Asserted or evidenced. Combined these two categories were considered to represent the total number of competencies that were "claimed" by the students. These claims are displayed in Figure 2, which represents the proportion of all competency profiles in which each competency was claimed by students.

It is immediately apparent from Figure 2 that the competencies are not equally prevalent across the students' profiles. Four competencies each appear in more than half of all competency profiles, with a further three appearing in more than a third. These seven competencies alone represent 40.6% of all competency claims across the entire dataset.

Furthermore, the distribution of the areas is skewed so that reflected competences (shown in yellow) are extraordinarily little claimed, whereas the problem-oriented competences are heavy in the top. Most of the interpersonal competences are loaded in the high end of the occurrence. The structural competences are more evenly distributed but not often chosen except for *Managing time and activities*.

These most prevalent competencies represent the classic PBL story: *Problem solving, Management of time and activities, Problem identification, Team collaboration, Problem analysis, Conflict management* and *Collaboration with external partners.* These competencies are a key part of the intended graduate attributes of AAU; moreover, these are the competencies that are tacitly reinforced throughout the recurring projects in the curriculum as these are required activities throughout. Conversely, there also are specific competencies that are emphasised within the curriculum and the vision of the institution but nonetheless are not prevalent within the dataset. *Ethics* in particular was only claimed 8.4% of students as a competency in their profile.

The imbalance between the four categories of competencies becomes even clearer when considered in the aggregate (Figure 3). While *Problem Related competencies* and *Interpersonal competencies* each represent around a third of all claims, *Structural competencies* and *Reflective competencies* are under-represented in the students' reports. While students are prompted to be balanced in their profiles, it is clear that not all of the categories are equally prevalent in their responses.

The PBL competency framework represents a wide range of skills that can be developed within the PBL environment. What is clear from the data is that when prompted to reflect and report on their competencies within this framework, the students are focussed on only a small subset of these competencies. Their focus lies mostly with the competencies that relate to the problems they are solving, and on the interpersonal competencies they need in their teamwork environment. Reflective competencies are for the most part not emphasised by the students in the dataset.

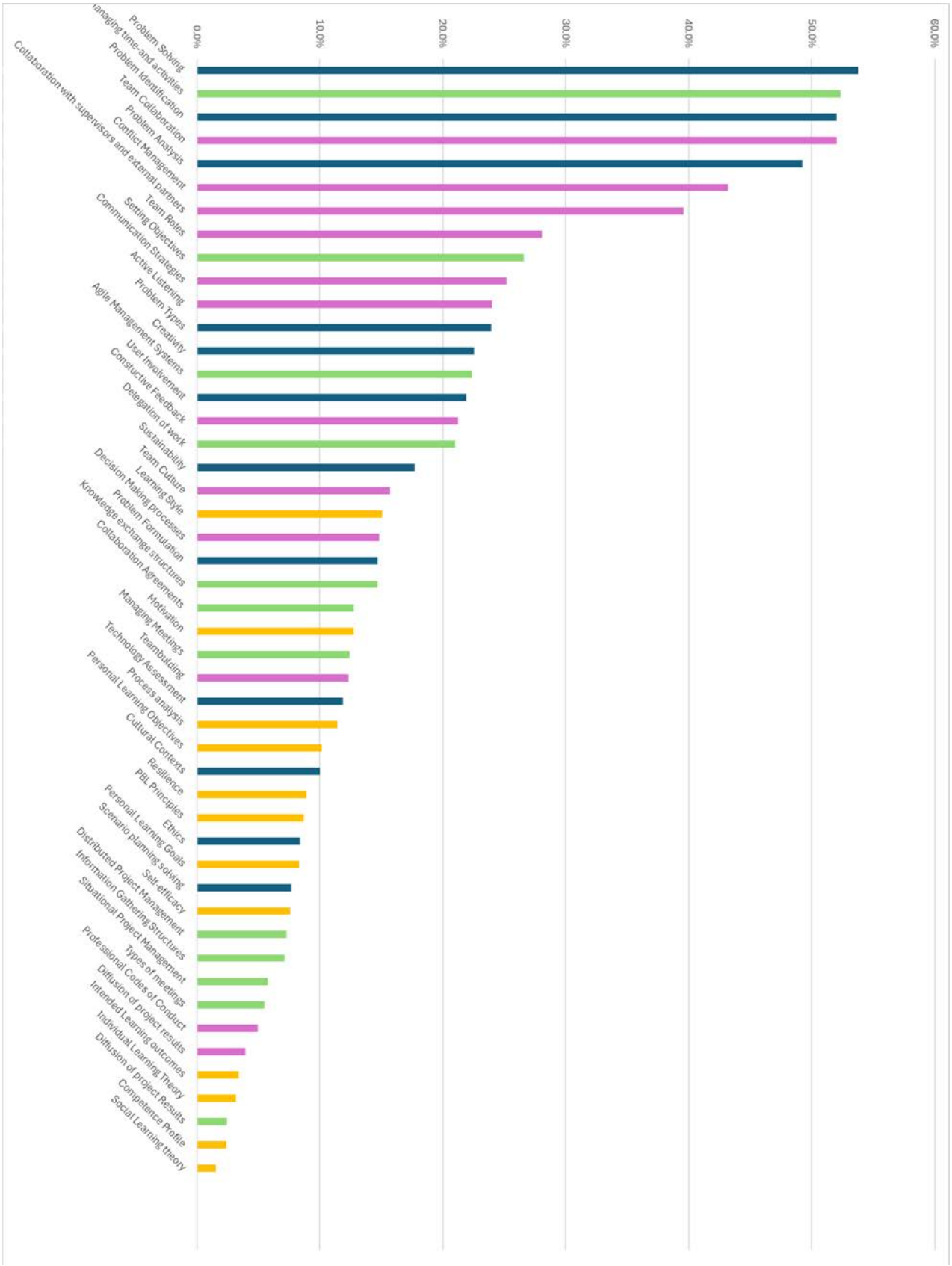

Figure 2: Competencies claimed by the students, sorted by prevalence

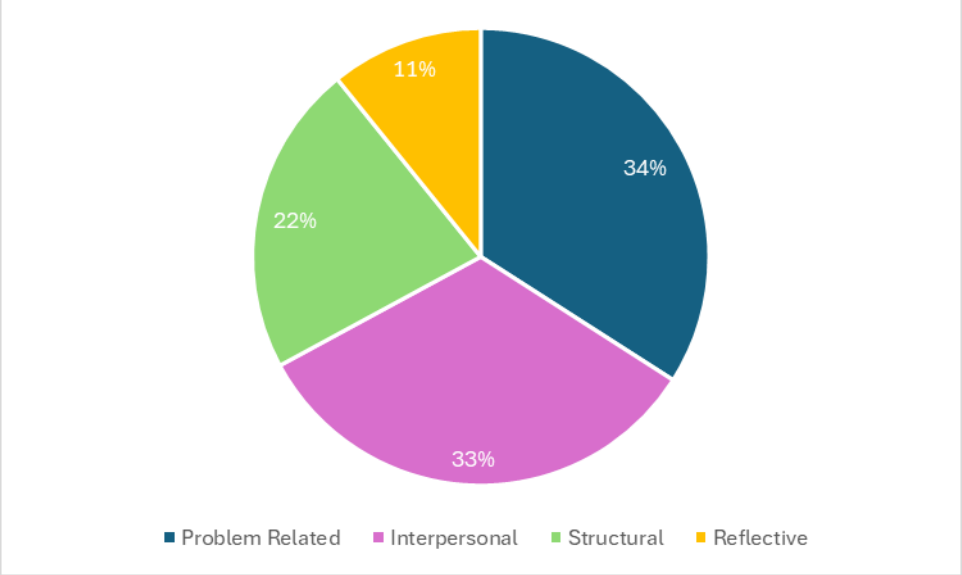

Figure 3: Relative prevalence of competencies claimed by the students, by category

5 Finding Two: Students do not support their claims with evidence

Students are instructed to provide evidence to support their competency claims within their PBL competency profile. Despite this instruction, however, only around a third (3501/9444) (37.1%) of competency claims were evaluated as evidenced by the markers (figure 4):

Figure 4 shows which competences are evidenced most. It confirms the same structure as Figure 2, with the same seven competencies appearing the most often, albeit with the rank ordering within that subset changed. Students were most likely to provide evidence regarding *Managing time and activities*, followed by *Problem solving*. The overall trend of reflective competences not being addressed continues also in this analysis.

The re-ordering between figures 2 and 4 is indicative of a difference in the proportion of competency claims that are evidenced by the students. Indeed, there is significant variation in the relative proportions between asserted and evidenced claims across the 48 competencies (figure 5):

Figure 5 shows that the competence least like to be evidenced is *Individual learning theory* (14.3%) while the most likely to be evidence is *Agile Management Systems* (64.7%). For the most commonly appearing seven competencies, the proportions for which evidence is provided range from 34% to 48%.

Functionally, the data in figure 5 suggest that students only actually provide evidence around a third of the time when claiming to have developed a particular competence, while asserting their competence without evidence the remaining two thirds.

It is not immediately clear from the data why there is such variation in the proportion of competence claims for which evidence is provided, nor why these rates are overall so low. However, a first hypothesis could be that not all competences are equally easy to support with evidence, and not all evidence fits neatly within the page limit of a PBL competency profile. That competences such as 'Agile Management Systems' and 'User involvement' move up in comparison with Figure 2 strengthen this hypothesis since these are very tangible and method-oriented competences which have been taught as opposed to the four least-evidenced competences that all relate to learning awareness. Whether the cause of this low rates of evidence is because students cannot, will not or do not include evidence in their profiles requires further investigation.

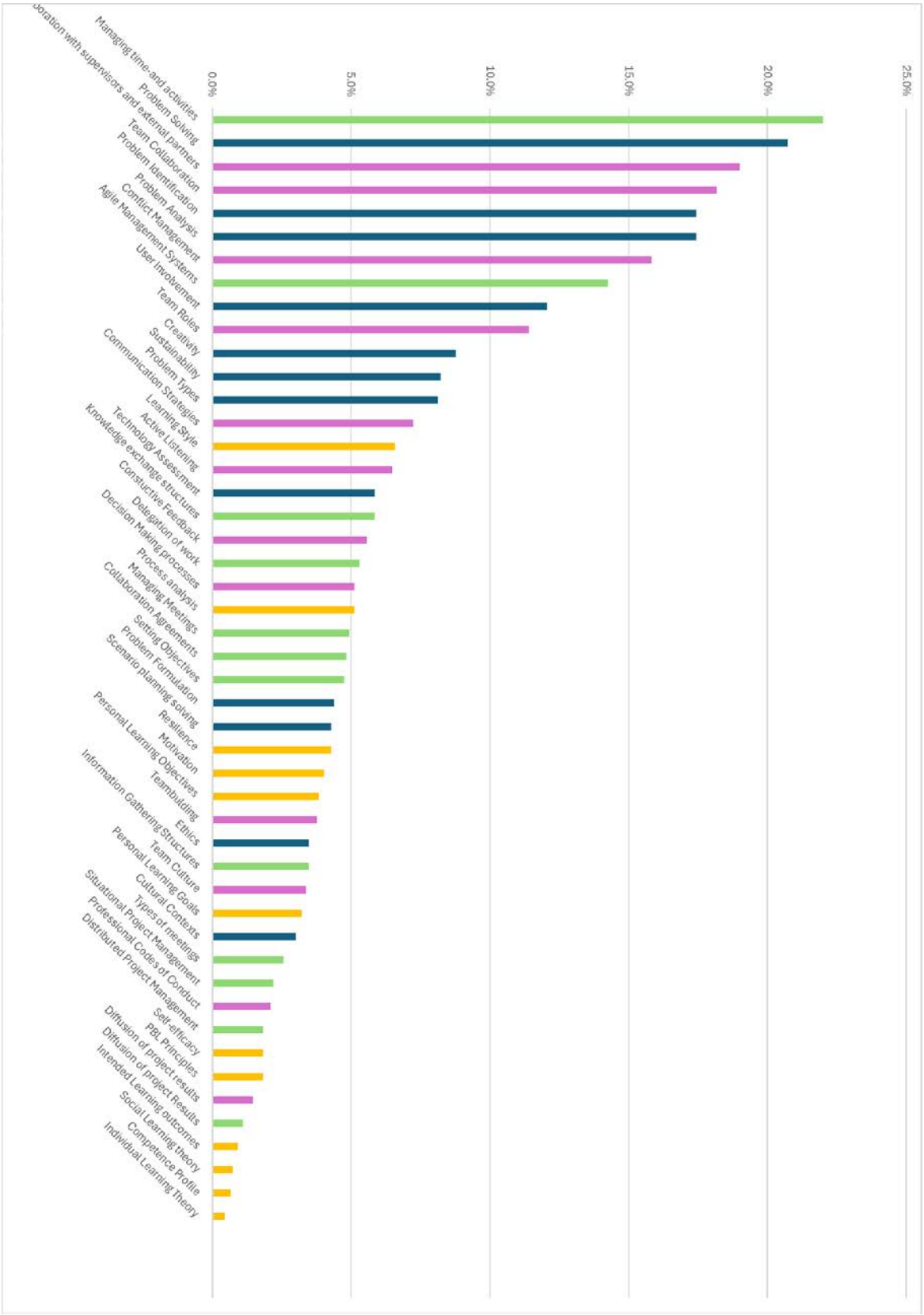

Figure 4: Competencies evidenced by the students, sorted by prevalence

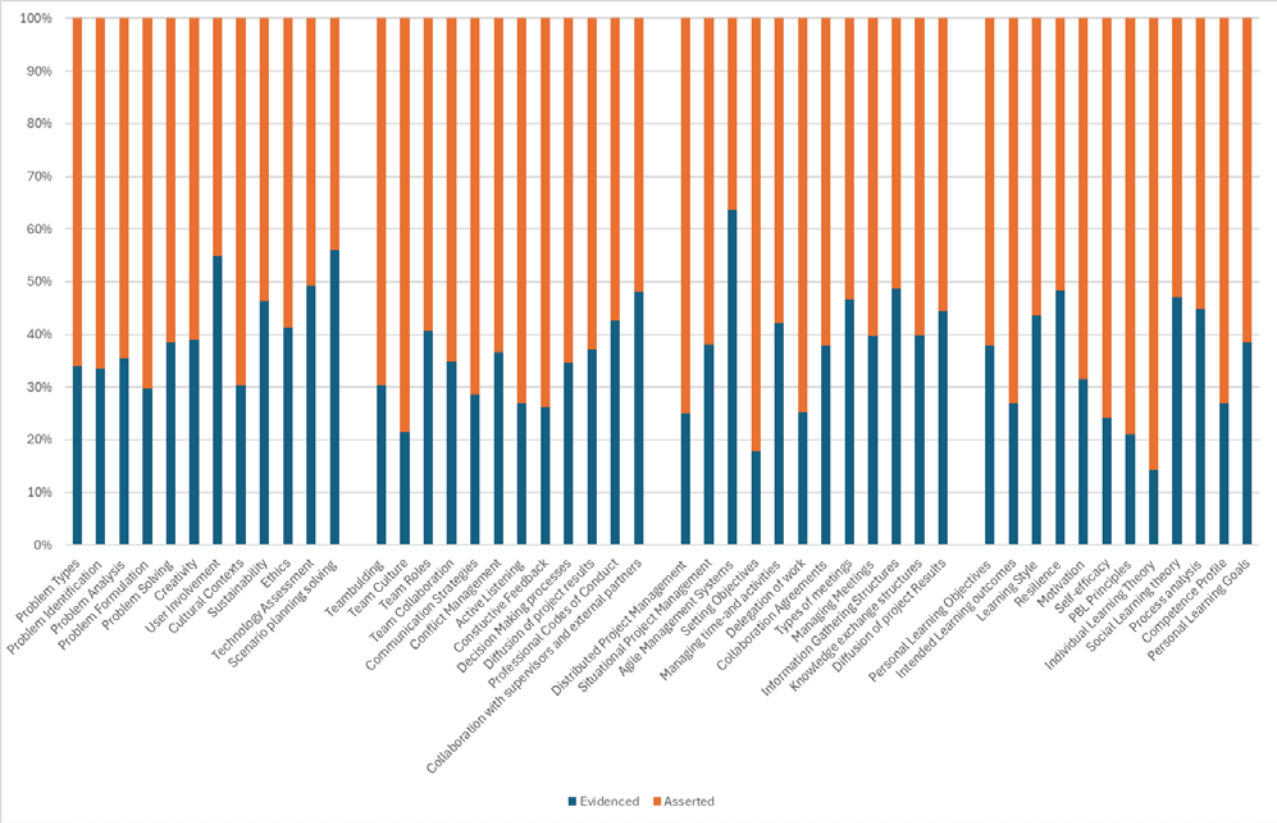

Figure 5: Proportions of asserted and evidenced competencies, grouped by category

6 Conclusion

PBL is a pedagogical approach that supports the development of a wide range of technical and professional competencies. When asked to reflect and report on their development of their competencies, however, students tended to focus upon a small subset of these competencies – those that most closely align with the overarching theme of team-based project work.

Reflective competencies in particular are not well represented in the competency profiles of the students. The lack of reflective competence further manifests when it comes to students evidencing their claims of competence. Only around a third of all competency claims presented by students are actually supported with evidence, with the majority comprising simply assertions of competence.

These results must be considered through the lens of a single, space-constrained self-reporting of competencies. While we cannot generalise from any particular students' profile, we can generalise from the aggregation of 1000+ profiles. The profiles are, in part, a reflection of how students engage with the overall curriculum, and of what they perceive as being the most important parts of that curriculum.

Overall, this analysis suggests that students are not claiming the full range of PBL competencies targeted by the PBL competency framework. Students clearly appreciate the competencies in the tacit curriculum, but are not embracing the broader curriculum. These insights will support the development of teaching approaches targeting these competencies within the curriculum as well as continued development of the PBL competency framework itself.

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Defining the Supporting Roles of Facilitators in Project-Based and Work-Based Learning

Cody Mann

Minnesota State University, Mankato, USA, cody.mann.2@mnsu.edu

Darcie Christensen

Minnesota State University, Mankato, USA, darcie.christensen@mnsu.edu

Abstract:

It is well known that staff roles are critical in higher education. A university in the Midwest region of the United States of America offers unique student-facing support through a work-based learning program by coaching students who learn on the job while working for companies throughout the final four semesters of their undergraduate degree. Prior to the final four semesters of working on the job, students are also supported through a preparation project-based semester. The support staff in this program are referred to as facilitators. This paper aims to address the critical roles of facilitators as they directly pertain to project-based and work-based learning. The unique work-based learning model covered in this paper implements project-based learning in a way that isn't found anywhere else in academia, and it continues to be a successful model of education. The following two questions will be explored: How are facilitators engaging in each of their job description roles? How do facilitators perceive and describe each of their job description roles? This paper will broadly define each role of a facilitator by including an analysis of qualitative reflections by a professor and a director in this work-based program. It will also include quantitative data that discusses the facilitator's self-reported median and average values of time spent in each of the roles. This will result in recommendations to other higher education programs to begin creating facilitator positions that add value to other project-based learning models.

Keywords: Facilitators, work-based learning, project-based learning, higher education, and student support.

1 The Motivation Behind and Background of Iron Range Engineering

Iron Range Engineering (IRE) started as a unique project-based model in a rural part of the upper Midwest in the United States of America in 2009 (Ulseth, 2019). After nearly 10 years of operation, IRE transformed from a project-based model into a work-based learning model. Instead of bringing engineering projects from various industries to the classroom, students began going to the various industries to work on full-time engineering jobs to work on projects in an authentic environment for the final two years of their education (Johnson et al., 2018). While project-based learning is still high-value, work-based learning adds an element to project-based learning as students are situated within an actual practice setting while applying the knowledge gained alongside practicing professionals who assist in the learning process (Mann et al., 2021). The transition to work-based learning freed up physical space on campus that was once approaching a limit at this rural institution. Instead of spending four semesters onsite at a rural institution's campus, students now spend one semester onsite developing skill sets that help them thrive in their classroom-to-workplace transitions (Christensen et al., 2023). They then transition to positions across the country while continuing their education in the evenings. This meant that not only could the IRE program serve more students from the local area, but it could also serve students from various parts of the country and world who have the autonomy to choose their location for the final two years of their education.

Around the time of the transition to the work-based learning model, IRE created a facilitator position. One of the motivators behind IRE's creation of the facilitation position was to provide assistance in increasing student enrollment with a national outreach in the United States of America. Along with the focus on enrollment came the need for additional guidance in the students' job search process and mentorship while they were transitioning from the classroom to the workplace (Fifolt & Searby, 2010; Van den Bogaard & Strobel, 2023). They needed a liaison between their academic studies and work experiences, which was difficult for Ph.D.-holding professors to deliver on their own in addition to traditional responsibilities. The students also needed continuing support in their design and professional growth as they prepared for and participated in engineering positions. Facilitators possess bachelor's and/or master's degrees in an engineering field of study, and most have industry experience of their own to provide valuable expertise when coaching students. Because of these qualifications and the evolving needs of the work-based program, the facilitator role evolved to include six main roles: Career Development, Instruction, Learning Coach, Recruiting, Student Life, and Other. At this point, there has not been any extensive research done on facilitators, but now that the work-based program has been in existence for six years and has graduated six cohorts of students, lessons learned need to be shared. There is also very little existing literature on Facilitators, as this position does not exist anywhere else in higher education. This paper helps to provide insight into the various roles of a facilitator in a higher education work-based engineering program. This will be done based on the facilitators' perceived contributions and experiences, as self-reported.

2 Methods

The two research questions for this study come from a mixed-methods approach, as the first question relates to both quantitative and qualitative research, and the second question is qualitative.

RQ1 - How are facilitators engaging in each of their job description roles?

RQ2 - How do facilitators perceive and describe each of their job description roles?

A series of six surveys was created to capture data within each of the six primary roles of a facilitator. The surveys were administered via Qualtrics. The Minnesota State University, Mankato Institutional Review Board (IRB) approved all data-gathering procedures for this study. There were 12 participants invited to be a part of the study. The chosen study group represented the entire population of facilitators at the Iron Range Engineering program. Each of the surveys represented one of the six primary roles of a facilitator as outlined by the institution's program director. The goal of administering the surveys was to determine engagement with the six roles of a facilitator's position as defined by their job description and lived experiences. Both quantitative (e.g., hours of work performed in that category) and qualitative data (e.g., How do you contribute as an instructor in the program?) were collected in the surveys. It was communicated to all participants that their decision to participate and the answers they provided would not be a form of job performance evaluation.

The surveys were sent to participants on a rolling basis, meaning none of them were sent on the same day. The reason for this was to capture as much data within each role as possible while also attempting to mitigate survey response fatigue. The surveys were administered during business hours over two weeks. Of the 12 facilitators, 11 participants responded to the career development survey, 10 responded to the instruction survey, 12 responded to the learning coach survey, 11 responded to the recruiting survey, 11 responded to the student life survey, and 10 responded to the "other" survey.

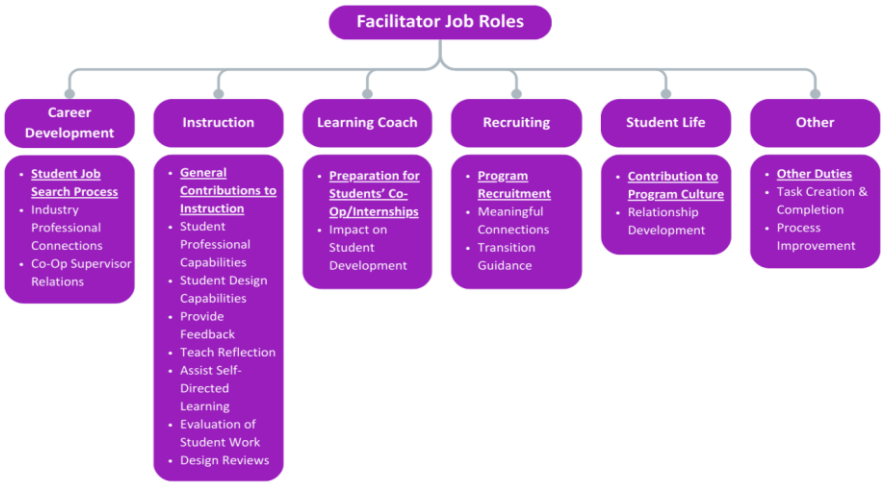
Identifying information was removed from all data before being thematically coded. Generative AI tools (Microsoft Copilot, 2025) were utilized to help in the beginning stages of categorizing job functions. Two coders then took those initial ideas for job functions that fell within each job role and manually coded

participant responses, which led to alterations in the job function coding schemes by combining, adding, and deleting functions. This was done until a consensus was reached.

Figure 1 displays the six job roles of the facilitators and the associated functions within each. Because of the extensive data available in each of these categories and given the scope of this paper, the primary job function (i.e., the first in each of the bulleted lists that are bolded and underlined is focused on their contribution to the overarching purpose of that job role) for each of the job roles is the focus of this study. Future work will utilize the remaining job functions and associated data to further analyze the facilitator perceptions and provide more depth to each facilitator role.

Figure 1

Primary Facilitator Job Functions Associated with Each of the Six Facilitator Roles



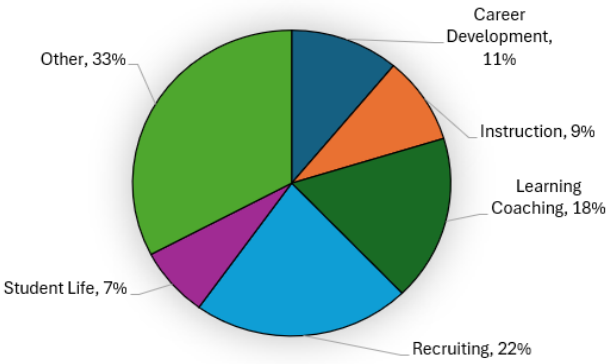
Note: the function of interest for this study is bolded and underlined

3 Results

From the data collected, it was found that the median weekly hours reported across the job description categories for all of the facilitators was 27 hours, and the average was 33 hours. It should be noted here that some facilitators are full-time and others are part-time, so a number lower than 40 hours is anticipated, and the median better captures the overall time spent. Also, it is recognized that some facilitators spend more time in certain categories than others; for example, some facilitators focus more highly on recruiting, while others are more in charge of student life. Thus, the median is more representative of the time spent., The facilitators also did not respond to all of the surveys at the same time, so they may not have tracked the number of hours that they had reported on the other surveys. Figure 2 shows the percentage of time spent in each job description category based on median times.

Figure 2

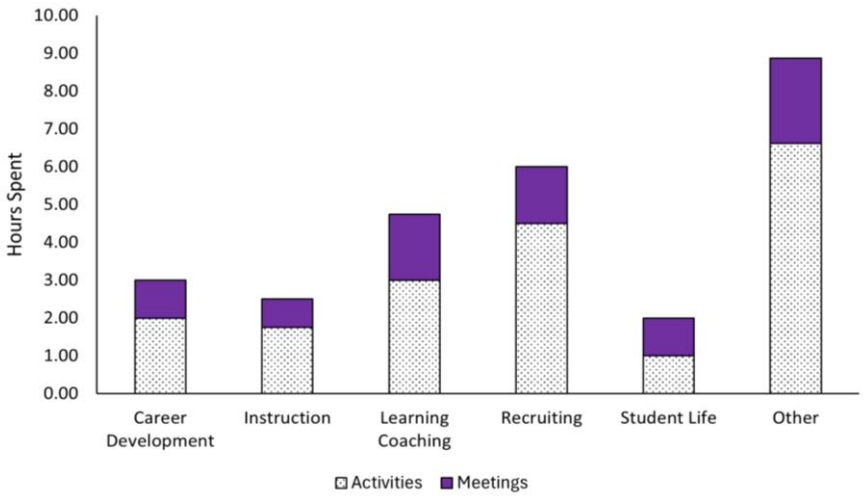
Percentage Breakdown of Facilitators' Time Spent in Job Description Categories



Facilitators also reported how much time was spent on meetings versus activities in each category. This breakdown is shown in Figure 3, which is also based on the median reported times.

Figure 3

Median Hours Spent on Activities versus Meetings in Job Description Categories



As shown in the methods, there were multiple functions under each role category. The first function for each of these is based upon the general involvement and contributions made within that role. That primary function will be discussed in the upcoming sections, with the emerging themes within each function being bolded and elaborated upon with examples, summaries, and representative quotes. Quotes from participants may have grammatical errors as they were left unedited to maintain the authenticity and integrity of their original words.

Career Development

As part of the student job search process within career development, facilitators **regularly have discussions** with students about their job search progress. These one-on-one job search discussions happen weekly or biweekly. Facilitators also **lead career development workshops.** These workshops consist of topics like writing cover letters, conducting interviews, and building resumes. Students in the program receive **personalized support** from facilitators, which includes guidance on future planning, professional references, guidance on further developing a cover letter and resume, mock interviews, and shared best practices in the job search process. Working on developing **industry connections** is another way facilitators add value throughout the job search process. These connections help students find viable options for work opportunities. They also help obtain industry projects for students to work

on and develop design skills in the Bell Academy semester. As one facilitator stated, “These projects sometimes act as ‘feeders’ into internship and co-op offers” (F10). The last theme for facilitators helping in the student job search process is **giving general career advice**. This includes guiding students who are in need of immediate or future employment, answering questions regarding the application process, providing general job search tips, and generally being very involved in the student job search process.

Instruction

Facilitators provide general contributions to instruction in four primary ways. **Grading and evaluation** is the first theme, and this consists of grading design papers (i.e., papers capturing their design learning in the workplace or on projects), fundamental principle exams (i.e., cross-cutting exams that require retrieval practice for students to reflect on all of their engineering learning), systems engineering exams, design reviews, weekly learning journals, student-led advanced (SLA) courses (i.e., courses students are developing in conjunction with their engineering work and interests), and IRE Talks (i.e., a TED-like Talk). Facilitators **provide workshops and review sessions** as needed, such as professionalism workshops (e.g., time management, emotional intelligence, leadership, etc.), design workshops (e.g., poster creation, conflict management, SCRUM, etc.), lab sessions, and industry exchange sessions that emphasize public speaking development on engineering topics. Facilitators also provide **design project coaching and mentorship**, which consists of instructing various parts of the design process, project management, general professional skills, explaining design assignments, and sharing best practices in hands-on engineering design work. Lastly, **planning and creating curricular deliverables** play a large role in facilitator instruction. As one facilitator states, “prepping fundamental principle quizzes, helping plan and lead industry exchange, [and] scheduling the learning journal assignments” (F3) are all part of their instructor role. Facilitators also spend time working on collaborative teams with professors and other facilitators to plan and create curricular deliverables.

Learning Coach

Personalized student coaching is a critical role of each facilitator. One function of this role is to prepare students for their co-op/internships. It starts by **setting expectations and sharing best practices.** This includes reminders on what to bring for the first day of work, to take good notes, to ask questions, and to meet and network with co-workers. Facilitators serving as learning coaches also discuss how the students’ experiences in the Bell Academy semester (Christensen et al., 2023) have prepared them to be successful on the job. Learning coaches set expectations in the first meeting with their students. This includes being on time, taking initiative, being mindful, and being self-aware. They also discuss employer expectations to ensure they are growing on the job. Learning coaches provide **personalized career development support and guidance**, which slightly crosses over with the career development role, but focuses on each individual instead of the entire student body. In addition to job search assistance, the learning coach discusses the need for students to be properly equipped with personal protective equipment (PPE). A learning coach will also spend time discussing career choices, developing communication skills, solving open-ended problems, transitioning between co-ops and internships, and explaining how students should interact with their supervisors.

Real-life scenarios emerged as another theme, as learning coaches share tips regarding lessons learned from successes and failures from their own experiences working as engineers in various industries. Facilitators serving as learning coaches will also coach students through working with other people. As one facilitator stated, “I often tell students that engineering is easy, it’s the people that are difficult” (F8). Learning coaches also emphasize **open communication**, which includes answering any questions students have and remaining available if anything comes up at work, at home, or in their personal lives. The last theme related to learning coaches preparing students for their internships and co-ops is **well-being & time management.** Facilitators will coach students on building out a schedule to balance their

school work with co-op/internship work, as well as their personal lives. Many of the weekly or bi-weekly coaching conversations start with assessing the student's well-being with a list of prompting questions. As one facilitator said, "If the student is stressed and worried, then I help build up their confidence by letting them know they are not alone and reassure them that they are going to be okay" (F5). If students are nervous, learning coaches will provide tools to help alleviate the nerves. Facilitators help students to handle a wide variety of topics they may experience along their engineering journey. As stated by one facilitator, "I think I help support them through the unknowns and hurdles they face. They know they have someone unattached to the company and work they are doing that they can talk to and go to for advice. I often help them come up with action items to help them deal with situations that arise or navigate different scenarios. This allows them to work on their communication skills with myself while also learning professional skills for navigating on-the-job situations themselves. I also am always there to celebrate their successes and I have had a number of students personally reach out to me with exciting news and accomplishments related to their co-ops. I believe this positive reinforcement gives students additional confidence as they continue with their work" (F6).

Recruiting

Unlike many other university programs that have designated recruiters, facilitators play a major role in program recruitment to continuously improve enrollment numbers. **High school and college outreach** is the main way facilitators recruit students to the program. They build connections with community college and high school faculty and staff so they can go out on a recruiting trip to present to students in their classroom(s). These classroom presentations help to introduce the program and raise awareness about the work-based engineering program at Iron Range Engineering. Students are then invited to attend a **campus visit**, which is the next step in the process, where facilitators (as well as other staff and faculty in the program) help in the recruitment process. Community college students from around the country and local high school students visit Iron Range Engineering's campus to learn more about the program and network with facilitators, professors, and students.

Program recruitment also includes **background work**, such as analyzing colleges or high schools for potential new partnerships, managing the prospective student database, scheduling application interviews, and sending program acceptance emails to students who apply. Facilitators focus on **engagement and personality** throughout the program recruitment process. As one facilitator stated, "Personality is significantly more likely to help you succeed than intelligence. I try to be interesting, relatable, and fun" (F2). As with many parts of their roles, facilitators focus on **networking and building relationships** to help with recruiting efforts. Facilitators have unique experiences working as engineers in various industries before transitioning into a staff position within higher education. They share these experiences with prospective students to build relationships. Facilitators also network with community college instructors and administrative staff from around the country. As one facilitator stated, "Building trust with students and their instructors is the real key to building a student base. Students today are not swayed by slick marketing so much as they are swayed by the word of those they know and trust" (F8). Once a facilitator connects with a student in their community college or high school classroom, they work closely with each prospective student. The last themes that emerged within program recruitment are **marketing and events.** This includes leading on-campus events, such as Engineering Expos (i.e., hands-on engineering information sessions), #Night (i.e., women in engineering event), and annual open house events. There are a few facilitators who collaboratively work with professors on the Iron Range Engineering marketing team, and that team oversees social media posts and website design.

Student Life

Facilitators make significant contributions to program culture. They start by creating and fostering a **positive and supportive environment** for all students**.** An example of this is having facilitators lead

student life activities to boost the morale of the group by creating an inclusive and welcoming environment. As one facilitator stated, “It was also important for me to dedicate events and little acknowledgments here and there to relieve stress and give students a break from the daily grind of engineering work. This promoted a caring and helpful culture” (F6). Students receive **personal support** from facilitators in the form of celebrating the diversity and successes of all students. Facilitators will also work with students on fun projects in the labs and at the local Makerspace. Facilitators focus on **engagement and activity** when it comes to student life events that contribute to program culture. They help to plan, execute, and take part in all student life activities that the program puts on for students. For example, many facilitators participate in welcome week activities, community meals, happiness week activities, and EngFest! (i.e., end-of-the-semester celebration event) activities. Facilitators work to provide opportunities for students to build strong relationships with others in their on-site Bell Academy semester, and they also help to plan virtual events for students working on co-ops and internships.

Another theme that emerged is that facilitators practice being **consistent and reliable** to ensure all students have an outlet to escape the stress they may be under at school, work, or in their personal lives. Facilitators recognize that many of the students at Iron Range Engineering are away from their families and friends, so it’s important to be consistent by having a regular and open presence for students. Facilitators also try to live by program ideals. As one facilitator stated, “I also try to maintain the IRE values and all things out if behavior goes outside the bounds” (F2). The last theme that emerged in the facilitator’s contributions to program culture is **safety and security**. Examples of this include truly taking care of students and helping them to achieve goals, promoting self-care, and maintaining a safe learning environment for all students. As one facilitator puts it, “If students don’t feel safe, it would be extremely harmful to the culture. If it isn’t a safe, collaborative, inclusive space, the entire culture of the program suffers” (F10).

Other

There are five job roles above that capture specific elements of a facilitator’s job responsibilities. The remaining job roles and functions are determined to be other duties, and many of these other duties are niche areas of work that may only apply to a select few facilitators. For example, a few facilitators do very intensive work related to **event planning**. This includes tremendous logistical planning and organizing for events such as EngFest!/graduation week, which involves student travel and transportation, meals, lodging, activities, and more. Some facilitators also have a critical role in updating and maintaining **facilities and vehicles, as well as providing IT support**. Two or three facilitators lead in this area, but many contribute to helping the leads out with tasks such as oil changes, cleaning out lab spaces, and organizing facilities. Facilitators also work a lot within the realm of **program administration**. Examples of this include participating in divergent thinking sessions for program innovation purposes, staff meeting participation, search committee participation, purchasing card reconciliation, general email management, administrative paperwork, shipping items to students, taking professional headshots/photos of students, utilizing and learning modern tools, and meeting with campus visitors or stakeholders of the program. Many facilitators focus on **community engagement** to ensure there is time for team bonding, support for all students, faculty, and staff, and building meaningful relationships with colleagues. The last theme that emerged within other duties is **team coordination**. Many facilitators work on collaborative teams with other facilitators and professors, and examples of these teams include the accreditation and assessment team, the scholarship committee, and the campus visit team. Some facilitators help coordinate with other campus personnel to reserve spaces for events, create effective cleaning schedules on campus, and troubleshoot any network/wi-fi issues. One facilitator said, “I try to be the learning coach for the other facilitators the best I can. That means stepping up when needed for them or sometimes taking on additional duties when they need to step back” (F2).

4 Discussion & Recommendations

The results from this research have generated insight into the facilitator position directly from the facilitator's perspective. The many quotes highlighted the uniqueness of this position in higher education, and there were many ties to meeting the needs of students in project-based and work-based learning environments. There are many student needs in every higher education program. Once the student needs have been identified within each institution, these facilitator positions could be implemented and utilized to meet said needs within these roles.

While examining the qualitative and quantitative results, it was recognized that the facilitator's role has three distinct divisions: **direct formalized student support/mentorship, community building and support, and program development and maintenance**. Facilitators spend about one-third of their time in each of these three areas. Direct formalized student support/mentorship is a student-facing category. Developing and maintaining the program includes non-student-facing or "behind-the-scenes" work. Community building and support includes both student-facing and non-student-facing work. It is suggested from this data analysis that all institutions considering implementing the facilitator position should carefully plan work within these three distinct divisions to ensure student needs are being met, a strong culture and community are being developed, and the program continuously improves.

With regard to **direct formalized student support/mentorship**, it was apparent that mentorship is key in this space. While students traditionally have professors and peers they can turn to, facilitators serve as mentors in between those two spaces - someone who isn't at the exact spot they are but also doesn't have as large a perceived power differential that may exist with a professor who is leading their technical learning. As such, other programs should consider ways that they can provide approachable mentors who are integrated with their programs formally but also have experience and job titles that may serve as extraordinary resources throughout the learning process in project-based and work-based learning models.

Regarding **community building and support**, a positive and supportive environment is highlighted as a critical element in boosting overall morale and building an inclusive community. While formal support is important to student success, it's also critical to be consistent and reliable in showing up for students outside of the structured learning environment. This is where deeper connections can be made with students, which can also create safe spaces for students to ask for any form of help from mentors when needed. Other programs should consider their community and culture and work to foster it.

With regard to **program development and maintenance**, facilitators provide support within the realms of administration, IT, facilities, fleet services/vehicles, and events. Instead of having faculty and staff solely rely on the support of other departments within the same institution, facilitators can help provide similar supportive services while fully integrating with the program. This results in quick fixes, continuous improvement processes, and logistical support that can reduce the cognitive load of professors and students. The tasks performed within this section by facilitators were related to the niche roles that some take on that aren't shared responsibilities with other facilitators, and focused more on the tasks that students don't necessarily see. For example, not all facilitators plan events, and not all help upgrade lab spaces. Other institutions should consider how to spread this load among different facilitators.

As the authors of this paper, we suggest that there could be future improvements to the current facilitation model and believe that further research can be done to uncover best practices within the given context. We also suggest that others adopt similar facilitator positions within their own institution to provide more support for their students, faculty, and staff. There are student needs in project-based and work-based programs left to chance, and the facilitators at IRE provide the structure necessary to meet many of these needs.

5 Limitations & Future Work

The main limitation of this study was that the population was limited since the facilitator position largely only exists in the IRE model, which limits the amount of data and the generalizability of the work. Nonetheless, diving deeper into the facilitation model from multiple perspectives is warranted based on the positive outcomes of the IRE model. Since the facilitator position does not widely exist, no instruments related to gathering this data exist. Future iterations of this survey outside of this pilot study could be revised and more fully validated.

For the instrument, one limitation is that facilitators were asked at just one time point how much time they were spending. These were one-time estimates. Future work could have them track their time spent in each of these bins for multiple weeks at different times of the year, since they work on a 12-month contract, but the academic year is only 9 months.

One-on-one follow-up through semi-structured interviews will be conducted as member-checking to see if there is anything missing in the data that can be identified by facilitators after sharing the themes with each of them. Also, this follow-up could provide further context and clarification surrounding the themes that uncover best practices. Future research related to the impact of the facilitator position from the students' and professors' perspectives could provide another form of motivation for other institutions to adopt facilitator positions. Additionally, the rest of the functions related to each of the six facilitator roles will also be explored. Facilitators completed the surveys in this study separately for each of the roles, which may have skewed the time reported for each role. A time-tracking activity for the facilitators may help support a more accurate portrayal of the hours spent in each role.

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Designing successful and sustainable interdisciplinary PBL in engineering education: A cross-case analysis of System Projects in practice

Lykke Brogaard Bertel
Aalborg University, Denmark, lykke@plan.aau.dk

Pernille Scholdan Bertelsen
Aalborg University, Denmark, pernille@plan.aau.dk

Pia Rosenquist Kruse
Aalborg University, Denmark, prk@adm.aau.dk

Ove Kjeld Andersen
Aalborg University, Denmark, oa@es.aau.dk

Nicolai Brodersen Hansen
Aalborg University, Denmark, nbha@cs.aau.dk

Markus Löchtefeld
Aalborg University, Denmark, mloc@create.aau.dk

Jens Frederik Dalsgaard Nielsen
Aalborg University, Denmark, jdn@es.aau.dk

Ulrik Nyman
Aalborg University, Denmark, ulrik@cs.aau.dk

Maj-Britt Quitzau
Aalborg University, Denmark, quitzau@plan.aau.dk

Mateus Halbe Torres
Aalborg University, Denmark, mateusconsigo@gmail.com

Maiken Winther
Aalborg University, Denmark, maikenw@plan.aau.dk

Louise Møller Haase
Aarhus University, Denmark, haase@au.dk

Abstract

Interdisciplinary collaboration is considered a key competence for engineers and necessary to solve society's wicked problems in environmentally and socially sustainable ways. However, designing and developing successful and sustainable interdisciplinary PBL-projects that provide students with opportunities to engage in interdisciplinary learning, is no easy task. It requires cross-cutting collaboration, not only between students themselves but also between supervisors and facilitators, study management and administration. This paper provides indicative and explorative insights into potentials and challenges related to designing interdisciplinary PBL, exemplified through an empirical cross-case analysis of the "System Projects" initiative at the Technical Faculty of IT and Design at Aalborg University. Through in-depth interviews with project coordinators, we identify eight dimensions of system project integration and develop a curricular model for mapping variation within system projects: the System Project curricular spiderweb. We discuss key drivers for success and typical challenges, finding that successful interdisciplinary PBL can be achieved when the definition of the type of project is not too rigid, when we provide space for prototyping, experimentation and co-creation between staff, students and stakeholders, and when the objectives are perceived by all involved as engaging and important with purpose extending beyond just academic goals.

Keywords: system projects, interdisciplinarity, engineering education, problem-based learning, curriculum design

1 Introduction

In the face of escalating global challenges such as climate change and rapid technological advancement, the role of engineers is shifting. Contemporary engineering problems are increasingly characterized by their complexity and multifaceted nature, often transcending traditional disciplinary boundaries. Consequently, there is a growing need for engineers to not only provide technical expertise, but to possess interdisciplinary skills that enable effective collaboration across various fields, integrating diverse perspectives to design and develop sustainable solutions (Royal Academy of Engineering, 2025; UNESCO, 2021a). Engineering education is responding to this demand by increasingly integrating sustainability competences into curricula and providing students opportunities to engage in cross- and interdisciplinary learning, for instance, through problem- and project-based learning (PBL), recognizing that real-world problems seldom adhere to a single domain (Habbal et al., 2024; Guerra, Jiang & Du, 2022; Guerra & Rodriguez-Mesa, 2021; Lantada, 2020).

Previous research has categorized these into different project types, each varying in team composition and the breadth of disciplines involved (Kolmos et al., 2024). Among these project types, system projects hold particular significance in bridging the gap between theoretical knowledge and practical application as teams from related engineering disciplines engage to address components of a larger system (Kolmos et al., 2025). However, designing and developing successful and sustainable cross-disciplinary educational projects is no easy task and requires cross-cutting collaboration not only between students but also between supervisors and facilitators, study management, and administration (Routhe et al., 2024; Bertel et al., 2022).

In this paper, we explore the 'System Projects' initiative at the Technical Faculty of IT & Design at Aalborg University (AAU), which was initiated to provide students with opportunities to work across disciplines in PBL projects that strive to make a tangible difference in the world. Through an empirical cross-case analysis, the paper outlines potentials and challenges when integrating interdisciplinary collaboration into PBL curricula and proposes a curriculum model, inspired by the curricular spider web, to map variations herein.

1.1 System projects

While interdisciplinary collaboration is increasingly considered essential for addressing complex, real-world challenges, implementing such collaboration in engineering education presents several difficulties. One major challenge identified in the literature is resource allocation, as effective interdisciplinary teaching demands significant funding, materials, and trained personnel (Christiansen et al., 2023). Limited budgets

and institutional priorities can restrict the availability of these resources, making it difficult to support collaborative efforts across diverse disciplines (Bertel et al., 2022). Additionally, collaboration issues arise due to differences in teaching philosophies, communication styles, and levels of commitment among educators, and coordinating across departments thus often involves overcoming organizational silos and aligning varied goals and expectations, which can be time-consuming and complex (Routhe et al., 2024).

Another significant barrier is difficulty in establishing effective communication among students from different disciplines. Different terminologies and perspectives between fields can create misunderstandings and social distance, requiring enhanced efforts to build mutual trust and understanding (Routhe et al., 2021). Furthermore, classical curricula often prioritize disciplinary depth over interdisciplinary integration, making it challenging to overcome institutional barriers and academic silos and align interdisciplinary projects with existing study regulations while ensuring they meet diverse learning objectives (Bertel et al., 2022; d'Escoffier, Guerra & Braga, 2024).

To navigate these challenges, different models of interdisciplinary projects have been proposed, notably system projects and mega/mission projects (M-projects) (Kolmos et al., 2024; 2020). M-projects are large-scale, long-term, and highly complex interdisciplinary projects that require substantial investments and involve multiple disciplines, including both STEM (Science, Technology, Engineering, Mathematics) and SSH (Social Sciences and Humanities). Examples include infrastructure projects, space technologies, and renewable energy systems. The vast complexity and scale of megaprojects pose significant challenges in coordination, resource allocation, and integration of diverse disciplinary perspectives, making them difficult to implement within educational frameworks (Routhe et al., 2021; Bertel et al., 2022). While system projects, too, address and develop complex systems, they typically focus on collaboration among *related* engineering disciplines, such as electronics, material science, production, and civil engineering, illustrating the interdependencies within specific technological systems while maintaining distinct learning objectives for each engineering team (Routhe et al., 2024). This may result in looser coupling between projects, allowing for students to develop discipline-specific knowledge and skills while understanding how different engineering fields contribute to a cohesive whole (Routhe et al., 2024; 2021).

System projects might offer a feasible approach to interdisciplinary collaboration in educational settings due to their manageable scope. Unlike megaprojects, which demand extensive coordination and resources, system projects focus on narrower interdisciplinary collaboration within related engineering fields, making them more practical in terms of implementation, alignment with existing curricula, and engagement in interdisciplinary learning without the need for extensive curricular restructuring. Additionally, system projects provide focused learning objectives by concentrating on the interdependencies within technological systems, offering students a structured yet flexible environment to engage with real-world engineering challenges (Routhe et al., 2024; Kolmos et al., 2024).

To understand the variations, potentials and challenges of integrating system projects in practice in engineering education environments, this paper presents and analyses different and current aspects of system projects in the context of PBL at Aalborg University and develops a curriculum model for system projects visualizing these variations: the System Project curricular spiderweb.

2 Methodology

In this paper, we apply cross-case analysis of five different cases of system project integration at The Technical Faculty of IT and Design. As part of the case selection process, the deputy heads of departments of education at the faculty identified different relevant system projects to be considered relevant as cases for the analysis. The final selection was based on the following two criteria: 1) All selected cases align with the definition of system projects, meaning at least two or more student groups from two or more engineering disciplines are involved in the project, which includes a shared boundary object (Kolmos et al., 2024), and 2)

the selected cases reflect the variation of implemented system projects within the faculty, showcasing similarities and differences in the practical implementation of this particular project type.

The final case selection includes five system projects, one from the Department of Computer Science, one from the Department of Sustainability and Planning, and three from the Department of Electronic Systems.

In the data collection process, we focus on project coordinators, i.e. faculty members who initiate, develop and facilitate system projects across programs. We conducted in-depth semi-structured interviews with each of the five project coordinators (one for each of the cases), ranging from 63 to 79 minutes in length. The interviews covered themes such as the history and development of the system project, its structure and institutional framing, distribution of roles within the project (e.g. as facilitator, stakeholder representative, expert, supervisor etc.), progression within the project and expansion across programs, and finally perspectives on the potentials and challenges of system projects at Aalborg University, now and in the future. The full interview guide can be found in Appendix A. The interviews were conducted, recorded and transcribed online through Teams, upon which automated transcriptions were read through and minor corrections made by one of the two interviewers.

Focusing solely on project coordinators presents certain limitations to this study, i.e. prioritizing organizational perspectives on the part of the faculty, and the potentials and challenges related to the implementation of system projects in formal engineering curricula at the involved departments. Thus, the perspectives of students, domain-experts and supervisors, as well as external stakeholders involved in the system projects, that could have provided important additional insights into the potentials and challenges of system projects in engineering education as it relates e.g. to student experiences, learning and collaboration, external outreach and employability, is not included in this study.

The analysis was conducted in three phases including an inductive thematic analysis within each of the five cases, a cross-case comparison (a synthesis overview can be found in Appendix B), and a deductive exploration of cross-case patterns pertaining to specific aspects of system project implementation, which was synthesized into an eight-dimensional curriculum model, allowing for the mapping and visualization of variations in system project implementation.

3 Modelling System Project Dimensions

From the thematic analysis and cross-case synthesis, we identified the following eight dimensions of which each system project represents a particular variation: Curricular integration, system-level orientation, size/scale, interdisciplinarity, vertical integration, sustainability focus, student autonomy and external partnership. Based on these eight dimensions, we have developed a curriculum model for the design and implementation of interdisciplinary system project in engineering education (see figure 1).

This model is inspired by van den Akker's curricular spiderweb (van den Akker 2003; 2013). However, it is important to note that while Akker's model, as well as its recent appropriations within interdisciplinary engineering education (Beldad & Miedema, 2025) and Challenge-Based Learning (CBL) (Doulougeri et al., 2024) do indeed reflection curricular variation, the purpose of the original model and previous applications has been to assess curricula and identify "weak links" for improvement. This is not the intention with the System Project curricular spiderweb. Rather, it is to make visible the versatility and diversity of system project design, organisation and implementation and to inspire practice for further development.

In the following, we present this synthesized model (see figure 1) and provide a description of each dimension followed by the results of the cross-case analysis of the five system projects at the Technical Faculty of IT and Design as it relates to specific aspects of the system project variation.

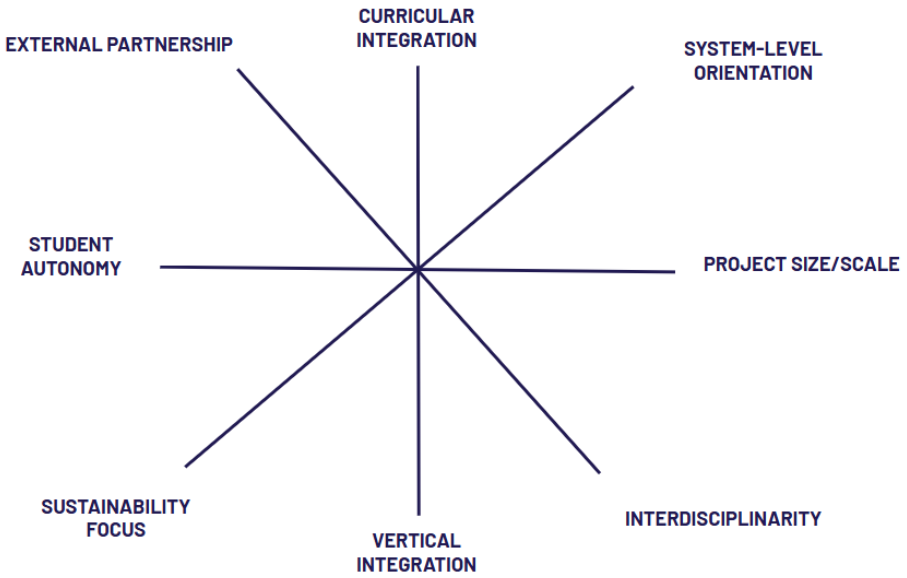

Figure 1. The System Project Curricular Spiderweb

Size/scale refers to the number of students and/or teams involved in the project, typically at least two or more different, but related, discipline-specific teams (Kolmos et al., 2024).

External partnership is the degree to which external stakeholders (e.g. companies, public organisations etc.) are involved in the project and in what role, e.g. either as informant or case on the one end, or as client or even partner at the other end of the spectrum (Holgaard et al., 2020).

Curricular integration refers to whether the project is integrated into the formal curriculum or considered extra-curricular, i.e. whether formal courses and structures support the project and explicit intended learning outcomes for the project are defined and assessed formally through study regulations and exam.

System-level orientation refers to the system perspective within the project. All system projects involve some engineered (non-natural/artificial) system, but the extent to which aspects of system integration and interaction with other boundary (technical, natural or socio-technical) systems are included, varies.

Interdisciplinarity refers to the range of disciplines in the project. In some cases, interdisciplinary collaboration is limited to programs within the same department, whereas other system projects include collaboration across departments and even faculties.

Vertical Integration refers to the extent to which projects are long-term and passed over from one semester to the next to build on lessons from others and strengthen continuity (Strachan et al., 2019). Especially projects that deal with functional solutions or technologies that are to be implemented in real-world environments are rarely completed within a semester. Thus, vertical integration or 'transfer' of knowledge from the previous project is crucial.

Sustainability focus refers to the extent to which sustainability is a focus of the project. In some cases, sustainability issues are key driving forces, while in other cases sustainability is less present or can be integrated as an add-on.

Student autonomy refers to the extent to which students can define the project scope, its problems and solutions, themselves. In some system projects, both problem and solution are pre-defined, and the students produce the best version of said solution through incremental innovation. In other cases, only the problem is defined, and students need to ideate to come up with ideal solutions, and in yet other projects students need to first identify and structure the problem.

4 Case analysis

In the following, we present each of the five cases and the results of the initial inductive thematic analysis, as well as the synthesis and cross-case comparison according to the System Project curricular spiderweb.

4.1 Graphic Interface foR Autistic Folks (GIRAF)

This system project at the Department of Computer Science focuses on ongoing software development of an app designed to support children with autism (Aalborg University, n.d.). The project has been ongoing since 2011. Initially, only students from Software participated, but since 2023 more education programmes at the department, including Interaction Design and Bachelor of IT, have joined and increased its interdisciplinary scope. As such, the project has progressed from a single 'inter-team' or multi-project to a more complex and cross-disciplinary system project that involves both horizontal (cross-disciplinary) and vertical integration, meaning students must describe and 'hand over' their work to the next student cohort to take over. This is explicitly stated and assessed as part of the formal learning goals, to be able to work asynchronously across semesters similarly to a 'real' software development unit, thereby training important competences needed at the labour market. While the project does involve long-term partnership with a special needs school, the system-level orientation is on the digital artefact and its sub-systems (rather than e.g. integration with other socio-technical systems) and the stakeholder acts more as informant or case, with the project coordinator as domain expert and primary point of contact.

4.2 AAU SAT

Satellite-related initiatives at Aalborg University (AAU) commenced as early as 2003, building upon the university's involvement in "The Ørsted Project," which led to the successful launch of Denmark's first exclusively national research satellite in 1999. AAU Student Space emerged, where students at the Department of Electronic Systems have since developed and launched 5 student-built CubeSats during the last two decades (AAU Space, n.d.). These projects are highly student-driven, vertically integrated and extra-curricular, although students can choose to integrate aspects of AAU SAT as a case into their semester project to be formally assessed as well. The overarching objective of AAU's satellite development activities is to cultivate advanced engineering competencies among students, surpassing the conventional learning outcomes of a typical master's degree program. Participants in these complex system-oriented projects include students from academic disciplines such as e.g. Electronic Systems, Antenna Technology and Automation. Throughout the years, over 200 students are estimated to have been part of the project. In AAU SAT, the role of the project coordinator has mainly been to ensure a physical space and infrastructure is available to students (i.e. lab settings and funding) as well as provide expertise in the form of informal and formative feedback during student-organized project meetings.

4.3 AAU SPACE ROBOTICS

Similarly, the AAU Space Robotics project is an equally highly student-driven, vertically integrated and extracurricular initiative where participants design and build robots capable of operating in space environments. Since 2023, students from various disciplines (and faculties) have participated, such as Materials and Production, Industrial Technology, Energy, Robotics, Media, and Design. Student teams compete in The European Rover Challenge (ERC), an international competition where university students from all over the world compete to build the most optimal rover, fostering both academic growth and practical experience (AAU Space Robotics Team, n.d.). Similarly to AAU SAT, the project exemplifies interdisciplinary collaboration and high student autonomy, as students balance this voluntary effort alongside their formal studies, although students have the option to incorporate elements of the initiative into their semester projects. The role of the project coordinator has been to initiate the project and ensure lab facilities as well as support students with fundraising. In some cases, the project coordinator has also supervised semester projects that integrate the system project as a case in their formal education.

4.4 Sustainable Development Lab

This curricular system project initiated in 2023 (IAS PBL, n.d.) with the first mixed-micro group of students participating from Information Studies (Department of Communication and Psychology), Sustainable Cities and Techno-Anthropology (Department of Sustainability and Planning), respectively. Six education programs are currently involved (as supervisors and/or teachers) and all students are invited to join. It is aimed at addressing complex sustainability challenges through collaboration among students, supervisors, and public and private organizations, taking point of departure in the UN's Sustainable Development Goals at a system level. The lab focuses particularly on green transition, encouraging all semester projects to integrate this perspective. It provides a learning framework to develop competences such as adaptability, interdisciplinarity, and systemic thinking, and creates opportunities for hands-on experience in addressing sustainability challenges in systemic ways. The semester projects and scope are made in cooperation with external partners, for example a local amusement park or recycle station. Participation is voluntary but integrated into the curriculum (if students choose the project) and the role of the coordinator has been to align the project with formal learning goals and develop suitable assessment methods (i.e. interdisciplinary exams) as well as act as censor at the exam. At this exam, an examinator and censor is present from each of the participating educational program to ensure the fulfillment of discipline-specific learning goals.

4.5 BRASILIA RECYCLE PROJECT

In 2018, Latin America's largest open landfill in Brasília, Brasil, was closed. This marked a difficult transition for the more than 1,000 children and adults who survived by scavenging for food and items in the garbage. A support program was organized to help waste pickers adjust to the new reality, and this recycle-focused system project emerged in this context, starting as a collaboration between students from AAU and students from the University of Brasília. Today the system project has been extended as part of an Erasmus program. Four countries are involved, with students from the Netherlands, Portugal, Brasilia and Denmark. The students have differentiated learning goals depending on their specific curriculum (or extracurricular activities) and involved education programs but cooperate across countries and educations. In the system project the collaboration across countries is organized deliberately on low dependencies on deliveries and working both synchronously and asynchronously with each other as it fits their specific educational programmes and semester projects.

4.6 Cross-Case comparison

While all five cases share some similarities, e.g. with regard to their focus on the development of a (socio)-technical system and (complex) problems that require interdisciplinary collaboration, they also vary significantly across the eight identified dimensions, as we will elaborate below.

As for the ***size and scale***, some projects are stille quite new, such as the Sustainable Development Lab and Space Robotics, while other projects such as GIRAF and AAU SAT have years or even decades of student cohorts participating. With regard to scale, most of the cases could be scaled up to mega- og mission (M) projects i.e. larger-scale multi-team projects with broad interdisciplinary, and potentially transdisciplinary, collaboration (Bertel et al., 2023; Kolmos et al., 2024), depending on the scope. In particular, projects that deal with contextual implementation and multiple stakeholders, such as the Sustainable Development Lab and the Brasilia Recycle project, however these cases currently focus on specific problems and solutions within the overall system, thus adhering to the system project definition.

As for ***external partnership***, in some projects (such as GIRAF), the role of the external stakeholder is to provide or offer access to specific domain knowledge, data or processes without active involvement in the research or project development, although potentially benefitting from the resulting analyses and solutions. In other projects, the external stakeholder acts more as a 'client', defining project scope and objectives, or particular criteria for the solution. This is the case for AAUSAT and AAU Space Robotics, although the external stakeholder in these particular projects (such as ERC) does not necessarily have a specific 'stake' in the project

and whether it succeeds. In some system projects, external partners and students engage in somewhat of a joint research initiative, both contributing resources and expertise and working together towards shared goals and long-term strategic alliances, through which new system projects can emerge. This has been the case with the Brasilia project, as is the intention with Sustainable Development Lab. These projects share an inherent ***sustainability focus*** (e.g. on green transition and social sustainability), while in other cases sustainability is less present or can be integrated as an add-on (e.g. thinking about sustainable power supplies in space). It could be argued, that while system projects do not always centre on sustainability issues, any project that *do* in fact address sustainability issues must always approach these from a systemic perspective.

For ***curricular integration***, the cases also present different end points of a spectrum. For instance, projects such as AAU SAT and Space Robotic are not explicitly part of the formal curriculum, but students can choose to use a specific aspect of the project (e.g. developing a prototype of a system component) as a case study for their semester project, which is then formally assessed according to study regulations, while other projects such as GIRAF and Brasilia are fully integrated into the curriculum and somewhat mandatory. Although ***student autonomy*** and curricular integration can be related, they are not necessarily interdependent. Formal PBL-curriculum models often will allow for high student autonomy with regards to choice and scoping of problem and project design even though they are formally assessed (as is the case with Sustainable Development Lab), whereas extra-curricular projects such AAUSAT and AAU Space Robotics, despite their very nature as entirely voluntary, might have very specific goals or requirements and thus in principle lower student autonomy with regards to problem definition and solution.

While all projects are concerned with engineered (artificial/technological) systems of some sort, the ***system level orientation*** is somewhat flexible and a matter of 'zooming in or out'. For instance, in the GIRAF project, the focus is on a specific digital artifact (an app) and its integration within one particular context and target group (a special needs school). The project is further divided into sub-systems (e.g. frontend, backend, etc.), thus there is a 'zooming in' and division of work based on system components within this one artifact. This is the case for AAU SAT and Space Robotics too. However, hypothetically, students could eventually 'zoom out' too and look at relevant boundary systems such as the education system, health system, transportation system, energy system, planetary system or any other relevant natural or socio-technical systems that the system of interest could interact with. At the other end of this spectrum are projects such as Sustainable Development Lab and the Brasilia, that take point of departure in overarching and emergent issues or change processes within larger, interconnected and socio-technical system, with multiple stakeholders, technologies and potential target groups, and through this explore ideas for engineered solutions, of which some can be digital artifacts (and thus potentially subject to a subsequent process of 'zooming in'). This aspect thus highlights the need for students to develop systems thinking to understand the interconnectedness of problems, systems and disciplines and to define the boundaries of a given problem and system before designing and developing suitable and sustainable solutions.

This too raises questions about the definition of narrow and broad ***interdisciplinary collaboration,*** and whether it is defined by somewhat artificial institutional boundaries, or whether it relates more to e.g. scientific paradigms and students' experiences of differences in expertise and problem-solving approaches. However, in all cases, the project coordinators were able to identify disciplines outside their domain that could be included in meaningful ways (e.g. social workers or psychologists for GIRAF, or energy engineers for AAU SAT), thus there seems to be a potential to use a system project as a leverage point for 'zooming out' and scaling up to M-projects with broader interdisciplinary participation.

Vertical integration can occur somewhat naturally in system projects that deal with functional solutions or technologies that are to be implemented in real-world environments and thus rarely accomplishable within one semester (such as AAU SAT or Brasilia), or it can be purposefully designed this way as a formal requirement to practice this particular skill (GIRAF). In either case, project coordinator emphasized having a knowledge-sharing platform (such as GitHub) as important to facilitate the transfer of knowledge, solutions, and documentation across student 'generations' and leadership. In some cases, multiple semesters are

involved simultaneously, working on different aspects of the solutions, such as the AAU Space Robotics project. However, according to the coordinator, the educational level in and of itself did not entail a certain hierarchy or specify level of leadership or management responsibilities. Rather, this was established based on personal interest or skill. Thus, a younger student could take on the role as project manager and lead their senior peers. The project coordinators all generally reflected on managerial roles and when to share this responsibility with (or leaving it entirely up to) students to support their motivation and their development of leadership skills.Below (figure 2) is a synthesized mapping of the five system projects according to the System Project curricular spiderweb. A mapping of each individual case can be found in Appendix C.

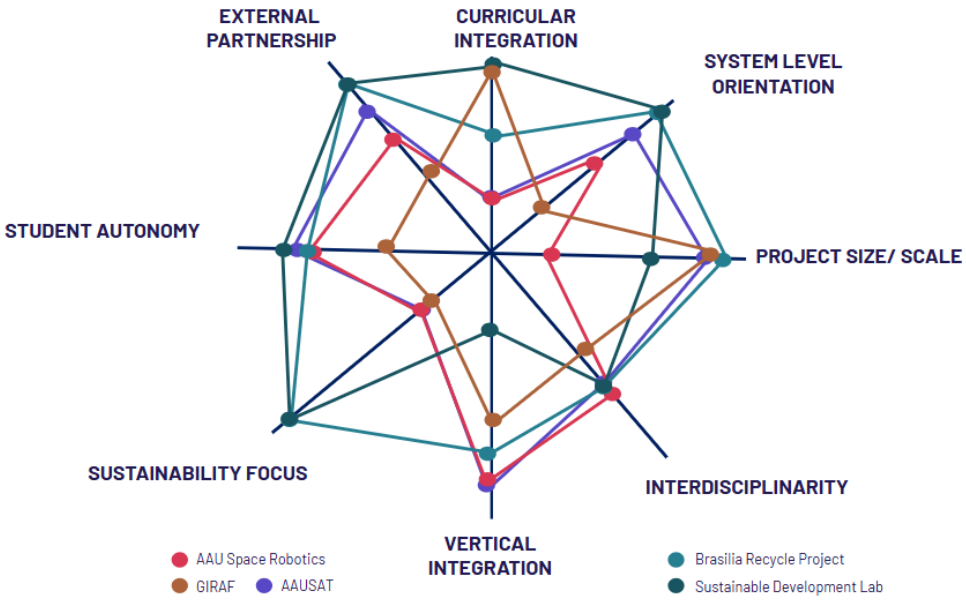

Figure 2. Variation in System Project implementation at TECH

5 Discussion

While such a mapping provides insights into decisions and priorities to be considered when implementing system projects, it is important to note that this mapping only represents a “snapshot” of each case. Projects can grow in scale over time or shift in system-level focus and new external collaboration might emerge between semesters. Similarly, changes can be made with regards to curriculum integration, both vertically and horizontally (e.g. expanding from narrow to broad interdisciplinarity) and formal assessment can be implemented later on with changes in study regulations. In this cross-case analysis, it should also be noted that the particular “snapshots” presented in this paper specifically represents project coordinators’ perspective. Thus, supervisors, students and external partners might experience e.g. levels of partnership, autonomy and interdisciplinary collaboration differently, just as other dimensions might emerge when exploring system projects from the perspectives of other stakeholders.

Furthermore, the model should not be considered ‘normative’, i.e. the scaling up or expansion of a system project is not a goal in and of itself. Rather, different project purposes call for different system project constellations, and while broadening the scope of a project will naturally increase its complexity, and thus the opportunity to develop transversal competences associated with complex problem-solving, it is variation that is key (Kolmos et al., 2025). Ideally, students should be able to experience different kinds of interdisciplinary PBL projects, and even, different kinds of system projects, as they progress through their education. Here, the awareness of this variation, of the shifts in system-level orientation, requires systems thinking abilities on the part of both students and facilitators.

Systems thinking is a higher order thinking skill that enables students to identify, understand, predict, and suggest improvements of every aspect of a technological system, including the way these aspects inter-relate within the system and with other socio-technical systems on its boundary (Lavi et al., 2023; Bertel et al., 2025). All technologies can be considered systems, and these systems both consists of sub-systems and are themselves sub-systems within a larger technical or socio-technical system. As such, it could be argued that any discipline-specific or domain project could become a system project by 'zooming out', and likewise any mega- og mission (M) project could be split into multiple system projects by 'zooming in'. Thus, rather than a distinct and rigid system project definition, it might be beneficial to consider different project types as potentially related to or even embedded within one another.

Following this, it could be considered whether the definition of system projects should be extended to not only include criteria related to team constellation and presence of a specific boundary object (i.e. an artifact embedded in a technological system) but to also include intended learning outcomes related to systems thinking as well as engagement with boundary systems e.g. through the simulation of 'real-life' work conditions.

Finally, it is noteworthy that all project coordinators highlighted the fact that most successful system projects are student-driven or initiated by highly motivated staff through a bottom-up process, and with goals that are shared and co-created between students and external stakeholders and thus extend beyond merely academic interests. Project coordinators take on the responsibility of 'creating space' for collaboration, either by literally ensuring a physical (and sometimes digital) space for collaboration and experimentation, or by contributing to and facilitating the infrastructure (e.g. funding) necessary for the project to continue and evolve, often investing their free time in the project as well. Thus, for system projects, or other interdisciplinary project types, to be implemented at a curriculum level, acknowledging this investment at an institutional level is likely crucial.

6 Conclusions and future work

The aim of this paper was to provide indicative and explorative insights into the implementation and integration of system projects within engineering education at Aalborg University. Through a cross-case analysis of five distinct system projects, we identified key dimensions that influence the success and sustainability of interdisciplinary PBL initiatives. These dimensions include curricular integration, system-level orientation, size/scale, interdisciplinarity, vertical integration, sustainability focus, student autonomy, and external partnership. Our findings highlight that successful system projects are characterized by flexible project definitions, opportunities for prototyping and experimentation, and objectives that resonate with both academic and broader societal goals. The role of project coordinators is crucial in creating and maintaining the infrastructure and support necessary for these projects to thrive as well as student-driven initiatives and the co-creation of goals with external stakeholders.

The eight-dimensional System Project curricular spiderweb model developed in this study offers a valuable framework for understanding and visualizing the variations in system project implementation. This model can serve as a guide for educators and administrators aiming to design and support interdisciplinary PBL projects that foster systems thinking and complex problem-solving skills among engineering students.

Future research should expand on this study by incorporating the perspectives of students, domain experts, supervisors, and external stakeholders involved in system projects. This broader range of insights will provide a more comprehensive understanding of the potentials and challenges associated with interdisciplinary PBL in engineering education. Additionally, there is a need to explore the long-term impacts of system projects on students' professional development and employability. Longitudinal studies tracking graduates who have participated in system projects could offer valuable data on how these experiences influence their career trajectories and ability to tackle complex, interdisciplinary problems in their professional lives.

Further investigation into the scalability of system projects is also warranted. Understanding how these projects can be expanded or adapted to different educational contexts and disciplines will be crucial for their broader adoption. This includes examining the potential for integrating system projects into existing curricula without extensive restructuring and exploring the role of digital tools and platforms in facilitating interdisciplinary collaboration. Finally, future work should consider the development of assessment frameworks that capture the unique learning outcomes associated with system projects, particularly in relation to systems thinking, interdisciplinary collaboration and student leadership. Such frameworks will be essential for evaluating the effectiveness of these projects and ensuring that they meet not only educational and academic objectives formulated by the study programs, but also the personal, transversal and transformative learning goals that students engaging in system projects set for themselves.

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Appendix A: Interview guide

Project Overview

- Can you briefly describe the system project (what is it, why this project, how did it come to be) and your own role in it?

Framing of the project

- Can you describe the framing you/your team have set up for the students?
    - What are the thoughts behind creating a more or less fixed/flexible structure for the project?
    - How significant is the system project compared to each study group's semester project?
        - Were the involved study programs selected by you or invited through an open call?
        - Do students work on the system project alongside their semester project, or is it fully integrated?
        - How do you/your team want this balance to be perceived by students?
    - How well do the students' curricula/learning objectives align with the project's goals?
        - Have you defined specific (domain-specific or transversal) learning objectives for the system project?
    - Are the students working on a concrete product as part of the system project?
        - If yes, what impact do you think this has on the process when students collaborate on a tangible product?
- What structure is in place to support students in system projects?
    - What are the expectations for students regarding overall coordination and management between groups?
        - Were students informed about this at the start of the project?
        - How do you think students handle this responsibility? Are they capable of taking on this role?
    - Are there structures in place to scaffold this (e.g., status seminars, sharing platforms, physical space etc.)?
        - How important are these for the collaboration?

Roles

- How do you see your role as a facilitator (and potentially other roles if relevant, e.g. supervisor, examiner) in relation to the groups?
    - Do you act as a specialist—helping with a better understanding of the product/system or assisting with collaboration structures?
    - Do you notice a change in how much support students need throughout the project?
    - How involved are you in facilitating collaboration between groups?
        - How much support do you think students need in establishing and developing interdisciplinary cooperation?
    - Do you find your role in this project more challenging than in other "regular" semester projects?
- How much coordination takes place between the involved supervisors/facilitators?
    - How important do you think collaboration between staff is for the project?
    - Do you feel that supervisors need additional support in system projects?

Progression

- If the system project spans multiple semesters:

- Do you observe any development in the project's goals/structure over time?
- Do you observe any development/change in the support needs of students, supervisors, and yourself as coordinator?

Institutional anchoring and Expansion

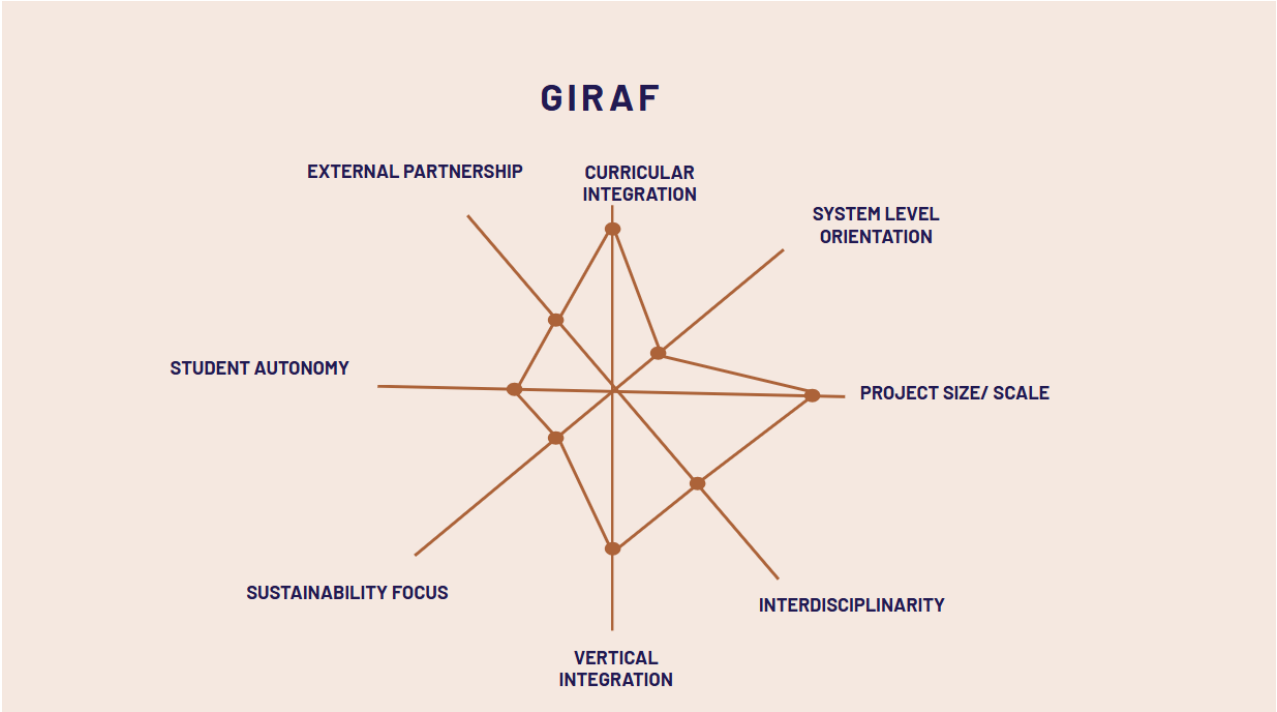
- In your opinion, what is needed to expand interdisciplinary system projects at AAU?
- What the advantages of system projects:
  - What are the biggest benefits for students?
  - What are benefits for supervisors
  - What are benefits for study programs, and AAU?
- What are the typical challenges/barriers for system projects:
  - For students
  - For supervisors
  - For study programs/AAU
- What could an ideal future scenario for system projects look like from your perspective?
  - What would it require to get there, in your opinion?

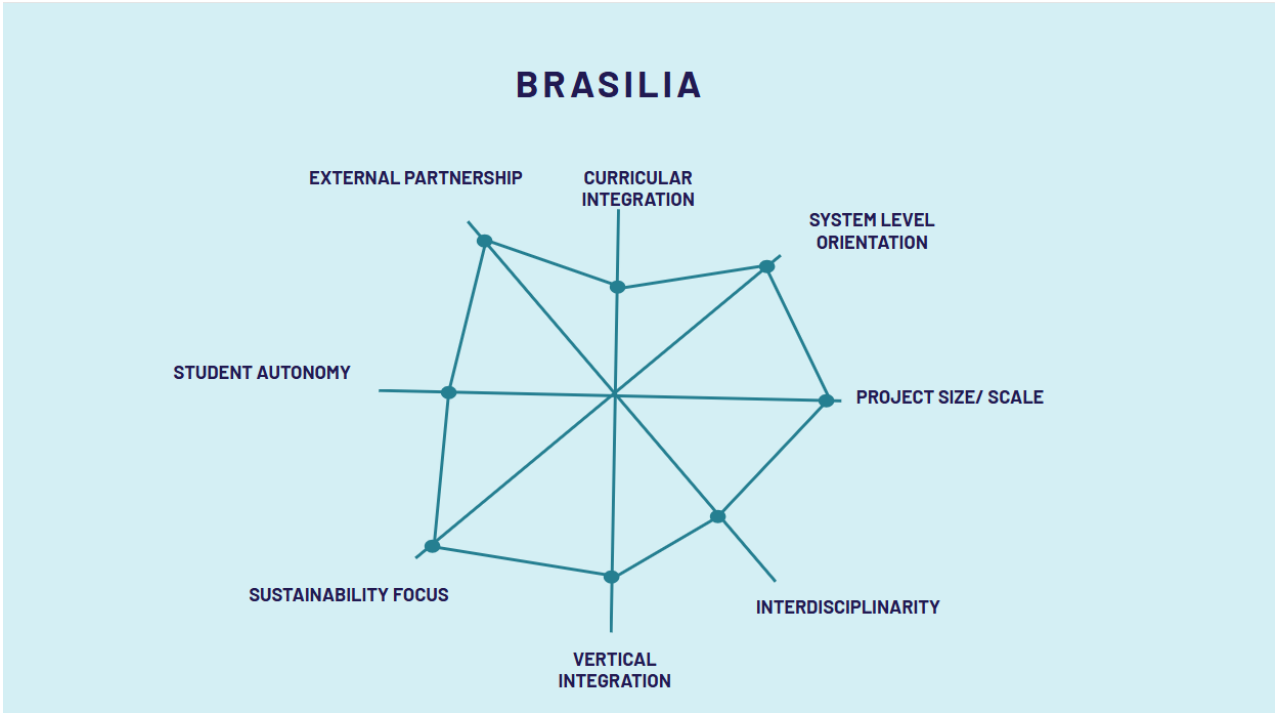
Appendix B: Cross-case synthesis

	Background/ History	Programs/ students involved	Project outcome/ Purpose	Curricular integration	Organisation and leadership	Strengths and barrierers identified by project coordinators
GIRAF	Title: "Graphic Interface foR Autistic Folks." Has been running since 2011. Referred to as a 'multi-project' at the department. Initial idea and collaboration with external partner was based on personal interest and network on the part of the first project coordinator. Current project coordinator is the 2nd coordinator.	Software development From 2023: + Interaction design + Bachelor of IT	Developing an app for autistic individuals. Collaboration with local special needs school. Resembling working as a 'software development unit'	Project fully integrated and mandatory on the 5th semester (15 ECTS) for Software students. Recently also Interaction design students, however ILO's not directly part of the curriculum – the focus is on collaboration. Should AI – does SW want it? Exam is group-based and discipline-specific. Common exception – shared section.	Semester Coordinator + Project Coordinator – becomes a "mini" Semester Coordinator -(Because many students are involved) – 50 hours allocated Project Coordinators. Stakeholders: Special needs school + S+ Gitte Østbæk (SUND) young people with cognitive challenges. + Inquiries from companies + Egebakken + Knowledge sharing: - Status meetings - Discord channel - GitHub (Package for the next group - students help the next batch (vertical sharing)	Strengths: Strong foundation/long history. Project theme is easy to scale up/relevant to other disciplines, e.g. social workers or other disciplines could come in later. If other disciplines are to be involved, they should come in as early as possible in the process. Coordinator has strong ties with external stakeholders – commitment and engagement. Student worker helps the transfer across semesters. Barriers: Aligning different curricula – some of which do not include ILO's specific to the project. Varied assessments/learning objectives. Inheriting previous students' work can be challenging.
AAU SAT	Since 1999. First send-off 2023	Electronic Systems, Antennas + Automation. Now 20-25 students at a time. At most: 70 students.	AAU SAT 6_ Live imagery for the mission. 5 own satellites. Project is evaluated based on the actual senf-offs (authentic) rather than specific intended learning outcomes.	Extra-curricular – however semester projects can be submitted as part of the AAUSAT project, but evaluations are independent of each other. No ILO's defined for the project.	Intially, the project was led by the coordinator, however students have taken charge –taking over from staff. Loose organization. Lab facilities play a key role in creating a space for organizing the collaboration. Discord is used for communication. Students attend the send-offs.	Loose frameworks create opportunities and development. Bottom-up is essential. Material costs are high, thus internal or external funding is important.
SPACE ROBOTS	Rooted in a specific robotics competition that evolves over each year. Drawing on previous experience with AAU RACING and LeadENG.	Materials and Production, Global business engineering, Energy, Robotics. Recently also Media and design. Bachelor and master students.	To compete in the yearly European Rover Challenge.	ILOs: Adapted to fit. Project not mentioned in the curriculum. Project transitions from semester to semester and year to year, following the competition criteria.	Grassroots-type leadership. Participation in competition is voluntary. Entire groups can be part of the space team, or one or two members from a group. Elected students serve as project leaders for the task. The task is to participate in the competition – not	Primarily financial barriers. Funding was recently raised for PhD. There has been no conflicts within the student team. Perhaps because participation is voluntary. Frameworks in the laboratory. Self-registered leisure organization with a CVR number. Instructor/researcher passionate about the theme (anchoring).

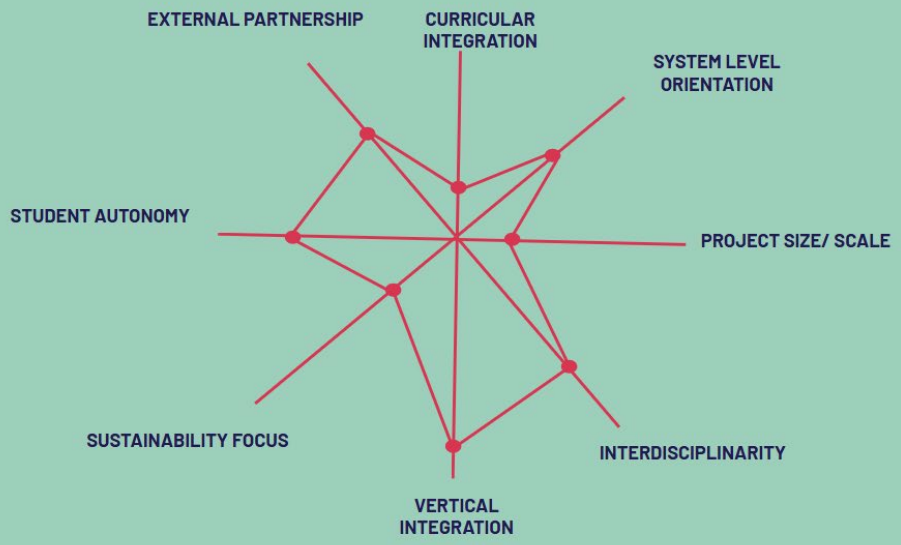
		One PhD student. A large mix of disciplines Currently, 25 students involved – previously 8.		The student team has been active for 1-2 years. Enthusiasts from the beginning have done significant work that has influenced success. Now in the 6th semester – started in the 2nd semester.	guided by supervisors but by students. The goal for the project coordinator is to interfere as little as possible.	Seed money – a lot can be accomplished with just 10,000 DKK.
SUSTAIN-ABLE DEVELOP-MENT LAB	Started E23 –with discussions and workshop. F24 – planning + initiated E24. 7th semester. International students seem to be interested as it provides collaboration with industry.	Techno-anthropology – fairly easily integrated into conver-sations/revis ions of study regulations. Information studies (Humanities). Mixed groups from different disciplines.	The purpose is specifically inter-disciplinarity. External partners: TIVOLI and a recycling stations (ARK).	Fully integrated into the curriculum with learning objectives from each program and a shared exam. Bringing subject expertise into it. Explicit ILO's addressing sustainability competences. Workshop courses with an introduction to topics. Established agreements/meetin gs once a month.	System projects from IASPBL – interdisciplinarity is the focus and supported by PBL research. Initial meetings with interested instructors. Groups + WS offerings. Midterm seminar and exam. 2 external examiners and 2 supervisors. Resources – supervisor hours followed the students	Strengths: Interdisciplinary knowledge – challenging to meet each other's expertise and collaborate = gain. Improved understanding of one's own discipline. Parameters for learning and reflection. Barriers: Exams were not uniform – caused some challenges. Differences in approval based on learning objectives and study boards. Another study board did not agree (too many offerings for the students). (Other initiatives: "Jernbanebyen". Techno-anthropology and urban planning – cross-disciplinary groups on sustainable urban development. Connecting disciplines). 90 students – most declined. Difficult group formation process.
BRASILIA – RECYCLE PROJECT	Eligitarian _ EU project/ Erasmus Clear need in Brasilia. Started in 2018. 2019 – waste managers. 2030 agenda. 2023 – Portugal, Netherlands, Brasilia and Denmark.	**First:** AAU and University of Brasilia PBL structure – due to AAU + Production Engineering Techno-anthropology + Computer Science + Cyber & Computer Technology + Software (40 students). 35 pr. semester/70 a year from AAU.	Multiple sub-projects have different purposes. Example: Data manager project Special purpose (SDG) – incentives to change according to the learning goals.	Integrated into curriculum – part of semester project. Fits learning goals of the semester and education programs. Supervisor there to secure – fits the education programs.	Project owners –across semester. Mostly students from Brasil. "Guardian of the project" – help in the transition to secure the cohesion. Project manager officer – managing in the country (section). Student-driven organisaton – Erasmus criteria.	ORGANISATION**:** Supports the project well as it is now. To succeed it needs administration, to provide structure and funding. It helps the students – university positive. Recommendations for collaboration across scientific/ education background: minimize dependencies, generic learning goals that you formulate together with students, electives.

Appendix C: Individual mapping of system projects

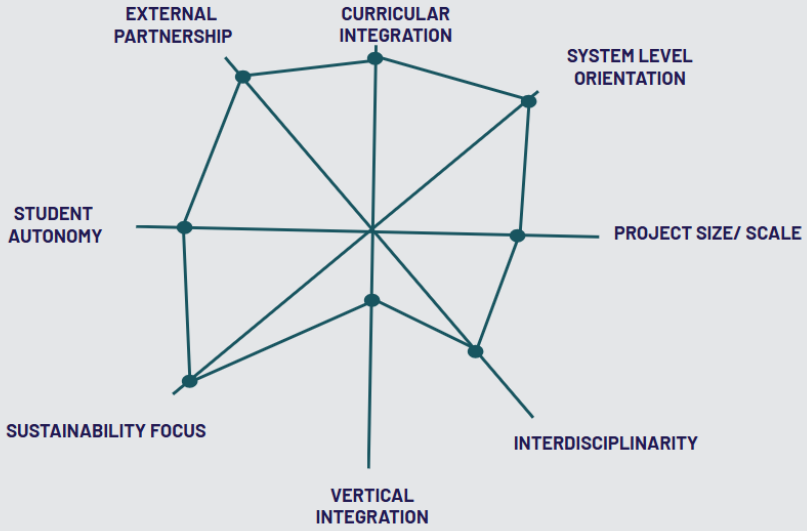


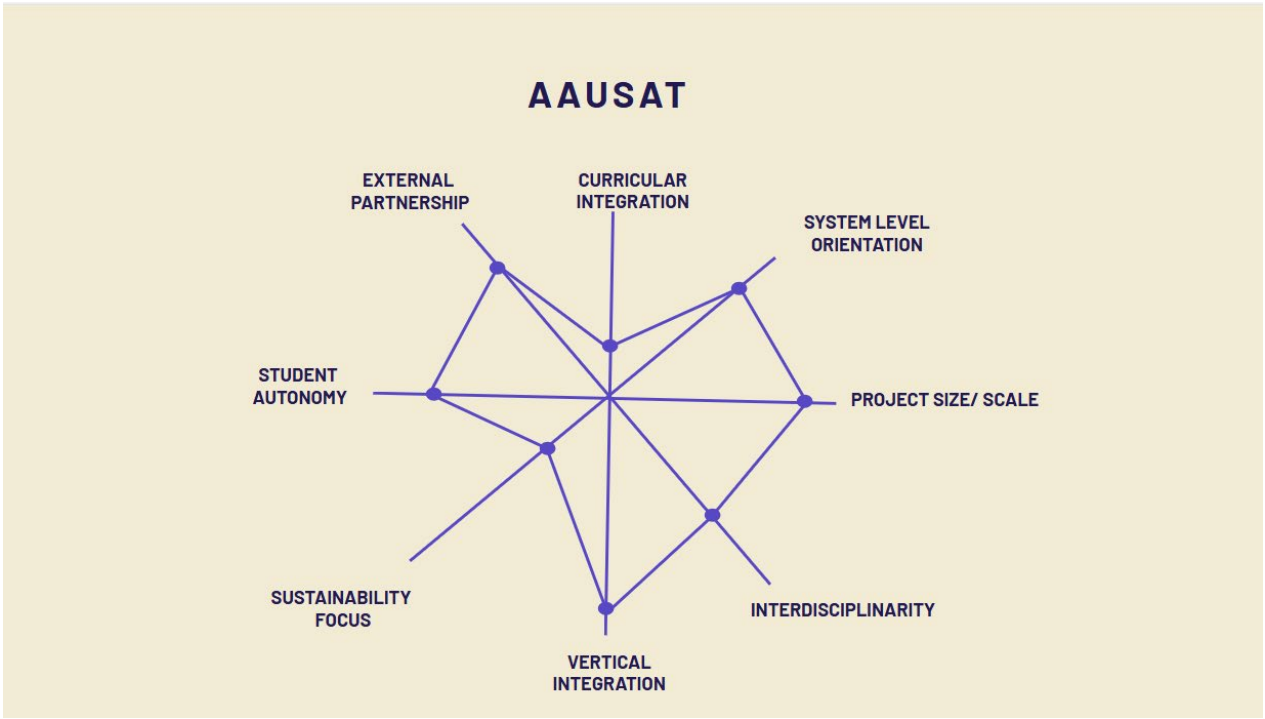


AAU SPACE ROBOTICS



SUSTAINABLE DEVELOPMENT LAB




AAUSAT
EXTERNAL PARTNERSHIP
CURRICULAR INTEGRATION
SYSTEM LEVEL ORIENTATION
STUDENT AUTONOMY
PROJECT SIZE/ SCALE
SUSTAINABILITY FOCUS
INTERDISCIPLINARITY
VERTICAL INTEGRATION

The Bigger the Team, the Bigger the Dream: Navigating the Madness of Leading Large-Scale Interdisciplinary Projects

Fiona Truscott
Centre for Engineering Education, University College London, UK, *f.truscott@ucl.ac.uk*

Lelanie Smith
Faculty of Engineering, Built Environment and IT, University of Pretoria, South Africa, *lelanie.smith@up.ac.za*

Abstract

As engineering education responds to increasingly complex global challenges, the demand for interdisciplinary competencies continues to grow. Interdisciplinary team projects have become a key pedagogical strategy for developing these skills, but scaling such projects to accommodate cohorts of 900+ students presents significant challenges. This paper investigates the practical realities of running extremely large-scale interdisciplinary modules through a comparative narrative inquiry. Building on earlier studies that examined theoretical and pedagogical dimensions of large-scale teaching, this third paper in the series shifts focus to the day-to-day implementation strategies that make such teaching possible. Drawing on the experiences of two practitioners working in research-intensive institutions in the global north and south, the study explores how intentional activity design and assessment practices are adapted at scale. The findings highlight the importance of calculated decision-making, inventive resource use, and structured communication in managing complexity. Rather than offering a definitive model, the paper surfaces practical strategies and tensions that others may encounter when scaling interdisciplinary education. In doing so, it contributes to a growing body of work aimed at supporting educators and institutions navigating the realities of mega-class interdisciplinary project delivery.

Keywords: Keyword 1, Keyword 2, keyword 3, keyword 4, keyword 5

1 Introduction

As global challenges become increasingly complex, engineering graduates must develop interdisciplinary competencies that enable them to navigate diverse perspectives and integrate knowledge across fields. In 2017, UNESCO published eight sustainability competencies as part of a skill set for sustainable development, complementing the content outlined in the Sustainable Development Goals (UNESCO, 2017). These competencies align with broader efforts to transform engineering education, aiming to prepare students for the complex, socially embedded challenges they will face in their careers (Graham, 2018;

Gómez Puente et al., 2013). Engineers today must address open-ended and ill-defined problems spanning technical, social, environmental, and economic domains, which requires integrating knowledge from multiple disciplines (Barut et al., 2006; Lattuca et al., 2013). As such, interdisciplinary engineering education (IEE) is increasingly implemented in curricula to prepare students for this reality (Lattuca et al., 2004).

To foster interdisciplinary competencies, many institutions have adopted interdisciplinary team projects as a pedagogical tool. These projects engage students in experiential learning (Kolb, 2014), encouraging collaboration, communication, and ethical decision-making across disciplinary lines (Kolmos et al., 2024). While such team projects are well-suited to developing critical 21st-century skills, their implementation is far from straightforward. De Ruiter et al. (2024) point out the lack of clear rules and guidelines for interdisciplinary collaboration, noting that aligning norms, concepts, and practices across disciplines involves significant conceptual labour. These challenges are magnified in extremely large-scale teaching contexts.

Engineering education is also under pressure from government and industry to deliver more graduates without compromising quality. This tension is particularly acute in interdisciplinary and general engineering project modules, which are often taken by students across multiple programmes and can easily exceed several hundred students in a single offering. Although team projects are commonly studied in cohorts of 80–100 students, modules with 500 to 900+ students present significantly different challenges (Hernández-de-Menéndez et al., 2019). Van den Beemt et al. (2020) stress the value of authentic interdisciplinary experiences but highlight the limited understanding of how to scale these effectively. As the size of cohorts increases, educators must shift from traditional teaching approaches to become facilitators, curators, and project managers. This transformation introduces new pedagogical, logistical, and structural complexities.

This paper is the third in a series on large-scale interdisciplinary teaching (Smith & Truscott, 2025; Truscott & Smith, 2024). It builds on earlier work that applied Kimpton and Maynard's (2023) framework for successful team projects to the realities of teaching cohorts of 900+ students. Drawing on the experiences of two internationally recognized practitioners from the global north and south, this study focuses on the practicalities of assessment and activity design in mega-class environments.

2 Literature

Interdisciplinary Team Projects and Their Role in Engineering Education
Interdisciplinary collaboration has become essential in addressing complex, real-world engineering challenges (Kamp, 2016). Research highlights that interdisciplinary teamwork fosters improved communication, problem-solving, and adaptability, equipping students with essential professional competencies (Sahin, 2019). The shift toward interdisciplinary education aligns with the broader trend of authentic, project-based learning environments that prepare students for multi-stakeholder engineering challenges (Graham, 2018). However, existing research primarily focuses on small-scale implementations, where coordination, assessment, and disciplinary depth are more manageable. Scaling Project-Based Learning (PjBL) in Large Cohorts

Scaling project-based learning (PjBL) introduces complex pedagogical and logistical challenges, particularly in interdisciplinary modules. Once class sizes exceed 300 students, direct student-teacher engagement becomes difficult, requiring intentional design and structural adaptations to maintain quality. The definition of "large-scale" varies across institutions, depending on available staff, room capacity, and administrative infrastructure. At UCL, a standard module involves 50–100 students managed by one or two academics with full pedagogical control (Truscott et al., 2023). Beyond this, instructional complexity and resource needs increase substantially.

Interdisciplinary PjBL adds further complexity, requiring scaffolded activities, clear role definitions, and structured milestones to ensure productive teamwork. Joyner et al. (2023) emphasize that intentional course design helps mitigate confusion and disorganization, while Pauli et al. (2008) identify poor task structuring as a major contributor to negative group experiences. Multi-channel communication and flipped or asynchronous formats can support scale, but automation must be balanced with meaningful engagement through mentorship and guided peer interaction.

We define four categories of large-scale teaching:

- Large Classes (100–300): Can still be split for interactive group activities.
- Massive Classes (300–500): Less flexible, but manageable with TAs and structure.
- Mega Classes (500–1,000+): Require multiple lecturers and coordinated planning.
- MOOCs (10,000+): Depend on automation and asynchronous tools.

These categories reflect the practical constraints and pedagogical adaptations needed at each level. While research often explores the shift from small to large teaching, the realities of mega-class education remain under examined. This paper builds on our prior work (Truscott & Smith, 2024; Smith & Truscott, 2025) by exploring the structural, instructional, and design choices that support effective interdisciplinary teaching at this scale.

The Changing Role of the Educator in Large-Scale Interdisciplinary Teaching

Large-scale interdisciplinary teaching shifts educators from content delivery to facilitation, coordination, and project management. This transition demands adaptability, mentorship skills, and comfort with uncertainty—often without formal training (Truscott & Smith, 2024). Educators must balance structured guidance with student autonomy while managing institutional pressures and logistical complexity. Diverse backgrounds can enrich facilitation, but sustained support is essential to prevent burnout. Faculty development, peer mentorship, and recognition of these evolving roles are critical. Technology can streamline logistics and feedback (Joyner et al., 2023), but ongoing course maintenance and alignment with learning goals remain significant challenges.

Project-Based Learning (PBL) and Vertically Integrated Projects (VIP) as Pedagogical Frameworks

Problem-Based Learning (PBL) is widely recognized for its real-world application, self-directed learning, and interdisciplinary integration (Kolmos, 1996; Mills & Treagust, 2003; Perrenet, Bouhuijs, & Smits, 2000). Savage, Chen, and Vanasup (2007) highlight how self-directed PBL enhances adaptability and fosters an appreciation for complex, interconnected problems. Research indicates that PBL improves conceptual understanding, problem-solving skills, and self-efficacy, making it an effective model for interdisciplinary learning (Dunlap, 2005; Mills, 2009; Prince, 2004; Gavin, 2011). However, Heitmann (1996) notes a persistent tension between product-oriented and process-oriented learning, as institutions often prioritize measurable outcomes over deeper competency development.

To address this and support scaling, many institutions have adopted Vertically Integrated Projects (VIP), which integrate students at different levels, enabling peer mentoring, research alignment, and multi-semester continuity (Pai et al., 1998). This shifts students from passive learners to active participants, aligning with interdisciplinary PjBL (Fung, 2017). VIP models enhance social support, conceptual understanding, and professional development beyond traditional PBL (Feldman, 2006; Strachan et al., 2019)

Another essential dimension for supporting Project-Based Learning (PBL) and Vertically Integrated Projects (VIP) at scale is team teaching. As Van Hattum-Janssen et al., (2022) argue, successful team teaching is not only crucial to the success of PBL in engineering education but also serves as a live model of collaboration for students themselves. In large interdisciplinary modules, teacher collaboration is essential for planning project themes, defining learning outcomes, and providing consistent support across disciplinary lines

(Powell, 2007; Guerra et al., 2017). Team teaching challenges traditional notions of teacher autonomy and disciplinary silos, requiring co-planning, shared responsibility, and active reflection grounded in constructivist learning theory (Vesikivi et al., 2019; Hannafin et al., 1997).

3 Context and Purpose

The scale and complexity of interdisciplinary education in engineering programs present unique organizational challenges that remain underexplored in the literature—particularly for in-person cohorts exceeding 900 students. While project-based learning (PjBL) is well-documented in small to moderately large settings, limited research exists on how to structure and sustain interdisciplinary teamwork at extreme scale.

This paper draws on two case studies from research-intensive institutions in the global north and south, each implementing interdisciplinary, team-based modules at a scale rarely documented. At UCL, the Engineering Challenges module involves 900–1,000 first-year engineering students across seven departments, integrating discipline-specific problem-solving within a structured, faculty-wide framework. At the University of Pretoria, the Joint Community Project (JCP) requires 1,650 second-year students across 18 programs to collaborate on community-based engineering projects in interdisciplinary teams. Despite contextual differences, both modules rely on extensive coordination, logistical planning, and intentional learning design to support student engagement and pedagogical integrity (Truscott & Smith, 2024; Smith & Truscott, 2025).

Rather than proposing a finalized model, this study continues our investigation into the evolving dynamics of facilitating interdisciplinarity at scale. We examine practical aspects of resource allocation, intentional activity design, and assessment strategies in Mega classes. As these modules grow, educators must shift from traditional lecturers to facilitators and project managers, constantly adjusting to balance oversight with student autonomy. Emerging challenges in assessment, particularly around feedback mechanisms, and the emotional demands on educators further complicate implementation. Within this paper, we discuss the overall picture of Mega class delivery however, we did not have enough space to fully unpack all aspects and so we link to two other papers (Smith et al., 2025; Truscott & Smith, 2025) where we have gone into more detail about certain aspects of delivery. By articulating these aspects through practical examples, this paper shares emerging strategies for sustaining depth, engagement, and educator well-being in large in-person interdisciplinary modules. While we do not yet offer a definitive framework, our aim is to contribute meaningfully to ongoing discussions on what it takes to teach interdisciplinary teamwork at scale.

4 Method

This study builds on prior research examining the facilitation of large-scale interdisciplinary teamwork modules in engineering education at research-intensive institutions in the global north and global south. While previous work explored teamwork development and interdisciplinary collaboration using autoethnographic writing (Ellis & Bochner, 1999; Choi, 2012) and shared narrative inquiry (Chase, 2005), it did not explicitly address the intentional design of learning activities and assessment strategies. This study extends that work by focusing on the assessment frameworks and activity design choices that underpin teamwork development in these courses. To reflect the pedagogical and logistical complexities of courses with 900+ students, we introduce the term Mega Classes, moving beyond a description of scale alone to explore the intentional structuring of student learning, assessment, and teamwork in these environments.

The facilitators engaged in structured shared narrative inquiry, continuing their collaborative discussions while incorporating first-hand observations from institutional visits. These visits provided direct exposure to

each other's teaching practices, assessment structures, and student interactions, enriching their reflections with new contextual insights. Each facilitator documented and exchanged reflections, revising their narratives through an iterative feedback process. This was complemented by a comparative instructional analysis, in which the facilitators systematically reviewed study manuals, assessment rubrics, and instructional materials to examine the alignment between assessment strategies and learning outcomes. Key themes emerging from this analysis were synthesized into practical recommendations for structuring teamwork assessment and activity design in Mega classes.

5 Findings

Teaching teamwork in a Mega class environment (900+ students) requires a structured approach that minimizes direct lecturer-student interaction while sustaining clarity, engagement, and pedagogical quality. The focus shifts to clear communication, automated guidance, and structured peer engagement. Without these systems, misunderstandings, disengagement, and administrative overload quickly escalate. The challenge lies in helping students understand what to do, how to do it, and why it matters—without constant oversight.

5.1 Observations from JCP

Success in the Joint Community Project (JCP) module hinges on automated support systems, structured peer interaction, and a layered mentorship model. A vertically integrated mentorship system mirrors professional hierarchies: students manage their projects as "junior staff," mentors offer strategic guidance, and faculty provide high-level oversight. This structure reduces dependency on faculty, promotes student independence, and models workplace dynamics. The JCP Online Platform supports this system with automated FAQs and logistical information, minimizing unnecessary communication and freeing faculty for critical learning interactions.

5.1.1 Structuring Teamwork Development: Processes and Tools

Effective teamwork at Mega scale requires more than simply grouping students—it demands structured scaffolding to build essential collaboration skills. JCP Week serves as a critical onboarding phase, introducing foundational concepts of teamwork, leadership, and professional engagement. Before the week begins, students are placed into diverse teams of four to five using an automated system, simulating real-world project conditions where teams are rarely self-selected. They then participate in mentor-led introductions, exploring backgrounds, motivations, and expectations to establish early cohesion and identify potential conflict areas.

To formalize collaboration, each team creates a group contract that outlines shared values, meeting routines, and conflict resolution strategies. This proactive step fosters accountability and helps address challenges—like uneven participation—before they escalate. Simultaneously, students develop their project proposals, considering feasibility, resource needs, and ethical dimensions. These are structured through prompts that guide students in applying systems thinking from the outset, nudging them from passive learners toward independent problem-solvers.

Students also receive targeted professional development. Enneagram-based exercises help them understand their communication styles, while scenario-driven leadership and conflict management training prepares them for real-time interpersonal challenges. These preparatory activities offer not only a framework for collaboration, but also mirror the skills expected in professional environments.

This structured setup—explored further in (Truscott and Smith, 2025)—allows students to begin their interdisciplinary projects with confidence and clarity, building autonomy while reducing the demand on teaching staff at scale.

5.1.2. Assessment at Scale: Managing Feedback and Engagement

Assessment in a Mega class must be both meaningful and scalable. With such a large number of students, traditional feedback models become unsustainable, requiring an approach that is structured, automated where possible, and designed to guide learning rather than merely evaluate performance. The assessment process in JCP is built around layered evaluation methods that integrate self-assessment, peer feedback, mentor input, and community partner evaluations.

One of the most crucial assessments occurs early in the course, with the submission of the project proposal. This one-page document forces students to think critically about their project's objectives, feasibility, and anticipated challenges. The structured nature of the proposal ensures that students engage in focused, strategic planning without being overwhelmed by unnecessary complexity. Faculty review is streamlined using a highly standardized rubric, allowing for fast, consistent feedback that enables students to refine their approach before moving forward.

Throughout the semester, students complete bi-monthly reflective check-ins, connecting their experiences to concepts introduced during JCP Week. These short reflections prioritize the process of thinking rather than content depth. Faculty and mentors scan them for relevance and completion, offering marks for engagement rather than detailed critique. At this scale, the act of structured reflection is more valuable than the individual insights themselves. The final assessment consists of a dual-component video submission, requiring students to showcase both the outcome of their project and their personal growth throughout the process. The first component, a project execution video, provides a professional-style summary of the team's work, while the second, a structured team reflection video, captures individual insights and learning experiences. This format not only makes assessment more engaging but also ensures that students develop essential communication and storytelling skills.

5.1.3. Communication, Logistics, and Automation (see Smith *et al.*, 2025)

Managing a course of this size effectively requires a meticulously structured communication system. Without clear guidelines, administrative burden can spiral out of control. To prevent this, a strict hierarchy of information access has been put in place. Students are first directed to the JCP Online Platform, where they can find detailed explanations of assignments, structured FAQs, and automated responses to common queries. If their concerns are not addressed there, they are expected to consult their team members or their assigned mentor before escalating their query.

The vertically integrated mentorship model plays a crucial role in ensuring that students receive the support they need without overwhelming faculty resources. Within this system, mentors are trained extensively in facilitation techniques, allowing them to guide students rather than simply provide answers. This approach not only fosters student independence but also strengthens the mentorship experience itself, as mentors gain valuable leadership and coaching skills.

By structuring communication through multiple layers of support, JCP has managed to maintain high student engagement while keeping the administrative workload under control. The use of automated query responses, structured announcements, and clear escalation protocols has been essential in making this model work effectively at scale.

5.2. Observations from Engineering Challenges

Engineering Challenges spans seven departments at UCL, requiring careful coordination of a large, distributed teaching team. Each department contributes 1–3 academic staff (departmental leads) who tailor aspects of the module to align with their curricula. While this ensures disciplinary relevance, it limits oversight of the module as a whole. The module lead—uniquely focused on the full cohort—must maintain coherence across departmental adaptations. Around 45 postgraduate teaching assistants (PGTAs) support

delivery, though their work is often siloed, adding complexity to communication and consistency across the module.

5.2.1 Structure (see Truscott & Smith, 2025)

The structure of Engineering Challenges is central to managing both student learning and teaching team coordination across seven departments. It functions as a roadmap, aligning with communication strategies to signal each stage of the project and reduce the need for continual reminders. While the structure is simplified to support clarity, the module's complexity and distributed teaching team limit how much streamlining is possible. Departmental leads focus on their own segments of the course and may not always see or understand the broader rationale behind specific constraints. The module lead must maintain coherence by balancing local flexibility with module-wide consistency.

Importantly, the structure is not only logistical but pedagogical. It models real-world project workflows, helping students understand how to plan, communicate, and collaborate effectively. Project milestones are intentionally aligned with common professional decision points—for example, students must present their experimental plans before accessing lab time, mimicking client or manager approvals. This intentional structure reduces reliance on staff for routine clarifications, allowing them to concentrate on higher-level interventions like team mediation or supporting students with additional needs. By encouraging students to manage tasks independently, the structure fosters resilience and problem-solving—skills critical for engineering practice.

5.2.2 Communication (see Smith *et al*., 2025)

Effective communication is crucial, as no message will reach 100% of your cohort (or staff!). On Engineering Challenges, we use multiple channels such as workshops, Moodle, and forums to increase coverage as much as possible. This is particularly clear when you need to communicate a change in what's happening. Some students will miss any update and work with old information. Thus it's essential to get communications as clear and accurate as possible the first time. This avoids the need to issue constant clarifications, which may cause more confusion, and avoid receiving a lot of emails asking further questions or if something is true. Regular reminders are also essential—frequent updates for students during term and annual reminders for staff help reinforce key information.

Avoid overwhelming students with too much information at once, especially at the start of a project. This is a particular challenge in Engineering Challenges because of the timing of the module - first year, first term. During this period, they are navigating the shift from school to university —managing their own schedules, living independently, and, in UCL Engineering's case, adapting to active learning environments. With so much to take in, students often disengage quickly and may be reluctant to revisit information later due to feeling overwhelmed.

5.2.3 Assessment (see Truscott & Smith, 2025)

Providing timely, consistent feedback at scale is a persistent challenge. In Mega classes, instructors must choose between fast or thorough feedback—rarely both. Mid-module assessments amplify this tension, especially when juggling hundreds of submissions alongside teaching and communication duties.

Using multiple markers can help distribute the workload, but it introduces variation in marking interpretations, particularly in open-ended assessments such as ethics or sustainability reports. Extensive moderation is often required, but can delay feedback and feel disconnected from original comments. Without it, inconsistencies raise fairness concerns. In a 1,000-student class, even a 10% error rate could generate 100 student queries—creating a heavy communication burden. To mitigate this, live assessments are used during the project to provide timely, formative feedback when students can still act on it. Written submissions are scheduled for the end of the module, when feedback urgency is lower and harmonisation

time is available. Live assessments bring their own logistical challenges—scheduling in a packed timetable and ensuring fairness across presentation slots. Engineering Challenges addresses this by running parallel assessment panels in a single workshop, drawing on faculty, departmental leads, and PGTAs. These sessions also build shared understanding of the module among staff.

Complex assessments enhance authenticity but require meticulous communication. Students must know what is expected and when. Multi-step assessments demand consistent messaging and robust follow-up mechanisms. In large cohorts, even small miscommunications scale quickly, so clarity and consistency across all teaching staff are essential to manage expectations and maintain engagement.

5.2.4 Logistics

As mentioned earlier, logistics becomes a major concern when working at this scale. Booking classroom space, for example, requires detailed strategies and contingency plans rather than a simple request through the timetabling system. When your cohort can't fit into a single room, you quickly become familiar with all the university's large spaces, who else might need them, and how to secure those slots. Managing this requires plans for splitting the cohort across multiple rooms and ensuring clear communication with staff and students.

Key considerations include:

- How close can you get to room capacity—can you risk being slightly over the limit, knowing not all students may attend every class?
- Do you have enough staff to split a class if needed?
- Can the session be moved, or must it happen at a specific time?
- Which activities require flat space, and which can work in a lecture theatre?
- How far apart are available rooms, and can staff move quickly enough between them to manage back-to-back sessions or swap mid-class?
- Will departmental leads be open to these adjustments, and what teaching adaptations are required as a result?

These just aren't issues when you have 30 students on your module. The module lead must balance the demands of central timetabling services, the module's requirements, and the preferences of departmental leads—who may not always understand the broader university constraints. Ultimately, managing these logistics becomes a form of large-scale project management, with contingency planning built into every decision.

6 Discussion and Implications (see Smith *et al.*, 2025; Truscott & Smith, 2025)

The findings from this study highlight the complexities of facilitating interdisciplinary teamwork at Mega scale and the evolving strategies needed to maintain engagement, structure, and assessment integrity. While multiple factors contribute to successful large-scale implementation, this discussion focuses on two key themes: Intentional Activity Design and Assessment at Scale. These elements are fundamental to sustaining meaningful student experiences in large cohorts while ensuring the feasibility of instruction at this scale.

6.1 Intentional Activity Design: Structuring Teamwork for Scale

Interdisciplinary teamwork requires carefully designed scaffolding to ensure students can collaborate effectively without direct faculty intervention. Both case studies—JCP at UP and Engineering Challenges at UCL—demonstrate how structured mentorship, strategic communication, and phased onboarding support large-scale teamwork.

At UP, the vertically integrated mentorship model reduces the burden on faculty by establishing clear communication hierarchies. Students first consult teammates, then escalate issues to their assigned mentor, ensuring faculty time is reserved for higher-level interventions rather than routine clarifications. This mirrors a professional organizational model, reinforcing autonomy while providing structured support. Importantly, the mentorship structure serves multiple purposes—it not only provides social connections for students within the class but also allows senior students to develop leadership, management, and mentorship skills. At the same time, it alleviates some of the workload pressures on faculty by distributing support more equitably across different layers of mentorship. At UCL, teamwork structures focus on aligning departmental autonomy with a shared module framework and framing for teaching teamwork. While departmental leads adapt content for their specific disciplines, the overarching module design ensures consistency, preventing fragmentation. Structured milestones, such as team-based presentations and progress check-ins, mimic real-world project workflows, guiding students through key decision points.

A shared challenge in both models is ensuring that students are equipped with the skills needed to navigate interdisciplinary work before they begin project tasks. UP addresses this through JCP Week, an intensive onboarding program covering teamwork dynamics, conflict resolution, and leadership. Another critical consideration in structuring large-scale teamwork is the role of in-person engagement in building relationships and enhancing collaboration. Both case studies emphasize that while online platforms and automation are essential for managing scale, there is no substitute for in-person interactions, particularly at the start of a project. At UP, JCP Week was introduced as a dedicated period where students engage with their teams, mentors, and faculty in structured, intensive sessions. Given the logistical challenge of scheduling across 18 programs, this required rethinking the traditional academic timetable—exploring whether activities could take place outside standard term time, weighing the trade-offs, and implementing contingency plans for students unable to attend. While such structural changes introduce complexity, they are crucial for establishing early team cohesion and ensuring smoother collaboration throughout the module. UCL integrates early-stage structured teamwork assessments, ensuring students engage meaningfully from the outset. A skills module runs alongside Engineering Challenges providing just-in-time teaching for skills as they are used by students within the project, allowing for a highly practical approach to teaching and giving students space to put their learning into practice straight away. These structured interventions build a foundation for independent problem-solving, an essential skill at this scale.

Effective resource use is another fundamental aspect of successful large-scale teaching. Given the constraints of faculty time, physical space, and administrative resources, both modules rely on innovative decision-making to optimize their teaching approaches. The ability to make calculated, strategic decisions ensures that resource allocation is not only efficient but also serves multiple functions simultaneously. For example, structured peer mentorship in JCP simultaneously builds student leadership skills, reduces faculty workload, and fosters a sense of community—demonstrating how decisions at scale must be multi-purposeful rather than merely reactive. In UCL the use of live assessments reduces staff load and makes the module more authentic.

6.2 Assessment at Scale: Balancing Structure and Flexibility

Scaling assessment presents unique logistical challenges, requiring efficient evaluation processes that provide meaningful feedback without overwhelming faculty resources.

At UP, the JCP module prioritizes process-oriented assessment, emphasizing the act of reflection over detailed faculty review. Given the impossibility of reviewing 1,600 individual reflections every two weeks over a 6 month period, the focus shifts to ensuring that students complete reflections meaningfully rather than scrutinizing content at a granular level. Short response prompts guide student thinking, and assessments are graded for completion rather than depth. This approach reinforces learning without creating unsustainable faculty workloads. At UCL, balancing timeliness and depth in feedback is a critical

concern. Live assessments are used strategically, offering immediate formative feedback during project milestones, while written assessments are reserved for the end of the project. A carefully structured moderation process ensures consistency across multiple assessors, reducing discrepancies in grading and preventing excessive student queries.

One of the greatest challenges in Mega scale assessments is maintaining transparency and fairness while managing high student expectations. Both institutions emphasize clear, structured communication around assessment criteria and expectations. By using multiple communication platforms, structured feedback loops, and transparent assessment frameworks, students are better able to navigate assessment requirements independently, reducing unnecessary escalations.

6.3 Emerging Insights and Future Considerations

This study offers a framework for scaling interdisciplinary team projects by integrating:

- Teaching methodologies that support large cohorts without sacrificing depth.
- Assessment strategies that ensure equitable and constructive evaluation.
- Coordination approaches that account for institutional and cultural differences.

While no single model applies to all contexts, these findings provide a roadmap for institutions looking to implement large-scale interdisciplinary projects while maintaining quality and engagement. Additionally, this study identifies commonalities and variances in integration approaches, examining context-specific adaptations required for implementation in South Africa and the factors influencing successful scaling in different institutional settings.

While this study highlights promising practices in teamwork structuring and scalable assessment, key challenges remain. The need for adaptive mentorship models, sustainable feedback mechanisms, and institutional support is evident. Moving forward, further research should explore how technology can enhance real-time student support, how interdisciplinary coordination can be further streamlined, and how faculty can be better prepared for the evolving role of large-scale facilitation. By sharing these insights, this study contributes to the broader conversation on scaling interdisciplinary education while maintaining depth, engagement, and sustainability. While we continue to refine best practices, these findings provide practical considerations for institutions seeking to implement large-scale interdisciplinary team projects effectively.

7 Conclusion

Successfully scaling interdisciplinary teamwork in Mega classes requires a structured yet flexible approach. A key lesson from both JCP and Engineering Challenges is that students thrive when given a clear framework combined with the autonomy to navigate their learning journey. Moving from faculty-driven instruction to peer-led facilitation has proven essential in fostering student ownership, reducing faculty workload, and enhancing teamwork dynamics.

As these modules continue to evolve, innovative solutions such as AI-supported assessment, structured peer engagement, and automation tools are being explored to enhance learning at scale. Despite these structured approaches, assessment remains a challenge, particularly in providing meaningful individualized feedback. Peer and mentor evaluations help distribute the workload, but efforts are ongoing to integrate AI-driven assessment tools that offer automated yet personalized feedback on student reflections.

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The WOW Project: An Experiential Learning Approach to Developing Teamwork and Project Management Competencies in South African Engineering Education

Ann Lourens
Nelson Mandela University, South Africa, ann.lourens@mandela.ac.za

Curwyn Mapaling
North-West University, South Africa, curwyn.mapaling@nwu.ac.za

Nicole Truter
Nelson Mandela University, South Africa, nicole.truter@mandela.ac.za

Abstract

This paper examines the implementation and impact of a Workplace Orientation Workshop within a South African industrial engineering programme, designed to cultivate essential graduate attributes mandated by the Engineering Council of South Africa. The study was guided by three research questions: how the WOW Project aligned with ECSA's GA8 criteria, how student participation contributed to teamwork and project management competencies, and what insights student reflections offered about the role of experiential learning in shaping responsible engineering practice. Employing a qualitative methodology, the study analyses student reflections on their participation in the Workplace Orientation Workshop Project. The analysis revealed three prominent themes: (i) preparation for professional transition; (ii) project management and leadership experience; and (iii) enhanced communication and interpersonal skills. Grounded in situated learning theory and problem-based learning principles, the WOW Project provided a practical platform for students to apply engineering management principles and develop critical competencies through experiential learning. Findings highlight the effectiveness of the WOW Project in bridging the gap between academic learning and professional readiness, fostering responsible engineering practices. Recommendations include expanding the scope of future Workplace Orientation Workshop Events and implementing structured feedback mechanisms to enhance student learning outcomes.

Keywords: Experiential learning, graduate attributes, engineering education, situated learning, problem-based learning

1 Introduction

South African universities are mandated by the Engineering Council of South Africa (ECSA) to integrate and assess eleven graduate attributes (GAs) within their engineering programmes (ECSA, 2018). These attributes ensure that engineering graduates possess the necessary competencies to address complex societal and professional challenges. Among these attributes, GA8 focuses on individual, team, and multidisciplinary working, which are critical for shaping engineers capable of delivering responsible and impactful solutions.

GA8 requires students to demonstrate knowledge and understanding of engineering management principles and apply them effectively in their own work, as team members and leaders, while managing projects. The associated learning outcomes include the ability to plan, organise, lead, and control tasks; perform individual work strategically and on time; function as a team leader; and communicate effectively in diverse professional contexts. These competencies are foundational for fostering teamwork and project management skills that align with the broader goal of producing responsible engineers.

For this study, the GA8 definition was based on the 2018 version (E-02-P-Rev4-1, September 2020), which was the officially available standard during the implementation of the Workplace Orientation Workshop (WOW) Project. The revised GA8 criteria, published in August 2023, were only released after the project had been completed and are therefore is not reflected in this work. In 2023, a final-year module titled *Industrial Engineering Professionalism and Ethics* was introduced as a platform for assessing GA8 through an experiential learning approach. This approach emphasises active engagement with real-world scenarios, enabling students to develop teamwork and project management competencies through iterative practice. By embedding experiential learning principles into the module design, students were encouraged to reflect on their roles as individuals and team leaders while navigating multidisciplinary challenges.

This paper describes the development of the project-based learning activities embedded in the module, as well as the assessment processes designed to evaluate students' mastery of GA8. It explores how experiential learning strategies were employed as an approach to fostering the development of responsible engineers,

with a focus on equipping them with skills for effective teamwork, ethical decision-making, and project execution in the South African engineering context.

To guide the study, the following research questions were formulated:

- How did the design and implementation of the WOW Project align with ECSA's GA8 criteria?
- In what ways did students' participation in the WOW Project contribute to the development of teamwork, project management, and professional competencies?
- What insights from students' reflections illustrate the role of experiential learning in shaping responsible engineering practice in the South African context?

2 Situated learning theory

Situated Learning Theory (SLT) provides a foundational framework for designing educational experiences that mirror real-world application contexts, fostering problem-solving skills essential for engineering practice (Renkl, 2001). SLT explains how learning occurs when students participate in a community of practice (Lave & Wenger, 1991), where they engage in meaningful activities that develop internal knowledge structures (Newstetter & Svinicki, 2014). Within such communities, students' progress from peripheral roles as novices to central roles as experts through Legitimate Peripheral Participation, which enables them to acquire expertise by actively engaging in collaborative practices (Lave & Wenger, 1991). This process not only enhances technical skills but also cultivates teamwork and leadership abilities critical for responsible engineering.

Research supports that situated learning environments facilitate knowledge transfer to real-world contexts more effectively than traditional methods (Catalano, 2015). As students transition toward full participation in their communities of practice, they develop advanced skills in management, collaboration, and communication, key competencies for addressing complex engineering challenges responsibly (Herrera, 2020).

One instructional model aligned with SLT is Problem-Based Learning (PBL), which has been shown to promote deep learning approaches over superficial ones (Renkl, 2001). Deep learning, as first described by Marton and Säljö (1976), is characterised by intrinsic motivation, active engagement, and the intention to integrate and critically evaluate knowledge, leading to robust and transferable understanding. By contrast, surface learning, also conceptualised in their work, tends to rely on rote memorisation and fragmented knowledge, often driven by extrinsic factors such as exam performance (Marton & Säljö, 1976). This distinction is particularly relevant in PBL contexts, where learners are required to actively construct meaning through problem-solving and collaboration, thereby reinforcing the hallmarks of deep learning while countering tendencies toward surface approaches. For engineering students, PBL offers numerous benefits: fostering active learning, self-directed capability, interdisciplinary thinking, and transversal skills such as teamwork and project management (Cruz Moreno et al., 2023; Du & Kolmos 2009). Additionally, PBL enhances self-confidence, self-efficacy, a sense of belonging (Du et al. 2020; Kolmos & de Graaff 2014), and teamwork capabilities (Boelt et al. 2022). These outcomes align closely with GA8's focus on individual work effectiveness, team leadership, and communication.

The design of the GA8 assessment project drew heavily on these principles of SLT and PBL. By embedding situated learning practices into the module *Industrial Engineering Professionalism and Ethics*, students were provided with opportunities to engage in authentic problem-solving scenarios that developed their teamwork and project management competencies while preparing them to become responsible engineers.

3 Module structure and management

The GA8 assessment was embedded in the *Industrial Engineering Ethics and Professionalism* module through a carefully designed project that operationalised principles of both SLT and PBL. The Workplace Orientation Workshop (WOW) Project served as the central activity, providing students with an authentic context to develop teamwork and project management competencies while addressing ECSA's GA8 criteria. This section outlines the module structure, preparation steps, and pedagogical strategies used to scaffold student learning and ensure meaningful engagement with GA8.

3.1 Overview of the WOW Project

During the first class of the semester module, students were introduced to the WOW Project as a practical means of assessing GA8. The lecturer proposed that the assessment meet the following criteria:

- Be meaningful and contribute to student development;
- Provide a foundation for future cohorts to build upon;
- Serve the industrial engineering student community;
- Teach practical life skills to prepare students for the workplace; and
- Fulfil ECSA's GA8 requirements.

The WOW Project tasked students with organising, planning, and executing a series of workshops aimed at preparing industrial engineering students for workplace challenges. This was particularly important given that the current engineering curriculum does not include in-service training or industry-based experience. By addressing this gap, the WOW Project aligned with broader goals of shaping responsible engineers equipped for professional practice.

In this paper, the term WOW Project refers to the overall student assignment, which involved planning, organising, and managing workplace-preparedness activities, while the WOW Event refers to the culminating implementation day when the student-designed workshops were delivered.

3.2 Pedagogical design

To ensure successful execution of the WOW Project and foster GA8 competencies, five preparatory steps were implemented:

3.2.1 Team foundation

Thirty-four final-year students enrolled in the module were divided into eight teams. Teams consisted of two to five members each, reflecting real-world multidisciplinary work environments where team sizes vary based on project scope. Team formation provided students with an opportunity to engage in collaborative practices central to SLT's concept of Legitimate Peripheral Participation (Lave & Wenger, 1991).

3.2.2 Self-Reflection on strengths and weaknesses

Once teams were formed, students participated in a self-reflection exercise to identify their individual strengths and weaknesses as team members. Each student shared their reflections within their teams, fostering metacognitive awareness of their roles in contributing to project success. This activity encouraged students to take ownership of their personal development while promoting effective teamwork.

3.2.3 Learning styles

Students completed Kolb's (2014) learning styles instrument to identify their preferred learning styles: converging, diverging, assimilating, and accommodating. Each style reflects a distinct way of engaging with learning. *Converging* emphasises practical problem-solving; *diverging* draws on imagination and multiple perspectives; *assimilating* favours a concise, logical approach; and *accommodating* relies on intuition and

hands-on experience. Teams discussed how these styles could complement one another during project execution. This exercise helped team leaders allocate tasks strategically and anticipate challenges based on individual preferences. It also reinforced PBL's emphasis on self-directed learning, which refers to a process in which individuals take the initiative in diagnosing needs, setting goals, identifying resources, implementing strategies and evaluating outcomes (Knowles, 1975).

3.2.4 Conflict management

A workshop session introduced students to different conflict management styles (Thomas & Kilmann, 1974): avoiding, accommodating, and competing. *Avoiding* involves disengaging from the conflict; *accommodating* prioritises the needs of others; and *competing* focuses on asserting one's own position. Through discussion and role-play, students explored their preferred styles and developed strategies for navigating interpersonal challenges in collaborative work. This activity aligned directly with GA8's requirement for effective communication in multidisciplinary contexts.

3.2.5 Researching workplace preparedness

Teams conducted research into workplace preparedness using a Delphi process to identify key topics for the WOW Event sessions. The Delphi process is a structured communication technique used to obtain a consensus of opinion from a panel of experts on a particular topic, typically through a series of questionnaires or rounds of feedback (Hsu & Sandford, 2007). Students explored literature on what graduates need to know before entering the workforce, focusing on skills such as professional conduct, technical expertise, and adaptability. Six topics were selected based on consensus among teams. The selected topics and speakers are listed in Table 1.

Table 1: WOW topics and speakers.

Topic	Invited Speakers' Portfolio
Financial management, payslips, deductions, tax	Financial accountant
Professional communication, skills and conduct required	Networking expert and financial planner
Transitioning from campus to workplace, managing stress, work-life balance, being a woman in the workplace	Three former industrial engineering students
Entrepreneurship for graduates	PhD in Business Management and entrepreneur; and Entrepreneurial coordinator at a further education training college
Smart manufacturing and Industry 4.0	Founder of the Advanced Mechatronics Technology Centre
Resume writing and preparing for interviews	Senior company director and PhD in Human Resource Development Engineering manager

For the WOW Project, two dedicated project management teams oversaw the overall logistics, communication, and evaluation. One team focused on overall project management, including securing the venue, managing invitations and RSVPs, handling marketing and technology, designing feedback forms, and compiling a final report. The second project management team coordinated the six 'action teams', ensuring they met deadlines, proofread communications, created a promotional video, and designed and managed the collection of feedback on the team experiences. Each of the six action teams, in turn, was responsible for

one specific topic. This involved contacting and briefing the speaker, introducing the speaker at the WOW Event, providing a vote of thanks, designing and summarising feedback questionnaires, and delivering both written and oral reports on the session.

3.3 Execution of WOW

As part of the broader WOW Project, each team was responsible for organising one workshop session during the semester. Teams determined dates, invited speakers from industry or academia, planned logistics, and prepared content tailored to their chosen topic. The workshops provided practical insights into workplace demands while fostering transversal skills such as leadership, collaboration, and communication, all key components of GA8.

By engaging in these activities, students transitioned from peripheral participants in their community of practice to active contributors capable of managing complex projects collaboratively (Herrera, 2020). The WOW Project exemplified SLT's emphasis on situated contexts while leveraging PBL principles to promote deep learning and interdisciplinary skill development.

3.4 Contribution to responsible engineering

The WOW Project was structured to address GA8 competencies by providing students with opportunities to engage in teamwork, project management, and ethical decision-making tasks, thereby supporting the development of responsible engineers prepared for professional challenges in diverse contexts. By designing workshops that served their peers and future cohorts, students demonstrated leadership qualities aligned with societal responsibility, a critical attribute for modern engineers.

Owing to the nature of the project, close interaction and communication amongst teams and team members were vital for the success of the project. Students commented that they made new friends and connections creating a greater sense of community among the cohort.

The assessment of GA8, as detailed in the next section on research method, required students to submit a comprehensive document that included both team-based and individual components. The team sections covered the formation of the team, the identification of team values, the process for task allocation, and the rationale behind the selection of the WOW Event topic, supported by a reference list. Each team member was responsible for contributing a section that detailed their individual conflict management style, their assigned tasks within the project, and an explanation (with examples) of how they applied the principles of planning, organising, leading, controlling, communication, and time management. These individual sections also included a self-reflection on their learning experience, covering aspects such as project management skills, teamwork, professionalism, ethics, and stakeholder engagement. Finally, each submission included a reference list and a mark sheet.

4 Research method

This study employed a qualitative methodology (Borrego et al., 2009) to investigate the enactment and effects of GA8 assessment within a South African engineering education context. Grounded in SLT (Lave & Wenger, 1991) and experiential learning (Kolb, 2014), it examined how active participation in a real-world project facilitates the application and integration of graduate attributes into students' professional development, aligning with the goal of shaping responsible engineers. The descriptive and interpretative research design (Elliott & Timulak 2005; Kim et al., 2017) leveraged student self-reflections, akin to Kovanović et al. (2018), providing insights into their experiential learning processes and the development of key competencies. Data from eight student group reflections, generated during self-assessment exercises, team meetings, and the WOW Project execution, formed the basis of the core analysis. These reflections were scrutinised through content analysis (Vaismoradi et al., 2013), a systematic approach for identifying patterns, themes, and meanings within textual data. The content analysis process involved several key steps: (i) data

preparation, which included transcribing and organising the student reflections; (ii) open coding, where the researchers immersed themselves in the data to identify initial concepts and codes; (iii) category development, where related codes were grouped into broader, more meaningful categories; and (iv) thematic analysis, where the relationships between categories were explored to identify overarching themes that captured the essence of the student experiences. These reflections were used to extract themes related to teamwork, leadership, theoretical application, problem-solving, and growth, all of which directly correspond to the criteria for GA8 assessment. The analysis aimed to understand how the GA8 project contributed to the development of teamwork, project management, and responsible engineering competencies. Ethical considerations were rigorously followed, with university ethics committee approval ensuring ethical compliance, participant consent, and data confidentiality in the research process.

5 Results: Shaping competent and responsible engineers through experiential learning

The analysis of student reflections on the WOW Project revealed three prominent, interconnected themes: (i) preparation for professional transition; (ii) project management and leadership experience; and (iii) communication and interpersonal skills enhancement. These themes highlight the transformative impact of experiential learning in shaping competent and responsible engineers, aligning with the study's focus on ECSA's GA8 criteria and the broader goals of South African engineering education (ECSA, 2018). Each theme demonstrates how active participation in a real-world project facilitates the application and integration of graduate attributes into students' professional development (Kolb, 2014; Lave & Wenger, 1991). This section provides a more expansive and narrative version of these results, delving into the nuances of each theme and its sub-themes, while also connecting them back to the theoretical frameworks of SLT (Lave & Wenger, 1991) and PBL (Renkl, 2001).

5.1 Theme 1: Preparation for professional transition

All groups collectively emphasised the WOW Project's overarching goal of preparing students for the transition from university to the professional work environment. This theme encapsulated the essence of WOW as a pivotal platform for bridging the academic and professional realms, underscoring the necessity of equipping students with practical skills and real-world knowledge. The project served as a conduit for translating theoretical knowledge into actionable competencies, essential for navigating the professional landscape.

A critical component of this preparation was instilling a sense of *real-world relevance*. The necessity of real-world relevance was unanimously recognised across the groups, highlighting the project's role in providing tangible applications of academic learning. The students underscored the criticality of aligning educational experiences with industry demands and professional practices. For instance, Group 1 lauded the project for its ability to "equip students with the necessary tools and knowledge to transition smoothly into the corporate world", while Group 4 commended its "practical approach in preparing us for the realities of the working environment".

Another vital aspect of preparing for the professional world involved *skills development*. Skills development emerged as a key focus, with the WOW Project being perceived as a crucible for honing essential professional skills such as networking, personal branding, resume writing, and interview techniques. This facet of the WOW Project was particularly emphasised by Group 2, who noted the importance of "developing networking skills and understanding the value of a personal brand in the professional world". Similarly, Group 5 highlighted the WOW Project's focus on "the critical skills of resume building and interview techniques as vital for the job market".

Furthermore, the WOW Project fostered *collaborative learning*. This was a pronounced theme, reflecting the WOW Project's success in creating a community of learning and cooperation among students. This aspect

celebrated the diversity of perspectives and the richness of shared experiences that enhanced learning outcomes. Group 3 observed the "collaborative nature of the WOW Project, where students from different years and disciplines came together", whereas Group 6 pointed out the "shared experience and the collective effort in organising the event, which enhanced our learning and teamwork".

Finally, the students gained invaluable *professional insight*. The interaction with industry professionals provided students with real-life perspectives and practical advice on various career paths. Group 7, who valued "the insights gained from industry speakers", and Group 8 who appreciated "the opportunity to interact with professionals, gaining firsthand knowledge and advice on career progression", vividly captured this sub-theme.

5.2 Theme 2: Project management and leadership experience

The second prominent theme across the groups was project management and leadership experience, underscoring the WOW Project's role as an experiential learning platform (Kolb, 2014). This theme highlighted the practical application of project management principles and the cultivation of leadership skills through direct involvement in organising the WOW Event.

A critical aspect of this experience centered around *project planning and execution*. This was where students applied theoretical knowledge to real-world scenarios, navigating the complexities of organising a large-scale event. For example, Group 1 detailed the systematic approach to "planning, organising, and executing the workshop", reflecting the hands-on experience gained in project management. Similarly, Group 4 described their journey of "setting objectives, defining roles, and managing timelines", illustrating the practical application of project management skills.

In addition to planning, the WOW Project fostered *leadership development*. This sub-theme involved students reflecting on their experiences of leading teams, making decisions, and guiding the project to success. Group 2 highlighted the development of "leadership skills through steering committee meetings and decision-making processes", while Group 5 emphasised "taking initiative and leading various aspects of the event, which honed our leadership abilities".

The event also shined a light on *team collaboration and dynamics*. This area focused on the interpersonal and group dynamics encountered during the project. Group 3 noted the "challenges and learning experiences in team collaboration, enhancing our ability to work in diverse groups". Group 6 shared insights into "navigating team dynamics and leveraging individual strengths for collective success", demonstrating the importance of effective teamwork in project management (ECSA, 2018).

Finally, the WOW Project necessitated *problem-solving and adaptability*. This theme captured the students' ability to address unexpected challenges and adapt to changing circumstances. Group 7 recounted "tackling unforeseen issues and adapting our strategies", showcasing the critical thinking and flexibility required in project management. Group 8 discussed "the need for quick problem-solving and adaptability when facing logistical hurdles", highlighting the dynamic and unpredictable nature of managing real-life projects.

5.3 Theme 3: Communication and interpersonal skills enhancement

The third theme identified across the groups was communication and interpersonal skills enhancement, focusing on how the WOW Project contributed to the development of students' communication abilities and interpersonal interactions. This theme underscored the significance of effective communication and relationship-building in a professional setting, highlighting how these skills were critical for successful integration into the workplace (ECSA, 2018).

One crucial aspect was the development of *effective communication practices*. This theme emerged strongly, with students detailing how the WOW Project supported the honing of their communication skills. Group 1 emphasised "the importance of clear and concise communication in coordinating the event", showcasing the practical application of communication theory. Group 4 noted their growth in "articulating ideas and

presenting in front of an audience", reflecting on the enhancement of their public speaking and presentation skills.

The WOW Project also facilitated *building and networking*. Students acknowledged the WOW Project's effectiveness in fostering professional connections (Lave & Wenger, 1991). Group 2 highlighted "the networking sessions that allowed us to connect with industry professionals and peers", demonstrating the WOW Project's role in expanding professional networks. Group 5 pointed out the "opportunities to build relationships and expand our professional network", illustrating the event's contribution to their networking skills.

The event also emphasised *teamwork and conflict resolution*. Working in teams and resolving conflicts was another significant aspect of this theme. Group 3 described their experience in "learning to work collaboratively and resolving disagreements constructively", showing the WOW Project's influence on team dynamics and conflict management. Group 6 shared their approach to "open dialogue and mutual respect in overcoming team conflicts", emphasising the development of teamwork and interpersonal skills (ECSA, 2018).

Finally, many students reflected on the importance of *listening and empathy*. This was a key insight, with students reflecting on these crucial communication aspects. Group 7 discussed "the practice of active listening and showing empathy in team interactions", underscoring the WOW Project's role in enhancing emotional intelligence. Group 8 mentioned "enhancing our ability to empathise and understand diverse viewpoints", highlighting how the event helped in developing their listening and empathy skills.

In summary, the analysis of student reflections revealed three interconnected themes demonstrating the effectiveness of the WOW Project: enhanced preparation for professional transition, significant gains in project management and leadership experience, and notable improvement in communication and interpersonal skills (Kolb, 2014; Lave & Wenger, 1991; Renkl, 2001). These findings underscore the value of experiential learning in fostering competencies aligned with ECSA's GA8 (ECSA, 2018), indicating the WOW Project's success in providing students with practical skills and experiences relevant to their future careers.

6 Conclusion and recommendations

This study addressed three guiding research questions. First, it demonstrated how the design and implementation of the WOW Project aligned with ECSA's GA8 criteria by embedding teamwork, leadership, communication, and project management tasks within an experiential learning framework. Second, it showed that student participation in the WOW Project contributed to the development of essential competencies, as evidenced by reflections on teamwork, project planning and execution, leadership, and professional readiness. Third, it highlighted, through students' qualitative reflections, how experiential learning created opportunities for shaping responsible engineers prepared for ethical decision-making and professional practice within the South African context.

The WOW Event, integral to the *Industrial Engineering Professionalism and Ethics* module, therefore proved to be a pivotal initiative for bridging the gap between academic learning and professional readiness for final-year engineering students. By organising and participating in the WOW Event, students were able to apply engineering management principles in real-world scenarios, acquire project management and leadership experience, and enhance communication and interpersonal abilities. These findings reinforce the value of experiential learning as a pedagogical approach that strengthens the integration of graduate attributes into engineering curricula.

For future initiatives, it is recommended to broaden the scope of the WOW Event to include workshops on emerging industry trends, ethics in engineering practice, and strategies for lifelong learning. Additionally, implementing structured feedback mechanisms, such as pre- and post-event surveys, would provide quantitative data to complement the qualitative reflections and inform continuous improvement processes.

It is important to acknowledge the limitations of this study. The reliance on self-reported data introduces the potential for bias (Gonyea, 2005; Rosenman et al., 2011), and the study's scope was confined to a single university context and a specific cohort of students. Future research should consider incorporating objective measures of skill development (e.g., performance evaluations) and expanding the study to include multiple institutions and longitudinal data collection to assess the long-term impact of experiential learning on career trajectories. Furthermore, exploring the influence of individual learning styles and personality traits on the effectiveness of such programmes could provide valuable insights for tailoring experiential learning opportunities to meet diverse student needs.

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How to teach teamwork in a PBL curriculum

Carola Hernández Hernández, Liliana Maritza Melo Ramos
Associate Professor Universidad de Los Andes, Colombia, c-hernan@uniandes.edu.co; Doctoral Student in Engineering Universidad de Los Andes, Colombia, lm.melo11@uniandes.edu.co

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☒	Research paper (length max. 10 pages, excl. references and appendices)
☐	Practice paper (length max. 5 pages, excl. references and appendices)
☐	Workshop (length max. 5 pages, excl. references and appendices)

Abstract

The needs of the globalized world and the transformations that different organizations undergo make being competent in teamwork a necessity. Therefore, the education sector must give it the appropriate relevance and concern itself with developing this particular competence in higher education. A Colombian university has a course called Engineering and Science: A Shared World, which has a PBL curriculum and aims to train this competence explicitly. The course design included a theoretical presentation on what a team is and its main characteristics, postulated by Johnson, D.W., Johnson, R., & Smith, K. (1998), and activities to evidence these characteristics and their importance to work adequately. This text presents a case study that seeks to identify the learning outcomes related to teamwork within the PBL proposed in this course. To achieve this, qualitative information was collected through the products created during the course: the class activities, the contracts, a group of team health activities, the final reflections, and the co-assessments. This information was analyzed through predetermined categories based on the course objectives and the dimensions of teamwork; no new categories emerged. The data analysis revealed that students identified and conceptualized elements such as individual responsibility or face-to-face interaction properly and as essential for team building and development. Still, positive interdependence and a proactive approach to communication and conflict were challenging to conceptualize and exemplify. Finally, many of the students identified that although team monitoring activities were carried out in class concerning the progress of socio-emotional skills, such as anticipating conflict or managing agreements, it was new for them. Their teams did not take full advantage of these spaces that, reflecting on the entire process, were as important as monitoring the products to be delivered.

Keywords: Teamwork competency, Engineering PBL, Higher education, Qualitative research

1. Introduction

Multiple aspects have radically shaped and changed the demands on the competencies students must develop through their university studies. In the last 15 years, different authors have attributed these changes to highly complex phenomena such as technological and industrial advances, the development of new specializations in all fields of knowledge, globalization, and the need for interdisciplinarity to solve complex

problems, among others (Wnag et al., 2024; Galloway, 2007; Gaskins et al., 2015). Unfortunately, these changes have revealed multiple inconsistencies between the competencies required by a rapidly changing society and the competencies developed by higher education programs.

The benefits of teamwork encompass various characteristics that allow any institution to advance its objectives quickly and effectively. For example, teamwork enables the creation of new and disruptive ideas through co-creation, incorporating different perspectives, experiences, and diversity that contribute to creativity and innovation in the workplace (Tucker & Abbasi, 2012). Furthermore, the exchange of ideas and the scalability of the ways of thinking of several people with different skills and knowledge allow for the resolution of highly complex problems presented by a highly globalized and developed world—problems that would take a disproportionate amount of time for a single person to solve. Likewise, teamwork enables social and inclusive sharing, increasing participants' morale (self-perception) and creating a system in which the quality of work, efficiency, and effectiveness increase in direct proportion to the underlying trust and empathy within the team (Katzenbach & Smith, 1993). Therefore, the education sector must give it appropriate importance and consider how to develop this particular competency in higher education.

However, a common phenomenon in developing this and other competencies is that lectures and passive interactions between students are insufficient to foster the development of a competency as complex as teamwork (Passow & Passow, 2017). On the contrary, competency development requires active learning, commonly described as carefully designed activities to ensure student engagement and motivation (Felder & Brent, 2016).

Additionally, there is a lack of accuracy and explicit elements when developing teamwork in a higher education classroom. On the one hand, teachers commonly understand teamwork as any activity developed in groups of students within an educational context, as well as an underestimation among teachers and students about the true nature of competence. On the other hand, many teachers mistakenly believe that exposing students to different work activities with their peers can implicitly lead them to develop teamwork. However, research in the field has shown that the absence of explicit theorizing about teamwork and its characteristics can inevitably lead to an inferior understanding of the topic, with subsequent unfavorable performance of the competency (Goldsmith et al., 2024; Pinard et al., 2017; Therrien et al., 2017).

Unfortunately, the two scenarios described above lead to unpleasant experiences for students and, in general, a bad perception of working with peers. This is due to a poor understanding of what teamwork competence is, which leads to an overload of work for teachers, conversations within teams without a harmonious solution, and the so-called "free riders" phenomenon (individuals who transit for a while without contributing to the team and who benefit from the product of others). For example, Marin-Garcia (2008) describes how these factors affect teamwork in higher education students, who consider this type of activity overwhelming and challenging to manage within the allotted time, especially when teachers expect high-quality products from the teams.

Considering these two essential aspects, teachers who wish to develop this critical competence must be involved in active team supervision and management processes. Their central role is to generate scenarios where students can create a series of processes they are not accustomed to performing. Such an intricate task can be carried out successfully when efforts are oriented to provide a set of theoretical and practical activities related to teamwork competency; at the same time, students are sensitized to the importance of working harmoniously with their peers towards achieving objectives. This implies the need to align the teaching of competence with the curriculum (Biggs & Tang, 2011) by generating learning objectives, class activities, and assessments that truly allow students to learn about it.

In this sense, the first step is defining what teamwork means. There are various definitions in the literature, but in this document, we adopt the one made by Los Andes University in 2023: "Interact cooperatively with others to achieve common goals, recognizing the richness of individual differences and promoting equity and co-responsibility". It recognizes the institutional values and particular bets for its programs' curricula, shows that it is a process over time where students interact dynamically, and the result of their work depends not only on their individual qualifications but also on their ability to synchronize their actions, coordinate efforts, and establish effective communication to achieve common goals.

For this reason, curricular initiatives like PO-PBL are the ideal space for teaching teamwork. However, organizing student groups is not enough; pedagogical approaches are required to encourage them to collaborate in ways that transform them from a group of people working together into a team. Dahms et al. (2017) present that in the first-year curricula of the Faculty of Engineering and Science at Aalborg University, students take a course that includes specific activities that allow them to reflect on their experience in the projects. They also acquire tools to analyze the organization of teamwork to identify strengths and weaknesses, enabling them to propose improvements in similar future scenarios. However, these courses, which emphasize the need to explicitly develop pedagogical strategies for teaching teamwork, are not widely available in other programs. The purpose of this document is to identify the learning outcomes related to teamwork in a course that included a pedagogical design that explicitly introduces a theoretical presentation about what a team is and its main characteristics, postulated by Johnson, D.W., Johnson, R. and Smith, K. (1998), and activities to demonstrate these characteristics and their importance for adequate work in the development of the course project.

2. Context

"Engineering and Science: A Shared World" is part of a group of courses offered to all students at the University of Los Andes as part of their comprehensive education. Given its focus, the course explicitly addresses transversal competencies such as teamwork. The course has two objectives: First, by identifying the specificities of engineering and science as disciplines and their methods, students can analyze and propose multidisciplinary solutions to global problems associated with the SDGs. Second, students identify fundamental elements of teamwork competency and use tools to monitor their development throughout the course.

The course has one weekly two-hour session. During the first eight weeks, students complete two exercises using the 7-step PBL model (Wood, 2003) in loose groups. The goal is for students to meet several classmates; many deliverables are individual. In this phase, students delve deeper into the content associated with understanding engineering and science. Various activities are carried out to promote collaboration and peer assessment of products for grading. At the same time, the sessions put into practice some of the elements proposed by Johnson, D.W. et al. (1998) for collaborative work, which are the foundation of teamwork.

In week 8, students work in pairs to develop an initial conceptualization of the elements proposed by Johnson, D.W., Johnson, R., and Smith, K. (1998) and use it to analyze one of the previous lessons in the course. These elements are: 1. Individual responsibility for tasks; 2. Positive interdependence; 3. Face-to-face interaction that promotes mutual support; 4. A proactive approach to communication and conflict; 5. Frequent self-assessment of team functioning. As Figure 1 shows.

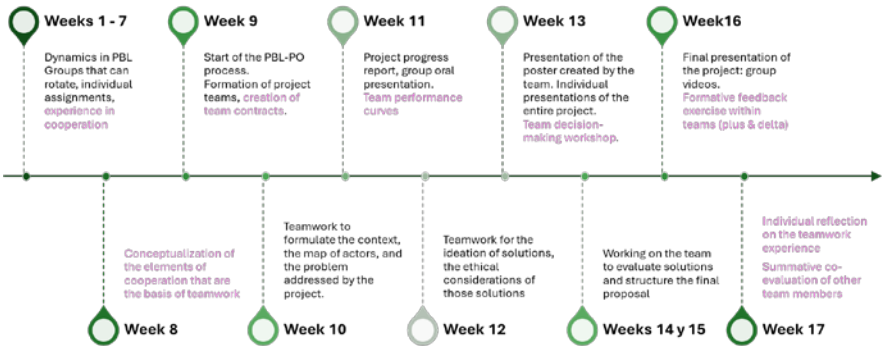

Figure 1. Weekly timeline of activities carried out throughout the course

In the second 8-week cycle, a project is developed using the PBL-PO model (Dahms et al., 2017; Hernández et al., 2016). Students, in fixed groups of 4 or 5, define a problem framed within a range of SDGs (Development of structures for housing, work, and recreation; Sustainable production of new foods; and Information management and security). They then propose alternative solutions through ideation processes, select some, and finally identify the knowledge required to implement the project in engineering, science, and other disciplines. The project has graded presentations every three weeks, and all team members must participate in these activities.

This phase uses the Hernandez and Gómez (2020) proposal to develop teamwork skills (Figure 2). This model takes Kolb's (1984) learning cycle and explicitly uses it throughout the project's development, drawing on the team's experiences between deliverables. Thus, each team experiences working together to produce a deliverable. This is followed by a process of individual and collective reflection on team functioning, seeking to develop element five proposed by Johnson and colleagues, and using questioning on elements 1 through 4. Teams are then asked to review their operating rules or elements that need adjustment to improve team functioning. This process occurs three times for the teams.

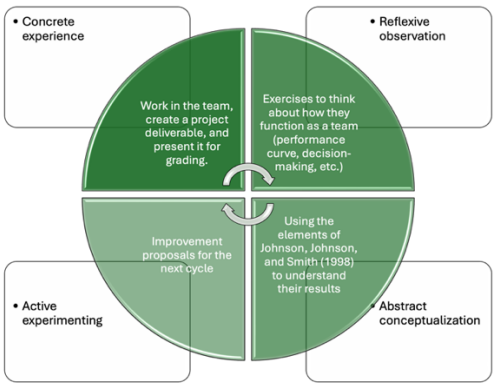

Figure 2. Model for experiential learning Teamwork (Hernández & Gómez, 2020) takes up Kolb's proposal and proposes explicit actions for students to reflect on the functioning of their team.

As Biggs and Tang (2011) suggest, assessment must be aligned to promote the learning desired by the instructor. In this case, teamwork evaluation is an independent component of the team's products. At the end of the project, a formative feedback activity is conducted within the teams (plus & delta) to express face-to-face the strengths and areas for improvement of each person on the team. Finally, summative evaluation using a rubric and a peer-review process by other team members. In this component, there is no grading by the professor, as the professor cannot fully demonstrate the relationships that develop within the teams.

The course closes by asking students to write a letter to a new student using the elements proposed by Johnson, Johnson, and Smith (1998) to share their experience working in a team in the course and offer advice for successful results. The research question arises: What learning outcomes related to teamwork do students in the course achieve?

3. Methodology

It is a descriptive study from a critical and hermeneutic perspective. This perspective enables understanding a phenomenon both globally and in detail, strengthening and consolidating a valid and pertinent discourse concerning the reality of the subject studied (Alvesson & Skoldberg, 2009; Goetz & Lecompte, 1988). This study's participants were 31 students organized into six teams. They were selected using a fixed sampling method: all the students enrolled in the course in the fall semester of 2024.

The data were collected from four sources: the documents produced in the classroom activities, the team contracts made when the teams were formed for the PBL-OP, the records of the team performance

curves written as part of a team performance monitoring activity, the final reflections (84.4% of students did it) and the final team co-evaluations documented with the tool used to carry them out (60% of the students did it).

The documents were organized and analyzed using the five elements of teamwork proposed by Johnson et al. (1998); they were triangulated to characterize the process of developing teamwork skills in students and to identify the skills learned. Finally, the relevant fragments were translated from Spanish to produce a narrative in English, so the fragment S1T4 means that it was written by student 1 of team 4. The results are presented below, highlighting the voices of the course participants for each category of analysis to provide evidence of the students' understanding of each and the progress they made during the course.

4. Results

Individual accountability for tasks means that each person is responsible for their own work and is accountable to the team for their development. To achieve this, it is essential that each individual's contributions be relevant to achieving the final objective and that they be known by all (Johnson et al., 1998). The analysis of the final reflections found that 26 students explained this element as the responsibility to complete assigned tasks concerning the final product of each delivery, for example, "...*each member was assigned clear responsibilities...there were times when some members did not have available time to meet, which slowed the group down. This aspect taught us the importance of regular reporting and ensuring everyone understood their contributions' relevance*." S1T4 or "*Each one assumed their specific tasks, developed them, and we communicated days before the deliveries to consolidate them correctly*" S3T3.

Three students expressed that individual accountability involves ensuring that other team members also know about each other's work: "*I understood that it is not only important to delegate tasks, but also to make sure that everyone is aligned with the common vision and with the final goals of the project.*" S5T5; and finally, two students related it to the responsibility to identify their skills to contribute better: "*There are people who prefer to lead, there are people who want to execute, there are people who are more creative, and there are people who are more analytical, it is your responsibility to find your strength and use it to help the group*." S1T1.

Positive interdependence refers to the understanding of each team member that their individual success is intrinsically linked to the team's. Each member recognizes that their contribution is unique and indispensable to achieving the common goal and that the team's progress depends on all efforts and collaboration. (Johnson et al., 1998). During the analysis, a significant group of students limited positive interdependence with shared responsibility and affected the team by not doing their part: "*This means, in other words, that not performing one's own task not only has negative implications for oneself but for the whole group*." S5T1.

Several reported not having experienced it in their team, but managed to identify that it was important to have a better performance: "*Everyone did their part separately, and we were unable to prepare a joint presentation. As a result, we ran out of time when it was time to present*" S2T1. Finally, some students defined it adequately: "*This sense of interdependence was clearly manifested when Student 1 struggled with a technical tool. Although we initially thought he should solve it alone, Student 4 and I offered to help him, which allowed us to learn something new in the process.*" S3T6 or "*bring ingredients to prepare sandwiches and share drinks. This exercise allowed us to observe how individual compliance affects the team: a sandwich without bread is just a salad, and one without protein is bread with vegetables. This example summarizes positive interdependence, an essential principle of teamwork. Each member took responsibility and delivered, making for a successful breakfast*." S5T6.

This element is complex, and some students narrate how they came to experience interdependence through taking a more active role in their team: "*The fact that everyone contributed different ideas and then*

discussed them helped a lot, including that of the final solutions taken was one of the ideas that I presented, which would not have happened if I had taken a passive attitude in the group." S3T4. Some identify that achieving these skills will be essential for their life: "*There will always be input from people who do not do the same as us, who do not think like us, who simply are not like us. That is why... a good team is better than an outstanding individual. Teamwork is crucial to solving challenges in our work lives, even our personal lives*" S4T3.

Face-to-face interaction that promotes mutual support refers to interactions established between members in which they encourage and facilitate the work of others to complete tasks and produce assigned work to achieve the planned objectives (Johnson et al., 1998). In this category, 26 students recognize this element of teamwork as crucial and express an understanding of the importance of good communication, which occurs most effectively in face-to-face interaction, for achieving common goals. It is another of the elements that are well-defined and characterized by the students. Figure 3 shows the results of this element for several of the teams. It can be identified that Team 4 best responded to the recommendation to generate spaces for face-to-face interaction and presented it as a fundamental element for its good performance. Other teams, such as Team 1, show that the difficulty of this type of interaction (prioritizing only written chat) made it difficult to move from the individual to the collective, impacting their progress as a team.

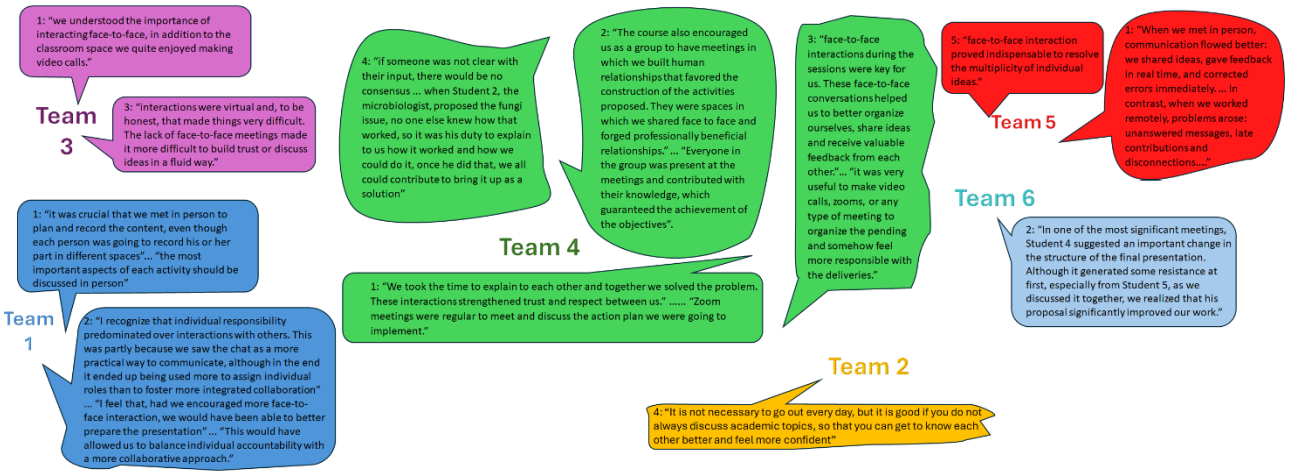

Figure 3. Results on Face-to-Face Interaction. Each team's balloons are a different color, corresponding to a different student's statement. Balloon density shows how many team members report on this element.

The proactive approach to communication and conflict management states that teams cannot function effectively if their members lack and do not use the necessary interpersonal skills. It is crucial for team members to know and trust each other and to communicate correctly and unambiguously. Each member needs to address conflict directly and constructively, helping to manage or resolve it in a way that strengthens team cohesion and effectiveness. Figure 4 shows excerpts from the student's reflections on this element. Team 6 reported having had conflicts that they could resolve through respect-based communication and expressing the value of each team member's contribution. In the same way, team 4 made it (although we do not present it in **¡Error! No se encuentra el origen de la referencia.**; however, in **¡Error! No se encuentra el origen de la referencia.** of the face-to-face interaction, they refer to conflicting moments).

The other teams reported having had no conflicts, and only a few students in each team referred to conflict situations, as seen in the figure for teams 1 and 2. Four people expressed that because they did not trust or know each other well, discussing mistakes was very difficult, and they noticed avoidance of discussing potentially conflictive situations. In this way, they, along with 22 students, confirm the importance of having a space for socializing to build trust and get to know each other, allowing them to have uncomfortable conversations that benefit a positive team atmosphere.

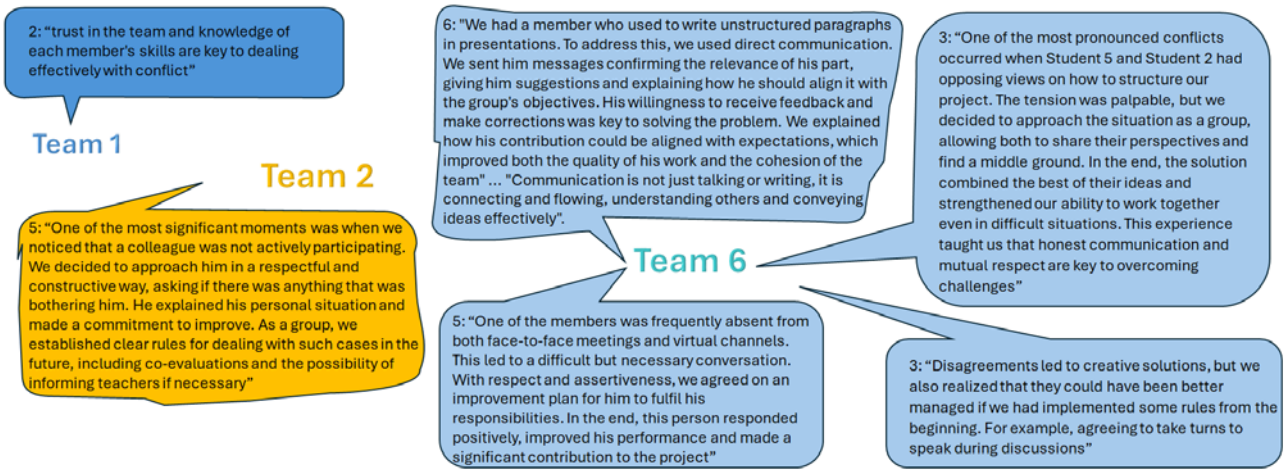

Figure 4. Results for the category "Proactive Vision" in Communication and Conflict Management. Each team's balloons are a different color, corresponding to a different student's statement. The balloon density shows how many team members report on this element.

Frequent self-evaluation of group functioning refers to the fact that groups need to set aside specific time to discuss how well they meet their objectives and maintain effective working relationships among their members. They should discuss their feelings about the team, their performance, the most valuable contributions, and what practices need to be strengthened or changed.

T1			
S1	S2	S3	S5
S2: S1 did a good job, fulfilled its responsibilities, and did it correctly.	S1: S2 completed all relevant activities and attended everything punctually and correctly. S2 made no mistakes in group work.	S1: S3 completed all activities, communicated well, and was respectful at all times.	S1: S5 completed all the tasks and could perhaps communicate a little more in meetings.
S3: You could communicate more and be more punctual, but you do good work and make good research.	S3: Everything was impeccable, and S2 was always punctual and responsible. She was a good leader, and without S2, many things would not have been accomplished.	S2: The work carried out was consistent and the dedication demonstrated individual responsibility, which contributed to cooperative work.	S2: S5 contributed to the work with individual responsibility, and his contributions met expectations. S5 also contributed his ideas to the group.
S4: A good teammate and willing to help. He contributed good ideas.	S4: Very good initiative in all the work	S4: A very good teammate, S3 contributed good ideas and was very responsible	S3: Good research and contributions
S5: Good teammate who actively participates in activities	S5: A good teammate who shows considerable initiative and participation during group activities.	S5: Good teammate who actively participates in activities	S4: Good teammember with a great work attitude.
Itself: I fulfilled all the necessary requirements for the class, completing all assignments and submissions on time. I communicated with my team and carried out all relevant activities.	Itself: I believe that my contributions to the work were timely and I kept an attention on its completion. Likewise, I tried to keep an eye on my group in their individually assigned responsibilities and fulfill my own as expected.	Itself: I can improve	Itself: More in-depth research is needed.

Figure 5. Segment of the co-evaluation of team 1, each column includes comments about the other team members. Green fragments are about communication, and red pieces are about individual responsibility for tasks.

The findings indicate that, in this element, students demonstrate a propensity to restrict the self-evaluation of team performance, opting instead for the collective assessment of each individual's contributions or outcomes: "*These sessions were not always easy, as they sometimes involved constructive criticism, but they always helped us move forward. In one of these reflections, we realized that some members were taking on a heavier workload than others, which led us to redistribute tasks more equitably.*" S2T6 or "E*very time someone contributed, they would ask for feedback from the group and correct where necessary.*

Before any major deliverable, we would review everything together to ensure we did not miss any mistakes." S1T6. This is also evident in a segment of Team 1's final co-evaluation shown in Figure 5.

Additionally, they illustrate the interconnection between team self-assessment and conflict management: "*Although we did not conduct formal self-evaluations frequently, we did reflect at key moments on how we were working as a team. For example, after deciding to exclude a member, we discussed how to avoid similar problems. Overall, our group functioned well, but I believe that more time spent on self-evaluation would have been beneficial to improve our dynamic" S3T3 further*. The ability to manage conflict is a complex skill, and evasion is a common strategy employed in some situations: "*This was one of the aspects that we practiced the least and that, in retrospect, could have improved our performance the most ... On the few occasions we did, we identified problems such as a lack of clarity in responsibilities, but we did not implement significant changes*." S1T4.

Furthermore, the results obtained demonstrate the efficacy of targeted reflections in fostering self-evaluation among teams. This process, however, is recognized to present challenges. Nevertheless, it is acknowledged that it contributes to an enhanced awareness amongst students regarding the significance of this component: "It is *difficult to have sincere conversations with people you know very little about. So, out of a desire to look good, none of us could talk about our obvious flaws as a group. Everything was discussed superficially"… "The only time we discussed the goals achieved by the group was when we had to place our group on a teamwork curve in class*" S4T2.

It was reported by both Teams 4 and 5 that this was the element with which they had worked least extensively during the course: "A*fter the delivery of activities, we always had a space to give a little feedback either in class or through the group we had on WhatsApp ... I insist that we did not have much communication in person, nor did we integrate with activities that were not academic, which for me represents a shortcoming.*" S1T5

In Team 1, the health spaces and activities designed for the class are used as spaces for self-evaluation as a team: "*In the last class, we did an activity called "Plus and Delta", where each team member had to give two positive aspects (Plus) and two aspects to improve (Delta) to each teammate ... the observations helped me to reflect and identify areas where I can improve*" S4T1. However, their colleagues have posited that if more of these activities had been carried out, the team performance would have been enhanced: "*It would be ideal to have established regular face-to-face or virtual meetings to plan and monitor the progress of each stage of the work. This way, we could have detected potential problems and adjusted our strategy to deal with them effectively*." S2T1.

As demonstrated in Figure 6, the results of the teams' performance curves indicate that the teams identified for enhancement just fulfilled compliance with the roles (none of them modified the initial contracts) and required additional time for the course topics. This would entail meeting overtime as stipulated in their contracts.

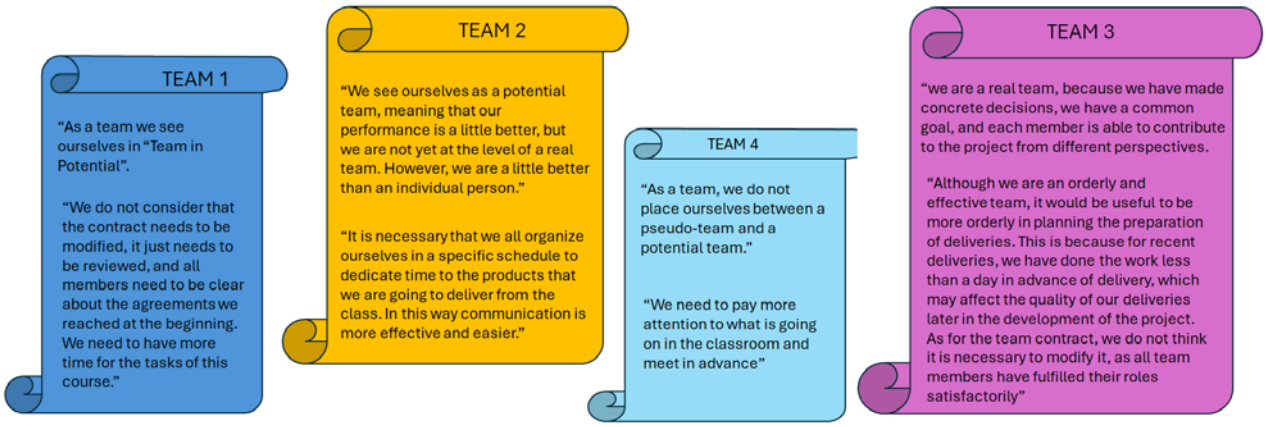

Figure 6. Results of equipment performance curves.

5. Discussion

The triangulation of the data shows that throughout the course, students identified and conceptualized the main characteristics of teamwork. The two elements most students adequately conceptualized were individual responsibility and face-to-face interaction, considering them essential for team formation and development. Regarding positive interdependence, the conceptualization is less clear and is often easily related to shared responsibility, which affects the team but not to better collective construction. Regarding communication and conflict management, most students considered it very important and beneficial to have spaces for collaborative building and generating trust, allowing them to have difficult conversations in a better team environment. Regarding the last element, frequent self-evaluation of group functioning, many students identified that, although team monitoring activities were carried out in class on the progress of socio-emotional skills, such as conflict anticipation or agreement management, this was new to them. Their teams did not take full advantage of these spaces, which, when reflecting on the entire process, were just as important as monitoring deliverables.

These learning processes occur through concrete reflection on the processes they experience, as proposed by Kolb (1984). These reflections show that learning can happen in two pathways: the first occurs when students are part of a team where these characteristics are incorporated. The monitoring and dialogue processes are more effective, so they appropriate the skills. The second occurs when team interaction is not necessarily effective, but students can identify which characteristics could be improved and should be implemented in new processes. In this case, the experiential learning strategy proposed by Hernández and Gómez (2020) allows students to advance their understanding of teamwork, from the collective development of products to a complex skill that involves coordination to achieve a common goal.

This does not imply that all teams are successful or that they achieve the best experiences. However, it does show that, as Biggs and Tang (2011) suggest, curricular alignment is essential to promote specific learning outcomes in students. In this particular course, the design of the deliverables that all team members must submit orally and team health activities, such as the construction of performance curves or individual formative peer assessments (plus-delta), allow for reflection on team functioning and the learning of teamwork skills. This completely transforms students' experience with teamwork, distancing them from the negative experiences of working in groups without guidance or explanation about what teamwork is, what its elements are, and how it is managed internally, as described by Goldsmith et al. (2024).

Finally, students recognize that communication and active participation in meetings are essential for team performance, as they foster a more collaborative environment where there is trust to participate. At the same time, as Katzenbach and Smith (1993) suggest, a high level of trust is an indispensable component of an honest and beneficial self-assessment, and it is these internal assessments within the team that allow them to achieve better organization and self-management increasingly. Therefore, this pedagogical design, incorporated into several courses, would strengthen the learning of this competency through specific peer assessments on teamwork skills.

6. Conclusions

From all the results presented, the design of activities aligned with the learning objectives, particularly in the case of teamwork, is key to ensuring competency-based learning. Activities should include individual reflections and group peer assessments so that students recognize and place greater importance on face-to-face interactions to work on consolidating their deliverables, strengthening personal interactions, and generating an environment of team trust that allows conflict resolution and avoidance.

Positive interdependence was evident as an element that is not easy to understand and is one of the elements that requires the most time to understand. The students' reflections show that building an environment of trust within teams is potentially the space where self-assessment of team functioning and,

consequently, the construction of positive interdependence can be improved. This is closely linked to the quantity and quality of face-to-face interactions that can be encouraged.

Therefore, this case study contributes to the creation of curricula or course programs that explicitly include teamwork development. Carrying out activities that explicitly involve teamwork allows for the conceptualization and development of this competency and avoids negative experiences resulting from inadequate support and guidance in team building. This is a common practice when teachers only assign group work but do not explain or provide advice on what teamwork is and how to work as a team.

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Enhancing Student Engagement: A Toolbox for Systematic PBL Implementation

Meng Yuan
Department of Sustainability and Planning, Aalborg University, Rendsburggade 14, 9000, Aalborg, Denmark, mengy@plan.aau.dk

Juebei Chen
Aalborg Centre for Problem-based Learning in Engineering Science and Sustainability, Aalborg University, Aalborg, Denmark, juebei@plan.aau.dk

Dennis Friedrichsen
Aalborg Centre for Problem-based Learning in Engineering Science and Sustainability, Aalborg University, Aalborg, Denmark, friedrichsen@plan.aau.dk

Izhar Mithal Jiskani
Department of Sustainability and Planning, Aalborg University, Rendsburggade 14, 9000, Aalborg, Denmark, imj@plan.aau.dk

Sara Bjørn Aaen
Department of Sustainability and Planning, Aalborg University, Rendsburggade 14, 9000, Aalborg, Denmark, sara@plan.aau.dk

Xiangyun Du
Aalborg Centre for Problem-based Learning in Engineering Science and Sustainability, Aalborg University, Aalborg, Denmark, xiangyun@plan.aau.dk

Abstract

To foster student engagement and improve learning outcomes, there is a growing shift from traditional teacher-centered, lecture-based teaching to student-centered, constructivist approaches. This paper proposes a student engagement toolbox designed to promote active student engagement in a systematic problem-based learning environment. The toolbox includes tools that support diverse teaching contexts, such as the 1-2-Team model, digital interaction tools, teamwork on cases, random interviews, and flipped classroom activities. To offer deeper insights, an example of applying the elements of the toolbox in a specific course at Aalborg University is presented. Furthermore, the practical implications of the toolbox are discussed, including application scenarios, advantages, potential risks, strategies for mitigating those risks, and authors' reflections on its implementation. The findings highlight the importance of selecting tools and designing courses according to the teaching contexts to promote psychological safety and foster student interactions. This approach ultimately contributes to an improved learning experience by creating an inclusive and supportive atmosphere, empowering students to take an active role in their education.

Keywords: Problem-based learning, Student engagement, Constructivist teaching, Toolbox

Type of contribution: Research paper

1 Introduction

The teacher-centered, lecture-based teaching approach has been adopted widely in universities globally, which positions the teachers as the primary sources of knowledge. While this method provides structured content delivery, it can also result in students becoming passive recipients, potentially leading to disengagement, disenchantment, and missed opportunities for deeper learning (Wedemeyer, 2010). To address these limitations, there has been a growing shift toward more student-centered, active learning approaches (Wright, 2011).

From the perspective of constructivist learning theory, knowledge is actively constructed by learners rather than passively received. This theory emphasizes the importance of hands-on experiences, collaboration, and

reflection in building understanding (Hendry et al., 1999). Engagement in learning activities promotes deeper cognitive processing, enabling students to connect new information with prior knowledge, understand complex concepts, and develop essential problem-solving skills. When students are actively involved, they are more likely to be motivated and take ownership of their learning (Parsons & Taylor, 2011). Existing higher education research also shows that the extent to which students are engaging in activities is linked with high-quality learning outcomes (Krause & Coates, 2008), and have an impact on the learning experience, competence development, and, ultimately, life success (Bundick et al., 2014). Moreover, a higher level of engagement is characterized by students producing additional outputs or products beyond the provided learning materials (Du et al., 2020). This suggests that designing suitable learning activities that stimulate students' thinking and reflection is essential for fostering meaningful learning experiences. Biggs's three-level teaching model (Biggs, 2003) further enriches this understanding.

With the overarching goal of enhancing students' active engagement during lectures, this study proposes a student engagement toolbox comprising adaptable tools suitable for diverse teaching contexts and designs. Each tool emphasizes student-centered practices, which have the potential to increase learners' interest and engagement. The toolbox is the result of a collaborative effort based on the authors' teaching experiences during the University Pedagogy (UP) Programme at Aalborg University (AAU) in 2024. This programme is a comprehensive, research-based pedagogical competence development course designed for early-career academics.

The development of the student engagement toolbox is motivated by the authors' shared experiences with challenges encountered in teaching at AAU. At AAU, problem-based learning (PBL) serves as the core pedagogical approach at the curriculum level (Aalborg University, 2015). The Aalborg PBL Model emphasizes collaborative, problem-oriented learning, where students work in groups each semester to develop projects, drawing on theoretical and methodological insights from their courses, with students placed at the center of the learning process as they take responsibility for identifying and solving problems, while teachers serve as facilitators, guiding and supporting their learning (Kolmos et al., 2004). However, based on the authors' teaching experiences and peer discussions, traditional teacher-centered approaches are still commonly used in lectures to deliver content. This presents challenges for students in actively engaging during lectures and in making meaningful connections between lecture content and their project work. As a result, the potential of lectures to support project development may be diminished, which limits opportunities for reflection and deep learning.

The proposed student engagement toolbox offers a flexible framework, which allows educators to select and implement the tools that best align with their specific teaching goals. The structure of the paper is as follows: Section 2 presents the overall framework of the proposed student engagement toolbox. Section 3 provides an example of its implementation. Section 4 discusses the practical implications of the toolbox and the authors' reflections, and Section 5 concludes the paper.

2 Teaching design - Student engagement toolbox

The tools included in the proposed student engagement toolbox are described below. This toolbox was developed primarily based on teaching experiences gained from the authors during the one-year University Pedagogy Programme, as previously mentioned, and supplemented by insights from other teaching contexts. The authors, though from the same department at AAU, come from diverse academic backgrounds and teach in different programmes. The tools were collected, discussed, and implemented across various courses, including those with a focus on engineering education. However, due to page limitations, only one example of the implementation of the toolbox is presented in Section 3 later on.

2.1 1-2-Team Model

The 1-2-Team model, developed through empirical research and teaching practices in a PBL context at Aalborg University (Hansen & Christensen, 2024), offers a structured approach to enhancing student

engagement in both classroom activities and teamwork. This model operates through three interconnected phases: individual creative thinking, paired sharing, and team discussion. This allows students to reflect, share ideas, and make decisions collaboratively in a playful and supportive environment. The model emphasizes two steps for operation, including open mode and close mode (Hansen & Christensen, 2024). The open mode involves individual thinking, pair sharing, and group sharing, during which students are not required to comment on others' ideas; instead, the focus is solely on idea sharing with everyone's engagement. This mode fosters free expression and collaboration, encouraging innovation by allowing students to explore diverse perspectives. In contrast, the closed mode involves analyzing, commenting on, and suggesting improvements to ideas, as well as making decisions. This structured approach emphasizes analytical thinking, ensuring clarity and workflow efficiency. By separating these modes, the model enables students to balance creative exploration with focused problem-solving, enhancing overall learning outcomes. In practice, students are typically divided into small groups of 4–6 members to tackle key questions posed by the teacher. The learning process begins with individual reflection, where students formulate their own thoughts. This is followed by the pair phase, where students share and refine their ideas in smaller groups of two, creating opportunities for peer-to-peer learning. Finally, during the team discussion, all students come together to share their insights, facilitating broader participation and collective decision-making. This progression allows every team member to engage meaningfully, ensuring that all perspectives are considered in a supportive and dynamic classroom environment.

A significant strength of the 1-2-Team model lies in its ability to address the limitations of traditional classroom dynamics, where discussions are often dominated by outspoken students. By incorporating individual reflection and small-group interactions, the model ensures that quieter and introverted students have the time and space to articulate their ideas, fostering a more inclusive learning environment. This approach prevents the learning experience from being dominated by a select few, promoting equal participation and ensuring that all voices are heard. Moreover, the model promotes a sense of social connection by providing a structured, safe space for students to engage with their peers. This sense of belonging is critical for maintaining student motivation and attendance, which in turn supports both academic success and retention(Jensen & Cross, 2021; Verdín et al., 2018). Ultimately, the 1-2-Team model creates a dynamic, student-centered classroom where all students feel valued, empowered, and motivated to actively participate in the learning process.

2.2 Digital Interaction Tools

Digital tools help transform the classroom into a more inclusive and interactive learning environment (Moorhouse & Kohnke, 2020). Various digital tools—such as Slido, Mentimeter, Teams Whiteboard, and Quizlet, enhance in-class interactions by promoting active student participation, providing real-time feedback, and enabling dynamic learning experiences. Platforms like Slido and Mentimeter support anonymous participation, encouraging students—especially those hesitant to speak in traditional settings—to share their ideas more comfortably. These tools integrate seamlessly with PowerPoint, allowing teachers to visualize results instantly. Educators can engage students by using features like live polls for multiple-choice questions and word clouds for collecting text responses.

Additionally, collaborative platforms such as Teams Whiteboard and Padlet provide spaces for students to co-create knowledge, discuss ideas, and explore course material more deeply. These tools are particularly valuable for asynchronous participation, enabling students to engage in discussions or group work at their own pace beyond scheduled class hours. As a result, they are also supportive tools for online courses, enhancing both flexibility and collaboration in digital learning environments.

2.3 Teamwork on Cases

Teamwork on cases uses small, fictionalized problems to stimulate creativity, engagement, and critical thinking. By adding humorous or exaggerated elements, students navigate group dynamics in a light-hearted

yet impactful manner. This approach enables students to explore key topics in PBL like conflict management and task delegation through interactions with characters exhibiting extreme personality traits. The use of fictional characters provides emotional distance, enabling students to reflect critically on their behaviors, reactions, and interpersonal dynamics. For example, a 3x3 grid with nine different fictional characters can be used in a PBL course on conflict management, where student groups can be given a hypothetical scenario and asked to consider their perspectives and actions as if one of the fictional characters was a group member. Despite the humorous nature, observations showed that the 'third other' (i.e., the fictional group member) can provide a valuable reference point for students to discuss challenging topics, such as team members' lack of effort, tardiness, rudeness, and the balance between sociability and professionalism. Overall, this 'Teamwork on Cases'-tool promotes meaningful discussions and self-awareness in a playful, interactive environment.

2.4 Random Interviews

Random interviews, though a relatively small intervention compared to the other tools, are highly effective in capturing students' attention, especially when the discussion topic is controversial and involves diverse opinions. The teacher can present a multiple-choice question to the class using digital tools like Mentimeter or Slido and randomly select students to explain the reasoning behind their choices. The question can be open-ended, without a fixed correct answer, which allows the students to explore the consequences of each option during the discussion. Since the selection process is random, students may feel slightly nervous but, at the same time, remain highly engaged and attentive. This method fosters critical thinking and encourages active participation, and helps students develop their ability to defend their viewpoints.

2.5 Various Flipped Classroom Activities

The classroom can be flipped via some fun student engagement activities where the students are the main actors instead of the teachers, and the students can play the main role in a relatively relaxing atmosphere. The potential flipped activities include Role Play, Pecha-Kucha Presentations Task, Board Games and other Game Workshops such as LEGO Serious Play, etc. Each of these activities is briefly introduced below.

Role Play is an activity where the students are divided into different groups and assigned different roles within a given scenario, with the teacher or students acting as facilitators. **Pecha-Kucha** is a presentation style in a structured format where presenters show 20 slides in 6 minutes and 40 seconds (each slide displayed for 20 seconds). The teachers can organize a Pecha-Kucha task for the students on a given topic for students to present in the course. Different **Board Games and Game Workshops** can also facilitate learning if the content is integrated into the course. For example, two games available for the students in the energy field include CATAN New Energies and REWARDHeat Serious Game.

3 Example of toolbox implementation

The toolbox was implemented by the authors in various courses across different disciplines at AAU, spanning both bachelor's and master's levels, as part of the University Pedagogy Program during 2024. A brief example of its implementation in a master course is presented below. Further details of course design, data collection and analysis of other courses can be found in Ref. (Chen et al., 2024).

3.1 Teaching context

An example of the teaching practice took place during a two-hour lecture in the Energy System Analysis course for first semester master students enrolled in the Sustainable Energy Planning and Management Program at Aalborg University in autumn 2024. The class consisted of 13 students, with a gender balance of 54% female and 46% male, and a diverse mix of backgrounds, including 30% international students. Before implementation, a questionnaire via Mentimeter was sent to the students to assess their self-perception of course engagement. Results showed that 75% of the students were moderately engaged in the lecture by

sometimes reflecting, joining the discussions, or asking questions. In contrast, 25% of students were slightly engaged in the course by mainly paying attention to the lectures but rarely joining discussions.

3.2 Course design and data collection

Three interventions based on the 1-2-Team Model were designed for the lecture, as shown in Table 1. These interventions, placed at the beginning, middle, and end of the lecture, gradually increased complexity. In the first and second interventions, students work in teams to find answers to a given problem through individual thinking, group discussion and class presentation, considering time limitations. A digital interaction tool Mentimeter (live vote polls), was used in the first intervention. The third intervention consists of two rounds, where students first find a problem themselves and then solve it. A digital questionnaire, also designed on Mentimeter, was shared at the end of the lecture to gather student feedback on their level of course engagement, the effectiveness of specific interventions on learning outcomes, and overall course satisfaction.

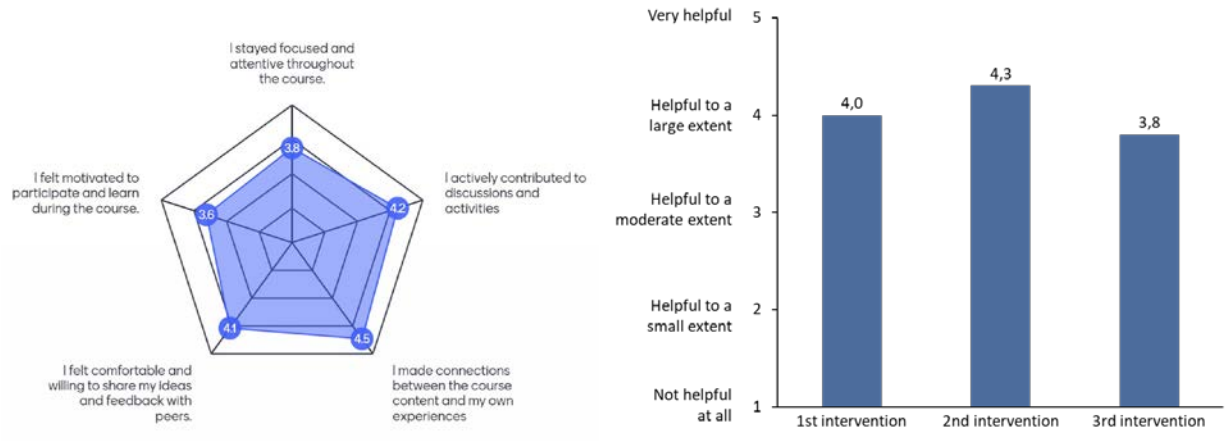
Table 2: Intervention design

No.	Problem to be investigated	Intervention implementation steps	Complexity
1st	Which renewable energy source accounts for the largest share of the total RE supply in EU? (Close question)	Step 1: Individual thinking Step 2: Group discussion and vote in Mentimeter Step 3: Show vote result & group presentation	Simple
2nd	Is biomass really sustainable and what are the potential risks? (Open question)	Step 1: Individual thinking Step 2: Group discussion Step 3: Group presentation	Medium
3rd	What challenges does solar PV face? Each group prepares three challenges for another group to choose and solve. (Open question)	*Round 1* Step 1&2: Individual thinking & Group discussion Step 3: Each group proposes challenges to another group in turn for *Round 2* *Round 2* Step 4: Group discussions to find solutions to the challenge Step 5: Each group presents solutions to the opponent group and receives peer-feedback	High

3.3 Data analysis

Figure 1 (a) evaluates the level of student engagement from five different dimensions. In the results, “1” represents “not engaged at all”, while “5” represents “very engaged”. Results indicate that the scores of all dimensions are above 3.5, which means that the students were engaged in the lectures at a quite good level in their own self-perception. The students scored relatively higher on “make connections between the course content and own experiences” and “I actively contributed to discussions and activities”, which are 4.5 and 4.2 respectively. Figure 1 (b) quantifies the effectiveness of different interventions in enhancing learning outcomes. The results indicate that all interventions contribute to students’ learning, however, their varied effectiveness is identified. An average score of around 4 for the three interventions shows that the student finds the interventions helpful to enhance their learning gains to a large extent. A little decreased effectiveness was observed in the third intervention compared to the first two interventions, which involve peer feedback. According to a talk with the students, one possible reason could be the psychological safety issue. The setup of proposing challenges to another group made the students feel like competitors, which poses challenges of psychological safety because the lecture was placed at the beginning of the first semester

and the students were still in the early stages of building relationships and trust with each other, and they are reserved with engaging with unfamiliar peers.



(a) (b)

Figure 1: Results of student self-perception of course engagement and learning gains. (a) The level of student engagement. (b) The impacts of the interventions in enhancing the learning outcomes

4 Practical implications of the student engagement toolbox

Besides the example presented, Table 2 summarizes additional practical implications of implementing the student engagement toolbox. Educators in various contexts can use this table as a reference. The effectiveness of student engagement, potential application scenarios, possible risks, and corresponding risk mitigation strategies for each tool are summarized based on the authors' experience.

Table 2: A summary of the toolbox

Tools	Class size	Advantages	Potential risks	De-risk suggestions
1-2-Team	S	• Boost in-depth brainstorming • Offer opportunities for quiet students • Process can be adjustable and flexible	• Time-consuming for full process • Quality of group formation is critical	• Only take part in the process if time limits • Ensure diversity in group formation
Digital interaction tools	S/L	• Increase interactivity • Support anonymity • Facilitate teamwork • Support online teaching	• May not be feasible in resource-limited areas • Potential technical issues • Requires technical literacy	• Use non-digital alternative in resource-limited areas, e.g., sticky notes
Teamwork on cases	S/L	• Opportunities for sharing perspectives • Safe space to discuss expectations	• Potentially time-consuming • No tangible output unless exercise is expanded	• Set time limits and ask specific questions to avoid confusion and uncertainty

		• The fun aspect makes cases approachable and light-hearted	• Not all students respond well to fictional scenarios	• Clarify on a meta-level how this exercise is helpful and productive
Random interview	S/L	• Attract attention effectively • Facilitate discussion in complex open topics	• May cause student anxiety	• Create a psychological safe environment • Gradual implementation
Various Flipped Classroom Activities	S	• Boost learning in a fun atmosphere [a,b,c] • Improve communication skills[a, b] • Encourage teamwork & collaboration [a, c]	• Time-consuming [a,b,c] • May challenge psychological safety for introverts [a, b] • Resource limitations in a large class, e.g., purchase of games, lack of teaching assistant [c] • Students may focus on winning than reflection [c]	• Allocate a dedicated session with enough time [a, b, c] • Create a psychological safe environment [a,b] • Organise class reflection session [c]

Notes: In Class size, S represents small class with fewer students while L denotes large size; Marks applied to Role Play (a), Pecha-Kucha (b) and Fun Games (c)

The context of the course matters significantly when choosing specific student engagement tools. For example, for first year students, it would be good to keep a fixed group formation and use anonymous digital tools if needed. A good course design requires periodic student engagement without disrupting lecture flow, so it can be helpful to combine some small interventions (e.g., questions) with larger ones (e.g., think-pair-share) in a lecture. Also, the complexity of interaction ideally increases gradually from the beginning of a course to the end.

It was also found that psychological safety plays a significant role in ensuring that the interventions can be implemented as expected. The teachers ideally focus on building a safe and inclusive environment where students feel comfortable when making mistakes, as this can reduce anxiety and encourage student involvement, regardless of the personality and gender of the students.

5 Conclusion

This paper presents a practical student engagement toolbox for systematic PBL setting in higher education, integrating various student-centered tools to enhance student participation and stimulate active learning based on constructivism theory. The toolbox offers flexibility through tools such as the 1-2-Team, digital interaction tools, and flipped classroom activities, making it adaptable to diverse teaching contexts. The findings suggest that creating a psychologically safe classroom environment is crucial for maximizing the effectiveness of these tools. A safe environment fosters student involvement, reduces anxiety, and encourages meaningful participation. Additionally, tailoring interventions to the course context and gradually increasing the complexity of activities contributes to a more engaging and dynamic learning experience.

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Comparing Retrospective and Pre-Post Survey Measurement of First-Year African Engineering Students' Skill and Perception Changes through a PBL Course

Yohance Lewis
Massachusetts Institute of Technology, USA, ylfl@mit.edu
Sampson Kofi Nani
Ashesi University, Ghana, sampson.nani@alumni.ashesi.edu.gh
Charity Ampomah
Ashesi University, Ghana, charity.ampomah@alumni.ashesi.edu.gh
Dr. Heather Beem
Ashesi University, Ghana, hbeem@ashesi.edu.gh

Abstract

For many first-year engineering students at Ashesi University in Ghana, the project-based learning (PBL) approach they experience in Introduction to Engineering differs from the rote-based pedagogies they have previously experienced. The authors' previous efforts to understand this pedagogy's impact on the students have relied on pre-post survey tools. For some responses, higher-than-expected scores on the pre-survey have been noticed. This study aimed to understand whether a different methodology, a retrospective pre-post survey, would yield similar results and what reasons may underlie any differences.

A mixed-method approach was deployed with students in the 2024 cohort of the course. They completed two surveys – one at the beginning (pre-survey) and one at the end of the course (retrospective pre-post survey). Five skill/perception categories were deployed with Likert-scale questions. T. tests revealed no statistically significant difference in the traditional pre-post analysis, while in the retrospective analysis, all five categories had statistically significant increases with small to medium effect sizes. Interviews with select respondents revealed self-assessment bias, as they tended to overestimate their skills at the beginning of the course. These results suggest that the retrospective approach may be better suited for studies on this target group.

Keywords: Retrospective survey, first-year, self-assessment bias, Dunning-Kruger effect, memory/recall bias

1 Introduction

1.1 Previous work with this population

Over the last few years, the authors have investigated the impact of project-based learning (PBL) on first-year students in an Introduction to Engineering class at their university - a small private institution in Ghana. These studies have sought to understand the students' experience, especially as many of them

encounter a PBL approach for the first time in this course. The studies have looked at how constructs such as self-efficacy are impacted (Beem, 2021a; Beem et al., 2023a; Ampomah & Beem, 2024), whether the physical environment plays a role (Beem, 2022), and whether this impact was experienced in an online format (Beem et al., 2023b). The methodological approach for conducting these investigations has been the use of a traditional pre-post survey.

Past work has focused on self-efficacy as the dominant construct in view, but it is worth expanding the scope to identify other constructs that may capture any impact the course has on these students. It is worthwhile to investigate a broader set of skills and perceptions that the students may increase or change through this course.

1.2 Survey types

The pre-post survey methodology is the traditional way of measuring the impact of interventions through self-assessments and has therefore been utilized in many studies (Davis et al., 2018; Ferguson et al., 2012; Hufford, 2010). This approach compares self-reports of perceptions at the beginning of an intervention with self-reports soon after the intervention (Kowalski, 2023). This is a highly popular method due to the straightforward nature of its deployment and analysis. This method could, however, be considered somewhat time-consuming and may result in respondent fatigue since the survey is conducted multiple times (Porter et al., 2004). When the author administered pre-surveys to this student population in the past, higher-than-expected scores were observed in some instances (Beem 2021a; Beem, 2021b). This was surprising since most students stated they had limited experience with the topics to be covered in class. This observation has motivated the exploration of other measurement approaches. An alternative means of measuring the impact of interventions through self-assessment is the retrospective pre-post survey. In this model, the post-test and pre-test are administered simultaneously at the end of the intervention through a single survey. The respondent is asked to rate themselves at both timepoints by reflecting on where they started as well as where they are now. This reduces the number of surveys that the respondent is asked to complete and can offer them an opportunity to more accurately reflect on the learnings gained. Both the traditional pre-post and the retrospective pre-post surveys have their vulnerabilities (Lamb, 2005; Nimon, 2014). Kowalski (2023), therefore, advises evaluators to determine which design is most likely to provide the most accurate results. This study incorporates a qualitative phase to further explore the causes of any inconsistencies between the two methods.

1.3 Participant biases

A commonly cited limitation of self-assessment surveys is their vulnerability to response-shift bias (Drennan & Hyde, 2008; Hill & Betz, 2005). The response-shift bias refers to the changes in internal standards of evaluation (Howard et al., 1979). The response-shift bias may arise from changes in participants' levels of self-awareness before or after an intervention. Response-shift is more likely if the intervention being administered increases a participant's awareness of the changes being measured (Moore & Tananis, 2009). In addition to the response-shift bias, several other biases may also be at play.

Another commonly cited bias is the Dunning-Kruger effect. This applies when individuals who are either underperformers or overperformers tend to underestimate or overestimate their abilities, respectively (Dunning, 2011). Hence, this bias causes participants to inaccurately assess their own capabilities. Similar biases include impact bias, self-serving bias, and overconfidence bias. Impact bias refers to the tendency to overestimate emotional responses to events and experiences (Grimes et al., 2015). This bias leads individuals to assume that specific tasks will be easier to perform without considering the task's long-term

emotional impact. The overconfidence bias also refers to the tendency to believe one is better than one actually is. While this bias can boost morale and ambition, it may also result in faulty assessments, unrealistic expectations, and poor decision-making (Fowler & Johnson, 2011). The self-serving bias, as defined by Forsyth (2008), is the inclination to attribute positive outcomes to internal factors and negative outcomes to external circumstances. This bias makes individuals absolve themselves from the negative effects of their actions and credit themselves for positive outcomes.

Another type of bias is the hindsight bias. Also known as the *"knew-it-all-along"* effect, this phenomenon leads individuals to believe that they should have anticipated the outcomes of an intervention after the results are known. Hindsight bias can be influenced by fleeting emotions (Zurbriggen et al., 2021). This positive anticipation can create a false sense of awareness in individuals, causing them to make inaccurate self-evaluations.

A final type of bias is the influence/response bias. This captures the tendency of survey respondents to alter their answers in order to align them with socially acceptable norms (Wetzel et al., 2016). Paulhaus (1991) also defines influence/response bias as the "systematic tendency to respond to a range of questionnaire items based on factors other than the specific content of the items" (p. 17). There are several types of influence/response biases, which are detailed in Table A1 of the Appendix, as posited by Wetzel et al. (2016). Within these types, Meade and Craig (2012) identified respondents' interest and the length of the survey as major factors. For longer surveys, it is reasonable to expect that respondents' attention may wane over time, leading to an increased likelihood of random responses, especially towards the middle or end of the survey (Baer et al., 1997; Berry et al., 1992).

There is a need to examine the influence of various biases on the survey responses provided by students in the authors' context. Hence, this paper seeks to answer the questions;

1) What transformational changes beyond self-efficacy are seen in first-year engineering students in a Project-based Learning (PBL) course?

2) How do pretests and retrospective tests compare in the design of surveys for a PBL course?

2 Methodology

This mixed-method study leveraged tools to conduct both quantitative and qualitative analyses. The two types of surveys were first administered to ascertain any differences in what the participants self-reported. Then, interviews were conducted with select participants to elucidate the reasons for any differences. This research was conducted with the student cohort that participated in Ashesi's Introduction to Engineering course from January to April 2024. Ethical clearance was received from Ashesi University's Institutional Review Board (IRB), with application number 1282023, which was valid until May 2025. To ensure informed consent, participants received detailed information about the study and were informed that they could opt out anytime. The invitation email for scheduling interviews emphasized that participation was voluntary and that they could withdraw without consequences. During the interview meeting, the researcher once again reminded participants of the voluntary nature of the research and sought their consent before proceeding with the questions. Labels were used to represent the participants instead of their names to ensure their anonymity. No other identifying information was used. The interview data is stored securely online, with access shared only with the author team.

2.1 Surveys

Two surveys were designed and deployed for the quantitative analysis: a pre-survey and a retrospective pre-post study. Both surveys asked participants to assess themselves along five categories, using the same Likert-scale questions (scale of 1 to 10). The extreme scores of 1 and 10 indicated "strongly disagree" and "strongly agree", respectively. These categories included students' perceptions of their Group Work Skills, Interpersonal Skills, Problem-Solving Skills, and Potential Within Africa and Self, and other questions. The full list of questions is provided in Table A2.

These questions had been formed as a result of interviews with this student population, which sought to elucidate those constructs that they self-reported as being noteworthy from this course. Whereas the immediate prior work deployed surveys with constructs that the author team determined best fit the context (Beem et al., 2023a), the author team sought here to allow the students' voice to inform the selection of constructs. Interviews were carried out with twenty-six participants who had participated in the course in the past. Questions asked in these interviews can be found in Table A3. Ten out of the twenty-six transcripts were determined to have enough substantive reflection to warrant further use. Participants who had had at least one year elapse since they took the course tended to provide deeper reflection in their responses. Twenty-four codes were derived from the ten transcripts, and these were grouped into the six categories stated above. These categories were expected to describe significant changes in skill and perception that students in this first-year engineering PBL course experience. Questions on Group Work Skills were obtained from the *"Development and Validation of group work skills questionnaire for higher education*" whilst questions on problem-solving skills were obtained from "*Development of Problem-Solving Confidence Questionnaire: Study of validation and reliability*" (Cumming et al., 2015; Gok, 2012). The other questions, such as Potential within Africa and Self, were drawn from insights gained in mock interviews run prior to the actual interviews.

The pre-survey was conducted in the first week of the course, and the retrospective pre-post survey in the last week of the course. The aim of this approach was to compare the same students' responses at different time points. That is to compare their pre-course score as they self-reported at both the beginning and end time points. Across both cohorts for the course, 82 students completed both surveys, representing approximately 87% of the whole class. Of these 82 students, 43 identified as male, and 39 identified as female. Students were also asked questions that captured whether they had previous design-build experience or not.

2.2 Quantitative analysis

Two sets of quantitative analyses were conducted on the survey data- one to determine the internal consistency of the surveys and one to determine any statistical significance between student responses at the various time points. Exploratory Factor Analysis (EFA) was used to determine whether the answers given by the students were correlated with others within the same category within each survey. A varimax rotation was conducted on each of the three sets of results (pre-survey, retrospective pre-test, and retrospective post-test). All factor loadings with an absolute value < 0.5 were ignored. For the sake of space, each question has a label corresponding to its section: GW (Group Work Skills), IP (Interpersonal Skills), PS (Problem-Solving Skills), PIA (Potential in Africa/Self), and OT (Other) questions.
Additionally, the statistical significance of the differences in the responses of the pre-survey and retrospective pre-test surveys, compared to those of the retrospective post-test surveys, was determined. To achieve this, paired two-tailed t-tests were used with a 5% threshold value. A Hedge's g-test was used

to determine the effect size of any statistically significant differences. The effect size was considered small if |g|>=0.2, medium if |g|>=0.5, and large if |g|>=0.8.

2.3 Qualitative analysis

From the quantitative analysis, it was seen that many participants rated themselves lower in the retrospective pre-test self-assessment than in the pre-survey. There was a need to understand the cause of the discrepancies between these two data points; hence, a qualitative approach was pursued. Participants who had the largest differences were identified. This was done by comparing their average scores within each transformation and comparing the difference between the two pre-course data points. Students whose scores were most distinct from each other were highlighted, emailed, and invited to an interview. Three people, 2 females and 1 male, volunteered and were then interviewed by the second author. The timeframe for these interviews was in February 2025, which was about ten months after the end of the course.

The interviews lasted roughly twenty minutes for each participant. The interview was semi-structured to elicit more insights into the differences between the pre-survey and retrospective pre-test self-assessments. The following four interview questions were used:

Interview Question 1: At the beginning of the class, you rated yourself a (score) out of 10 across the various categories. Can you reflect on what led to that self-assessment?
Interview Question 2: We observed an interesting trend across much of the class, which was that the pre-scores provided at the end of the course were relatively lower. You also fell into this trend, rating yourself around a (score) out of 10 in this. Can you reflect on what may have led to those differences for you?
Interview Question 3: Before starting the course, did you feel you had a clear understanding of its content in relation to the areas addressed in the survey? What do you think the course had to offer regarding the transformations?
Interview Question 4: In what ways, if any, did your perceptions of your skills change from the beginning to the end of the course?

The interviews took place online, with participants asked to select a meeting time of their convenience. The session was recorded on Zoom and transcribed using the Otter AI transcription tool. The interviewer then corrected discrepancies between the transcribed text and the audio recording.

Qualitative analysis was utilized to identify relationships and themes present in the data obtained through the interviews. This initial coding process utilized the descriptive and in vivo coding techniques. The in vivo analysis is best suited for this part of the study because it prioritizes the participant's voice. The descriptive code aims to answer the question "What is going on here?" (Saldaña, 2009, p. 70) and is also essential for assessing longitudinal participant change over time (Saldaña, 2003, 2008). In this study, the descriptive codes used were predetermined from the set of cognitive biases identified in Section 1.4. These codes were assigned to respondents' portions of the transcripts. The second level of coding was pattern coding, where similar and repetitive codes were categorized under overarching themes. Through pattern coding, this study was able to ascertain the major themes in the codes and patterns in the cause of discrepancies in the retrospective pre-test and pre-survey answers. Participant 1's transcript was coded to generate a codebook. The codebook consists of four columns: the code, the definition, the description, and an in vivo description of the code. During meetings with the principal investigator (fourth author), the elements in the codebook were critically assessed to ensure they captured the data from the participants. The codebook was then adopted and used to code the remaining transcripts.

The first cycle coding (structural coding) of the raw data developed the memocode, in which the following predetermined codes were assigned: Dunning-Kruger effect, overconfidence bias, anchoring bias, optimism bias, planning fallacy bias, Illusion of control bias, hindsight bias, self-serving bias, and impact bias. Pattern coding was utilized during the second-level coding process.

3 Results

3.1 Internal consistency of the surveys

The EFA carried out on the pre-survey answers yielded 9 factors that loaded haphazardly onto the survey questions. In each section of the survey, except Personal Evolution, there was one question that was not strongly loaded onto any factor. Despite the many factors, some categories loaded together on certain factors. Five of the seven questions in the Interpersonal Skills category loaded together, and five of the seven questions in the Personal Evolution category loaded onto one or more of two different factors. There are two factors that only have a strong negative correlation with one question each. Because of the volume of factors, it is difficult to assign a meaning to each factor.

The EFA carried out on the retrospective pre-test survey answers yielded 4 factors. This is shown in Table A4. The first factor loaded strongly onto all of the questions in the Group Work and Interpersonal Skills sections, as well as one question in the Problem-Solving section. This suggests that Group Work and Interpersonal Skills can fit together in one category of questions. The second factor loaded strongly onto every question in the Personal Evolution section and the first four questions in the Potential in Africa/Self section. This factor seems to depict individual self-assessment. The third factor loaded strongly onto one question in the Group Work section and all of the questions in the Potential in Africa/Self section. This suggests that the context of Africa makes it such that the first four questions in this section obtain information that is separate from self-assessment. The fourth factor loads strongly onto the first five questions in the Problem-Solving section, showing that the questions are correlated and give unique information. The sixth question in the Problem-Solving section is the only question without a strong loading onto any factor.

The EFA carried out on the post-retrospective survey answers yielded three factors. These overlapped across the various groupings. The first factor loaded strongly onto four of the seven questions in the Group Work section, one of the questions in the Interpersonal Skills section, five of the questions in the Problem-Solving section, eight of the nine questions in the Personal Evolution section, and all of the questions in the Potential in Africa/Self section. The second factor strongly loaded onto all of the questions in the Group Work Skills and Interpersonal Skills sections, along with one question in the Problem-Solving section and two questions in the Personal Evolution section. This further suggests that the Group Work and Interpersonal Skills questions extract similar information. The third factor only loaded strongly onto question six of the Problem-Solving section and question 2 of the Personal Evolution section.

Table 1 shows Cronbach's alpha scores for each set of survey responses. With each set of responses having a score of over 0.9, it can be said that these surveys are reliable.

Table 1: Cronbach's alpha scores for survey questions

Survey	Cronbach Alpha	Number of Questions
Pre-Survey	0.941	40
Retrospective Pre-test	0.986	36
Retrospective Post-test	0.988	36

3.2 Comparison of the two surveys

There were no statistically significant differences between the answers given on the pre-survey and the retrospective post-test survey. If one were to look solely at that dataset, one may determine that this class had no impact on the students. However, based on the comparison of the data within the retrospective survey (retrospective pre-test and the retrospective post-test), statistically significant increases were achieved across the board. As shown in Table 2, statistically significant increases were seen in all five categories. This happened with a small effect size on Group Work Skills, Interpersonal Skills, and Problem-Solving Skills. This happened with a medium effect size on how much the students believed that they had grown and the potential of engineering to produce positive change within Africa.

Table 2: p-values of differences in results between retrospective pre-test and retrospective post-test data

Category	P-value	Hedge's g value	Effect Size
Group Work Skills	6.34 E-10***	0.454	Small
Interpersonal Skills	5.07 E-06***	0.201	Small
Problem-Solving Skills	1.90 E-11***	0.426	Small
Potential in Africa/Self	4.83 E-17***	0.572	Medium
Other	1.13 E-16***	0.582	Medium

**p<= 0.05*
***p<= 0.01*
****p<=0.001*

These trends are largely mirrored in the disaggregated data. Across both genders, both cohorts, and students with/without previous design-build experience, statistically significant increases with small to medium effect sizes were measured. Exceptions to this include the Interpersonal Skills category, which saw no effect size for the following disaggregations: Females, Cohort B, and students with previous experience. Students with previous experience only showed an increase of small effect size in Potential in

Africa/Self. And for these two disaggregations- Females and students with no previous experience- there was an increase of medium effect size in Problem-Solving Skills.

3.3 Qualitative Results

In the interviews, the participants reported significant gains from the course. For example, Participant 2 noted substantial improvements in her skills. She stated, "*We had experience with SolidWorks. We learned about the design cycle and programming in C*." The tasks assigned in class, which initially seemed out of scope, helped her develop an anticipation for future tasks and laid a strong foundation for her engineering journey. She said, "*Building a rocket is obviously not something that first-year students typically do. So, at the beginning of the semester, even though we didn't know the full scope of what we were doing, we had an idea.*"

The gains they articulated aligned with the changes reported on the retrospective pre-post survey. Coding of the interview data revealed nine biases that contributed to discrepancies between the two datasets in this study. These nine biases were coalesced into three overarching categories: Self-Assessment Bias, Memory/Recall Bias, and Influence/Response Bias.

Self-Assessment Bias: From the interview data, the Dunning-Kruger effect was prevalently exhibited by participants as the cause of the discrepancy in their pre-survey and retrospective pre-test assessments. All three participants said they rated themselves highly in the pre-survey due to their experiences in high school. Participant 2 specifically mentioned her high school Physics experience and the fact that some concepts at the initial stages of the course were related to that; hence, she rated herself highly. The high school experience, coupled with initial experiences in the first few days of taking the class, also constituted an anchor bias- the situation where participants rely on previous experiences (the anchor) to assess present conditions. She went on to say, "*I guess [the high score in the pre-survey*] *was based on what I felt I had experienced, not exactly proficiency, but I mean, I've encountered this before*." Participant 3 also rated himself highly in the retrospective pre-test survey because, before coming to the university, he had always known himself to be a good student. Some participants also exhibited an overconfidence bias. Participant 2 was overly confident in her abilities as a "*fast learner*," believing this quality would help her overcome any potentially challenging topics that might arise in the course, such as programming. With this initial belief, she rated herself highly (an average of 8.34 out of 10) in the pre-survey. After realizing that some more complex skills are harder to acquire, she then rated herself relatively lower (an average of 7.13 out of 10) in the retrospective pre-test survey.

Memory/Recall Bias: Participants also exhibited hindsight bias- they anticipated the course to be easy before taking it and realized there was more to it than they initially envisaged. The anticipation of ease led to relatively higher ratings in the pre-survey, and they readjusted the score in their retrospective pre-test survey. Participant 2 mentioned, "*I wouldn't say I entirely struggled completely in Intro* [to Engineering]*, but it wasn't as easy as it looked like at the beginning of the semester.*" As part of the course, students were exposed to coding in C++. Some participants were excited about the prospects of learning how to code; however, they were unaware of the challenges that could arise from this new endeavor. The initial excitement led to high ratings in the pre-survey. Participant 1 mentioned, "*I realized that [programming] wasn't one of my strong suits.*" She conceded to having overestimated herself going into the course. "*I would say I overestimated how smooth the course would be for me. Yes, I overestimated that.*"

Influence/Response Bias: There were elements of careless responses in some of Participant 3's responses, which adversely affected his overall average. Even though he could not justify his self-confidence or how

well he worked in a team, he went ahead to complete the survey with some responses, and conceded that "*I don't know why I rated myself lower*." This concession may be due to his forgetting his scores in both surveys or his desire to express socially desirable qualities, which may not have entirely represented his reality. He may have felt he needed to find a way of reporting a transformation after taking the course, even if it was not the case. Such response biases can present inaccurate self-ratings and end up altering the quality of the data. The length of the survey questions may have also contributed to the careless responses in Participant 3's responses. This study had 44 and 81 Likert-scale and short-phrase questions in the pre-survey and retrospective survey, respectively.

These results are summarized in Figure 1, which depicts the three overarching biases elicited through the interviews and their components.

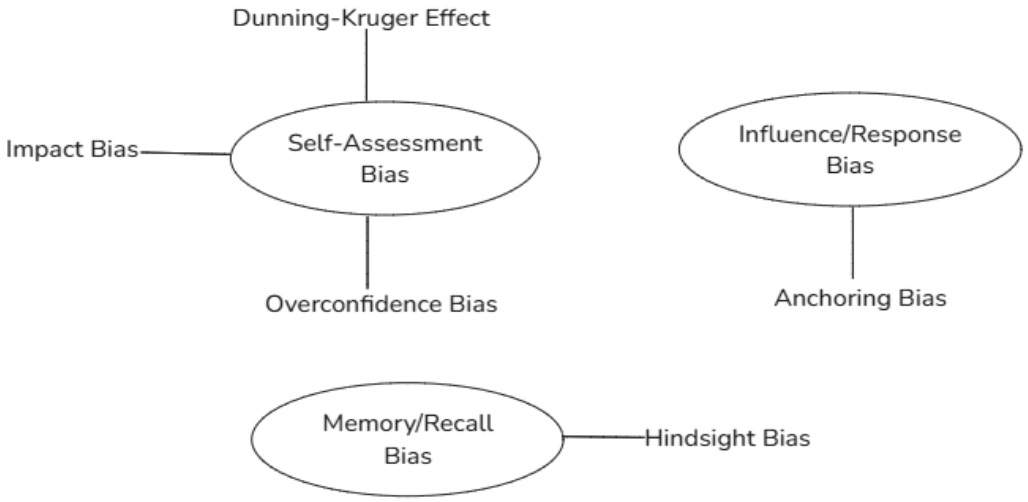

Figure 1: The overarching biases and their components.

Discussion and Conclusion

4.1 Limitations

The qualitative aspect of the research was limited by the sample size and the time that had elapsed between the end of the course and the interviews. Although 20 potential participants were identified through the steps outlined in section 2.3, only 3 signed up to participate, despite multiple email reminders. While this number is generally adequate for qualitative studies (Robinson, 2014), a larger sample might have generated more insights and enriched the findings. To boost sample size in future studies, the authors will consider offering rewards such as phone credit, shopping coupons, or souvenirs to motivate greater participation. Additionally, the course concluded in April 2024, while the qualitative phase did not begin until February 2025, nearly a year later. The demands of their current courses might have overshadowed their memories of their previous courses, making it difficult for them to accurately recall details of their experiences.

4.2 Future Work

This mixed-method study with first-year engineering students in Ghana has shed insight into relevant survey questions and survey types for their context. EFA on the newly developed set of survey questions

was shown to be internally consistent. Factor loadings on the retrospective pre-test were clean and can be used to identify improvements that can be effected in the next deployment.

The factor loadings seen in the retrospective post-test differed somewhat. This could be due to the fact that there are a large number of students answering “10” on the survey questions, leading to some form of ceiling effect. More investigation should be done to identify any actions to be taken to reduce the impact that this effect might have on future surveys.

4.3 Conclusion

All five skill/perception categories showed statistically significant increases with small to medium effect sizes in aggregate. This indicates that each of these does indeed align with what students experience and grow through this course. Interpersonal Skills is perhaps the weakest of these, as it showed no effect size for select disaggregations. Potential in Africa/Self showed one of the greatest changes and is therefore worthy of continuing to dig deeper to uncover the exact causes and mechanisms for this, so that other African universities can similarly cultivate this in their student population. The increase in this category had, however, a lesser effect for students who had some previous design-build experience.

Although the response-shift bias was expected to be a contributor to differences between the two survey types deployed here, it appeared to play a lesser role than the self-assessment bias in this study. The Dunning-Kruger effect and related biases in which the respondents overestimated their ability at the beginning came out the most strongly. The anchoring bias and hindsight bias also emerged as secondary biases at play. Given the small sample size, these insights should be interpreted as pointers to what can be further investigated in the future.

These results suggest that the retrospective pre-post survey may be superior to the traditional pre-post approach in this context. This was seen in a few ways: 1) Although both survey methods were reliable, the retrospective surveys had a slightly higher Cronbach's alpha. 2) Data from the retrospective surveys loaded cleanly onto a few factors, compared to the many factors produced by the pre-survey. 3) The retrospective surveys showed statistically significant increases in students’ perception of their abilities upon the completion of the course, while the pre-survey did not. This, combined with the fact that students in interviews stated that the course did have some transformative effects on them, indicates that the retrospective survey approach is more effective in capturing this transformation. Although likely superior, the retrospective survey may not be entirely exempt from biases, such as the ceiling bias. Perhaps for this or similar target populations, researchers should always consider including qualitative work to supplement surveys so as to cross-check any insights gained. Additionally, similar studies should be conducted in other African institutions to ascertain the extent to which the experiences captured in this study translate more broadly.

5 References

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Appendix

Table A1: Influence/response biases and their characteristics by Wetzel et al. (2016)

Influence/Response Bias	Characteristics
Acquiescence response style	Preference for categories stating agreement (e.g., agree, strongly agree).
Disacquiescence response style	Preference for categories stating disagreement (e.g., disagree, strongly disagree).
Careless responding	Inattentive responding.
Extreme response style	Preference for extreme categories (e.g., strongly disagree, strongly agree).
Midpoint response style	Preference for the midpoint of a rating scale (e.g., neutral).
Socially desirable responding	Tendency to describe oneself positively to reflect social norms and rules.

Table A2: List of survey questions asked, grouped by Transformation type

TRANSFORMATION	QUESTIONS
Group Work Skills	I remind the group how important it is to stick to schedules.
	I construct strategies from ideas that have been raised.
	I clearly define the roles of each group member.
	I move the group's idea forward towards a strategy.
	I evaluate how well the group is progressing toward the agreed goals.
	I provide constructive feedback on the group's progress towards agreed goals.
	I dominate in group discussions.
	I encourage everyone to set aside their personal agendas or their personal interest.
Interpersonal Skills	I provide emotional support to my group members.
	I am sensitive to the feelings of other people.
	I show that I care about my group members.
	I can be open and supportive when communicating with others.
	I can be there for other group members when they need me.
	I encourage the group to set goals that are challenging and attainable.
	I believe that group members are capable of completing their share of the work.

Problem-Solving Skills	I am sure that I can solve a problem.
	I try too hard when I cannot solve the problem.
	I am self-confident in problem-solving.
	I do my best to be successful in problem-solving.
	I struggle with a problem until I find the correct answer.
	Preconceptions prevent me from solving problems.
	I am interested in problem-solving.
	I enjoy solving a problem.
	I like to solve a problem.
	I do my best to solve the problem, no matter how difficult the problem is.
Potential in Africa/Self	I see myself as capable of solving problems around me.
	I am capable of designing and building solutions to problems I identify around me.
	I see myself as a local innovator.
	I see myself as capable of creating technologies that will improve lives.
	I see the possibility of technological advancement in Africa.
	I see Africa as a place where technology and innovation can be produced.
	I believe Africa's technical challenges can be addressed by local engineers.
	I see myself being part of the engineering workforce that leads Africa's development.
Other	I see engineering to be difficult.
	I have the ability to recover quickly from difficulties when working on an engineering project.
	I can continue working on an engineering project even though it is difficult.
	I have the ability to commit myself to my engineering project.
	I am sure of my ability to work on an engineering project.
	I want to know or learn more about engineering.
	I take charge of my learning.

Table A3: List of interview questions prior to survey

Interview Questions
1. As a first-year African student, can you describe your expectations towards enrolling in a course that gives you practical experience?

2.	How important was it for you to get good grades in the course, and why?
3.	Can you describe the usefulness/helpfulness of the course to you in the first year?
4.	Can you describe your level of interest in the course?
5.	In what ways did you adjust to any challenge you may have faced in the course?
6.	What did you learn about yourself as you took the course?
7.	How did the course help you make real-world connections?
8.	What did you learn about yourself by working with other people?
9.	How did the course affect your mindset toward engineering?
10.	In what ways did the course affect how you see yourself? (eg. Confidence, competence)
11.	What activities are you currently engaged in that were inspired by the course?
12.	How did the course affect your ability to make decisions?
13.	How did your experiences result in your developing an interest in the course?

Table A4: Factor loadings of retrospective pre-test survey questions

	Component			
Question	**1**	**2**	**3**	**4**
GW01	.691			
GW02	.655			
GW03	.553		.583	
GW04	.613			
GW05	.725			
GW06	.679			
GW07	.705			
IP01	.778			
IP02	.819			
IP03	.836			
IP04	.821			
IP05	.773			
IP06	.730			
PS01				.509
PS02				.620
PS03				.658
PS04				.572
PS05	.526			.571
PS06				
OT01		.574		
OT02		.772		
OT03		.711		
OT04		.737		
OT05		.666		
OT06		.755		
OT07		.604		
OT08		.685		
OT09		.640		
OT10		.624		
PIA01		.600	.568	
PIA02		.592	.512	
PIA03		.550	.622	

PIA04	.509	.664
PIA05		.771
PIA06		.700
PIA07		.810

Integrating Project-Based Learning and Cooperative Education for Future Engineers: Insights and Best Practices from the Iron Range Engineering Bell Model

Yuezhou Wang
Minnesota State University, Mankato, USA, *yuezhou.wang@mnsu.edu*

Ron Ulseth
Minnesota State University, Mankato, USA, ron.ulseth@mnsu.edu

Cody Mann
Minnesota State University, Mankato, USA, cody.mann.2@mnsu.edu

Abstract

The Iron Range Engineering (IRE) Bell Model combines project-based learning (PBL) with cooperative education to enhance students' technical and professional skills. The program begins with the Bell Academy—a semester-long bridge emphasizing foundational engineering principles, design thinking, and career development. Students then undertake 24-month paid co-op placements while completing remote coursework, supported by learning coaches who foster self-directed learning and reflective growth. Recent data highlight high co-op placement rates and a strong sense of community, demonstrating the model's effectiveness across diverse student populations. This paper discusses key strategies, including assessment tools, self-directed learning, student recruitment, and support, which have been integral to the program's success. By sharing these best practices and lessons learned, we aim to present an adaptable model for other institutions seeking to integrate experiential learning into their engineering curricula, ultimately promoting both academic excellence and career readiness.

Keywords: Iron Range Engineering, Project-based Learning, Work-based Learning, Cooperative Education

1 Introduction: an overview of Iron Range Engineering (IRE) program

The Iron Range Engineering (IRE) program, an upper-division engineering initiative supported by Minnesota State University, Mankato, exemplifies a transformative model in engineering education. Founded in 2009 and inspired by the globally renowned Aalborg University PBL model (Kolmos, Bøgelund, Spliid., & Monrad, 2019), IRE bridges the gap between theoretical instruction and industry practice (MacLeod, et al., 2020) through a comprehensive methodology combining project-based learning (PBL), work-integrated experiences, and self-directed learning (Johnson, Ulseth, & Wang, 2018). It challenges conventional frameworks prioritizing technical expertise while underemphasizing professional and workplace competencies. The program also addresses educational disparities faced by geographically isolated and diverse student populations, often referred to as "engineering education deserts," (Hillman, 2016) by collaborating with community colleges nationwide to create streamlined transfer pathways (Maki, et al., 2019). IRE's curriculum emphasizes developing "whole engineers" by integrating technical knowledge, professional growth, ethical responsibility, and adaptability across three core domains: technical learning, design thinking, and professionalism. Its innovative approach has earned notable recognition, including the ABET Innovation Award in 2017 and being identified as an "emerging world leader" in engineering education in MIT's Global State of the Art in Engineering Education report (Graham, 2018). Since 2019, IRE has gradually integrated co-ops into PBL curriculum known as the Bell Model. This version of the program was inspired by the Charles Sturt University engineering program in Australia (Lindsay & Morgan, 2021). Currently, the IRE Bell Model has graduated 96 students and achieved a five-semester graduation rate of 80%.

2 Program Structure in IRE Bell Model

Students start their first semester at Bell Academy (BA), a semester-long bridge program designed to support them in transitioning from foundational STEM coursework to industry placements. BA equips students with technical, design, and professional competencies necessary for successful co-op placements and future careers in engineering (Christensen, Singelmann, & Mann, 2023). The program implements a traditional way of implementing PBL, where students collaborate on industry-related design projects and receive training in technical subjects through 6 modular one-credit courses in Mechanical and Electrical Engineering (Fig. 1). These one-credit courses focus on the fundamental principles essential for passing the Fundamentals of Engineering (FE) exam, a key step toward becoming a licensed professional engineer. Each course also requires students to complete a deep learning activity—such as a simulation, experiment, or technical report—related to the course content. Professional skills such as leadership, conflict management, and public speaking are integrated into the 3-credit design course, which is a semester-long industry project. There are two highlights in furthering students' career preparation. First, the BA fosters self-directed learning by

encouraging reflective practices and personal development, ensuring students are prepared for real-world engineering challenges while building a strong professional identity. Second, learning coaches guide students in developing comprehensive job packages, including resumes, cover letters, mock interviews, and career fair participation. To maximize job placement success, students are encouraged to apply for approximately 50 positions within one month into the Bell Academy (Rogalsky, Johnson, & Ulseth, 2020).

Following Bell Academy, students enter 24-month paid, full-time industry positions while completing their technical courses remotely (Figure 1). They receive support from faculty to develop self-directed learning plans. There are also ABET-driven assessment tools (discussed in the next section) to ensure high-quality learning when they are remote learners. From the perspective of financial stability, students typically earn $21-$23 per hour for a 40-hour work week (Spence, Siverling, Karlin, & James, 2023), often covering tuition and living expenses. This unique model ensures graduates emerge not only with strong academic credentials but also with extensive industry exposure, enhancing their competitiveness in the job market.

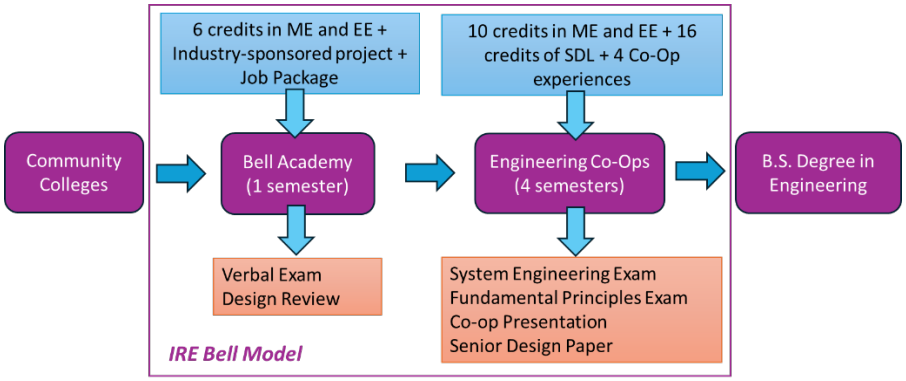

Figure 1 IRE Bell Model structure and major assessment tools

3 Best Practices in the IRE Bell Model

3.1 Self-directed Learning

Self-directed learning (SDL) at IRE is a core element of its PBL framework, empowering students to take ownership of their educational journey. SDL begins in the Bell Academy, where students are introduced to cognitive frameworks like goal-setting, self-regulation, and reflection (Clausen, Ulseth, & Johnson., 2021). These foundational skills enable students to manage their learning effectively. During the co-op phase, SDL becomes more prominent through Student-Led Advanced (SLA) courses up to 16 credits. In SLAs, students identify a technical topic relevant to their work or personal interests, and then design a personalized syllabus specifying learning outcomes, deliverables, and timelines. After gaining approval from the faculty advisor, they will independently engage in the coursework. This culminates in a thesis-style verbal exam where students present their deliverables and demonstrate their mastery. The entire process requires high levels of initiative, critical thinking, and problem-solving while fostering adaptability and confidence in tackling complex engineering challenges.

3.2 Assessment Tools

IRE employs a variety of assessment tools (Figure 1) across its diverse learning formats to gauge students' understanding of engineering fundamentals and their capacity to apply these concepts in design work. Among these methods, verbal examinations (Christensen, Singelmann, Sleezer, & Siverling, 2023) stand out for evaluating both technical competence and the ability to convey complex ideas—a critical yet often underdeveloped skill among engineering students. These exams are aligned with the course's predefined learning outcomes and are supported by formative assessments like reflective journals, quizzes, and project deliverables. During each verbal exam, students respond to structured and adaptive questions,

demonstrating not only their problem-solving acumen but also their communication strategies. Immediate feedback reinforces IRE's learner-centered pedagogy and fosters continuous improvement. A standardized 5-point grading scale (Singelmann, Wang, & Christensen, 2023) assesses performance. The numerical grade is associated with the "job satisfaction" level in industry: 1 – unacceptable and 5 - exemplary, which encourages iterative growth and feedback over static grades. For students in co-op programs, four main assessment tools evaluate technical growth and professional development every semester:

Systems Engineering Exam: Students present real-world projects—ranging from HVAC systems to telecommunications networks and solar panels, focusing on key components, interactions, and maintenance strategies. Tackling complex systems transform uncertainties into opportunities for deeper learning.

Co-op Presentations: Students share on-the-job project experiences, detailing technical challenges, skill development, and professional advice. These conference-style presentations allow peers to learn collectively about industry practices and standards.

Fundamental Principles Exam: By explaining concepts such as virtual work, diodes, heat convection, and PID controllers, students develop a strong understanding of key principles essential for the FE Exam. Through solving related closed-ended problems, they reinforce their problem-solving skills. Students are encouraged to define or illustrate each concept, discuss a real-world application, and connect it to other principles, deepening their comprehension and strengthening their analytical abilities.

Table 1 A typical structure of an IRE Senior Design Paper

Chapters	Key Components and Associated ABET Performance indicators
Introduction	Personal background, motivation, and program impact on professional development.
Technical Learning	Literature review of technical knowledge, key engineering principles and documentation of co-op/project applications. (ABET 1)
Design Learning	Design principles, tools, standards, stakeholder analysis, and real-world project applications based on co-op projects (ABET 1, 2 & 8)
Professionalism Learning	Analysis of skills like teamwork, conflict management, communication, and inclusivity. Documentation of experiences in professional environments (e.g., inter-team communication and leadership). (ABET 4)
Reflection	Self-assessment of growth as an engineer, including technical persistence, empathy, and understanding. Discuss how the educational and professional journey has shaped the individual's identity and future aspirations as an engineer.

ABET 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics. ABET 2: an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. ABET 4: An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts. ABET 8: An ability to incorporate an entrepreneurial mindset, including value creation for a broad spectrum of stakeholders, across the breadth of engineering design work.

Senior Design Paper: This paper functions as a comprehensive, reflective, and technical capstone that consolidates each student's academic and co-op experiences into a single, cohesive document (Table 1). It typically includes a robust technical literature review and detailed design methodologies, supported by modern engineering tools such as CAD and FEA. Students examine stakeholder interests, conduct feasibility analyses, and address professional skills like communication, teamwork, and conflict resolution. By showcasing how theoretical principles are applied to real-world challenges, this paper fulfills ABET performance indicators (ABET Engineering Accreditation Commission, 2020) and underscores readiness for complex, interdisciplinary environments. In detailing their accomplishments and reflecting on pivotal learning moments—from breakthroughs to setbacks—students also articulate the evolving sense of identity and emotional investment that accompanies their transformation into industry-ready engineers.

3.3 Student Support from Learning Coaches

Learning coaches play a pivotal role in bridging the gap between academic learning and professional development. Unlike traditional faculty roles, learning coaches are engineering professionals with industry experience who provide personalized guidance to students throughout their educational journey (Christensen, et al., 2024) in three major areas. First, they provide clear communication and alignment among students, their work supervisors, and professors, forming a supportive triad that keeps everyone's expectations in sync. Second, they oversee weekly written reflections where students answer targeted prompts to identify strengths, set goals, and reinforce new knowledge, as well as regular verbal reports over the phone or online to dive deeper into personal growth. By customizing these discussions while drawing on a shared library of reflection topics, they help students cultivate a continuous improvement mindset (Wang & Ewert, 2021). Third, they also guide students in balancing their work, academic, and personal lives, offering strategies for time management, schedule adjustments, and holistic well-being (Spence, Nyberg, Chasmar, Nelson, & Tsugawa, 2022). These combined efforts make learning coaches a key connector, mentor, and advocate, helping students excel throughout their co-ops and internships in the IRE program.

3.4 Student Recruitment Strategies

Recruiting is achieved through building meaningful relationships with community college partners around the United States. The transfer process for students can be a daunting task, and staff and faculty at the university level must work collaboratively with community college partners to make personal connections with students and support them in the transfer process (Mann, et al., 2022). The combination of university and community college collaboration and intentional relationship-building builds personal connections and helps to increase student engagement, attainment, and satisfaction (Doss, 2021).

Instead of solely attending transfer fairs and handing out flyers, IRE staff visit classrooms at community colleges to provide a brief overview of the program face-to-face. During these visits, students are introduced to the unique work-based/experiential learning model that sets IRE apart from typical transfer opportunities. The introduction is kept short to highlight the program's distinctiveness and allow students to ask questions. Interest cards are distributed, and students can provide their contact information if they find the program appealing. When students express interest, it's essential to follow up promptly via email or text, inviting them to continue the conversation. These follow-ups often lead to in-person or virtual meetings via Zoom or Microsoft Teams, where detailed information is shared, questions are answered, and students are formally invited to engage with the IRE community through a virtual visit with faculty, staff, and current students.

Students who reach this stage and demonstrate strong interest are invited to an onsite campus visit in northeastern Minnesota. This visit includes a campus tour, meetings with program-level advisors to discuss course equivalencies and transfer requirements (Bates, 2024), and opportunities to strengthen connections with faculty, staff, and current students. Additional support is provided for resume building, updating LinkedIn profiles, and exploring personal interests. These strategies help students feel integrated into the IRE community and offer valuable networking experiences, even for those who decide not to transfer.

4 Program Evaluation

4.1 Demographics and Inclusivity

IRE attracts a diverse student population, reflecting its commitment to expanding access to engineering education. Currently, IRE is recruiting students from 20+ community colleges nationwide and serves a demographic comprising 60% white students, 16% Hispanic, 11% African American, and 10% Asian. Additionally, 31% of students identify as female, and 36% are first-generation college students. The program also supports a significant proportion of non-traditional students (35%), underscoring its adaptability to varied educational backgrounds and career trajectories. These statistics showcase IRE's ability to attract underrepresented groups in engineering, contributing to the diversification of the profession.

4.2 Student Progress and Co-op Placement

In a recent survey of 93 current students, 80 successfully secured co-op positions during the Bell Academy, demonstrating the program's effectiveness in linking students with industry opportunities. Among these students, 43 transitioned to new co-op roles while 34 chose to remain in current positions. These findings highlight the flexibility and agency students experience in tailoring their learning and professional pathways.

4.3 Student Feedback and Challenges

A strong sense of community and self-identification as engineers are hallmarks of the IRE experience. In the same survey, 71 students reported feeling well-supported and accepted as integral members of the IRE community. This robust sense of belonging is reinforced by social events and peer interaction, which foster collaboration and camaraderie. Furthermore, 82 students rated their agreement with the statement "I see myself as an engineer" at 5 or higher (scale 1-6), indicating that the program successfully cultivates a strong engineering identity among its participants.

Student feedback (Table 2) also reveals several aspects that are particularly appreciated. The flexibility in learning approaches allows students to adapt their educational experience to their individual needs and preferences. Interactions with learning coaches are highly valued, providing personalized guidance and mentorship. The Bell Academy is lauded for its role in developing professional skills and fostering a sense of belonging through structured social events. Nonetheless, many felt overwhelmed creating and following SDL plans, unsure how to apply these methods across diverse engineering disciplines. Others noted inconsistent connections between courses, making it difficult to manage various aspects of their studies. The heavy emphasis on writing and metacognition was also cited as a stressor, with some students feeling reflective assignments were overly demanding. To address these issues, the program could offer more structured mentoring, guiding students in designing and maintaining checkpoints in self-directed learning. Additionally, streamlining the curriculum with clearer links, along with communicating the value of writing assignments, may ease workload concerns and better support students' professional and academic growth.

Table 2 Student feedback from graduating seniors

Most enjoyable experiences	**Most challenging experiences**
Flexibility of learning	Lost on developing self-directed learning plans
Working with learning coaches	Lack of consistency and connection between courses; Hard to manage learning various aspects of engineering
Strong professional skills developed	Overwhelming writing and metacognition
Sense of belonging and social events	Lack of professional development opportunities

5 Future Directions

IRE Bell Model will examine its long-term influence on graduates' careers, covering leadership roles, technical contributions, and overall professional growth. Adapting the model to a wider range of institutions, including those in underserved regions or global settings, could greatly expand its reach. Integrating AI-driven analytics and adaptive learning could strengthen the assessment of self-directed learning and professional skills. Offering interdisciplinary and global collaboration opportunities—like virtual co-ops and cross-cultural projects—would prepare students for increasingly interconnected engineering challenges. The recently published Engineering Mindset Report (Bertoline, 2024) proposes many themes for improvement in the future of engineering education and includes the following directions that IRE is considering: 1) Efforts to boost underrepresented groups' participation, coupled with mentorship and culturally responsive teaching which could foster greater diversity and inclusion. 2) Investigating the model's economic benefits, such as workforce development and reducing students' financial burdens, may further enhance its value. 3) Experimenting with curriculum refinements, like hybrid or shorter co-op cycles, can help balance academic and professional commitments, ensuring the model's broader applicability and long-term viability.

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Integrating Problem-Based Learning and Design Thinking for Sustainability: A Practical Approach to Teaching Real-World Problem Solving in Undergraduate Education

Sanjay Hanji
MIT Vishwaprayag University, India, *sanjay.hanji@mitvpu.ac.in*

Veeranna Yempally
MIT Vishwaprayag University, India, veeranna.yempally@mitvpu.ac.in

Preethi Baligar
MIT Vishwaprayag University, India, preethi.baligar@mitvpu.ac.in

Krishnendu Jana
MIT Vishwaprayag University, India, krishnendu.jana@mitvpu.ac.in

Avinita Gautam
MIT Vishwaprayag University, India, avinita.gautam@mitvpu.ac.in

Gopalkrishna Joshi
MIT Vishwaprayag University, India, ghjoshi@mitvpu.ac.in

Abstract

This practice paper presents the development, implementation and evaluation of a course, Design Thinking for Sustainability, a university core course for first-year students from undergraduate programs in Technology, Business administration, Computer applications and Design. As a greenfield private university in India, we integrated Design Thinking into the core curriculum to enhance problem-solving abilities. The course addressed real-world, ill-defined challenges through the United Nations' 17 Sustainable Development Goals (SDGs), equipping students with practical, creative problem-solving skills. Offered as a 21-day pre-semester credit course, it fostered interdisciplinary collaboration on sustainability-driven challenges.

Using Problem-Based Learning (PBL) approach, students worked in teams, applying the five stages of Design Thinking—Empathize, Define, Ideate, Prototype, and Test—to develop innovative, sustainable solutions. The design thinking process encouraged iteration, collective work, and optional participation. With this first version of the course, the focus of evaluation was to explore the challenges faced by faculty members and students, which allow for revision during the next iteration of the course.

The findings bring out various challenges perceived by our students and faculty members, and various strategies to overcome them. The challenges stated were psychological readiness for open ended problem-solving, struggle to identify and define real world problems, lacked access to stakeholders and sustainability related data. However, collaborative teamwork, prototyping and stakeholder feedback helped them to overcome the challenges and come up with feasible and workable solutions to the problems thereby developing problem solving skills. Faculty stated that they did not know design thinking whereas they learned it while during the course. Secondly, they had to put significant effort in designing, teaching and assessing in a way to promote active learning. They were agile during the course and did minor adjustments to the course during the course delivery. Overall, this paper provides practical insights for educators who will be seeking

to integrate PBL and Design Thinking into their curricula, particularly with inclusion of sustainability-driven innovation and active learning.

Keywords: Problem-Based Learning, Design Thinking, Higher Education, Problem Solving, Course Design.

1 Introduction

As technology trends evolve, students going to higher education, implicitly hope they have already acquired the skills to implement solutions for real-world problems. Traditional classrooms seldom advocate for a composite, abstract, or unknown solution approach. Thus, graduates fail to navigate uncertain situations. One site which does demand on such 'unpredictable –complex –unknown' character is the sustainability; it's a pressing global issue that calls for a level of focus of transdisciplinary and all-inclusivity which is very much beyond the normal expectation of teaching learning. Sadly, relative to the classroom, students rarely get opportunities to learn that sort of inclusionary skills and real, practical problem-solving operations based on collaboration systems. Thus to address the need, a multi-disciplinary faculty team at a private, greenfield university in India, designed a university core course titled, "Design Thinking for Sustainability" which is common to all first-year students from undergraduate programs namely Technology (B.Tech), Business Administration (BBA), Computer Applications (BCA) and Design (B.Des).

This is taught as a pre-semester credit course that runs for 21 days. While several universities in India offer design and sustainability courses are in tier-I cities, this course is offered in tier-2 city and seeks to understand the societal problems to ensure sustainable solutions for local problems which the students are grounded in.

Driven by three key motivations, the course aims to:

- Develop Problem-Solving Skills: Shift from passive learning to active, structured problem-solving using Design Thinking to create and test solutions.
- Embed Real-World Sustainability Challenges: Apply the 17 SDGs to local problems, ensuring authentic, hands-on learning.
- Foster Interdisciplinary Collaboration: Promote teamwork across technology, business, and design for holistic problem-solving.

This 21-day course equips students with practical problem-solving skills, an empathetic mindset, and a commitment to sustainability and community impact, setting a strong foundation for their academic and professional journey. While the course is aspirational, the first offering in this course was evaluated for the challenges that faculty members and students faced in order to redesign the course for the next offering during the academic year 2025-2026..

2 Literature Review

2.1 Design Thinking in Education

Design Thinking (DT) is a creative, structured, human-centered process used to solve problems (Brown, 2009). DT equips pupils with 21st-century skills that give them an advantage over others. In a higher education setting, DT is something that allows students to think critically and is transferrable skills needed to approach and solve problems in the real world (Razzouk & Shute, 2012). Almost all degrees in higher education have incorporated problem-solving into their curricular design and assessment for the success of graduates that needed to occur. The only drawback is that the DT classroom experience needs an adjustment by the participants of the standard classroom experience, which makes faculty confused who cannot easily defer from the guided exploration and start getting frustrated at the ambiguous experiences (Goldman et al.,

2009). A great tool to utilize in determining proper problem-solving strategies and a perfect precursor for PBL, DT is excellent.

2.2 Problem-Based Learning (PBL) and Interdisciplinary Approach

An approach similar to Design Thinking (DT) is Problem-Based Learning (PBL) in which students engage with real-world problems and an interdisciplinary approach to teamwork (Barrows, 1986). This increases student engagement and knowledge retention in the long term (Hmelo-Silver, 2004) and is often found in the fields of medicine and engineering (Schmidt et al., 2011). However, it also requires curricular reformation and trained facilitators (Dolmans et al., 2005). However, if this can be achieved, PBL develops essential teamwork and critical thinking skills across the disciplines and therefore would be highly effective for sustainability education.

2.3 Sustainability Education and the SDGs

Sustainability education is connected to the United Nations Sustainable Development Goals (SDGs) and seeks to prepare learners to combat anticipated challenges to future environmental, social, and economic well-being (UNESCO, 2017). In the realm of scholarship, much relative research exists at the collegiate level with sustainability projects through cross-disciplinary efforts and interprofessional research (Lozano et al., 2015). However, institutional barriers and faculty expertise gaps slow adoption (Sterling, 2011). When combined with DT and PBL, sustainability education fosters innovative, real-world solutions.

3 Methods

3.1 Course Design & Implementation

This course was offered a 3-credit, first-year course titled “Design Thinking for Sustainability” at a private engineering university in India. This course equips students with design thinking and sustainability skills through hands-on, collaborative learning. Offered as a Pre-semester, PBL, credit course for 21 days, the students define problems using design thinking tools, work in teams, and develop sustainable solutions that are environmentally, socially, and economically viable for the tier-2 city Solapur, Maharashtra. Following an in-semester to end-semester assessment ratio as 80:20, the course followed a typical three reviews during the milestones of problem definition, Ideation and Prototype, and testing. The students worked in teams of 6 with a gender-balanced team composition. A total of 24 projects focused on various SDG goals were completed by students that identified problems in Solapur region Project Titles.pdf. The key SDGs addressed were SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Other SDGs covered included SDG 4 (Quality Education), SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 15 (Life on Land).

3.2 Evaluation of the Course

For both faculty and students, this was the first time in designing and undergoing a design thinking course, respectively. Thus, this study employed a qualitative research approach using semi-structured interviews either in-person/online mode to gather insights from 05 faculty members and 11 students about the challenges they faced. The interviews were stopped after reaching the theoretical saturation. Ethical considerations, including informed consent and confidentiality, were ensured. Thus, the interviews focused on the same elements for both: Challenges faced in teaching and learning as listed in Appendix A. Thematic analysis was used to identify patterns and themes within the data (Braun & Clark, 2017).

4 Findings

This section separately presents the challenges that both faculty and students faced while designing and implementing, and undergoing the course, respectively. These challenges will be used as inputs during the redesign of the course for the next offering for the academic year 2025-2026.

4.1 Findings from Students

The findings from the analysis of student and instructor responses lead to a nuanced understanding of the challenges. The 11 codes that emerged from the thematic analysis of the student responses lead to seven broad but connected themes as shown in figure 1.

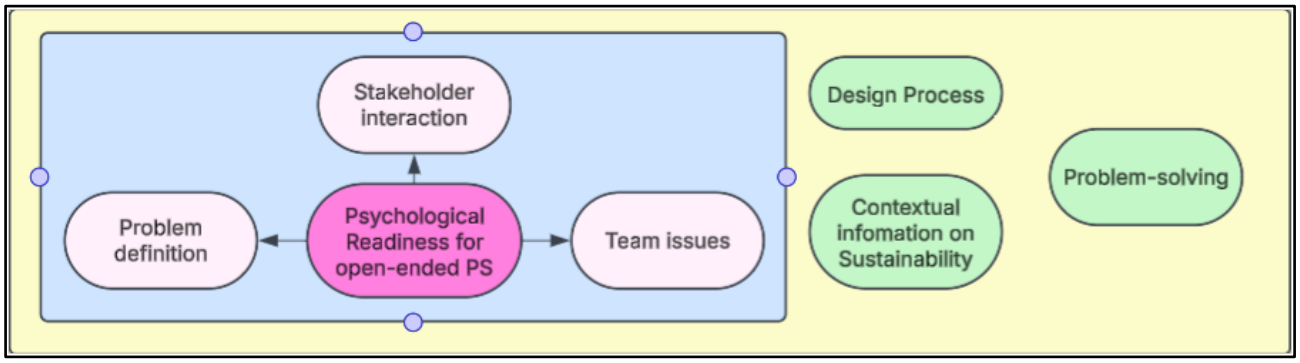

Figure 1 Challenges faced by students

The psychological readiness for open-ended problem-solving emerged as a critical challenge for students accustomed to structured, textbook-based exercises. The lack of predefined solutions led to initial uncertainty—“We felt lost initially, but breaking the problem into smaller parts helped.” To navigate this, students adopted a segmented approach, focusing on specific aspects such as “workload, problem parts, and budget” to manage complexity. Another challenge was identifying the difficulties, as students found it difficult to characterize actual sustainability issues. The interconnected nature of sustainability made narrowing their focus difficult—One of the biggest challenges was defining the problem itself, “Problems of sustainability are connected.” This is learned because much was spent on figuring out the technological viability and scope of a project before moving on to the next step. The second hardest part was assessing stakeholder engagement—students didn't always have access to their users—“We weren't able to do as many user interviews as we wanted.” Thus, their potential to validate or invalidate their assumptions and adequately pivot their problem statements was constrained. However, there was within the design process, they could prototype and get feedback through iteration. Students acknowledged the role of testing—“Prototyping and testing helped us refine our solutions”—but also noted constraints such as time pressure—“The 21-day duration forced rushed decisions, limiting research and iteration.” Team dynamics played a crucial role in problem-solving effectiveness. Some students faced disengagement from teammates, impacting collaboration—“Some teammates did not take it seriously.” However, structured communication and role delegation helped—“Once we defined each person’s role, collaboration became smoother.” Access to sustainability-related information in the local Solapur context was a barrier, as students struggled to find credible and relevant data to inform their solutions. Finally, the course was able to challenge students to think critically and develop structured problem-solving skills by engaging with real-world sustainability issues “"The DTS course pushed us beyond our comfort zones, encouraging us to think critically and creatively about sustainability. While there were challenges, they ultimately helped us grow and develop a structured approach to solving complex problems".

4.2 Findings from Faculty

The authors observe that the challenges faced by faculty lie at the intersection of multiple themes, making it difficult to delineate them precisely. The 11 codes emerging from thematic analysis led to three

interconnected themes as shown in figure 2. Faculty readiness, the effort-intensive nature of active learning, and the need for agile course development are deeply intertwined, influencing each other throughout the course implementation.

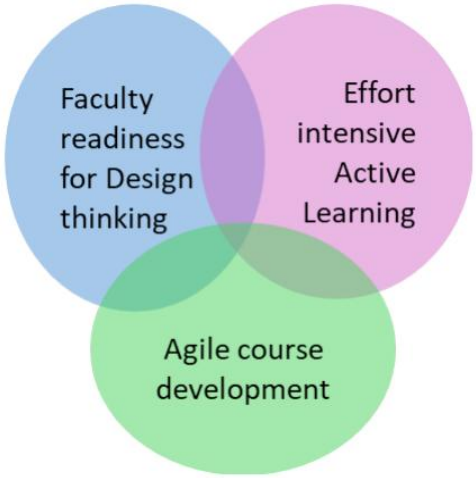

Figure 2 Challenges faced by faculty

Faculty faced multiple challenges in delivering this intensive course, primarily due to **limited prior exposure to design thinking**: "I learned about problem-solving using design thinking, which I had never encountered before." The lack of structured training led to inconsistencies: "Prior training was not conducted due to time constraints, causing inconsistencies." **Active learning** demanded significant effort, particularly in assessment: "Assessing individual performance was tough because they worked in groups." Faculty managed workload by sharing resources: "We ensured two faculty members per class by borrowing from other departments." **Agility** in course delivery was crucial, with real-time adjustments necessary: "Some activities in the empathy module were modified as they weren't feasible in class." The need for structured training and better planning was evident.

5 Conclusion and Recommendations

While the faculty team believes that the course enabled students to address wicked problems at a tier-2 city through a problem-based learning experience and focus on the SDGs, the findings sought to understand the challenges that faculty members and students faced which opens-up opportunities during the course redesign. To effectively address the challenges faced by faculty, the following recommendations are suggested: first, it is imperative to design a university specific induction program which also includes structured faculty training on design thinking courses and active learnings strategies (Goldman et al., 2009; Dolmans et al., 2005). Second, as courses like this need quick response even during delivery, the faculty must be trained on real-time course adaption techniques which leads to an agile course-redesign process (Sterling, 2011; Desai et al., 2025).

In addition, the students could benefit from structured orientation program that introduce to the ambiguity and ill-structuredness (Baligar, Joshi & Shettar, 2021) in sustainability related problems in our society. Second, to be able to implement a guided problem decomposition, it is also essential to include sessions on systems-thinking and stakeholder interaction. Lastly, problems transpired among group sizing for effective communication and capability, interdisciplinary teams, and time restrictions that prompted student feedback and adjustment in project development, which can be overcome by designing team interactions using cooperative (Baligar et al., 2022) or collaborative learning methods (Mercier et al, 2023; Desai et al., 2024).

Although design thinking gave a valuable, systematic method of guiding students through real world sustainability issues, we acknowledge that there are several drawbacks to the process. One criticism is a tendency to rush to solution generation and at times oversimplifying complex, systemic problems. To overcome this, we made a heavy focus in our course on staying with the problem in the Discovery and Define phases. The techniques including the 5 Whys, stakeholder mapping, systems diagrams, and reframing of the problem were also included to promote the higher exploration prior to ideation. This strategic orientation allowed the students to understand the relatedness of the sustainability challenges and generate solutions that were more appropriately addressed to the root causes.

Overall, to enhance future iterations, extending the course duration and reducing group sizes will allow for deeper exploration and stronger student participation. Providing clearer assessment rubrics, and a standardized operating procedure (SOP) will improve course consistency and evaluation. Increasing access to expert mentorship, case studies, and stakeholder collaboration will further strengthen problem-solving outcomes (Lozano et al., 2015). Strengthening interdisciplinary collaboration and structured peer feedback will enrich the learning experience, ensuring students are better prepared to tackle real-world sustainability issues effectively.

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Appendix A
Semi-Structured Interview Questions

Students:

1. What challenges did you face while undergoing this course on Design Thinking for Sustainability?
2. How did you overcome those challenges?
3. Any other things which you think is relevant to share here
4. Was the course beneficial? If yes, how?

Faculty:

5. What challenges did you face in designing, delivering, and assessing this course?
6. How did you overcome those challenges?
7. What improvements would you suggest for future iterations?

Reflectively Mapping the Zone of Proximal Development in Industrial Engineering

Meelan Roopa
Department of Industrial Engineering, Stellenbosch University, South Africa, meelanroopa@sun.ac.za

Makoena Sebatjane
Department of Industrial Engineering, Stellenbosch University, South Africa, msebatjane@sun.ac.za

Karin Wolff
Faculty of Engineering, Stellenbosch University, South Africa, wolffk@sun.ac.za

1 Introduction

Industrial engineering (IE) is a multi-disciplinary field of study that relies upon four primary knowledge areas: manufacturing systems engineering, human factors engineering, operations research, and management systems (Salvendy, 2001). The major advantage of drawing from different knowledge areas is that industrial engineering graduates can find jobs not only in a variety of industries but also in a variety of roles. While this is a good thing in terms of career prospects after graduating, students do not always understand why they must take courses in all these seemingly disconnected knowledge areas. Consequently, this affects the level of effort they put into some of these courses, particularly the ones they deem to be less related to engineering (Murphy *et al.*, 2006). Furthermore, as motivated by Dwight *et al.* (2006), students do not immediately recognise how these knowledge areas contribute to the broader society in terms of sustainable development goals (SDGs) and graduate attributes (GAs). These are two key features of the new International Engineering Alliance (IEA) graduate competency guidelines (2021), which govern the Knowledge, Skills, Practices and Values expected of graduates upon successful completion of their degree or programs. Sustainability is woven throughout these guidelines. The SDGs are a set of global goals put forward by the United Nations (UN) in efforts aimed at ensuring prosperity and peace not only for everyone in the world but also for the world itself by tackling some of the world's most pressing social, economic, and environmental issues (United Nations, 2015). Engineering is the profession at the heart of achieving our collective SDGs, and engineering educators are tasked with the development of the GAs. The context for the paper is the IE programme at a research-intensive university in South Africa, where the researchers had noted that students do not always see the connection between some courses and their link to SDGs and GAs. Given our task of empowering engineers of the future who are able to implement creative solutions with broad societal impact, a need exists to integrate among these disconnected spheres using scaffolded teaching practices. Of particular concern in this IE programme are the Engineering Economics (E-Econ) and Enterprise Design (E-Des) courses, which students anecdotally perceive as low priority. This study set out to encourage these two IE student cohorts to collaboratively reflect on their respective module 'content', the three pillars of the SGDs (i.e., social, economic, and environmental) and two specific GAs (i.e., GAs 7 - related to sustainability and the impact of engineering activity, and GA 8 - team and multi-disciplinary working) as captured in figure 1.

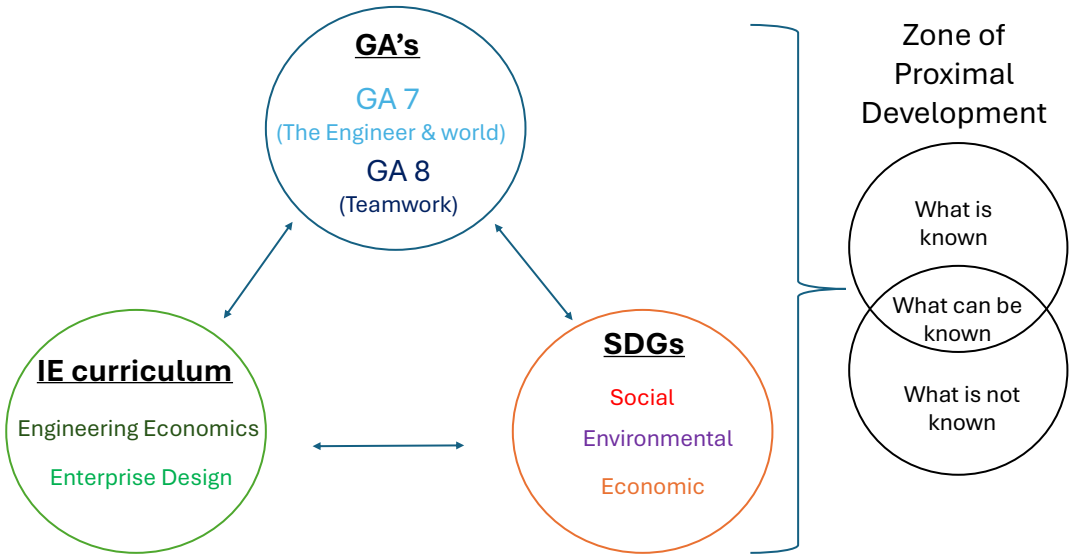

Figure 1 Course, GA and SDG contextualisation with ZPD

The programme in question is located in an engineering faculty which follows a socio-culturally mediated educational ethic. In other words, learning is seen as moving from the known to the unknown in a social context and is facilitated through mediating artefacts. These include texts, discussions, case studies and group work, all of which are intended to scaffold student learning. This scaffolding embodies Vygotsky's (1956) concept of the Zone of Proximal Development (ZPD) constructivist in nature (Payong, 2020), where

different students require different kinds of support to progress across three distinct ZPD stages: i) What is known, ii) What can be known and iii) What is not known. Using this as a framework, the research design (figure 1) is intended to determine the relationship and interactions between the student perceptions of their ZPD stages in two specific courses, the relevant GAs and the three pillars of the SDGs. The question for this exploratory practice paper is: What are our student' perceptions of the nature of and relationship between their curriculum, GAs and SDGs, and how can we better scaffold their learning and support integrative thinking?

2 Methods in context

On average, 100 students are enrolled annually in 3rd year E-Econ and 4th year E-Des. The course objective of E-Econ is to introduce students to macroeconomic concepts within companies, with a specific focus on time value of money and capital budgeting. E-Des is concerned with empowering students with the working knowledge and tools associated with the specification, design, analysis, development and implementation of new or existing features of an enterprise in its entirety. Both courses entail group work and case studies, which align with GAs 7 and 8, as well as the three SDG pillars. Conversations with current students and previous feedback supported the observation that these students experience a disconnect between the curriculum, SDG relevance and Graduate Attributes.

With the newly released International Engineering Alliance competency profiles foregrounding sustainability and inclusivity (IEA, 2021), together, these two courses offer an ideal opportunity to speak to the social, environmental and economic SDGs, and build in forms of pedagogic engagement that address the attributes needed to engage socially in the broader engineering environment.

Collaborating lecturers on the two courses designed a learning activity to investigate the level of disconnect, by using the three-stage descriptors of Vygotsky's concept of the Zone of Proximal Development: i) What is known, ii) What can be known; iii) What is not known.

The objectives were to 1) map the ZPD current state for both courses and 2) determine the possible interaction between the two courses, three SDG pillars and GA 7 & 8.

Students from both cohorts were first introduced to the intent of the research, the three pillars of the SDGs, adaptations of GA 7 and 8, and a reflection on course objectives. The second part of the activity tasked students with consciously reflecting on the content and having them complete the ZPD diagram by detailing each stage of the ZPD associations, as illustrated in Figure 1. The 3rd year E-Econ activity was done asynchronously with a Google Form, whereas the 4th year E-Des activity was done synchronously using a live Google Slides that the entire cohort completed simultaneously. A total of 92 students completed the tasks. All data were consolidated on a spreadsheet, and unique terms were included for analysis and categorisation according to the three ZPD stages. Findings are presented as graphic summaries using Figures 2 and 3 that visualise the ZPD for E-Econ and E-Des, with colour coding corresponding to those that featured in Figure 1. This has been colour coded such that "societal impact of investments" speaks to social sustainability (red) alongside GA 7 (light blue). The colour-coding technique is a visually illustrative and accessible means to immediately identify key patterns and clustering of student responses.

3 Discussion of Findings

3.1 Current state ZPD analysis

The E-Econ cohort mentions under 'what is known' the general curricular concepts already familiar to students, namely: course content, study units and course objectives to do with accounting practices, investments and stock markets They consciously recognise that they do *not* know, but *can* know how these concepts play out at both a macroeconomic level in the real world (GA 7, and the economic SDG pillar), as well as a micro, technical and software-orientated level. The feedback focuses on quantitative techniques,

software, visualization and coding in traditional hard sciences as elements that can be known. Interestingly, for what is 'not known', students mention "how the JSE works", despite having engaged in a collaborative JSE simulation activity which mimics real-world collaborative engagement (GA 8) which concerns the sustainability narrative (all three pillars). The activity requires students to collaboratively develop an investment portfolio (GA 8) and invest virtual money in the stock exchange. Students must then track the portfolio's economic performance in the market and reflect on the broader social and environmental sustainability implications of said performance (all pillars).

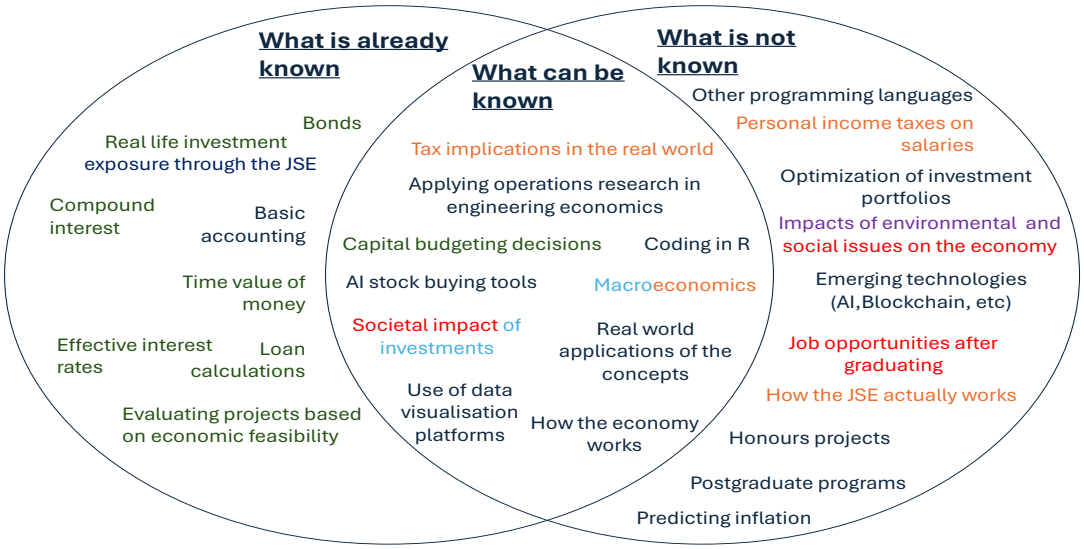

Figure 2 ZPD diagram for Engineering Economics cohort

The Enterprise Design cohort (Figure 3) provided a more industrial engineering-focused reflection on several topics tied to preceding courses under the 'what is known' category. As final-year students, this is to be expected.

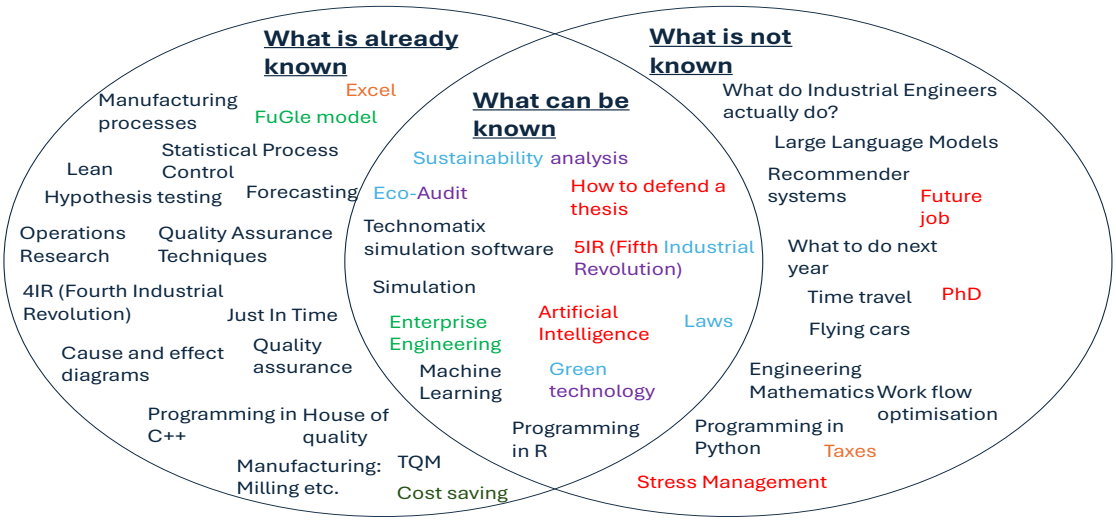

Figure 3 ZPD diagram for Enterprise Design cohort

Students identified the potential to learn about software packages as well as technology-driven and technical content. All the students on the programme do the same programming courses (namely, C++ and R). It is interesting that they perceive other possible useful programming languages (such as Python) as being within different ZPD achievability stages. This cohort is intrigued (can be known) by sustainability, 5IR and innovative future thinking as well, linking perfectly to the three pillars. In this cohort interestingly enough, "what

Industrial Engineers actually do" emerges as an unknown. However, there were no GA associations directly tied to teamwork. The only evident forms tied to laws, industry and the environment despite the group project within the course. This project tasks students with designing an enterprise from an idea to a coherent business plan.

Much like the E-Econ ZPD diagram, the focus for E-Des has evolved. The students from both courses list future personal and societal elements as key unknowns. Both cohorts also are interested in post-grad and job opportunities and the role IEs have in the workplace. They share concerns about their futures as functioning adults in society (e.g., taxes). The 4th year cohort is able to provide a holistic reflection across multiple knowledge areas. In contrast, the 3rd year cohort focuses on one knowledge area (economics) solely.

3.2 Alignment between GAs and SDGs with course intent

With these findings in mind, as well as a continuous improvement ethic, the collaborating lecturers highlighted key curricular themes as a stepping stone to developing a framework not only to better align the course objectives with the GAs and SDGs, but to enable a more explicit framing of their interactions (Table 1). These themes (as indicated by the colour coding in the ZPD diagrams in section 3.1) are unpacked so as to demonstrate the current interaction between the SDGs and GAs using the course-specific context. This collaborative exercise has pointed to insufficient alignment and reflectively enabled opportunities for more explicit leveraging and linking of the SDGs with GAs 7 and 8 using concepts already familiar to students in preceding courses (e.g. basic accounting for economic sustainability). Ultimately, this analysis creates more awareness and suggests opportunities for broader integration/collaboration across the two curricular domains through potential strategies such as shared case studies. through course content in broader contexts.

Table 1 Course alignment with GAs and SDGs

E-Econ						
Curricular themes	ECSA GA		Pillar			Context
	7	8	Ec	En	S	
Real life investment exposure		X				The investment simulation is done in groups, and teamwork is one of the three major components of GA 8.
Macroeconomics	X		X			Understanding macroeconomics can contribute towards efforts aimed at achieving sustained economic growth (SDG 8). Furthermore, an awareness of the macroeconomic impact of engineering activity is a component of GA 7.
Societal impacts of investments	X		X			An awareness of the societal impact of engineering activity aligns with GA 7. Societal impacts can contribute towards efforts aimed at reducing inequalities (SDG 10).
Tax implications in real world			X			Tax revenue can be used to fund industry, innovation, and infrastructure (SDG 9) and have effects on job creation and decent work (SDG 8) and reducing inequalities (SDG 17).
How the JSE works			X			Investments in stock market such as the JSE works can have major effects on the growth of economies (SDG 8).
Personal income taxes			X			Income taxes paid by individual can playing a major role in sustaining economic growth (SDG 8).
Job opportunities					X	Securing a good job after graduation is a form of decent work (SDG 8).
Environmental and social issues' impact			X	X		Responsible production (SDG 12) and climate action (SDG 13) are some of the environmental issues that are affected by economic decisions. On the social issues, economic decisions can affect efforts aimed at reducing poverty (SDG 1).
E-Des						
Curricular themes	ECSA GA		Pillar			Context
	7	8	Ec	En	S	
Excel			X			Financial management software to study economic growth (SDG 8)

Sustainability analysis	X		X	X	X	The impact of engineering activities tries to explicitly speak to sustainability narratives (e.g. carbon footprint) across all three pillars.
Stress Management					X	Stress management protects Good Health and wellbeing (SDG 3).
Thesis defence & PhD					X	The crux directly speaks to quality education (SDG 4)
Laws	X					Legal frameworks are a core component of the GA 7 definition. Peace, justice and strong institutions (SDG16) is directly governed by laws promulgated
5IR	X			X	X	5IR inherently speaks to sustainable and society which are subsets of GA 7. The definition of 5IR tries to remedy the environmental and societal disconnect from 4IR
AI					X	Quality education (SDG4) could be created with AI
Green technology	X			X		Affordable and cleaner technology (SDG 7) are a direct product from green technology
Eco-audit	X			X		SDG 12 on responsible consumption and production is facilitated by eco-auditing process
Future job			X			Decent work and economic growth (SDG 8) are supported by job creation and acquisition
Taxes			X			Economic growth (SDG 8) is instilled by the tax funding mechanism

4 Conclusions and recommendations

This study set out to map student perceptions of the course objectives, three SDG pillars (economic, environmental, social) and two particular GAs (engineer in the world, teamwork). Using three stages of the concept of the ZPD, students in two IE courses captured their perceptions as diagrams in an interactive learning activity. The analysis of the data demonstrated a distinct disconnect between the three sustainability pillars and the two GAs. The absence of explicit referencing of the GAs and SDGs in the ZPD diagrams reaffirms the disconnect. The connections between these concepts and the curriculum under study were siloed amongst course objectives, assessment and student perception. As part of an ongoing improvement initiative, the collaborating lecturers have developed a framework to more explicitly link the course objectives to the said SDGs and GAs. Furthermore, the framework offers opportunities to also model more detailed levels of scaffolding for the two courses, similar to the work executed by Burger (2022). The deficiency in GA and SDG alignment calls for innovative teaching practices that can introduce these concepts more explicitly in the curriculum, along with appropriate assessment strategies. The analysis portrays varied levels of understanding and scaffolding that the courses can create. Possible ways of expanding the study are to extend this to other courses in the programme, changing student perceptions or executing a cross-sectional study with other cohorts. Alternatively, the same learning activity can be repeated each year to monitor the impact of preceding course changes, which respond to the new GAs and the SDGs.

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A Framework for Implementing Flexible Project-Based Learning for Computing Education in Resource-Constrained Environments: A Case Study of the Namibia University of Science and Technology

Munyaradzi Maravanyika
Namibia University of Science and Technology, Namibia, mmaravanyika@nust.na

Abstract

Project-based and problem-based learning (PBL) has gained recognition as an effective pedagogical method for developing essential for employability skills. However, implementing PBL in resource-constrained environments poses significant challenge in these environments due to the limited infrastructure and institutional barriers (Okai-Ugbaje et al., 2022). This paper introduces the Flexible Project-Based Learning (FPBL) framework designed to facilitate the adoption in such environments though a three-tiered approach: the Basic Tier (minimal resources), Standard-Tier (moderate resources) and Advanced-Tier (comprehensive resources). Each layer incorporates Aristotle's four causes as structural pillars. Prelimary results from a case study at the Namibia University of Science and Technology involving focus groups with faculty (N = 5), industry stakeholders (N = 15), student representatives (N = 2) and administrative support staff (N = 4). Preliminary results from a case study at the Namibia University of Science and Technology (NUST) indicate that access to industry-grade infrastructure, partnerships, and readiness are essential for effective PBL implementation. The framework offers a possibly scalable solution for computing education in resource-constrained environments.

Keywords: Project-based learning, computing education, resource constrained environments, flexible framework, developing economies

1 Introduction

The computing field has been experiencing exponential growth and transformation, requiring Higher Education Institutions (HEIs) to continuously adapt their curricula to equip graduates with skills relevant to industry demands (Saad & Zainudin, 2024). Traditional teaching methods, with their focus on knowledge

transfer and acquisition, are increasingly inadequate for preparing students for the dynamic challenges of the modern workplace (Akour & Alenezi, 2022).

Project-Based Learning and Problem-Based Learning (collectively referred to as PBL) have emerged as viable alternatives to bridge the gap between academic knowledge and industry practices. These approaches engage students in authentic real-world challenges through extended projects and systematic problem-solving inquiries (Kokotsaki et al., 2016). However, while PBL has proven effective in well-resourced environments, its implementation in resource-constrained settings remains fraught with challenges.

Resource-constrained environments in this context are defined as settings characterized by limited access to reliable electricity, high-cost internet connectivity, low-bandwidth networks, insufficient access to industry-standard hardware and software, and cultural barriers such as limited digital literacy (Magunje, 2024). These constraints directly impact PBL implementation in several critical ways. The implementation of PBL practices in resource-constrained environments faces multiple interconnected challenges that significantly impact educational outcomes (UNESCO, 2025). These foundational constraints further limits students' ability to participate in authentic project experiences that mirror professional environments (Magunje, 2024). Moreover, persistent connectivity issues create additional obstacles by disrupting real-time collaboration capabilities and preventing consistent access to online resources that are critical for effective problem-solving activities (Wawak, Domingues & Sampaio, 2024). The challenges extend beyond technological limitations to encompass broader systemic issues, particularly the scarcity of industry partnerships which significantly reduces opportunities for students to engage with authentic project contexts (Bozalek et al., 2013). These interrelated barriers create a complex web of challenges that must be addressed holistically to enable effective PBL in resource-constrained educational settings.

The Namibia University of Science and Technology (NUST) exemplifies these challenges. Despite adopting flexible hybrid learning policies, NUST's Faculty of Computing and Informatics operates with limited digital infrastructure, large student cohorts, and internet connectivity challenges. These constraints hinder the effective implementation of transformative pedagogies, creating a critical gap between academic preparation and industry requirements (Chipere, 2017).

Computing industry stakeholders consistently report that graduates require up to six months of additional training before achieving workplace productivity (NUST Bachelor of Informatics Honours Programme Advisory Committee feedback, 2024). This highlights the pressing need for innovative pedagogical approaches that can function effectively within resource constraints while improving graduates' employability and professional proficiency.

This paper proposes the Flexible Project-Based Learning (FPBL) framework to facilitate the adoption of combined project-based and problem-based learning approaches for computing education in resource-constrained environments.

2 The FPBL Framework

The proposed FPBL framework attempts to address the challenges of implementing PBL in resource-limited settings by combining both project-based learning (focused on creating tangible products or solutions) and problem-based learning (emphasising systematic inquiry and problem-solving processes).

Based on Aristotle's four causes, the FPBL framework provides a systematic approach for PBL implementation, ensuring adaptability and effectiveness across varying resource contexts. The four causes serve as analytical pillars. The FPBL framework is structured around four fundamental causal dimensions that shape the educational experience.

The Material Cause encompasses the resources, tools, and infrastructure required for effective learning, serving as the foundational layer that enables all educational activities. This dimension includes everything from hardware and software to learning spaces and technological platforms that students and educators utilize. The Formal Cause defines the structure and methodology of learning experiences, establishing how educational content is organized, delivered, and assessed. It represents the pedagogical architecture that gives shape to the learning process, including project designs, curriculum frameworks, and instructional strategies.

The Efficient Cause focuses on the human agents and their roles in the learning process, recognizing that education is fundamentally a human endeavor driven by the interactions between faculty, students, industry partners, and other stakeholders. These agents serve as the catalysts who activate and guide the learning journey through their expertise, collaboration, and mentorship.

Finally, the Final Cause articulates the intended learning outcomes and objectives, representing the ultimate purpose and goals of the educational experience. This dimension encompasses the competencies, skills, and capabilities that learners are expected to develop, ranging from fundamental technical abilities to advanced innovation capacities and industry readiness. Together, these four causal dimensions create a comprehensive framework that addresses both the practical requirements and philosophical foundations of PBL in computing education.

2.1 The Basic Tier (Minimal Resources)

The Basic Tier provides an entry point for institutions with severely limited resources. This tier emphasizes offline capabilities and locally available technologies to minimize infrastructure dependencies. The tier emphasises the need of institutions to operate with minimal resources, for example, utilising open-source software, offline educational materials, basic computing equipment, and locally available technology. This tier specifically addresses contexts where reliable internet connectivity and expensive software licenses are unavailable (Agbeyangi & Suleman, 2024), ensuring that resource constraints do not become barriers to quality computing education.

The formal cause suggests that institutions should emphasise small-scale, contextually relevant projects that combine both product creation and problem-solving inquiry, where students engage in community-based challenges using available resources to develop both technical solutions and analytical thinking skills. The driver of the implementation is primarily faculty and student-driven initiatives with minimal external stakeholder involvement. The ultimate goal is the development of fundamental computing competencies, adaptability skills, and context-specific problem-solving abilities that directly address local community needs, ensuring that even in resource-constrained environments, students acquire essential skills that are immediately applicable to their local context.

2.2 The Standard Tier (Moderate Resources)

The Standard Tier targets institutions with moderate resource availability and some infrastructure stability. These institutions have the ability to leverage cloud-based tools, virtual learning environments and have periodic access to industry-standard software. The institutions exhibit improved connectivity infrastructure and the potential to harness emerging technologies while maintaining cost-effectiveness (Hu & Raman, 2024). The formal cause encompasses guided projects and structured mentorship programs that integrate both extended project work and systematic problem-solving methodologies, enabling students to engage in medium-scale challenges with industry relevance. The efficient cause manifests through enhanced collaboration involving faculty, students, and limited industry partnerships, where external mentors provide

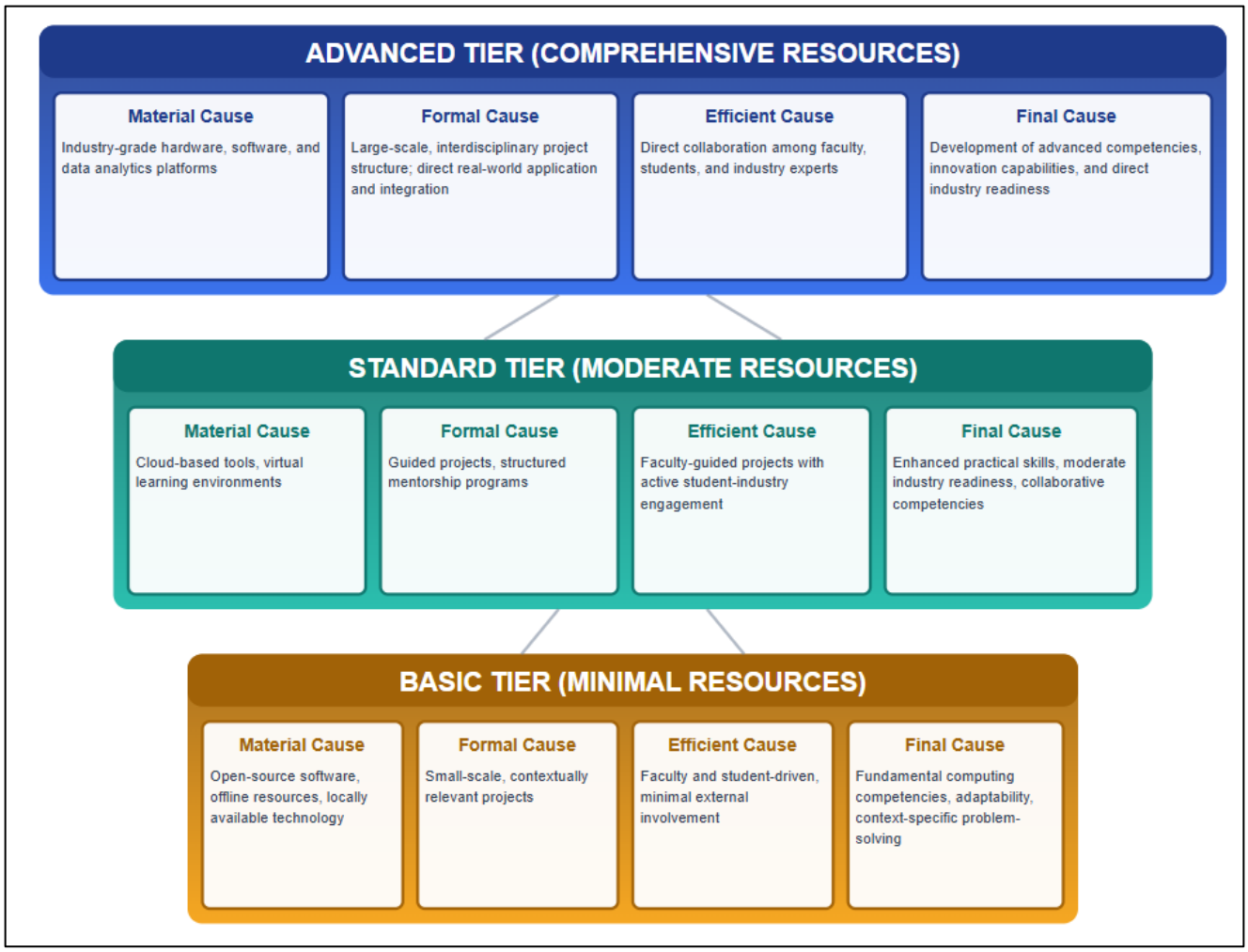
periodic guidance while faculty maintain primary oversight responsibilities. These final cause represents an integrated approach that ensures that students develop both technical proficiency and professional capabilities within a resource-conscious framework.

2.3 The Advanced Tier (Comprehensive Resources)

The Advanced Tier targets institutions with comprehensive resources and strong infrastructure capabilities, providing the foundation for sophisticated project-based learning experiences. At its material foundation, this tier leverages industry-grade hardware, professional software licenses, advanced data analytics platforms, and reliable high-speed connectivity, creating an environment that enables authentic professional experiences (Hernández-de-Menéndez et al., 2019). The formal structure encompasses large-scale, interdisciplinary projects that incorporate both extensive product development and complex problem-solving scenarios, establishing direct industry collaboration and real-world application that extends beyond traditional academic boundaries. This ambitious scope is realized through the efficient cause of direct collaboration among faculty, students, and industry experts, which creates dynamic learning environments that effectively bridge academic and professional contexts. However, as Khlaif, Hamamra, and Hussein (2025) cautions, institutions must carefully maintain educational objectives and avoid unhealthy dependence on industry partners that might compromise pedagogical goals, ensuring that commercial interests don't overshadow learning outcomes. The ultimate purpose of this tier manifests in the development of advanced competencies, innovation capabilities, direct industry readiness, and leadership skills necessary for immediate professional contribution, preparing graduates who can seamlessly transition into demanding professional roles.

It's crucial to understand that the framework's tiered structure should not be viewed as strictly hierarchical, where the Advanced tier is inherently "best" or most desirable. Rather, each tier represents an appropriate adaptation to specific resource contexts while maintaining educational quality and relevance, acknowledging that excellence in education can be achieved through different pathways. The choice of tier depends on institutional capacity, student needs, and available resources rather than prestige or aspiration. It is important to recognise that effective PBL can be implemented successfully across varying resource environments when thoughtfully adapted to local contexts and constraints (Omelianenko & Artyukhova, 2024).

Figure 1: The FPBL Framework



3 Implementation and Evaluation Methods

The FPBL framework is currently in the design phase at NUST, with planned integration into new postgraduate certificate programs emphasizing combined project-based and problem-based learning philosophies. The implementation follows a phased approach tailored to NUST's specific resource constraints and institutional context.

3.1 Implementation at NUST:

The initial framework development involved extensive consultation with NUST's Programme Advisory Committee (PAC), which includes industry representatives, faculty, students, and alumni. The PAC ensured alignment between the preliminary framework and both industry requirements and institutional objectives. This collaborative approach addressed curriculum standards, exit-level outcomes, content structure, and industry partnership facilitation essential for authentic project and problem-solving experiences.

3.2 Evaluation Methods:

While comprehensive evaluation is pending implementation, initial feedback from comparative case studies informed framework development. Analysis of successful PBL implementations at Aalborg University (Denmark), known for its problem-based learning model, and Riga Technical University (Latvia), recognized for project-based approaches, provided valuable insights for adapting the FPBL framework to NUST's context.

3.3 Data Collection:

Initial data collection included PAC focus group interviews (N = 26), individual interviews with experts from benchmarking institutions, and observational studies at Aalborg University to evaluate framework components and their significance for resource-constrained environments.

3.4 Future Implementation:

The FPBL framework will be piloted in upcoming postgraduate certificate programs at NUST using the tiered approach. Each tier will be assessed for effectiveness in addressing resource constraints while achieving educational outcomes. The PAC will maintain oversight responsibilities, providing continuous feedback to ensure framework effectiveness and relevance.

4 Challenges, Lessons Learned, and Future Perspectives

4.1 Challenges

The PAC identified several implementation challenges specific to resource-constrained environments. Insufficient technological infrastructure remains a primary barrier, as limited access to industry-standard tools restricts authentic project and problem-solving experiences. Institutional resistance to pedagogical change, particularly from faculty perceiving PBL as additional workload, presents significant obstacles. Faculty and administrators often hesitate to transition from traditional lecture-based methods to PBL approaches, especially with large student cohorts common in developing contexts.

Resource volatility poses unique challenges for small economies like Namibia, where limited access to industry partnerships can hinder sustained project progression and long-term initiative maintenance. Additionally, policy constraints and rigid national educational frameworks may limit pedagogical innovation beyond resource limitations alone.

4.2 Lessons Learned

Several critical insights emerged from the framework design process. Flexibility is paramount; the tiered approach enables institutions to adapt to varying resource levels while ensuring continuity and sustainability. Industry collaboration proves essential but must be carefully managed to maintain educational objectives while providing authentic learning experiences. Faculty development emerged as crucial, requiring regular professional development workshops to equip educators with necessary pedagogical skills for confident PBL facilitation.

4.3 Future Perspectives

Future developments focus on framework expansion and refinement. Extending the framework to additional institutions with similar socio-economic contexts may enhance relevance and applicability, enabling broader student access to innovative pedagogical approaches. Incorporating FPBL into formal institutional policies could facilitate wider adoption, embedding it more thoroughly within computing education programs across developing contexts.

5 Critical Reflections and Implications for Other Contexts

The FPBL framework represents both a pedagogical and institutional approach to computing education in resource-constrained environments. While maintaining core PBL educational principles of active learning, collaboration, and authentic problem-solving, FPBL necessarily incorporates organizational and technical adaptations to function within resource limitations.

Key educational differences between traditional PBL and FPBL include: (1) explicit resource-constraint consideration in pedagogical design, (2) flexible implementation allowing for offline and low-technology approaches, (3) community-based problem contexts replacing industry-standard scenarios when necessary, and (4) tiered progression enabling institutional growth and development over time.

The framework addresses industry expectations, institutional challenges, and resource variability while fostering an educational ecosystem connecting theoretical learning with practical applications. The tiered approach enables effective PBL implementation regardless of resource limitations, thereby improving computing education quality and impact in developing contexts.

The framework's adaptability, collaboration focus, flexibility, and practical application orientation make it a significant resource for practitioners and policymakers implementing technology-enhanced learning in constrained contexts. Implementation insights from NUST provide guidance for other institutions facing similar challenges, facilitating transformation toward sustainable educational practices that maintain pedagogical integrity while acknowledging resource realities.

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AAU Professional skills Lab (ProLab): Promoting Transversal Skill Development in STEM through Student Self-Selected Interdisciplinary Workshops

Nicolaj Riise Clausen
Aalborg University, Denmark, Nclausen@plan.aau.dk

Lykke Bertel
Aalborg University, Denmark, lykke@plan.aau.dk

Bente Nørgaard
Aalborg University, Denmark, bente@plan.aau.dk

Niels Erik Ruan Lyngdorf
Aalborg University, Denmark, nel@plan.aau.dk

Giajenthiran Velmurugan
Aalborg University, Denmark, vel@plan.aau.dk

Aida Olivia Pereira de Carvalho Guerra
Aalborg University, Denmark, ag@plan.aau.dk

Abstract

The growing demand for well-rounded STEM professionals underscores the importance of developing non-technical professional skills like communication, collaboration, critical thinking, AI literacy, and systems thinking, or *transversal skills*, alongside technical expertise. Aalborg University (AAU) has long refined methods for fostering such transversal skills within its PBL framework. This paper presents AAU ProLab, a new initiative that replaced program-specific workshops with full-day interdisciplinary workshop events, bringing together students from various programs and semesters across the faculties of Engineering, Natural Science, and IT & Design. The initiative aimed to enhance motivation by allowing students to choose workshops aligned with their interests and connect across disciplines.

The evaluation, based on an online student survey, included three quantitative questions on recommendation, relevance, and achievement of learning objectives, alongside qualitative feedback. Results showed high satisfaction, with students valuing interdisciplinarity, workshop diversity, and freedom of choice. Suggestions for improvement centered on clearer communication, streamlined registration, and strengthening active learning.

Subsequent editions have already addressed these issues through a dedicated Moodle space for information, a simplified registration model, and revised workshop allocation. Most workshops now emphasize interactive, application-oriented learning, supported by feedback from both students and facilitators. ProLab thus represents a promising platform for supporting interdisciplinary learning and transversal skill development.

Keywords: Transversal skills, Interdisciplinarity, Active Learning, Evaluation

1 Introduction

In response to the increasing demand for well-rounded STEM professionals Aalborg University (AAU) launched a new experimental framework to support students' development of strong non-technical professional skills, or *transversal skills*, such as communication, collaboration, critical thinking, systems thinking, and digital literacy alongside their technical expertise. As society continues to grapple with increasingly complex and interdisciplinary challenges, universities are continuously rethinking engineering and science educational programs to foster broader skill sets that extend beyond disciplinary knowledge and support life-long learning (International Commission on the Futures of Education, 2021; OECD, 2018).

While the Aalborg problem-based learning (PBL) model does aim to foster initial development of generic competences in first year engineering education as well as progression throughout the education (Boelt et al., 2021; Clausen, 2021), students are often struggling to apply these competences in practice, particularly in interdisciplinary settings (Bertel et al., 2022). Thus, in 2024 Aalborg University piloted a new initiative, the AAU Professional skills Lab (ProLab), to consolidate previously local and isolated program-specific workshops into full-day interdisciplinary events open to students across all programs at the Faculty of Engineering and Science and the Technical Faculty of IT and Design. The initiative was deliberately designed to align with the progressive PBL learning objectives embedded within the curricula of the participating study programs. In this way, ProLab activities are closely connected to students' disciplinary and methodological competency development throughout their studies, while demonstrating transferability in an interdisciplinary setting.

AAU ProLab, running over several weeks across three campuses in Esbjerg, Aalborg and Copenhagen, featured joint introductions, multiple workshop rounds, and opportunities for cross-program networking. Students freely selected workshops based on their interests and needs, from a selection of topics such as ethical technology assessment, SCRUM techniques, conflict resolution, and AI in study practice. The workshop format of the initiative especially aimed at encouraging interdisciplinary collaboration and foster intrinsic motivation by allowing personalized learning paths and student self-direction. This paper presents findings from an evaluation of the inaugural AAU ProLab, in which both the successes and areas for improvement were highlighted by the students. Further, implications for future practice are discussed.

1.1 Background:

The ProLab concept was developed by AAU's Aalborg Centre for Problem Based Learning in Engineering Science and Sustainability under the auspices of UNESCO. The initiative was designed to replace a previous implementation with local, program-specific PBL workshops with joint, full-day yearly recurring events featuring a large selection of workshops open to science and engineering students across faculties. The rationale for the development was threefold:

1. To foster interdisciplinary collaboration by bringing students together across different programs and campuses.
2. To strengthen transversal professional competencies aligned with the evolving needs of industry and society.
3. To increase intrinsic student motivation through self-direction, allowing participants to choose workshops based on their interests and perceived needs.

One important practical implication of ProLab was that the pooling of more students allowed for a much more personalized learning experience for the individual student, since it afforded the organisers the opportunity to offer up and host a much wider selection of workshops. In developing these workshops, particular attention was paid to formats that reflected real-world relevance and encouraged active student participation.

Semester
2nd: 340
4th – 6th: 348
Campus
Aalborg: 495
Copenhagen: 168
Esbjerg: 25

ProLab was implemented as a series of events throughout March and April of 2024, hosted at the Copenhagen (CPH), Aalborg (AAL), and Esbjerg (ESB) campuses. A total of 688 students registered to participate across all campuses and semesters, as elaborated in Table 1. Students could receive a digital diploma or badge for participation, although the badge distribution process was noted to be complicated and in need of improvement.

Each ProLab day followed a standard format:

- 08.30 – 08.45: Joint Introduction
- 09.00 – 10.50: Workshop Round 1
- 11.00 – 12.50: Workshop Round 2
- 13.00 – 14.00: Lunch and networking (including optional student poster sessions)
- 14.00 – 15.50: Workshop Round 3

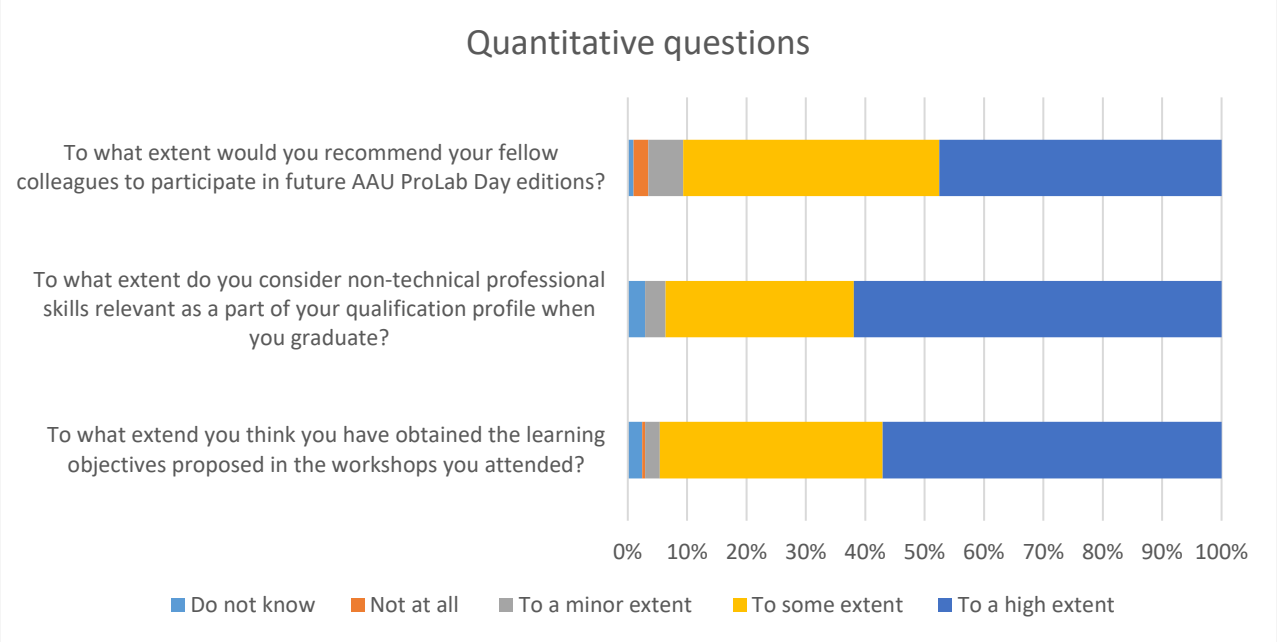
During the joint introductions students were introduced to the format of the day, workshops, their facilitators and reasoning behind the ProLab initiative. During the lunch break, some campuses offered an open poster session where students could present project pitches and their peers as well as academic supervisors were invited to participate and provide feedback.

Workshops were organized around cross-cutting themes such as conflict resolution, systems thinking, ethical technology assessment, digital project practices, and generative AI in project work. The workshops were adapted to perceived semester-specific needs, e.g. 2nd semester students were offered more foundational topics such as interdisciplinary problem design and work-life balance, while 4th and 6th semester students engaged in more advanced sessions related to e.g. leadership, creativity, professional identity, and entrepreneurship. Across the board, students could choose from a wide range of topics as can be seen in table 2.

2nd Semester	**4th and 6th semester**
Interdisciplinary problem design	Designing and solving complex problems
Systems thinking in engineering	Systems thinking in engineering
Ethical technology assessment	Ethical technology assessment
Conflict resolution strategies	Conflict resolution strategies
Collaboration across disciplines	Culture, group dynamics and safety
Facilitating productive meetings	Professional communication with external partners
Further development of digital practices in project work	Project management and leadership
SCRUM techniques in project work	Further development of digital practices in project work
Generative AI in study practice	Professional identity development
Motivation, well-being and work-life balance	Creativity and entrepreneurship

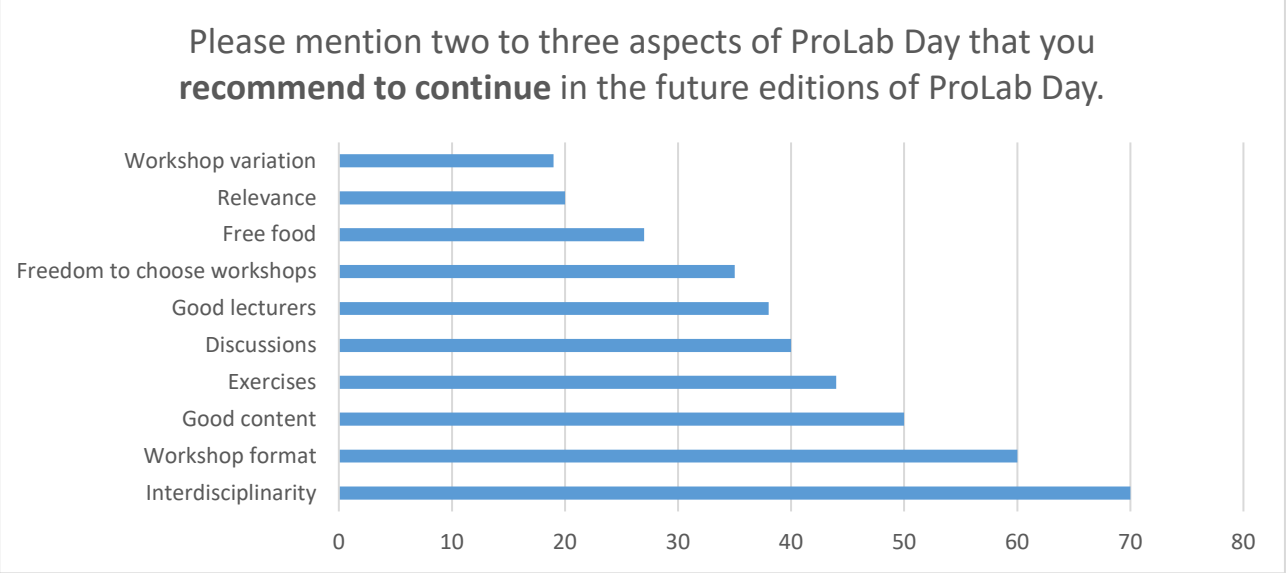
2 Evaluation

The ProLab pilot was evaluated through an online student survey distributed throughout the events where students answered 3 quantitative and 2 qualitative questions. 209 students answered the evaluation survey amounting to a response rate of about 30% of all registered students, however it is important to note that not all registered student attended the events, so the actual response rate is somewhat higher than the reported. All data analysis for this paper was conducted in MS Excel, Nvivo 14 and SPSS 29. The students answered the below quantitative questions on a 4-point scale:



Overall, the results from the quantitative part of the evaluation suggest that more than 90% of the students would to some or a high extent recommend their fellow colleagues to participate in future AAU ProLab days, consider non-technical professional skills relevant as a part of their qualification profile upon graduation and think that they have obtained the learning objectives proposed in the workshops they attended. The results indicate that the students value transversal skills and that they feel that the format and execution of ProLab support their development. While not all students found each workshop equally worthwhile, the evaluation indicate an overall satisfaction with and engagement in the themes of the ProLab concept.

The students also answered two qualitative questions where they were asked to note two to three things they would suggest improving or continue doing in future iterations of ProLab. The answers were submitted as free text and was later analysed and coded in Nvivo 14 by the authors according to the overall theme of the suggestions.



Three overall themes emerged from the question about what to continue in future editions of ProLab:

Interdisciplinarity (mentioned in 70 responses):

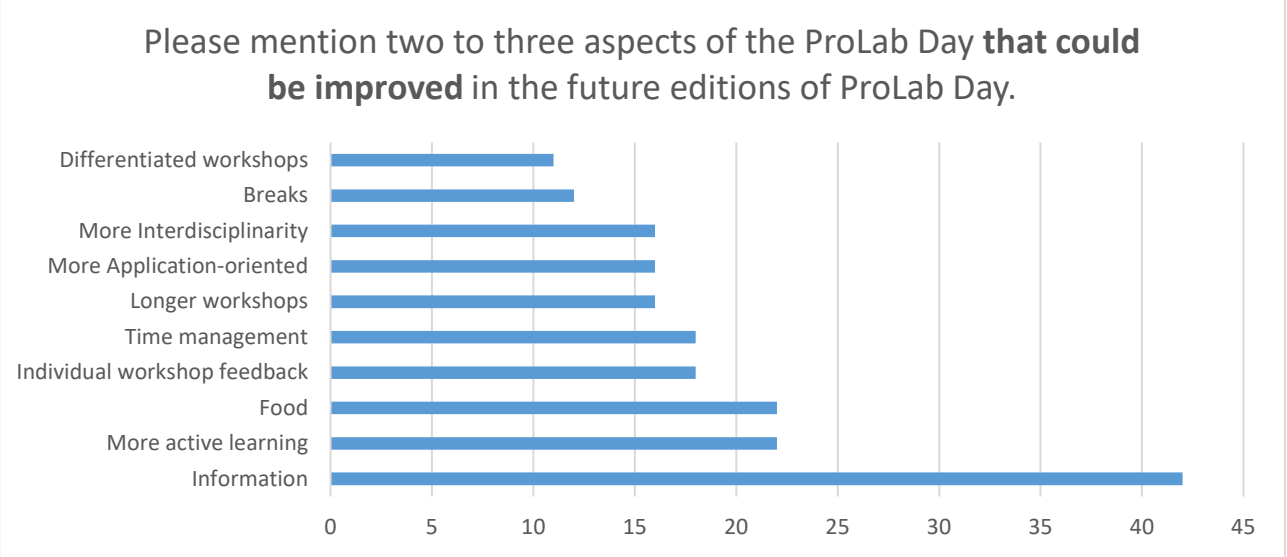
Students greatly valued the opportunity to work with peers from other study programs. One student described how the workshop context revealed how different academic competencies contributed to interdisciplinary collaboration. Another noted that being placed in diverse groups helped make the discussions and exercises much more interesting. Several students also indicated that the challenge of communicating their student work and projects to students from other educational programs was very rewarding.

Workshop format, Exercises and Discussions (mentioned in 60, 44 and 40 responses):

Students also greatly appreciated the workshop structure. Most workshops were made up of short presentations followed by exercises and/or discussions. Comments praised the use of analogue materials (e.g., paper, pencils, post-it notes, and other physical materials) for visualization and found the presentation–group work–presentation cycle applied in some workshops appropriate and effective. The participants also indicated that the format helped them relate abstract concepts to practical hands-on situations and stay focused and engaged throughout the day.

Freedom to choose workshops (mentioned in 35 responses):

Many students also highlighted the motivational effect of being able to select workshops that matched their personal interests and learning goals. This level of self-direction helped students feel more involved in the experience and they indicated that they used this to both target specific interests and perceived weaknesses.



From the question of what to focus on improving for future iterations of ProLab a few themes also emerged:

Information (mentioned in 42 responses):

Inconsistent terminology in communications led to confusion. Students received mixed signals from organisers, semester coordinators, supervisors etc. Some students also indicated that they had difficulties in finding and accessing adequate information on workshops, registration, schedule updates etc. Students indicated that these issues impacted both attendance and preparedness.

More Active learning, Application-oriented and Interdisciplinarity (mentioned in 22, 16 and 16 responses)

Along the same lines of the elements to continue, several students indicated that the interdisciplinary and active format of the workshops were greatly appreciated. Some students who had been in different workshops with differing levels of active learning indicated that the ones with the least active components could benefit from a redesign along more active methods.

3 Discussion

Our evaluation of the inaugural AAU ProLab, based solely on student feedback, suggests that the initiative was generally well received and perceived as a meaningful learning opportunity. The findings indicate that students appreciated the interdisciplinary format, the freedom to choose workshops based on personal interests, and the participatory and active learning formats. Several students pointed to increased motivation and engagement and highlighted how discussing and working with peers from other educational programs enhanced discussions and prompted reflections about their own professional discipline and competencies. The evaluation further suggests that students recognize the value of transversal competencies such as collaboration, communication, systems thinking, and digital literacy etc. and perceive them as relevant to their education and future. Furthermore, the evaluation suggests that these skills are perhaps better taught in contextually rich, interdisciplinary settings.

The evaluation however also points to areas needing improvement. Several students expressed confusion about registration procedures, workshop descriptions, and scheduling, indicating that clearer and more consistent communication across all channels is necessary. The perceived shortcomings also indicate that the foundational principles of active engagement, discussions and interdisciplinarity can, at least in some workshops, be enhanced and emphasized to an even greater extent.

Given the limitations of this evaluation, particularly its reliance on a limited self-reported survey and a response rate of around 30% of registered students, the conclusions should be interpreted with caution.

While the student feedback provides valuable insight into perceived strengths and weaknesses of the ProLab format, further evaluations could benefit from additional data sources, such as facilitator reflections, observational data, or follow-up interviews, to build a more comprehensive understanding.

In response to identified challenges, several concrete revisions were implemented in the subsequent edition of ProLab in the Spring of 2025. All information and communication were consolidated into a dedicated Moodle space, providing students with one point of entry through a familiar platform. However, timely and standardized dissemination at semester start remained a challenge, with a planned introductory video for coordinators suggested as one potential solution for the Spring og 2026. Registration has been streamlined through a single contact email and a revised allocation model that pre-determines workshops based on demand, thereby reducing complexity and improving fairness. Finally, concerns about active learning appear largely resolved in the 2025 edition, with workshops now consistently emphasizing interactive and application-oriented elements. To strengthen evaluation, feedback is also collected from both students and facilitators, offering a more comprehensive view of workshop quality and engagement as well as suggestions for new workshops for future editions of ProLab.

In summary, this initial student evaluation indicates that ProLab holds potential as a platform for fostering interdisciplinary learning and supporting the development of transversal competencies for AAU students. Conversely, the findings highlight several practical considerations for refinement that should be taken into consideration in planning future iterations of ProLab. With careful attention to communication, workshop design, and integration into broader educational initiatives, ProLab may continue to evolve as a valuable component of AAU's approach to problem-based learning.

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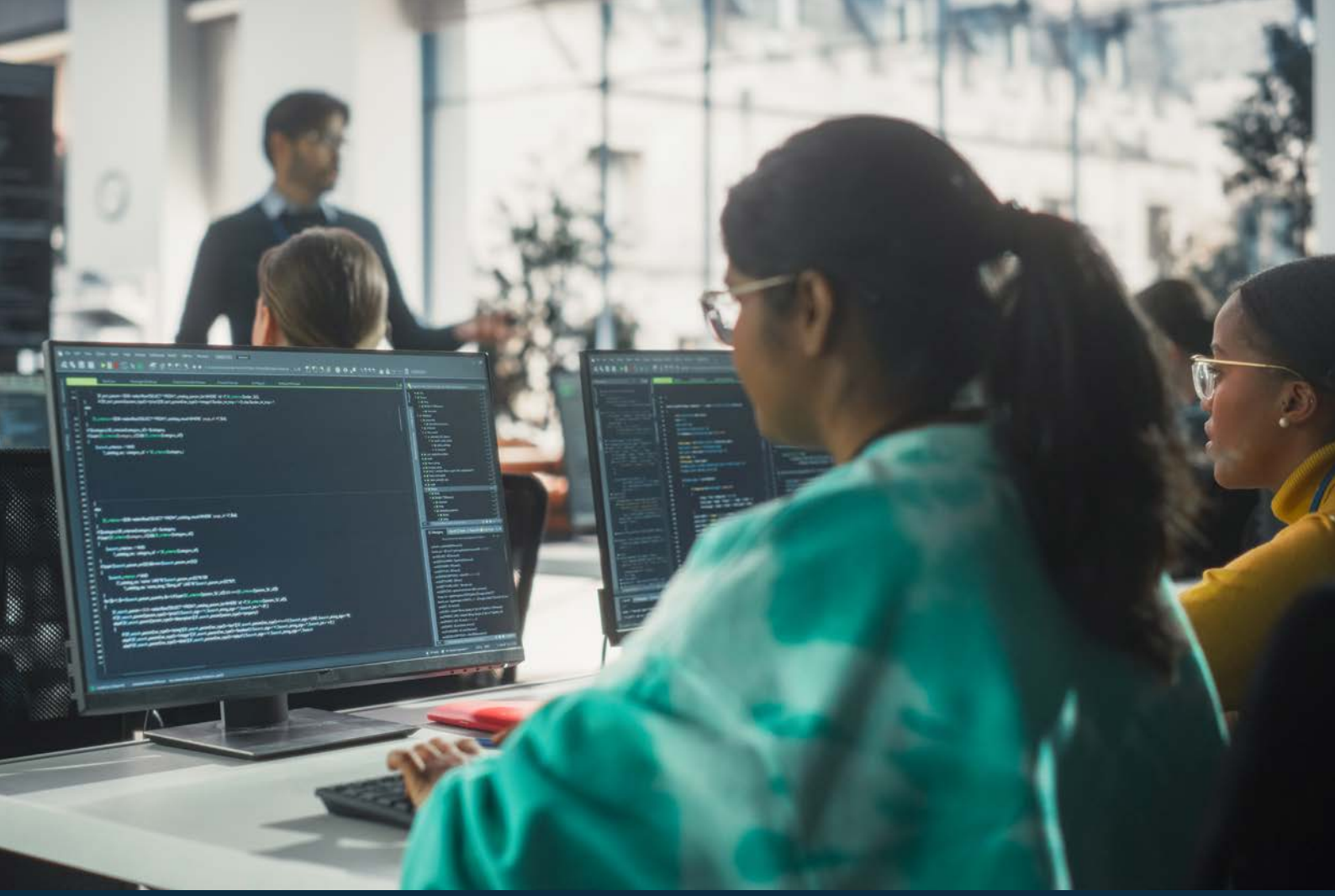

Institutional Implementation and Research Perspectives in STEM Education

A scientometric study of contributions by African-affiliated authors to engineering education research journals 2004-2023

Bill Williams
CEGIST, Instituto Superior Técnico, Universidade de Lisboa, Portugal and TUDublin, Ireland, *bwbillwilliamsbw@gmail.com*

Andrew Valentine
University of Melbourne, Australia, *andrew.valentine@unimelb.edu.au*

Abstract

Engineering education research has grown considerably as a field of inquiry over the last 20 years, particularly in the US, Europe and Australia. This study applies a scientometric approach to the contributions from Africa-affiliated authors to 19 engineering education research journals, 2004 - 2023.

In the 385 journal articles published, South Africa was notably the most prolific contributor with 147 articles, followed by Egypt, Nigeria, Botswana and Tunisia. While this research output is comparable with that of other regions in the Global South, it remains significantly lower than that of regions in the Global North. It was noted that the annual average article output was 11 in the period up to 2015 whereas from that year onwards it rose to 28 per annum.

Authors from South Africa and Botswana tended to co-author with colleagues from the US whereas those from Tunisia partnered with Saudi Arabian co-authors. The most common keywords were students, engineering education and E-learning. Three engineering education research centres were identified, two in South Africa and one in Nigeria. We believe that these findings can serve as a useful baseline to allow scholars to monitor the evolution of research in engineering education by African educators over future decades.

Keywords: Engineering education research; scientometric; research output; authors

1. Introduction

Although there has been a growing recognition in the Global North that effective education requires sustained attention and research, until recently, few institutions in Africa have recognised this as a valid research focus in engineering (Winberg et al., 2018). This has resulted in a lack of capacity for engineering education research (EER) and it is claimed that many African educational innovations are not represented in the research literature (Wolff et al., 2022, Inglis and Matemba, 2021). Matemba and colleagues point out that "African engineering education teachers and researchers are thus informed by studies from elsewhere in the world, and find themselves seeking support from colleagues from different educational contexts to develop their educational expertise (Matemba et al. 2023).

There have however been recent initiatives to combat this situation such as the creation of the Engineering Education Research Network in Africa (EERN-Africa) in 2020 (Matemba et al. 2023), the launch of the Southern Journal of Engineering Education (SJEE) in 2022 (Kloot, 2022) and the partnership between the South African Department of Higher Education and Training (DHET), the UK Royal Academy of Engineering (RAE) and University College London to launch the Innovative Engineering Curriculum (IEC) project in 2023 (IEC, 2023).

While it is hoped that initiatives such as these will facilitate EER in the African context in the near future, it will be important to be able to measure progress in the evolution of the field by having data from the recent past to serve as a benchmark and to help provide an overview of the current landscape of African engineering education research publication. With this in mind, this paper presents a scientometric analysis of contributions by African-affiliated authors to eighteen English language engineering education research journals over the 20-year period from 2004 to 2023.

1.1 Literature Review

While scientometric analysis of general scientific publication output has shown that the number of scientific papers published by researchers in Africa has been rising faster than the total world scientific output in recent years (Confraria and Godinho, 2014) there has been little published scientometric data focussing specifically on the EER field. A general scientometric study of EER journal publications between 2014 and 2023 (Kondrashev et al., 2024) shows that the US, EU + UK, Australia and China dominate output in the field as shown in Table I.

TABLE I: COUNTRIES AND REGIONS THAT HAVE THE MOST PUBLICATIONS AND CITATIONS, 2014 - 2023 (KONDRASHEV ET AL., 2024)

Country	Articles	Country	Citations
USA	1924	USA	28,949
China	543	UK	6,948
Spain	493	Australia	6,612
India	329	Spain	6,025
UK	322	China	3,927

Those authors noted that in general “researchers from countries in South America, the Middle East, and Africa had limited contributions to scientific literature” (Kondrashev et al., 2024).

1.2 Research Questions

As there has been relatively little published literature studying the topic of African EER we opted for a broad exploratory approach in our original research question:

What can a scientometric analysis of twenty years of publication in English language journals tell us about the EER landscape in the African context?

We chose to characterise the landscape using the following indicators:

- global numerical evolution of publications by African-based researchers
- countries and individuals that had the highest number publications,
- co-authorship collaboration patterns with both African and non-African scholars
- the most common key-words assigned to the published journal articles

1.3 Positionality

The authors are based in Europe and Australia respectively. Although the first author worked as an educator in three African countries earlier in his career, neither has direct experience of education in African contexts over the last 20 years.

2. Methodology

The methodological process adopted followed best practice for scientometric analysis (Haghani, 2023; López-Pernas et al., 2023).

The methodology involved two primary stages. The first stage was to identify relevant engineering education journals in the Scopus database, while the second was to search these journals for publications which included authors from countries in Africa.

To identify relevant journals, the Scopus database was searched using the following search string: SRCTITLE ((engineer* OR ieee) AND (educat* OR pedag*)). This identified all source titles in Scopus with the words 'engineer' or 'ieee' in the title' as well as either words starting with 'educat' (e.g. education, educate, educational) or 'pedag' (e.g. pedagogy, pedagogical). Additionally, language was restricted to English, source type was limited to Journal only, while document type was restricted to Article, Editorial and Review. The time period was restricted to 2004-2023 to cover the last 20 years. The year 2024 was not included as at the time of writing not all publications from 2024 had been recorded in the Scopus database, meaning it was incomplete. This resulted in 14487 documents from 23 sources.

Next it was necessary to exclude journals to exclude journals that do not specifically focus on engineering education. Three journals that focused on broader fields were excluded, including (i) World Transactions On Engineering And Technology Education, (ii) International Journal Of Cognitive Research In Science Engineering And Education, and (iii) Energetika Proceedings Of Cis Higher Education Institutions And Power Engineering Associations. The 18 remaining journals were those in Table 2, and included 13,025 publications.

TABLE 2: JOURNALS ANALYZED IN THIS STUDY

Journal	ISSN	Years Covered by Scopus since 2003
Advances in Engineering Education	19411766	2009 to 2024
Australasian Journal of Engineering Education	1325-4340	2013, 2015 to 2024
Computer Applications in Engineering Education	1099-0542	2003 to 2024
Chemical Engineering Education	0009-2479	2003 to 2017, 2024
Education for Chemical Engineers	1749-7728	2006 to 2024
European Journal of Engineering Education	0304-3797	2003 to 2024
Global Journal of Engineering Education	1328-3154	2010 to 2024
IEEE Transactions on Education	0018-9359	2003 to 2024
International Journal of Continuing Engineering Education and Life-Long Learning	1560-4624	2003 to 2024
International Journal of Engineering Education	0949-149X	2003 to 2024

International Journal of Electrical Engineering and Education (formerly International Journal of Electrical Engineering Education)	0020-7209	2003 to 2024
International Journal of Engineering Pedagogy	2192-4880	2018 to 2024
International Journal of Mechanical Engineering Education	0306-4190	2003 to 2024
Journal of Civil Engineering Education (formerly Journal of Professional Issues in Engineering Education and Practice)	2643-9107	2020-2024
Journal of Engineering Education	1069-4730	2003 to 2024
Journal of Engineering Education Transformations	2349-2473	2018 to 2024
Journal of Pre-College Engineering Education Research	2157-9288	2014 to 2024
Journal of Professional Issues in Engineering Education and Practice	1052-3928	2003 to 2019

Following this, the time period was restricted to 2004-2023 to cover the last 20 years. The year 2024 was not included as at the time of writing not all publications from 2024 had been recorded in the Scopus database, meaning it was incomplete.

The publications were then filtered to only include those which included at least one author affiliated with a Country/territory from Africa (as reported by Scopus). As part of this process it was assumed that (i) Mauritius is part of Africa, (ii) Maldives is not a part of Africa, (iii) Malta is not a part of Africa, (iv) Reunion (France) is not a part of Africa (v) Spanish North Africa (Alhucemas, Ceuta, the Chafarinas Islands, Melilla, and Peñón de Vélez de la Gomera) are not a part of Africa. After the results were filtered to only include publications which had at least one author from Africa, 358 publications remained.

3. Results

Figure 1 shows the distribution of publications over time. Publications increased after 2016 to more than 20 per year (averaging approximately 28 per year), a number which has been continuously maintained until 2023. This contrasts to the annual publications before 2015 which averaged approximately 11 per year. This increase may be due to greater importance being accorded to EER in South African institutions as Table 4 shows that researchers from South Africa make up a major part of the authors of papers in our sample. In addition the launch of the first Biennial Conference of the South African Society for Engineering Education in 2011 may have laid the foundations for the higher number of journal articles published in the last ten years.

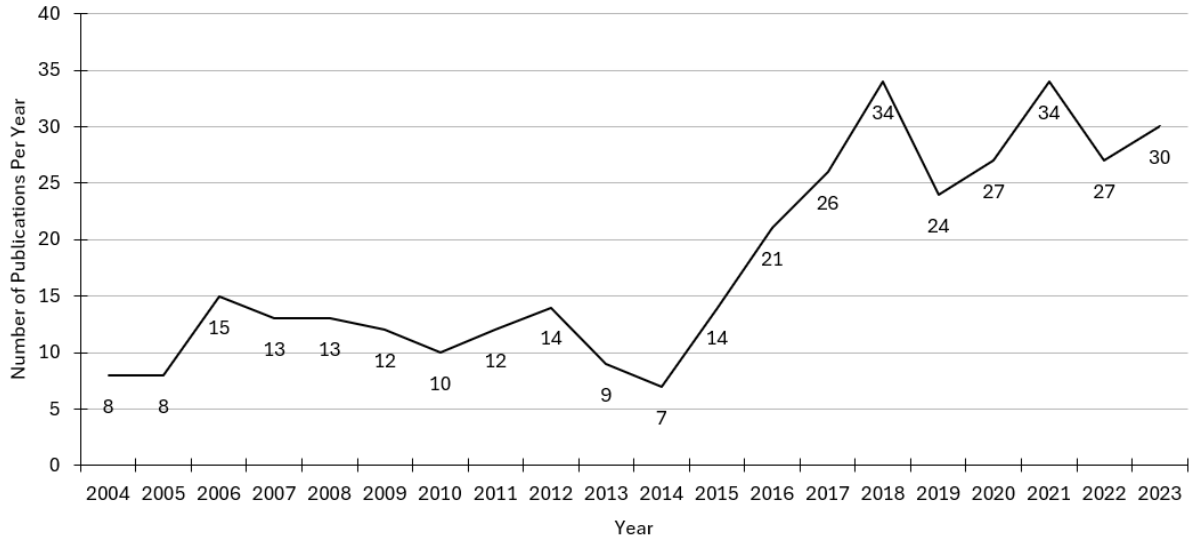

Figure 1: Number Of Publications Per Year By African Authors In English Language EER Journals (2004-2023)

Table 3 shows the number of publications by African-affiliated authors in each of the respective journals between 2004 and 2023. The European Journal of Engineering Education, International Journal of Engineering Education and Computer Applications in Engineering Education had the highest number of publications.

TABLE 3: NUMBER OF PUBLICATIONS BY AUTHORS FROM AFRICAN COUNTRIES IN ENGLISH LANGUAGE EER JOURNALS 2004-2023

Journal	Count
European Journal of Engineering Education	56
International Journal of Engineering Education	55
Computer Applications in Engineering Education	48
Global Journal of Engineering Education	31
International Journal of Engineering Pedagogy	27
International Journal of Electrical Engineering and Education (International Journal of Electrical Engineering Education)	26 (2)
Journal of Professional Issues in Engineering Education and Practice	22
International Journal of Mechanical Engineering Education	22
IEEE Transactions on Education	21
Education for Chemical Engineers	13
International Journal of Continuing Engineering Education and Life Long Learning	11
Chemical Engineering Education	9
Journal of Engineering Education Transformations	5
Australasian Journal of Engineering Education	5
Journal of Engineering Education	4
Journal of Civil Engineering Education	1
Advances in Engineering Education	0

Journal of Pre-College Engineering Education Research	0
TOTAL	**358**

Table 4 shows the number of publications by each country between 2004 and 2023. The total shown in Table 2 is 372 instead of 358, as some publications have authors from different African countries. South Africa notably has the highest number of publications at 147, followed by Egypt, Nigeria, Botswana, Tunisia and Morocco who each have approximately 30 publications. There are numerous countries which also have single digit publications, with five countries having only one publication each.

Also in Table 4 it can be seen that the countries with the highest number of co-authorship collaborations with other African countries are Kenya, South Africa, and Uganda. The countries with the highest number of collaborations with non-African countries are South Africa, Egypt, and Tunisia.

TABLE 4: NUMBER OF PUBLICATIONS FROM EACH AFRICAN COUNTRY THAT PUBLISHED IN ENGLISH LANGUAGE EER JOURNALS 2004-2023.

Country	Number of Publications	Number of Collaborations with Other African Countries	Number of Collaborations with Non-African Countries
South Africa	147	11	41
Egypt	37	0	18
Nigeria	36	5	12
Botswana	30	1	12
Tunisia	29	0	15
Morocco	25	1	3
Algeria	19	1	7
Ghana	12	0	7
Kenya	7	12*	3
Ethiopia	5	5	3
Mauritius	4	0	1
Uganda	4	9*	3
Libyan Arab Jamahiriya	4	0	2
Malawi	3	5*	3
Tanzania	3	2	2
Cameroon	2	0	0
Zimbabwe	1	0	1
Zambia	1	0	1
Sudan	1	3*	1
Rwanda	1	1	0
Mozambique	1	0	1
TOTAL	**372**	**21**	**136**

* NOTE: THE NUMBER OF COLLABORATIONS MAY BE HIGHER THAN THE NUMBER OF PUBLICATIONS IF THERE ARE MULTIPLE COLLABORATIONS PER PUBLICATION.

Table 5 shows the most common country collaborations between African and Non-African countries. As shown, the countries with the highest number of collaborations are South Africa-United States, Tunisia-Saudi Arabia, and Botswana-United States. Considering collaborations between all authors from Africa and non-African countries, Table 6 shows that authors from Africa most often collaborate with the United States, Saudi Arabia and the United Kingdom.

TABLE 5: NUMBER OF COLLABORATIONS BETWEEN AFRICAN COUNTRIES AND NON-AFRICAN COUNTRIES PUBLISHED IN ENGLISH LANGUAGE EER JOURNALS 2004-2023 (ONLY THOSE WITH A MINIMUM OF 5 COLLABORATIONS SHOWN)

Country A	Country B	Count
South Africa	United States	13
Tunisia	Saudi Arabia	10
Botswana	United States	9
South Africa	United Kingdom	6
Algeria	France	6
Egypt	Saudi Arabia	5

TABLE 6: NUMBER OF COLLABORATIONS BETWEEN ALL AFRICAN COUNTRIES AND NON-AFRICAN COUNTRIES PUBLISHED IN ENGLISH LANGUAGE EER JOURNALS 2004-2023 (ONLY THOSE WITH A MINIMUM OF 5 COLLABORATIONS SHOWN)

Country A	Country B	Count
All Authors from Africa	United States	36
All Authors from Africa	Saudi Arabia	17
All Authors from Africa	United Kingdom	12
All Authors from Africa	France	11
All Authors from Africa	Spain	6
All Authors from Africa	Australia	5

Table 7 presents the most common keywords between 2004-2013 and 2014-2023. The purpose of this is to observe how the most prevalent themes changed or remained constant during the two decades. 'Students' and 'Engineering Education' remained the most common keywords, while the next three remained in similar rankings. An observation is that 'Computer Simulation' which was ranked sixth between 2004-2013 disappeared from the rankings in the following decade, although 'Computer Aided Instruction' appeared. 'E-learning' became more prominent in the second decade.

TABLE 7: MOST COMMON KEYWORDS FROM PUBLICATIONS FROM TIME PERIODS 2004-2013 AND 2014-2023 ACCORDING TO SCOPUS

2004-2013		**2014-2023**	
Keyword	***Number of Occurrences (N=114)***	***Keyword***	***Number of Occurrences (N=244)***
Students	35	Students	108

Engineering Education	29	Engineering Education	90
Teaching	20	Education	42
Education	17	Curricula	31
Curricula	10	E-learning	30
Computer Simulation	8	Teaching	25
E-learning	8	Learning Systems	18
Technical Presentations	7	Professional Aspects	16
Professional Aspects	7	Education Computing	14
Engineering	7	Higher Education	13
Societies And Institutions	6	Computer Aided Instruction	13
Project Management	6	Surveys	12
Construction Industry	6	Engineering	12
Undergraduate Courses	5	Graduate Attributes	11
Higher Education	5	Problem Solving	9

TABLE 8: AUTHORS WHO PUBLISHED 5 OR MORE PUBLICATIONS IN ENGLISH LANGUAGE EER JOURNALS 2004-2023 WHILE ASSOCIATED WITH AFRICAN INSTITUTIONS. NOTE IT IS POSSIBLE AUTHORS MOVED LOCATION DURING THIS TIME PERIOD.

Author	Scopus ID	Number of Publications	Country of Affiliation (during 2004 - 2023)
Swart, Arthur James	8502923800	22	South Africa
Uziak, Jacek	6506665129	20	Botswana
Binous, Housam	6508118336	17	Tunisia
Bellagi, Ahmed	6602233624	10	Tunisia
Case, Jennifer M.	7103347500	10	South Africa
Kloot, Bruce Charles	33667766700	7	South Africa
Oladiran, Moses Tunde	6603525896	7	Botswana
Collier-Reed, Brandon I.	7202456093	5	South Africa
Engelbrecht, Johann	55244523100	5	South Africa
Wolff, Karin Elizabeth	55587842800	5	South Africa

From Table 8 we see that in terms of output per author, South African based scholars were in the majority, followed by those from Botswana and Tunisia.

The process of analysing the affiliations of the authors in the sample also identified three research centres that have a particular focus on engineering education:

- Africa Center of Excellence on New Pedagogies in Engineering Education, Zaria, Nigeria
- Centre for Research in Engineering Education, and Academic Support Programme for Engineering, University of Cape Town, Cape Town, South Africa
- Engineering Education, Faculty of Engineering and the Built Environment, Univ. of Johannesburg, Johannesburg, 2006, South Africa

4. Limitations

One limitation of our methodology is that it involves the use of affiliation data in Scopus to identify African authors. This means that the work of African-born researchers with affiliations in other parts of the world such as Esther Matembe (Australia), Abel Nyamapfene (UK) and Jennifer Case (US) is not fully included.

The study presented here is also constrained by limitations in the scope of the data available in Scopus. The authors appreciate the need for a more critical and nuanced interpretation of the emerging metadata to provide more actionable insights for future research in the field and to better engage with the perspectives of the African papers and their authors. Indeed "a proper scientometric method can not be complete without a nuanced qualitative view inspired by the other methods." (Lopez-Pernas et al., 2023, pp 80). However, such a content-analysis approach would involve the presentation and application of an additional qualitative methodology that is not possible within the page constraints for IRSPBL2025 conference submissions.

A further limitation is that we focus on the total number of journal publications without applying a quality criterion to measure their impact.

5. Future research

Future work aims to complement the data reported in this paper by introducing a quality criterion where we apply citation analysis to provide a measure of the impact of the publications in our sample. In addition, a content-analysis of the articles in our sample is expected to provide more actionable data for African scholars.

6. Conclusion

In our sample comprised of 358 articles with African-affiliated authors published in 18 journals from 2004 to 2023, the annual output of research publications in the field of EER was relatively low in the early part of the century, averaging 11 per annum, but more than doubled in the period 2015 - 2016 and it has remained relatively stable since then at an average of 28. We have not been able to attribute specific causes for the increase although we suggest it may be linked to developments in the South African context.

The three most popular publication venues are European Journal of Engineering Education, International Journal of Engineering Education and Computer Applications in Engineering Education. The countries with the highest number of co-authorship collaborations with other African countries are Kenya, South Africa, and Uganda. The countries with the highest number of collaborations with non-African countries are South Africa, Egypt, and Tunisia. the most common partnerships have been South Africa-United States, Tunisia-Saudi Arabia, and Botswana-United States.

According to the keywords listed in Scopus, “Students’ and ‘Engineering Education’ remained the most common keywords over the twenty-year period. ‘Computer Simulation’ was ranked sixth between 2004-2013 but disappeared from the rankings in the following decade, while ‘Computer Aided Instruction’ appeared. ‘E-learning’ became more prominent in the second decade and the pandemic years are likely to have contributed to this development.

Our analysis identified three research centres on the continent that have a particular focus on engineering education. This development, along with the growth in journal publications, is an indication that engineering education research has evolved from the relatively low level suggested by the limited research

output earlier in the century. While this output is comparable with that of other regions in the Global South, it remains significantly lower than that of regions in the Global North.

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Keeping Research Current: Using Living Literature Reviews in Educational Research

Anita L. Campbell
Academic Support Programme for Engineering; & Centre for Research in Engineering Education; & Centre for Wellbeing and Flourishing, University of Cape Town, South Africa, anita.campbell@uct.ac.za

Disaapele Mogashana
Department of Mechanical & Aeronautical Engineering, University of Pretoria, South Africa, disaapele.mogashana@up.ac.za

Abstract

Our previous systematic literature review on academic coaching interventions (Campbell & Mogashana, 2024) highlighted key features of effective approaches for undergraduate students but also revealed the challenge of keeping research syntheses up to date. Living literature reviews (LLRs) offer a solution by providing a continuously updated synthesis of new evidence. In this paper, we examine whether LLR methodologies can be effectively applied to academic coaching research, particularly when incorporating qualitative studies. We begin with an overview of systematic reviews and their limitations before introducing the LLR approach and its potential benefits for educational research. We then outline the methodological steps required to transition from a static systematic review to a dynamic LLR, detailing search strategies, inclusion criteria, and data management techniques. Implementation challenges—such as workload, methodological consistency, and publication concerns—are discussed alongside practical workarounds. Finally, we explore the role of AI tools in automating aspects of LLRs, including data extraction, citation tracking, and workflow optimization. By addressing these considerations, we aim to provide researchers with a roadmap for integrating LLR methodologies into education research, ensuring that evidence remains current, transparent, and accessible.

Keywords: Academic coaching, Living literature review, Undergraduate student success, Engineering education, AI in research.

1 Introduction

Systematic literature reviews (SLRs) help decision-makers by providing a comprehensive and structured analysis of existing research within a field. By identifying patterns, gaps, and key findings across multiple studies, SLRs inform both academic inquiry and practical applications. However, traditional SLRs have limitations, particularly in rapidly evolving research areas where new studies emerge frequently. To address this challenge, living literature reviews (LLRs) have been introduced as a dynamic alternative that allows for frequent updates of findings (Elliott et al., 2014).

1.1 Context of Our Study

Academic coaching has become a widely recognized intervention in higher education, supporting student success, retention, and well-being. In our initial systematic literature review (Campbell & Mogashana, 2024), we analysed 643 studies and identified 25 key articles that provided valuable insights into effective coaching interventions for undergraduate students. The findings highlighted that the most impactful programs lasted

at least 12 hours over four weeks, were preferably conducted in person, and were most effective when facilitated by professional coaches.

Eager to explore how the field had evolved in the 20 months since our first review—which covered journal publications from 2010 to May 2023—we conducted a follow-up review. To our surprise, we identified 466 new studies, with 15 meeting our inclusion criteria. The unexpectedly high number of publications led us to question whether a more dynamic, ongoing approach to literature synthesis could better capture emerging insights.

Our introduction to the LLR methodology offered a compelling solution. By transitioning to an LLR, we aim to ensure that research on academic coaching remains current and actionable, providing universities with up-to-date, evidence-based support mechanisms to promote student thriving.

1.2 Research Focus

Our initial SLR provided a foundational understanding of academic coaching interventions, but as the field progresses, new questions arise regarding the applicability and sustainability of these findings. This paper aims to explore whether and how the LLR methodology can be applied to research on education-related interventions, particularly qualitative and mixed-methods studies. Specifically, we investigate:

1. How do the methodological and practical differences between LLRs and SLRs influence their use in educational research?
2. What frameworks and guidelines currently exist for conducting Living Literature Reviews?
3. What methodological and technological adaptations are required to transition from an SLR to an LLR?
4. What are the main challenges of maintaining an LLR, and what strategies can be used to address them?

By addressing these questions, we seek to establish a replicable and adaptable LLR model that supports evidence-based education-related interventions. The insights gained from this work will inform future iterations of our research, including journal publications detailing findings from the LLR and strategies for sustaining long-term updates.

2 Background: Systematic Literature Reviews and their Limitations

2.1 Definition and Purpose of Systematic Reviews

SLRs are a rigorous method of synthesizing existing research to provide comprehensive, unbiased, and reproducible insights to further our understanding of a specific topic (Gough & Thomas, 2016). Unlike traditional narrative reviews, SLRs follow a structured methodology that involves defining a research question, systematically searching for relevant studies, applying inclusion and exclusion criteria, extracting and synthesizing data, and assessing study quality. The goal is to offer an evidence-based summary that can guide future research, policy decisions, and practice (Borrego et al., 2014).

2.2 Types of Systematic Reviews

SLRs come in several forms (Grant & Booth, 2009; Paul et al., 2023), depending on the research question and available evidence. Some common types include:

- **Quantitative systematic reviews**: These focus on synthesizing numerical data, often through meta-analysis, to determine the effect size of an intervention or relationship between variables.
- **Qualitative systematic reviews**: These integrate findings from qualitative studies to explore themes, patterns, and theoretical insights.
- **Mixed-methods systematic reviews**: These combine both quantitative and qualitative data to provide a more holistic understanding of a research question.

- **Rapid reviews**: These are condensed versions of systematic reviews that apply simplified methodologies to produce findings in a shorter timeframe.
- **Living literature reviews (LLRs)**: These are continuously updated systematic reviews that integrate new research findings as they become available.

2.3 Standard Methodology of SLRs

Traditional systematic reviews use a structured and transparent process to ensure rigor and reliability. Below are the eight key steps (Uman, 2011):

1. **Formulate the Review Question**
   The first stage involves defining the review question, forming hypotheses, and developing a title that indicate that the study is a systematic review and/or meta-analysis.
2. **Define Inclusion and Exclusion Criteria**
   Using the PICO (or PICOC) framework—Population, Intervention, Comparison, Outcomes (and Context)—helps determine study parameters, such as sample characteristics, study design, and outcome measures.
3. **Develop Search Strategy and Locate Studies**
   A well-designed search strategy ensures comprehensive identification of relevant studies. Consulting an information specialist or librarian can help optimize electronic searches. Common sources include electronic databases, article reference lists, key journal hand-searching, listserv postings, and expert contacts.
4. **Select Studies**
   After retrieving and screening abstracts, studies meeting inclusion criteria are reviewed in full. At least two independent reviewers should conduct this process to ensure reliability. Maintain a log of reviewed studies with inclusion/exclusion justifications, and contact study authors for missing data (e.g., means, standard deviations) and obtain translations.
5. **Extract Data**
   A standardized data extraction form or table helps organize study details (e.g., authors, year, sample size, age range, study design, outcomes). Data extraction by at least two reviewers enhances accuracy and minimizes errors.
6. **Assess Study Quality**
   Quality assessment frameworks such as the Consolidated Standards of Reporting Trials (CONSORT) Statement (http://www.consort-statement.org/) guide evaluations. Some metrics are heavily influenced by double-blinding, which is important for pharmacological trials but less applicable for psychological or non-drug interventions.
7. **Analyse and Interpret Results**
   Summarizing findings and providing recommendations for practice and future research are critical. This step outlines which interventions are effective, for whom, and under what conditions, as well as areas requiring further investigation.
8. **Disseminate Findings**
   Finally, results should be shared through academic publications, presentations, policy briefs, and other knowledge translation activities to maximize impact.

Reviews involving qualitative data can follow adjusted guidelines, such as given by Noyes et al. (2023) or Borrego et al, (2014). Following these steps provide a structured approach to conducting systematic reviews, ensuring a transparent and methodologically sound process.

2.4 Why Traditional SLRs May Become Outdated

While SLRs provide a robust synthesis of existing evidence, they have limitations, particularly in fast-evolving fields (Shojania et al., 2007). Traditional SLRs are time-intensive, often taking months or even years to complete. By the time they are published, new studies may have emerged, rendering their conclusions partially outdated. Additionally, updating an SLR requires repeating the entire review process, which is resource-intensive and impractical for many researchers.

2.5 Challenges of Keeping an SLR Updated in Non-Medical Fields

Updating SLRs is particularly challenging in non-medical fields, where research methodologies and reporting standards vary widely. In fields such as education and psychology, qualitative and mixed-methods studies are common, presenting challenges such as requiring subjective interpretation, which may evolve over time, and lacking uniform protocols for data collection and analysis.

2.6 Living Literature Reviews as a Solution

To address the limitation of becoming outdated, LLRs offer a dynamic alternative (). Unlike traditional SLRs, LLRs are designed to be continuously updated, ensuring that the latest research is incorporated as it becomes available (Iannizzi et al., 2023).

Living literature reviews address the problem of academic publications doubling every 12 years (Clancy, 2024) by providing continuously updated, accessible syntheses of research. Unlike traditional reviews, they avoid paywalls and jargon, ensuring clarity for non-specialists while maintaining rigor. If a single expert or a core team curates these reviews, they offer a consistent perspective while collaborating with others. Digital platforms enable updates, corrections, and broad distribution via websites, newsletters, and podcasts. By making research more accessible, living literature reviews foster interdisciplinary connections and inform policy and innovation.

3 Understanding the Living Literature Review Methodology

3.1 Defining Living Literature Reviews (LLRs) and Their Key Characteristics

Living Literature Reviews (LLRs) are a dynamic extension of traditional Systematic Literature Reviews (SLRs), designed to incorporate new evidence as it emerges. Unlike conventional SLRs, which offer a snapshot of existing research at a specific point in time, LLRs remain continuously updated. This approach ensures that the synthesis of research remains relevant, particularly in fields where knowledge evolves rapidly (Iannizzi et al., 2023).

The distinguishing feature of LLRs is their iterative nature. Instead of producing a static summary of literature, an LLR is structured to be revised periodically, integrating new studies that may refine or challenge existing conclusions (Elliott et al., 2017). This makes them particularly useful in areas where ongoing research can significantly influence best practices, policy decisions, or theoretical frameworks.

3.2 Criteria for Implementing an LLR

Not all research areas necessitate an LLR approach. The Living Evidence Network (2019) outlines three key conditions that justify adopting an LLR:

1. The research question must be important to practice or policy, either currently or in the near future.
2. There must be substantial uncertainty in the existing evidence, necessitating continual reassessment.
3. New studies are likely to emerge frequently and meaningfully impact the conclusions drawn from the literature.

In the context of academic coaching, these criteria are met due to the rapidly evolving nature of pedagogical approaches, increasing reliance on technological tools, and shifting student needs. Establishing an LLR for

this field allows for timely integration of new insights, ensuring that academic coaching interventions remain informed by the latest research.

3.3 Existing Guidelines for LLRs

The methodology for LLRs has been well-established in medical and health sciences research, where ongoing updates are needed for evidence-based practice (Aki et al., 2024). In fields such as education and social sciences, however, structured guidelines for implementing LLRs are still emerging. Frameworks developed for medical LLRs emphasize predefined update cycles, mechanisms for tracking new evidence, and clear reporting structures for changes in findings over time.

For qualitative and mixed-methods research, LLR methodologies must accommodate a broader range of data types and interpretative approaches. Unlike clinical studies, where new trial data can be systematically incorporated, qualitative research requires ongoing thematic synthesis, reflection, and adaptation. Emerging frameworks suggest flexible update intervals, integration of qualitative evidence synthesis methods, and consideration of methodological shifts within the field.

3.4 Relevance of LLRs in Academic Coaching Research

Academic coaching is an evolving field where interventions, strategies, and theoretical perspectives are continuously refined. The need for ongoing synthesis of evidence in this area is critical, given the diversity of coaching models and the varying contexts in which they are applied. A static SLR provides foundational insights, but without continuous updates, it risks becoming outdated as new studies emerge.

By transitioning to an LLR approach, this study aims to ensure that research on academic coaching remains responsive to new developments. This has practical implications for institutions seeking to implement effective coaching programs, as well as for researchers and policymakers shaping the future of student support systems.

Furthermore, establishing an LLR in this field presents methodological considerations, including decisions on how to refine the original search strategy, how to integrate new types of publications such as literature reviews, and how to balance comprehensiveness with manageability. These challenges underscore the importance of developing robust procedures for maintaining an LLR in an educational research context.

4 Methodological Steps in Transitioning from an SLR to an LLR

Moving from a traditional systematic literature review (SLR) to a Living Literature Review (LLR) requires thoughtful modifications to search strategies, data management, and reporting structures (Aki et al., 2017). Unlike static reviews, which capture research at a single point in time, an LLR remains dynamic, integrating new findings as they emerge. This approach ensures that academic coaching research stays relevant, reflecting the latest insights into student support and intervention strategies.

4.1 Revising Search Strategies for Continuous Updates

A key feature of an LLR is the ability to systematically refresh search results, ensuring that emerging research is incorporated in a structured manner. Rather than relying on one-off searches, the process must be designed for ongoing updates. This requires expanding search terms to capture new trends and leveraging AI-driven search tools to refine queries efficiently. Automated systems can help identify relevant studies as they are published, reducing manual effort while maintaining accuracy. Establishing clear protocols for when and how searches will be conducted—whether monthly, quarterly, or biannually—further ensures consistency.

4.2 Optimizing Search Frequency and Inclusion Criteria

Balancing comprehensiveness with manageability is essential in an LLR. While frequent updates improve relevance, excessive revisions can create unnecessary disruptions. A structured approach helps mitigate this challenge. Defining how often searches are conducted allows for systematic integration of new evidence, ensuring that updates remain meaningful rather than incremental. Additionally, setting clear inclusion criteria ensures that only studies meeting predefined relevance and methodological standards are incorporated. A threshold-based approach—where updates are triggered by a critical mass of new studies rather than each individual publication—prevents minor revisions from overwhelming the review process (Aki et al., 2017).

4.3 Managing Qualitative Data Updates and Refining Coding Structures

Incorporating new qualitative research presents unique challenges, as evolving themes and perspectives require continuous adaptation. Unlike quantitative reviews, where statistical synthesis dominates, an LLR in academic coaching must remain flexible in its treatment of qualitative data. As new studies emerge, thematic coding structures may need to be refined to reflect shifting patterns. Maintaining an iterative approach ensures that coding remains responsive to new insights while avoiding redundancy. Transparent documentation of these refinements is essential, providing a clear record of how interpretations evolve over time. Qualitative data management software, such as NVivo or ATLAS.ti, can support this process by enabling structured tracking of thematic changes and coding revisions.

4.4 Establishing Transparent Reporting in an LLR Framework

To ensure credibility, an LLR must adopt structured reporting mechanisms that provide clarity on how updates are managed. The PRISMA-LSR checklist (Aki, 2024) offers a useful framework for documenting changes. It outlines key elements such as update frequency, justifications for methodological adjustments, and a clear record of how new studies impact existing conclusions. Beyond simply reporting findings, maintaining an active review status and indicating when the next update is expected enhances transparency and usability for researchers and practitioners who rely on up-to-date evidence.

5 Implementing a Living Literature Review for Academic Coaching Interventions

5.1 Justification for Using an LLR in Academic Coaching Research

Academic coaching is an evolving field, with ongoing research exploring its impact on student success, retention, and well-being. Unlike medical research, where new findings may be published monthly or even weekly, educational research—particularly in academic coaching—tends to have a slower turnover rate.

An LLR ensures that academic coaching interventions remain informed by the latest research. This adaptability is helpful given the dynamic nature of coaching practices, which evolve due to:

- Shifting student needs and expectations (e.g., changes in motivation, mental health challenges, and learning preferences).
- Emerging pedagogical frameworks (e.g., new coaching models that integrate positive psychology or self-regulation strategies).
- Advancements in digital coaching tools (e.g., AI-driven tutoring, adaptive learning platforms, chatbots).

By maintaining an ongoing synthesis of research, LLRs provide researchers, educators, and policymakers with timely, evidence-based insights to refine coaching interventions. This approach enhances practical applicability, ensuring that academic coaching programs remain aligned with current best practices.

5.2 Adapting LLR Methodology for Qualitative and Mixed-Methods Research

While many SLRs focus on quantitative studies and meta-analyses, academic coaching research often relies on qualitative and mixed methods approaches. These methodologies introduce unique challenges for maintaining an LLR, requiring careful adaptation to ensure that diverse study designs are integrated meaningfully over time.

One key challenge is the inclusion of both experimental and non-experimental studies, such as case studies, interviews, and ethnographic research. Unlike quantitative studies, where effect sizes can be compared numerically, qualitative research demands thematic synthesis—a process that must evolve as new themes emerge. To manage this, LLRs must incorporate flexible coding frameworks, allowing researchers to refine categories as the field progresses.

Another challenge is the risk of thematic saturation. As an LLR continues over time, some qualitative themes may become repetitive rather than novel. Researchers must periodically assess whether newly included studies contribute fresh insights or simply reinforce existing findings. One strategy is to implement thematic saturation checks, ensuring that only studies that expand or challenge current understanding are integrated.

Moreover, qualitative synthesis in an LLR requires balancing interpretive depth with methodological rigor. As coding frameworks evolve, researchers must document changes transparently, ensuring consistency and reproducibility in how qualitative findings are interpreted over time. Mixed-methods research adds another layer of complexity, necessitating integration strategies that bridge numerical data with narrative insights, ensuring a cohesive synthesis rather than treating qualitative and quantitative findings as separate streams.

By adapting LLR methodologies to accommodate these complexities, researchers can maintain the richness of qualitative inquiry while ensuring that updates remain systematic and meaningful.

6 Implementation Challenges and Workarounds

6.1 Managing Search Strategies and Volume of New Studies

Given the dynamic nature of academic coaching literature, effective management of search updates is essential. Across six pilot LSRs analysed by Millard et al. (2019), search frequency varied from monthly to every three months, with some teams using machine learning and Cochrane Crowd to screen citations. Researchers should configure automated alerts for major databases (e.g., PubMed, Scopus, Web of Science) and integrate citation managers like EndNote or Zotero to streamline tracking. Where relevant, researchers should consider grey literature, including policy reports and dissertations, which could be reviewed quarterly through repositories such as OpenGrey. Refining keyword strategies with emerging terminology and controlled vocabularies (e.g., Medical Subject Heading or 'MeSH' terms) ensures comprehensive coverage.

The volume of new studies presents a challenge. The number of citations screened in the Millard et al. study ranged widely, from three to 300 per month, with review teams dedicating anywhere from five minutes to 32 hours per month to updates. To balance this workload, predefined inclusion thresholds should be established—immediate incorporation for impactful studies, while others can be batched for periodic updates. A structured decision-making framework should be used to assess new data's significance, considering its effect on key findings and underrepresented subpopulations.

6.2 Ensuring Methodological Consistency and Managing Workload

Maintaining uniform synthesis methods, such as meta-analyses or thematic coding, prevents inconsistencies. Clear documentation of methodological adjustments should be maintained in supplementary materials. Following a structured methodology, such as given by Wilson et al. (2023), ensures that new members in the review team have clear processes to follow, and that adjustments to processes are clearly documented.

Participants in the Millard et al. (2019) study emphasized the importance of a well-organized and motivated team, as well as technology enablers to improve workflow efficiencies. However, they also identified challenges, including the ongoing workload burden and limited long-term resources to sustain LSRs. Regular team discussions and expert consultations help address these evolving methodological needs.

6.3 Managing Authorship, Citations, and Publication Challenges

LLRs require careful version control. Each update should receive a unique DOI to maintain transparency in modifications. Structured documentation, such as the PRISMA-LSR checklist (Aki et al., 2024), should track changes in methodology and included studies. Citation complexities arise with multiple versions of an LLR, potentially fragmenting impact metrics. Future solutions may include linked DOIs or citation aggregation to consolidate references across versions.

6.4 Decision-Making for Updating or Ending an LLR

It may be necessary to discontinue an LLR. Murad et al. (2023) suggest that reviews should be retired when:

- New evidence is unlikely to alter conclusions.
- No meaningful effects are found.
- The research question loses relevance.
- No new studies are anticipated.

6.5 Example text for Methods

The following example texts based on examples in Aki et al. (2024) provide a structured approach to maintaining an LLR. Such text should be included in Methods sections.

> "*We will screen new citations from monthly searches immediately upon retrieval.*"
>
> "*When new evidence meeting the inclusion criteria is identified, we will extract relevant data, assess the risk of bias, and incorporate findings into the synthesis every four months, as appropriate.*"
>
> "*Decisions on whether to discontinue updates will be based on key considerations, including:*
>
> - *The likelihood that future updates will change conclusions,*
> - *The absence of meaningful effects in new evidence,*
> - *The review question no longer being a priority for decision-making, and*
> - *The lack of emerging evidence relevant to the review.*
>
> *We will follow best practices and ongoing research in this area to guide these decisions.*"
>
> "*An annual reassessment of the review scope and methodology will ensure alignment with evolving evidence. Expanding intervention comparisons or outcome measures may be necessary based on emerging trends. If resource constraints require discontinuation, we will transparently report the rationale for retirement decisions to ensure accountability.*"

7 Potential of AI Tools in Living Literature Reviews

7.1 Enhancing LLR Workflows with AI

Artificial intelligence (AI) has the potential to significantly streamline LLR processes by automating labour-intensive tasks, improving efficiency, and ensuring timely updates. AI tools can support LLRs by:

- Automating literature searches and citation tracking: AI-driven platforms can continuously monitor databases, refine search strategies, and retrieve new publications in real time. Machine learning models can rank articles by relevance, reducing the manual workload for researchers.

- Facilitating blinded screening and study selection: Tools like Rayyan allow review teams to conduct blinded screening of references based on inclusion/exclusion criteria, reducing bias and improving consistency in selection.
- Supporting qualitative coding and thematic analysis: AI-based text analysis tools can assist in identifying patterns, coding qualitative data, and detecting emerging themes. These tools can generate preliminary insights, allowing researchers to focus on higher-level synthesis.

By integrating AI into these stages, LLRs can remain dynamic, responsive, and methodologically rigorous while reducing the burden on research teams.

7.2 AI Tools for LLR Implementation

A variety of AI-powered tools are available to assist at different stages of LLR management, from literature searches to synthesis:

Citation tracking and reference management:

- Zotero, EndNote, and Connected Papers facilitate organized literature management and tracking of updates.
- Rayyan enables blinded screening, allowing reviewers to assess studies independently before resolving conflicts, enhancing transparency and reducing bias.

AI-assisted systematic searching:

- Elicit and Scite use natural language processing (NLP) to refine search queries and identify highly relevant articles.
- Semantic Scholar leverages AI to highlight key findings and assess study influence.

Thematic analysis and evidence synthesis:

- NVivo and ATLAS.ti incorporate AI-driven text analysis to detect patterns in qualitative data.
- ASReview applies active learning to optimize systematic reviews by prioritizing the most relevant studies first.

Thomas et al. (2017) suggest micro-tasks that can be distributed among team members to manage the workload in living literature reviews. By leveraging AI tools, LLR teams can reduce manual workload, improve accuracy, and accelerate the synthesis process while maintaining high methodological standards.

7.3 Ethical Considerations and Limitations of AI in Research Synthesis

While AI offers efficiency gains in managing LLRs, ethical and methodological concerns must be addressed:

- Risk of bias in AI-generated outputs: AI models are trained on existing datasets, which may introduce biases in search results, thematic identification, and synthesis. Researchers must critically evaluate AI-generated insights to avoid reinforcing existing biases.
- Transparency and reproducibility concerns: Many AI algorithms operate as "black boxes," making it difficult to trace decision-making processes. Ensuring transparency in AI-assisted literature reviews is crucial for maintaining research integrity.
- Need for human oversight in data interpretation: AI should be regarded as a support tool rather than a substitute for researcher expertise. While AI can assist with automation and pattern recognition, human judgment remains essential for assessing study quality, determining relevance, and synthesizing findings meaningfully.
- Data privacy and security considerations: When using AI-powered platforms, researchers must be mindful of data protection policies, particularly when handling sensitive or proprietary research information.

AI tools can enhance the efficiency and responsiveness of LLRs. Responsible implementation requires careful oversight, methodological transparency, and adherence to ethical research principles.

8 Conclusion and Future Directions

8.1 Adapting Living Literature Reviews for Educational Research

The integration of Living Literature Reviews (LLRs) into educational research offers significant benefits, yet it also presents methodological and practical challenges. Unlike traditional Systematic Literature Reviews (SLRs), LLRs enable research to remain current and actionable by continuously incorporating new evidence. This dynamic approach is particularly valuable in fields where emerging studies frequently shape best practices. However, effective implementation requires structured workflows, team coordination, and the strategic use of technology.

A major challenge of LLRs is managing high search volumes while maintaining methodological consistency. The need for frequent updates introduces logistical complexities, including publication options and evolving inclusion criteria. Addressing these challenges requires clear protocols for screening new citations, systematic risk assessments, and well-defined update cycles. Despite these hurdles, LLRs offer a powerful tool for ensuring that educational research remains aligned with contemporary findings and policy needs.

8.2 Future Research Directions

To strengthen the role of LLRs in education research, future studies should refine methodologies for integrating qualitative and mixed-methods research. Current LLR frameworks have primarily been developed for quantitative evidence synthesis, and adapting these approaches for diverse research designs is essential. Investigating how existing LLR guidelines can be tailored to different disciplines will further enhance their usability and impact.

Understanding how LLRs shape decision-making, influence teaching strategies, and inform institutional policies will provide valuable insights into their effectiveness. Comparative studies on the sustainability of LLRs across various research areas could also yield best practices for their implementation.

8.3 Concluding Thoughts on the Role of LLRs in Academic Research

By adopting best practices from established frameworks, such as the PRISMA-LSR extension (Aki et al., 2024), researchers can enhance the efficiency and methodological consistency of LLRs. As academic coaching and other education research fields continue to evolve, LLRs ensure that evidence remains current and actionable, supporting informed policy and instructional decisions.

Beyond their immediate applications, LLRs offer a transformative approach to evidence synthesis. Their ability to incorporate new findings in real time fosters a more responsive and adaptive research landscape. By refining LLR methodologies and addressing the challenges of ongoing updates, researchers can establish LLRs as living, evolving resources, ensuring that educational insights remain relevant and impactful.

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Implementing an institutional transformation in science and engineering: the University of Nairobi example

Anne Nkoidila
University of Nairobi, Kenya, annen@uonbi.ac.ke

Beatrice Ndaisi Kimuyu
University of Nairobi, Kenya, bndaisi@uonbi.ac.ke

David K. Kariuki
University of Nairobi, Kenya, kkariuki@uonbi.ac.ke

Thomas Ochuku Mbuya
University of Nairobi, Kenya, tmbuya@uonbi.ac.ke

Jackson Kivui Maalu
University of Nairobi, Kenya, jmaalu@uonbi.ac.ke

Jarrett Onyango Odwallo
University of Nairobi, Kenya, jodwallo@uonbi.ac.ke

Marc Zolver
ExpertiseFrance and University of Nairobi, Kenya, mzolver@uonbi.ac.ke

Abstract

Ten years ago, the University of Nairobi (UoN) in Kenya entered in a transformative reflexion to reform Engineering and Science Higher Education, Research and Innovation (HERI). Few years later, a concrete project emerged with the construction of a state-of-the-art academic building aiming at facilitating HERI by its own design, the Engineering and Science Complex (ESC), and the development of international cooperation, especially with French institutions and partners from Europe.

Six pillars of activities have been structured and launched in 2023 with six dedicated teams, mostly from the Faculty of Science and Technology (FoST) and the Faculty of Engineering (FoE): Governance, Curricula reform, Research excellence, Innovation culture, Company linkage and Internationalization.

This work-in-progress has been presented at IRSPBL2023 and is now in its implementation stage. New practices, key actions and capacity building per pillar are developed with strategic roadmaps, milestones and deliverables, learning and training programs, student and staff mobility, etc. The authors showcase concrete examples from each pillar and expose the key concept of international multi-disciplinary "Communities of Excellence" of the ESC. They emphasize the importance of international networks and partnerships, such as the AFRETEC network and the EU Global Gateway program, and share challenges and lessons learned.

Keywords: institutional transformation, industry Academia linkage, innovation ecosystem, community of excellence, internationalization, higher education infrastructure.

1 Introduction

African continent is at a crossroad of its future role and place in the global world. As a main key factor, and repeatedly brandished, its demography will be either a problem or an opportunity. On the one hand, African countries, under the pressure of their debt and international agencies, and seriously impacted by the Climate Change, might not be able to cope and answer the needs and expectations of their young generation "GenZ". Education won't tackle the massive demand, decent job market won't expand, public and private investments won't happen, and debt and Climate Change will remain dramatic for populations and their standard of living. A vicious loop could take place with massive undereducated and unemployed populations with no future perspective, and often irrelevant governance favoured by global north political drift in Russia, US, Europe, China… On the other hand, African countries can also enter in a virtuous loop in tackling the challenges with education reforms (from primary to higher), decent job creation and Climate Change adaptation, accelerated by dynamic research and innovation ecosystems, allowing Africa to enter in a new era of real prosperity and economic growth, relying on the capacity and creativity of its youth, and giving space to new models of relevant and inclusive public and private governance.

UoN has chosen the virtuous loop by engaging a transformational plan with the construction of the ESC and the reform of its educational programs, research and innovation, in order to support the country development and tackle its challenges. From the ideation in 2015 of the ESC until today, the university achieved some main milestones with feasibility studies in 2019, the French Development Agency (AFD) financial commitment in 2021 and the partnership agreement between UoN and 6 French higher education institutions in 2023. Although the construction of a new state-of-the-art academic building is the main backbone of the project, with a relevant and enabling design to be selected mid-2025 and a construction expected to take less than 2 years, this paper furthers the (Kerubo et al., 2023) paper and focuses on the "software" parts of the systemic transformation with the structure in pillars grouping people in action for the good implementation of the ESC. The Pillar structure is temporary and shall give place smoothly to "Communities of Excellence" that will be hosted in the ESC. Communities are sets of internal and external stakeholders that share the same sector and/or high value service. The ESC will be articulated and animated by these communities, ensuring its sustainable development and relevance.

2 The ESC Pillars

The academic community is not an easy one to engage in any institutional reform. Among others, (McGowan et al., 2022) have identified many obstacles and proposed key questions to address for maximising the chance of success: sharing the vision, defining the key drivers, proposing incentives and ensuring learning outputs. UoN applied a similar approach by answering these questions clearly and repeatedly under a tree structure maximizing communication, engagement and impact, and making the transformation truly systemic. From a core Project Management Unit (PMU) of 6 key people – one lead director, one project manager, one architect, one procurement officer, one finance manager and one foreign expert - six pillars are implemented: Curricula reform, Research excellence, Innovation culture, Internationalization, Company linkage and Governance. Each pillar is led by a duo of people from FoST and FoE in relation with their pillar's peer from French partner's institutions. Each pillar is then in charge to recruit its local members, 10 to 15, with the constrain to be balanced between FoST and FoE and as much as possible between men and women.

The pillars prepared their roadmap with key objectives, milestones and deliverables. They feedback to the PMU and implement their actions with the financial support of the AFD, controlled by the PMU. Different levels of synchronisations are active, the PMU with the pillar heads, the pillar heads and their teams, the PMU with a specific pillar, and of course all participants altogether, with punctual UoN top management meeting and exchanges within a steering committee. French peers are participating in due time at all levels. Hence, the agility of the project and its appropriation by people are concrete and efficient. PMU and pillar heads receive direct incentives and drivers, including financial compensation, while the pillar members and other stakeholders have indirect incentives and drivers, especially through "quick wins" (participation in international calls, link to international peers, priority access to grants and mobility…) and tangible learning outputs (capacity and network building).

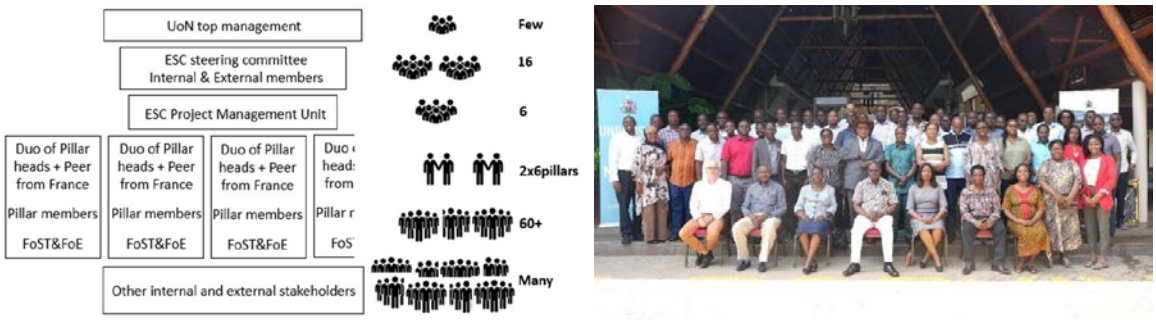

Figure 1: ESC project general organisation; 2024 pillars' global seminar group photo.

3 Pillar distribution and example of practices

The six pillars cover the 3 classical perimeters of higher education, research and innovation, crossed with 3 transversal perimeter of internationalization, academia-industry linkages and governance.

3.1 Education, Curricula reform

This pillar aims to update and/or create programs to be hosted in the ESC. After sound needs assessments, the pillar team has developed a roadmap to implement 3 main new and/or updated practices:

- **Module development:** competence and skill modules and short schools on professional communication, self-awareness, teamwork, innovation and entrepreneurship, digital and AI literacy, climate change… Implementation started in 2023 in particular with ***the company series***, a set of 5 workshops with industry experts to develop professional skills and self-awareness, to exercise teamwork and creativity, to understand PBL approach, to communicate efficiently, to interact with professionals and to participate in field visits. 150 students have experienced the series and have declared to be "satisfied" or "very

satisfied". ***Seasonal schools*** are also in development with annual editions in programming/machine learning, climate change, mathematics… with the same rate of success evaluated by students.

- **Professional inclusion:** Involving industry in the programs by teaching participation, Problem and Goal Based Learning, employability enhancement, mandatory attachment, field visits, mentorship… In addition to *the Series* and its activities, a ***mandatory attachment*** policy is under approval by the UoN senate for full deployment.
- **Program update:** Creating industry oriented Master programs possibly leading to international joint or double degrees with partners. A need assessment conducted in 2024 identified first priorities with ***AI and Data***, ***HealthTech and biomedical engineering***, ***Agriculture and Food***. In addition, ***International mobility*** and its recognition is part of program reform. In 2023, UoN has been awarded an EU intra-Africa Academic Mobility Scheme (GREEN-STEM) to sustain student and staff mobility. 90 people from Kenya, Nigeria, Rwanda and South Africa are benefiting from an academic mobility from few months to few years at MSc and PhD level. Coordinating such initiative is also key to understand and build capacities in international recruitment for joint programs or credit exchanges within the ESC initiative.



Figure 2: interactive company series workshops and "spaghetti bridge" challenge.

3.2 Research

The research pillar is instrumental to define the sectors of priority that will be operated in the ESC. To be really bottom-up and need-oriented, the pillar has supported international meetings, exchanges, some lab visits and preliminary joint activities. Thus, the pillar identified 6 topical key sectors for Kenya with: ***Agriculture and Food science, BioTech and Chemistry, Advanced manufacturing, Energy, HealthTech and Urban development***, and 2 capacitating sectors with ***Data/Artificial Intelligence and Innovation***.

The pillar has been able to engage new professional practices for research with ***Franco-Kenyan joint PhD programs*** and ***the development of industrial partnerships***. Joint research projects and micro to macro-chairs are actually proposed by UoN research departments to external companies.



Figure 3: Research seminar 2023 in Kenya and joint research staff with France.

The pillar is also very supportive of capacity building in grant writing and management, to allow more researchers to apply and get international grants. These new capacities are true enablers of professional competences and a window for international network and recognition.

3.3 Innovation

Closely intertwined with Research, the Innovation pillar has its own legitimacy. The main objective of the pillar is to ***engage and support new practices by a empowering and sustainable ecosystem***. The pillar shall

implement the new ecosystem in the ESC, linked with European ecosystems, especially with France, and other African ecosystems, thanks to UoN membership in the pan-African AFRETEC network, with institutions from Egypt, Kenya, Morocco, Nigeria, Rwanda, Senegal, Angola and South Africa. Meanwhile, the pillar has engaged its team in grant writing, especially under Horizon Europe framework program.

3.4 Internationalization

Within the ESC, curriculum, research and innovation new practices are strategically expected to have international outlook and partners. As a roll-out of this strategy, the UoN international office have been strengthened and now counts 6 junior/senior officers and program managers. It actively contributes in the organization of ***international mobility***, within different frameworks such as the European E+ program. Under the ESC, around 30 students and more than 65 staff have benefited from a physical mobility between France and Kenya in 3 years, for coursework, research and learning opportunities. Together with the pillar members, the international office also participated in the GREEN-STEM proposal and implementation since 2024, with MSc and PhD mobility. In support of the new practices of the curriculum pillar, it has co-organised seasonal schools such as the ***African School on Climate Change Adaptation*** and supported ***schools in computing/machine learning and in mathematics***. The schools attract 25 to 40 international students, mostly from Africa but also Europe, with a 95% satisfactory and above rating. At last, all the team with faculty members from other pillars are participating in the recent ***AFRETEC network***. This network is very active and counts 8 members, including UoN, from different countries in Africa. The AFRETEC pillars are totally convergent with the ESC pillars and act in synergy and a constructive approach as most of their members are shared AFRETEC/ESC.



Figure 4: African School 2024 with the Climate Fresk© and field visit to United Nations Nairobi headquarter.

3.5 Industry linkages

Company partnerships are crucial to develop relevant education and research programs, and to generate impactful innovation. Since 2023, the ESC project has raised 7 partnerships with French and Kenyan companies: ***Bureau Veritas, Olvéa Kenya, TotalEnergies, Schneider Electric, Bamburi Cement/Holcim, Elgon Kenya, Camco***, and two national companies, ***Kengen and Geothermal Development Company***. UoN is also member of ***the French Chamber of Commerce*** in Kenya. The content of the partnerships is yet mostly limited in human resources for the ESC activities, such as ***the company series***, ***seasonal schools***, ***ad hoc round tables***, ***fairs and events*** with students, ***field visits***, involvement in various ***ESC committees***… A more engaging collaboration by committing additional resources, including financial, and engagements, in Education, Research and Innovation is under development.



Figure 5: Industry experts in workshop, field visit and round table.

3.6 Governance

The ESC governance and its business model are strategic to implement these new practices with international partners and professional companies. From a steering committee, the PMU and the pillars (figure 1), the ESC governance shall transition to a proper ***board of directors***, with ideally 50% of external stakeholders, which will give direction and objectives to the ESC head office, under the recommendation of 3 advisory committees for studies, research and innovation, and industry. The business model will move from the AFD initial resources to a ***sustainable resource mobilization plan*** with new grants, fee paying programs, executive education, consulting, IP rights, company chairs or donations, investors, sponsors and donors, etc.

4 Communities of Excellence and next steps

The ESC pillars are temporary and shall transition in the next 2 years in "Communities of Excellence" (CoE). Six of the CoE will be topical around the six topics identified by UoN as strategic for Kenya: ***Agriculture & Food, Biotech & Chemistry, Manufacturing, Energy, Health and Cities***. Each of them shall develop new higher education programs, enhance research excellence and promote innovation culture with the objectives to generate impact and create jobs. They count internal stakeholders such as students, faculty members and staff, and external stakeholders such as companies, non-governmental and governmental organizations, agencies, community-based organizations and individuals from Society. New practices shall be ***multi-disciplinary, international and inclusive***. Two of the CoE will be transversal and service-oriented, with the ***ESC innovation ecosystem*** where trainings, supervision and exposure to market development will complement facilities, equipment and spaces, and the ***ESC Data and Artificial Intelligence platform*** where Findable, Accessible, Interoperable, and Reusable data and AI tools and software will be shared, and users from the diverse communities will be trained. Altogether, this is eight CoEs that will take place in the ESC, joining the FoST and FoE capacities with additional faculties such as Agriculture, Health, Built environment and Business. The CoEs will make use of national and international funding tools, such as the ones from the European commission under the Global Gateway, from France with its agencies and National Research Organizations (AFD and French CNRS in particular), and from other countries and their agencies (Germany, Finland, U.K., etc.)

5 Challenges and lessons learned

The academic community is a very independent, bottom-up and legitimacy-oriented community, that makes a transformational plan a huge challenge. The ESC tree organization is especially adapted to respond to this challenge, when professionally legitimated and recognized people are at the pillar heads. With agility, personal commitment and good leadership quality, they are then able to generate community engagement, especially from their peers and younger generation, and to make sense of the objectives of the project. They are also the ones who share and align the vision and can ensure the relevance of the actions, particularly by being the go-between the teams, the PMU and the steering committee.

Time frames must take place in a long term view and shall not be urged. Transformation can be seen as a danger and people need to feel secured and recognized in their participation. The role of the top management, the PMU and pillar heads is important to give the right space and timeline for new practice adoption, with no precipitation. Although, some "**quick wins**", such as (Kerubo et al., 2023) paper, EU proposal writings (successful or not), short programs development (attractive to good students), the company series (attractive to industry) etc., can fuel the team and generate adhesion to the project.

As projects of such ambition keep uncertainties, teams shall remain **agile and open to new opportunities and new stakeholders**. UoN has many strategical objectives, and a consolidating approach is needed to add synergy whenever possible. Communication and information shall then circulate and be shared in order that everyone can add value. In addition, a real **co-operation and peer-to-peer interaction** shall prevail with international partners in a **win-win spirit**, especially in Africa where South-North sensitivity is high.

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Experiences of the transition from a traditional to an integrative project-based curriculum

John Mitchell
UCL Centre for Engineering Education, UK, j.mitchell@ucl.ac.uk

Emanuela Tilley
UCL Centre for Engineering Education, UK, e.tilley@ucl.ac.uk

Abstract

In 2012, the UCL Faculty of Engineering Sciences made a major revision of its undergraduate curricula, through the implementation of the Integrated Engineering Programme (IEP). The academic year, 2023/2024, saw the IEP celebrate 10 years of new student intake into the reformed degree programmes which aimed to enhance the skills and societal awareness of graduates through a series of project-based learning experiences, integrated with a curriculum of instruction. Over these 10 years, it has evolved - through conscious action to improve but sometimes through unintended consequences of institutional initiatives or local developments. This paper documents the reflections of two leading members of the development team and shares experiences of implementing and maintaining a major curriculum reform focused on a student-centred, active and experiential approach to learning and teaching in a large, research-intensive university. It leverages a survey of alumni to highlight achievements, challenges and perceptions of this approach as seen by both staff and students. It considers the relationship between pedagogical ideologies and the practicalities of change within existing structures and the challenges of legacy within the institution. It aims to provide insight and support to those leading and managing programme-wide curriculum change.

Keywords: Curriculum Development, Staff Experience, Project-Based Learning.

1 Introduction

Over the last decade or two, new engineering education programmes have emerged, and many traditional programmes have looked to refine and revise their offerings to meet the changing needs of graduates, industry and programme accreditation standards (Goldberg and Somerville, 2014; Habbal et al., 2024). Different models have been adopted, depending on the context of programme and whether it is a new offering or the revision of an existing programme. There are, however, key features typically shared by these models. Most acknowledge that engineers will work beyond their traditional disciplinary silos and will need to be accomplished in working in interdisciplinary teams. They also bring a focus on authentic projects from early on in their programmes and support the development of professional skills and a perspective of the

engineer as a conscientious member of society who, as a designer and agent of change, will need to understand the responsibilities that they have to act ethically, sustainably and inclusively (Graham, 2018). Many examples of revisions follow established models such as CDIO (Crawley et al., 2014) which provide a framework for a curriculum that features many of these aspects.

In this paper, we offer a reflection on a major revision of existing undergraduate engineering curricula in a large, research-intensive, public university and in particular, consider what has been learned from the introduction of an integrated curriculum - one that looks to introduce the elements mentioned above, but also to ensure that they are connected and appropriately staged throughout the learning journey of the student. Although specific aspects of the change have been presented previously, (Roach et al. 2019, de Andrade et al. 2021, Hailes et al. 2021) this is the first reflective work which considers the education reform at a holistic level including feedback from graduates. We start by introducing the context of the revision and the positionality of the authors to set the background of the work. We then describe what we mean by an integrated curriculum, provide reflections drawn from the experience of the authors over the last ten years and present initial findings from an alumni survey.

1.1 Context of the change

University College London (UCL) is a large, multi-faculty and research-intensive institution comprising of 11 faculties, 76 Academic Departments, 50,000 Students and 16,000 Staff (~4500 Academic/Teaching Staff). It is currently the largest campus-based university in the UK. The UCL Faculty of Engineering Sciences is home to around 8,000 of these students and over 500 teaching staff. It has 10 departments, of which 7 offer undergraduate programmes in engineering or computer science with an intake from 2014 to 2023 of between 850 and 1050 students each year. The faculty enjoys one of the better gender balances in the sector at 37% with just over 70% of its undergraduate population being of international origin. The curriculum change process began in the 2011/12 academic session with the first cohort of students entering the revised programmes with inclusion of the IEP teaching framework in the 2014/15 session. At the time, a Royal Academy of Engineering report stressed that “change in undergraduate engineering education is urgently needed,” yet “transformation in the structure and delivery of undergraduate provision has yet to take place,” and a “pressing issue is not whether but how to change it” (Graham, 2012, p.2). The IEP and the radical revision of the existing degree programmes provides an example of the “how” for instantiating change. The IEP was enacted on existing programmes (with the exception of a new Biomedical Engineering programme) and followed existing university regulations. The roll-out started by implementing a completely new first year for all programmes in the 2014/15 session, while upper years followed the existing curriculum. The changes in the latter years then moved through the curriculum and followed the first inaugural cohort. The BEng/BSc programmes (three-year Bachelors undergraduate degree offering) saw their first graduates in 2017 while the first graduates of the MEng programmes (Integrated Masters – four-year) completed in 2018. To date approximate 8,000 students have graduated from programmes of the IEP. Further details of the IEP teaching framework can be found in Graham (2018) and Mitchell (2021). The authors are both engineering educators and educational researchers with leadership and Professorial positions in the UCL Faculty of Engineering Sciences, a research-intensive university in the UK. Mitchell is a white, western European, cisgender man with degrees in Electronic and Electrical Engineering and an MA in Teaching and Learning. Tilley is a white, first-generation Canadian cisgender female born of western European emigrated parents with undergraduate and post-graduate degrees in mechanical and civil engineering, respectively, who returned to academia after having worked for 8 years as a professional consulting engineer in the UK.

2 Implementing an integrated curriculum.

As identified above, many of the reformed programmes witnessed worldwide share the inclusion of similar themes: interdisciplinarity, active learning and/or project- or problem-based learning pedagogy, a re-centring of engineering within society, and an emphasis on skills and professional student development. However,

where they significantly differ is how they bring these elements together and how they ensure connectivity between these themes. This is the basis of the art and practice of curriculum development – the process of setting out the elements of the curriculum to ensure that they interrelate, support each other, whilst most importantly, for students, allows them to recognise an appropriate progression in terms of their depth and breadth of knowledge and skills as well as individual personal and professional development. When faced with the revision of an existing programme many competing factors, such as contextual and legacy administrative, educational, financial, and cultural structures, become critically important and can place significant constraints on how much disruption of the existing curriculum is possible and therefore how much integration can realistically be achieved. In revision programmes, curriculum designers have to be pragmatic on what aspects of learning (SLO, 2009; van den Akker et al., 2003) can be changed completely, what can be refreshed or revived, what will have to be minimally adopted, and what needs to be left untouched.

The concept of an integrated curriculum is not new and further details of our argument for its introduction can be found in Mitchell and Tilley (2024). When considering the key elements of a curriculum there are many options that could be integrated. Which become the primary focus, will depend on the nature and values/mission of the institution and the express aims of the programme, aligning with what is referred to as the *intended curriculum* (Goodlad, 1979). Within the IEP, we emphasised the integration of; the disciplines by creating multiple opportunities for students to work together, the development of the individual student both personal and professional in preparation for employment and making an impact beyond graduation, and the application of theory through engineering practice and skills-based learning, via a central spine of authentic projects (Roach et al. 2018, Mitchell 2021). Other reform programmes may choose different foci. For example, integration of workplace learning (Lindsay and Morgan, 2021) where experience in the workplace is integrated with university learning rather than more common models where university learning is somewhat segregated from industry experience.

3 Reflections on Change

This section provides some key reflections from the ten years that the revised programmes have been running from two engineering educators heavily involved in the progress, as leaders (i.e. Directors) in its development and implementation as well as its delivery and evolutionary phases. Although the process of implementing change is often the focus of popular discourse, the subsequent process of embedding and maintaining the change and ensuring it ‘sticks’ is just as important and just as difficult. It would be easy to assume that such a curriculum development simply involved a shift to a new model that would quickly become ‘business as usual’ and therefore be self-sustaining. However, our experience showed that integration needs to be continuously lead, nurtured, and maintained, with new governance structures required to ensure that once the fervour of the initial change project subsides there are processes in place that ensure continued collaboration and progression towards ultimately changing the culture of education within the institution/faculty/department(s) amongst staff and students. Over the course of 10 years, we have seen many of the original staff move to new roles and be replaced and therefore the establishment of faculty level committees with departmental educational leadership engagement that ensure collective memory and responsibility for the shared elements of the programmes have been vital.

As highlighted above, any revision to existing curricula is undertaken within the context of considerable legacy. The analogy of trying to ‘change a wheel while the car is still driving down the motorway’ is often used. This brings a sense of pragmatism that is not always necessary in the development of new programmes (at new institutions). It requires a clear vision to change what you can, revise what you must, and learn to live with what is beyond the reach of the project. One key success of the IEP framework was that it offers this level of flexibility. It embraces a variety of teaching methods and conceptions of what engineering is to allow departments to feel ownership of the curriculum while still achieving the core goals set out for the revamped degree programmes. While having some prescribed elements (predominantly those that were shared),

agreed with all departments, around them there was still significant space for departments to 'fill in the blanks' and to keep as much or as little of their existing curriculum as they needed. The newly hired central team of education-focused academic staff supported this transition, running workshops and creating cross-faculty communities of practice, to facilitate the construction of the discipline specific curriculum, which although still amounting to approximately 80% of the whole, was built around the core threads of projects, employability skills, applied mathematics and interdisciplinary minors. One key element of our learning in change management came from this process: while no change is ever wasted; small-scale change or isolated pockets of change can only go so far and may even serve to amplify the disconnect between active and passive elements of the curriculum. Our experience suggests that while change, by no means must be all-encompassing or total, it does need to be significant enough that it is felt - both by staff and students. Again, this speaks to the concepts unpinning integration and curriculum design. While it is likely (and arguably necessary), that much of the existing curriculum is reused or recycled post any revision, this must be by design. The danger of only addressing a small part of the total curriculum without any modification or reorganisation of the rest is that the result might form a bifurcated rather than an integrated offering.

The rearrangement of fundamental learning was necessary as the curricular concept implemented in many ways flipped the existing curriculum on its head in terms of its design. Typically, engineering programmes start by focusing heavily and giving all the time/space in the curriculum to teaching and assessing technical fundamentals with a high concentration of maths and science. Programme designs started at the discreet knowledge or element level, a single cog perhaps which constitutes a technical element of knowledge required for any one engineering degree like for example the topic of "thermodynamics", and then over the course of the programme developed, in stages to more complex designs - two connected cogs (i.e. thermodynamics I and thermodynamics II), and then a system of cogs (i.e. heat transfer or perhaps thermo-fluids), with more applications to actual engineering systems and their uses relevant to the discipline. The IEP reversed this. Students started with a holistic view of engineering projects – for example, they considered users in the first weeks of term and how engineering design innovations and systems might have a sustainable impact and how technology and people (and/or society) interact. Students are, of course, building technical knowledge in parallel, but this contextual shift provides a reframing of what engineering is and where its emphasis should be. Whether they work on scenarios related to biofuels, wearable technologies or the manufacturing of artisanal ice-cream and vaccines, student interviews show that working on sociotechnical projects during their degree contributed to a broader understanding of the nature of engineering practice, the potential long-term impact of engineering artefacts and their own professional identity as responsible engineers. When reorganising the curriculum, much of the skills content of latter years (originally introduced as it was necessary for accreditation), was brought earlier into the first year. This resulted in a first year with a balance between theory, skills, context, and application, all integrated and connected to provide mutual support for learning.

While interviews with first year students show an appreciation for this approach, the concept of starting with generalities and then progressively getting more discipline specific as the course progresses was not without controversy. The extant model positioning students as empty vessels, who must be filled with technical knowledge before they can engage in application was still pervasive. It is important to note that building the technical depth, rigour, and confidence within the students is still important. It is still a key KPI of most universities (including UCL) and staff, students, and employers still expect such technical depth. However, we argue, and our experience shows, that this reversal does not need to come at the expense of this depth but that by bringing authentic project opportunities and skills to the fore, students are much better placed to realise that these topics are important as they are more clearly signposted within the curriculum.

The resulting programme architecture provides a combination of foundational technical and employability skills, fundamental technical knowledge, combined with a progression of authentic projects undertaken in both interdisciplinary and disciplinary-based teams. The skills element of the IEP teaching framework was

originally based on a shared curriculum, partly taught by the faculty-based central team and partly taught by departmental academic staff. This has now evolved to departments taking full ownership of this thread of learning while still based on a common syllabus. The central team now works in partnership with departments to tailor and focus this thread to their specific needs. The nature of the faculty level team is vital. Sitting outside of a disciplinary department and serving students at scale, it allowed the formulation of a team with skills highly complementary to those usually found in departments – skills in supporting the teaching of teamwork and DEI, social concepts such as critical thinking, creative thinking and decision making, ethics, sustainability, entrepreneurship, and communications etc. which are not commonly the primary focus of the academic staff selection criteria used in research-based engineering departments. The team is now viewed as a 'go to' to support engineering departments in their support of student skills development. As the programmes have evolved, and as new demands have emerged from accreditation or through the rise of AI, DEI and sustainability, we have realised that the inherent architecture of the IEP teaching framework within the undergraduate degree programmes, with threads of projects, skills, applied mathematics and interdisciplinary learning, places us in an exceptionally advantageous position for integrating new topics as they become relevant. And because of the centrality of the faculty IEP team and cross-department nature of the delivery this can be done quickly and efficiently.

While there was an emphasis on the introduction of project-based learning, interdisciplinary learning, and enhancing the delivery of skills, attention was also paid to the mathematics curriculum. Engineering mathematics underpins a considerable part of any technical curriculum in engineering, but despite that, it is often taught by mathematics departments rather than being integrated within engineering. Our aim was to produce a highly applied curriculum that placed the teaching of mathematics firmly in the context of engineering and emphasised maths as a tool for modelling and analysis of engineering problems (de Andrade et al. 2022). It is fair to say that of all the revisions, this was perhaps the most debated across the faculty. Within departments, there were communities of academics who felt ownership of the mathematics curriculum, who had the strongest voices and opinions on how mathematics should be taught within their disciplines. While many were open to change and relished the opportunity to develop a progressive maths course, the necessary process of gaining agreement across multiple departments for the curriculum (and in particular, the order of the curriculum) and mode of delivery required considerable negotiation and compromise. The resulting model comprising a large lecture-based element to student cohorts of mixed disciplines which delivered the fundamental content followed by discipline specific workshops with a mixed portfolio of assessment (coursework, exam and mini-project) represented a considerable step forward. While COVID represented a significant challenge to the project-based learning thread of the integrated teaching framework, for the IEP integrated mathematical modelling and analysis modules, it represented an opportunity to take the next step towards a truly active learning approach and flipped all the lecture content online, whilst designing in a scenario-based approach to fundamental mathematical concepts. The result is an innovative curriculum and pedagogy that is structured around a series of week-long real-world challenges which provide the context for each technical mathematic topic within the syllabi. For example, students are introduced to climate change before exploring the differential equations that can be used to model it (Graham, 2021). These 'emergency' measures provided highly successful and have been adopted and expanded to become the core of the year 1 and year 2 mathematics courses.

An alumni survey is currently underway with graduates contacted via Linkedin – at the time of writing 110 responses have been received. It looks to collect reflections from graduates on key changes as a result of the IEP on the curricula. One of the most noticeable changes is the interdisciplinary nature of the IEP, and the connections encouraged between engineering disciplines. When questioned on the interdisciplinary nature of the programme, 70% responded positively with 51% saying that it may have or did indeed influence their career decisions and 87% highlighting that they often or regularly have to work with people outside their discipline in their current roles. This seems to validate its inclusion both in terms of the benefit to students but also due to its importance to the workplace. This is significant as creating (and maintaining) connections across departments is a major change management challenge. When asked, with free-text responses, what

their most memorable experience or activity with the degree programme was, 70% of those who responded identified a project-based activity. While, as expected project-based activities were seen as important to the development of employability skills, 55% of alumni respondents indicated that the IEP scenario weeks were seen as very or critically important for learning of technical knowledge while only 45% responded in the same way for lectures. This again validates our approach to creating space within the curriculum for an enhanced thread of project work.

4 Summary

Any level of curriculum reform is always a major undertaking. However, reform that crosses organisation boundaries within an institution adds additional complexity. By its very nature, an integrative programme must cross such boundaries and overcome the barriers that traditionally serve as boundary markers. We argue that while challenging, it is only with this type of integration within engineering education will we be able to create the types of graduates that are needed to meet the demands of humanity inhabiting an increasingly fragile planet in the latter half of the twenty-first century. This revision process targets both the curriculum and faculty development, as two major reviews of efforts to change engineering education (Seymour, 2001; Froyd et al., 2008) point to the importance of multifocal approaches.

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Towards Integrated Engineering Curricula: South African Case Studies in Context with UCL's IEP Approach

Lelanie Smith
University of Pretoria, South Africa, *Lelanie.Smith@up.ac.za*

Emanuela Tilley, John Mitchell
University College London, UK

Bronwyn Swartz
Cape Peninsula University of Technology, South Africa

Nicky Wolmarans
University of Cape Town, South Africa

Teresa Hattingh
University of Johannesburg, South Africa

Abstract

Engineering education in South Africa faces persistent challenges, including diverse student preparedness, limited resources, and high dropout rates. This paper presents a project that responds by supporting national curriculum transformation through integrated learning approaches that embed both technical and professional competencies. In collaboration with University College London (UCL) and 16 South African universities, the project explores how global models can inform local curriculum design without direct replication. This paper examines four institutional case studies using Harden's (2000) integration ladder and Fogarty's (1991) curriculum integration models to map intended and actual integration practices. The frameworks offered a structured tool for comparative reflection and opened up strategic conversations about future directions. However, several limitations were noted: the models do not fully accommodate the interdisciplinary nature of engineering, assume a linear progression not always observed in practice, and focus on individual teaching rather than program-level design. Despite these challenges, the mapping process helped leaders of the four case study institutions herein critically reflect on where they are, where they intend to go, and how integration frameworks could evolve to remain relevant in diverse and complex educational contexts.

Keywords: Curriculum Integration, Employability Skills, Problem-based Learning

1 Introduction

Engineering education worldwide faces increasing pressure to equip graduates with both technical expertise and broader professional competencies (Mitchell et al., 2021). The traditional model—where early years focus on disciplinary fundamentals and professional skills are addressed separately—has been criticized for failing to develop adaptable engineers who can navigate complex socio-technical challenges (McMasters, 2004; Spinks, Silburn, & Birchall, 2006; Rauhut, 2007). In response, universities are restructuring curricula to

integrate technical knowledge with interdisciplinary problem-solving, sustainability, and industry engagement (Mitchell et al., 2021; Hattingh & Inglis, 2024).

In South Africa, high dropout rates, varying student preparedness, and resource constraints pose additional challenges, requiring innovative curriculum strategies to support student success (Hattingh & Inglis, 2024). The *Transforming Systems through Partnerships - Innovative Engineering Curricula (TSP-IEC)* project, a national initiative involving 16 universities, aims to reimagine engineering curricula through integration, emphasizing sustainability and contextual problem-solving. This project aligns with international models such as UCL's Integrated Engineering Programme (IEP), which introduced a faculty-wide shift towards problem-based learning, employability skills, and interdisciplinary collaboration (Mitchell et al., 2021).

This study examines curriculum integration efforts at UCL and three South African universities—University of Pretoria (UP), University of Cape Town (UCT), and Cape Peninsula University of Technology (CPUT). Using Harden's (2000) integration ladder and Fogarty's (1991) curriculum integration models, as correlated by Husain et al. (2020), we explore how integration unfolds in diverse contexts, assessing intended designs versus current practices. The analysis also evaluates these models' applicability and limitations in capturing curriculum transformation complexities, contributing to the discourse on adapting integration frameworks for varied educational settings.

2 Literature

2.1 The Concept of an Integrated Curriculum

The need for curriculum integration has emerged in engineering education reform, with industry, professional bodies, and governments advocating for graduates who can bridge technical expertise and professional competencies (Mitchell et al., 2024; Spinks, et al., 2006; Rauhut, 2007). Traditionally, engineering curricula have been discipline-siloed, emphasizing mathematics and science fundamentals in early years and technical specialization later (Hattingh & Inglis, 2024). This fragmented approach has been criticized for failing to prepare engineering students for interdisciplinary, complex problem-solving (Graham, 2012).

Efforts to integrate curricula began in the 1990s, with research highlighting the need to embed communication, teamwork, creativity, and hands-on experience into engineering programmes (Shaeiwitz et al., 1994; Olds & Miller, 2004; Tryggvason et al., 2001). However, integration often remains limited to higher-year capstone projects, and is not embedded throughout the curriculum of an undergraduate degree program (Bailey and Aronson, 2005).

Institutions leading in curriculum integration include MIT's NEET program, which bridges theory and practice through interdisciplinary, project-based learning (Crawley, 2018); Tecnológico de Monterrey, where challenge-based learning fosters technical and professional skills for sustainability challenges (Caratozzolo & Membrillo-Hernández, 2021); and UCL's Integrated Engineering Programme (IEP), which embeds problem-solving, teamwork, and employability across eight departments, impacting nearly 10,000 students since its inaugural year in 2014 (Mitchell et al., 2021). These cases demonstrate that large-scale curriculum integration is achievable providing valuable insights for curriculum transformation in South Africa (Hattingh & Inglis, 2024).

2.2 Frameworks for Curriculum Integration

Harden's (2000) integration ladder and Fogarty's (1991) curriculum integration models are structured frameworks that define varying levels of integration. Husain et al. (2020) correlate these models to illustrate that curriculum integration is not binary, but rather a continuum, ranging from isolated disciplines to fully transdisciplinary learning experiences (Harden, 2000; Fogarty, 1991) as shown in Table 1:

Table 1: Models of integration (Husain, et al., 2020).

11 Steps of the integration model (Harden, 2000)	**Common Description**	**10 Ways to integrate curricula (Fogarty, 1991)**
Isolation	Various disciplines/departments organize their teaching without considering other departments or subjects	The fragmented model
Awareness	Teacher is made aware of what is covered in other subjects through appropriate documentation about aims and objectives of each course	
Harmonization	The disciplines remain separate but the teacher may make explicit connection within the subject areas to other subjects	The connected model
Nesting (Infusion)	The teacher targets within a subject based course, few objectives relating to the other subjects. Contents drawn from different subjects are used to enrich the teaching of a particular subjects	The nested model
Temporal coordination	Related topics within a subject are taught separately but are sequenced/arranged at the same time in consultation with other subjects.	The sequenced model
Sharing	Two disciplines may agree to plan and jointly implement a teaching program using overlapping concepts and ideas as organising elements	The shared model
Correlation	Within the subject based framework, integrated teaching sessions are introduced which bring together areas of common interest in each subject.	
Complementary programme	It has both subject based and integrated teaching. The basic difference with correlation in that the percentage of integrated sessions are increased.	Webbed
Multidisciplinary	The step brings together a number of subject areas in a single course with themes, problems or issues as the focus of teaching. The subject discipline still preserves their identity and demonstrates how they contribute to the understanding of the theme or problem.	
Interdisciplinary	The subject/discipline boundaries become blurred. There may be no reference to individual subjects or disciplines as they are not identified in the timetable. Interdisciplinary teaching implies a higher level of integration, with the content of all or most subjects combined into a new course with a new menu.	The integrated model
Transdisciplinary	There are no subjects or disciplines. There is only one subject for education, and that is Life in all its manifestation. The teacher provides the framework of learning opportunity and the integration takes place in the mind of the students based on situations of the real world.	Immersed

These models, as represented by Husain et al. (2020) and explored in this paper, provide a useful lens for evaluating curriculum integration efforts, guiding institutions in mapping progress and designing scalable curriculum changes.

3 Context and Purpose

The TSP-IEC project is a national, multi-institutional initiative in South Africa, that aims to transform engineering education by integrating technical skills with professional competencies through active learning approaches. The project team formally includes 12 South African universities and partners with UCL to leverage their experience in integrating curricula. In 2019, the project lead visited UCL to explore their Integrated Engineering Programme (IEP), and subsequent visits by the national TSP-IEC team occurred in 2023 and 2024, focusing on observing and adapting UCL's curriculum integration strategies to their local South African contexts.

4 Method

This qualitative multiple-case study explores curriculum integration across four engineering programs—UCL, UP, CPUT, and UCT—using Harden's (2000) and Fogarty's (1991) models. Curriculum leads rated their programs against integration levels in a shared excel spreadsheet, comparing intended design with current practice. Follow-up discussions helped identify gaps, patterns, and context-specific adaptations. Rather than assessing integration in isolation, the study maps how each institution navigates alignment between theory and implementation. It also reflects on the models' relevance, suggesting that adaptation is needed to suit the realities of engineering education across diverse institutional settings.

5 Case Studies

Implementing an integrated curriculum requires pedagogical innovation and institutional change. This section highlights how four institutions are combining technical content with professional competencies, interdisciplinary learning, and contextual problem-solving.

University College London (UCL)
UCL's IEP, launched in 2014, embeds project-based learning, applied mathematics, contextual and authentic learning, interdisciplinarity, teamwork, and employability skills across eight departments (Mitchell et al., 2021). UCL's experience shows that large-scale integration requires coordinated faculty engagement and a flexible model that aligns disciplinary depth with interdisciplinary learning. Key features include:

- Disciplinary and interdisciplinary design projects and scenario weeks that connect theory to real-world challenges
- Explicit and contextualised teaching of technical and transversal skills
- Active flipped scenario-based learning as a basis for the core applied mathematical curriculum
- Flexible delivery across departments
- Interdisciplinary Minors and a systems-thinking approach

University of Pretoria (UP)
UP's integrated first-year curriculum spans seven engineering departments, combining foundational modules—maths, science, engineering science, and professional orientation. UP's design integrates professional skill development alongside disciplinary learning, ensuring both technical and societal relevance. Key features include:

- Contextualized mathematics and coding
- Alignment of shared professional competency modules over six semesters
- Development of professional competencies through Engineers Without Borders (EWB) challenges and community engagement

Cape Peninsula University of Technology (CPUT)
CPUT's integration spans the first and final years. This two-stage integration links foundational learning with socially engaged engineering practice, ensuring students gain core competencies and engage with real-world challenges. Key features include:

- The First-Year Experience (FYE) integrates nine core modules with a focus on academic and professional competencies, including SDG themes across departments
- The Final-Year Integrated Learning Programme (launching in 2025) offers design challenges and entrepreneurship modules, simulating a pre-industry semester for students not in WIL

University of Cape Town (UCT)
UCT's Civil Engineering programme (2025) introduces project-based learning while reducing student overload. Key features include:

- An introductory semester project addressing local challenges such as informal settlements, integrating ethics, design, teamwork, and communication
- Twelve interdisciplinary projects connected to disciplinary courses
- Integration of programming, data science, and professional practice content
- Dedicated project weeks per semester for deep, uninterrupted engagement

These case studies show that integration takes diverse forms, but all institutions share a commitment to contextual relevance, professional competence, and alignment with industry needs.

6 Discussions

6.1 Practices and Language Across Integration Models

Both Harden's (2000) Integration Ladder and Fogarty's (1991) Ten Ways to Integrate Curriculum models present integration as a continuum, Fogarty's language draws from teaching practice and learner experience (e.g., "webbed," "threaded," "immersed"), whereas Harden's is more institutional and structural in tone (e.g., "correlation," "multidisciplinary," "transdisciplinary").

Across the four case studies, curriculum integration efforts span multiple points on both models, often simultaneously. UCL's IEP reflects elements of *harmonization*, *complementary programmes*, and *interdisciplinary* integration, mapping closely to Fogarty's *shared* and *integrated* models. Similarly, UP's common first-year structure aligns with *temporal coordination* and *nesting*, while its professional stream design matches Fogarty's *webbed* model. CPUT and UCT, at earlier stages of implementation, show practices consistent with *awareness*, *harmonization*, and emerging *multidisciplinary* approaches.

This comparison surfaced shared practices across all four cases:

- A strong emphasis on first-year structural integration (UP, CPUT, UCL)
- Project-based and socially contextual learning (UCT, CPUT)
- Integrated professional competencies (all cases, particularly GA6–11 in South Africa)
- Use of coding and data science to modernize the disciplinary core (UP, UCT)

Despite these overlaps, institutional language diverges. Some institutions foreground graduate attributes (UP, CPUT), while others lean on pedagogical terms like "scenario weeks" (UCL) or "interdisciplinary projects" (UCT). This variety highlights how different languages of integration reflect institutional culture and constraints.

7 Conclusion

Mapping the programs using Harden and Fogarty's frameworks offered a valuable lens for shared reflection and comparative analysis. It helped each institution position its integration efforts along a common continuum, prompting strategic conversations about future directions. However, the exercise revealed some limitations.

The frameworks are largely discipline-blind and do not account for how knowledge behaves across fields. In engineering—a multidisciplinary domain—transdisciplinary integration (e.g., Step 11) is less common and often less desirable than in more unified disciplines like medicine. Institutions noted that moving "up the ladder" may not always be appropriate, and that depth must be balanced with breadth depending on program goals. Many programs also resist linear categorisation. Characteristics from multiple levels often co-exist, suggesting that integration is better viewed as a spectrum than a strict progression. Additionally, while the frameworks focus on individual teaching practices, participants found more value in using them to reflect at the program level. Overall, the frameworks served as a useful conversation starter—enabling institutions to reflect on where they are, what's possible next, and how their integration efforts align with broader curriculum change.

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Collaborative Opportunity: Growing a Community around Integrated Engineering

Rebecca Bates
Minnesota State University, Mankato, USA, bates@mnsu.edu

Emanuela Tilley
University College London, UK, e.tilley@ucl.ac.uk

Jenna Carpenter
Campbell University, USA, carpenter@campbell.edu

Susan Lord
University of San Diego, USA, slord@sandiego.edu

Abstract

Integrated Engineering is emerging across the world. One commonality among programs is a desire to innovate in ways not seen as possible within traditional engineering disciplines. The inclusive pedagogical approaches seen in integrated engineering programs offer promise for truly transforming engineering education. These student-centered approaches align with caring pedagogies and provide sustainable infrastructure for supporting diverse student experiences. Innovation in engineering education can be challenging to implement and can be challenging to sustain. Community support can make a positive difference. Building on a series of community conversations at multiple international conferences as well as an international symposium in London during the summer of 2024, this paper will be used to spark a conversation about innovations related to integrated engineering. The goal is to include new voices to extend the existing community, build a stronger network, and provide an opportunity to reflect and plan implementation steps for enacting holistic approaches to engineering education.

Keywords: Integrated engineering, holistic pedagogies, community engagement

1 Context & Purpose

Integrated Engineering is emerging across the world (Graham, 2018). One commonality among programs is a desire to innovate in ways not seen as possible within traditional engineering disciplines. The variation in implementations is a strength in contrast to the homogeneity of traditional engineering disciplines. The inclusive pedagogical approaches seen in integrated engineering programs, including project-based, enquiry-based, skill-based, and work-based experiences, offer promise for truly transforming engineering education. These student-centered approaches align with caring pedagogies and provide sustainable infrastructure for supporting diverse student experiences. Any conversation about integrated engineering thus addresses three of the core themes of the conference: Caring Pedagogies and Sustainable Education, Community Engagement, and Creative Futures.

Innovation in engineering education can be challenging to implement and can be challenging to sustain. Community support can make a positive difference, especially for isolated innovators. Building on a series of community conversations at European Society for Engineering Education (SEFI), Frontiers in Education (FIE), and the American Society for Engineering Education (ASEE) conferences (Bates et al, 2022) as well as an international symposium in London during summer of 2024 (Tilley, 2024), the goal of this work is to present information about past interactions and spark ongoing conversation with new participants. In particular, the conversation can examine ways that current and planned innovations relate to integrated engineering, which can functionally be defined as integrating into engineering education a broad range of concepts, skills, motivations, and learning processes. The focus is on including new voices in the conversation to extend the existing community of people and institutions leading the way for a modernised approach to engineering education worldwide, building a stronger network, and providing an opportunity to reflect and plan implementation steps for enacting holistic approaches to engineering education with a supportive community.

2 Approach

The 2024 Symposium resulted in robust descriptions of experiences and aspirations from 30 programs across 13 countries. Analysis and clustering of these is in progress; however, the initial results indicate key questions for next steps (Tilley, 2025). In parallel, work in the United States to address ways to bring about a more

inclusive mindset within engineering education culminated in a report calling institutions and educators to action (Bertoline, 2024). The six recommendations from the ASEE Inclusive Engineering Mindset report include:

1. Create flexible program structures to remove barriers
2. Use evidence-based pedagogy: Creating a student-centered engineering education
3. Create an accessible and diverse engineering education learning environment
4. Prepare campuses for a student-centered engineering education
5. Leverage strategic partnerships
6. Engineer a new mindset for engineering education

While the context of the Inclusive Mindset report is within the USA, the basic recommendations are broadly applicable for innovations. Our call for integrating concepts, skills, motivations, and learning processes aligns with these recommendations and points to some of the challenges people have with actually implementing innovations that are contextually important.

The ten questions identified by Symposium participants for next steps correlate strongly with the six recommendations from the Inclusive Mindset report, while focusing on how to keep moving towards better experiences for students and faculty alike. The idea of an inclusive, accessible, and diverse learning environment is foundational for all integrated engineering programs (*Mindset 3*).

1. How do we shift from isolated initiatives to systemic transformation? *Mindset 4, 5, 6*
    - Change often starts with individuals or experimental programmes—but how do institutions scale and sustain integration across entire faculties or universities?
2. What narratives do we use to inspire and sustain change? *Mindset 6*
    - Storytelling about real student and community impact is essential for gaining support, shifting mindsets, and bridging silos.
3. How do we balance the need for speed with the necessity of trust-building? *Mindset 4, 6*
    - Institutions face pressure to act quickly, but integration requires slowing down to engage, listen, and co-create with diverse stakeholders.
4. What support structures are needed to legitimise pedagogical experimentation? *Mindset 1, 2, 4*
    - Educators need time, protection, and recognition to innovate—especially when working against traditional norms of teaching and research excellence.
5. How do we reframe resistance as a productive force in change? *Mindset 4, 5*
    - Tensions and discomfort should not be avoided but embraced as part of a deeper learning and institutional growth process.
6. How do we build distributed and shared leadership? *Mindset 4, 5*
    - Avoiding heroic narratives, change must be collective, networked, and sustained through communities of practice rather than top-down mandates.
7. What does a truly inclusive and context-aware change process look like? *Mindset 6*
    - Leadership must honour the diversity of institutional cultures, faculty identities, and local communities, recognising there is no one-size-fits-all path.
8. How can we redefine excellence and realign reward structures? *Mindset 4*
    - Promotion and evaluation systems need to value interdisciplinary, community-engaged, and integrative teaching and research.
9. How do we cultivate and support staff capacity for integration? *Mindset 1, 4*
    - Faculty and professional staff need ongoing development, peer support, and access to collaborative spaces that foster integrative pedagogy.
10. Are we preparing for the next generation, not just the next academic year? *Mindset 1, 2, 3, 4, 5, 6*
    - Change must be intergenerational, patient, and purpose-driven—focused on shaping future-ready institutions and graduates.

These findings are presented as foundational context for a longer conversation about potential next steps that can be taken to further explore holistic approaches inspired by the outcomes. It is hoped that conversations will allow participants to 1) consider the ideas presented (as well as inspirational ideas from the rest of the conference), 2) connect these ideas to their local context, 3) brainstorm ways to implement components that resonate with them, and 4) build connections to and within a larger network of support.

Examples of "integrated engineering" that facilitate a broad range of positive experiences from students can be seen from the integration experiences of the authors (Bates, Pluskwik and Ulseth, 2020; Bates, et al., 2024; Bertoline, 2024; Bertoline, 2025; Carpenter and Rynearson, 2017; Gelles and Lord, 2021; Lord, Przestrzelski and Reddy 2019; Mitchell, Nyamapfene, Roach, and Tilley, 2021 and 2019; Spence et al., 2022) and others who participated in the Symposium (e.g., Smith et al., 2024; Magnell, Geschwind, and Kolmos, 2016; Ford and Riley, 2003; Langie and Craps, 2020; National Academies of Sciences, Engineering, and Medicine, 2018). These include curricula that provide a variety of options, multidisciplinary experiences driven by student interests, project-based experiences at multiple education levels, connecting a sense of vocation and purpose to engineering learning, connections to industry experiences, and strong respect for students, their goals, and their interests.

3 Anticipated Outcomes

The ideas and concepts that will be used as the starting point for conversation include information about aspirations and challenges for education innovation. Participants in the 2024 Symposium included programs that have been running for over a decade as well as programs that are in initial stages of transformation. Some of the US participants worked with a larger team to create a blueprint for action that provides further examples of change processes for innovation in engineering education (Bertoline, 2025). These points, both constructive and cautionary, gathered from many nations, can be used as guideposts, inspiration, and a shared sense of experiences for participants, whether they are experienced innovators or new to the challenge of change in engineering education.

We plan to participate in conversations about ways to support not just change in individual teaching practice but program-level transformation that provides infrastructure for sustained changes in individual teaching and learning experiences. In the context of the IRSPBL Anchoring Conversations conference, this paper provides supportive content for reflection and planning, which can increase the impact of experience. We welcome a wide range of voices in this conversation and hope to include people who can share their stories of innovation as well as people who are just getting started. These stories can be captured and shared at the new Integrated Engineering website (integratedengineering.org).

4 Summary

Because of open-ended conversations related to this material, we hope participants and readers will have at least one concrete action planned as well as new connections to others who are implementing change. These connections should strengthen and expand an existing network of engineering educators working to create sustainable educational experiences that focus on students, that include faculty holistically, and that will be of support as they return to their home institution.

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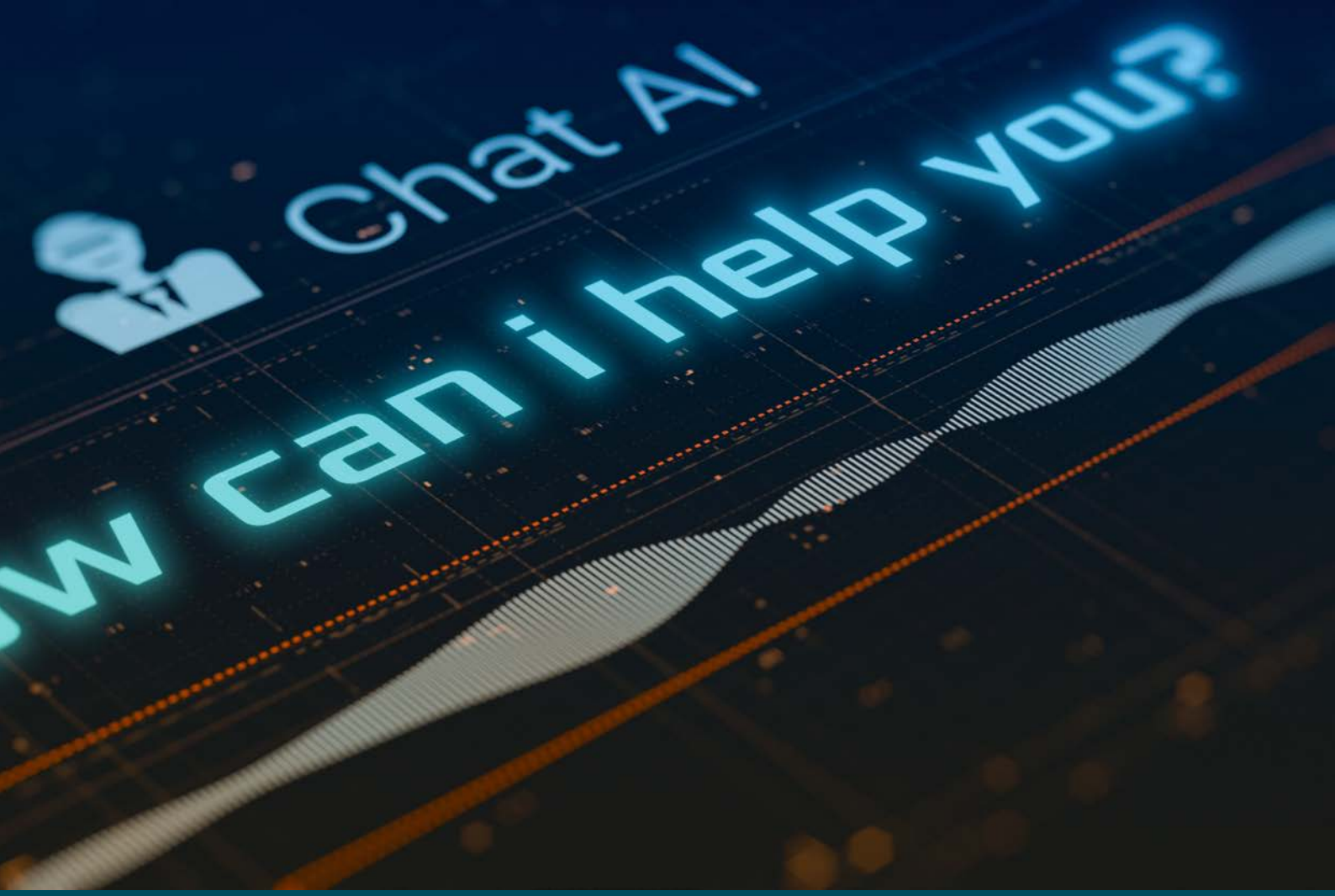

Technology, AI, and Digital Learning in STEM Education

Scalable VR Solutions for Engineering Education: A Continuous Improvement Framework

Clint Alex Steed
Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa, steed@sun.ac.za

Mia Mangaroo-Pillay
Department of Industrial Engineering, Stellenbosch University, South Africa, miamangaroopillay@sun.ac.za

Karin Wolff
Dean division, Faculty of Engineering, Stellenbosch University, South Africa, wolffk@sun.ac.za

Abstract
The increasing use of technology in higher education, especially in resource-constrained environments, is reshaping how students engage with industrial experiences. Virtual Reality (VR) offers a solution to the challenges posed by growing class sizes and limited real-world access, supporting holistic Graduate Attribute Development and addressing global SDG challenges in engineering education.

This paper explores how VR can enhance student engagement with complex technological topics like Industry 4.0. It examines the effectiveness of a VR-based framework for improving student emotional responses and interest in technology, while assessing the scalability of such approaches for larger classes.

A pilot study was conducted with third- and fourth-year students participating in a voluntary virtual facility layout activity. Emotional response surveys showed that fourth-year students were more comfortable with the technology, as expected, but both groups reported increased interest in technological topics. The study uses a dynamic response evaluation model informed by these surveys, and the organizational distinction between development teams and lecturing staff enables the framework to scale effectively.

The findings demonstrate that VR can improve student engagement and comfort with emerging technologies, making it an important tool for resource-constrained environments. This framework provides a method for continuous improvement, quantifying the long-term impact of VR on engineering education curricula. By enabling adaptable, scalable learning experiences, it helps prepare students for complex engineering challenges and future technological changes, offering a valuable contribution to the ongoing evolution of engineering education.

Keywords: Virtual Reality (VR), Engineering Education, Industry 4.0, Emotional Response, Virtual Learning Environments, Continuous Improvement, Curriculum Development

1 Introduction

Engineering graduates are required to integrate Sustainable Development Goals (SDGs) and Industry 4.0 concepts into their skillsets. Additionally, the revised International Engineering Alliance (IEA, 2021) competency framework emphasizes holistic skills, including psychosocial and sociocultural awareness, with significant implications for undergraduate engineering education. A critical challenge for educators in supporting students cognitively, affectively and systemically (Tait, 2000) is bridging theory and practice, particularly as growing class sizes make traditional industrial site visits less feasible due to logistical and safety constraints (Dorfling et.al,2019). Large groups also limit meaningful student engagement, reducing the effectiveness of such visits.

Virtual reality (VR) offers a potential solution, aligning with the National Academy of Engineering's Grand Challenges for advancing personalized learning (NAE, 2024). The declining cost and increased accessibility of stand-alone VR headsets, remote management tools, and free development platforms make large-scale VR labs

viable for engineering education. Thoughtful integration of technology can enhance learning, particularly for underrepresented groups, by providing equitable exposure to emerging tools.

However, educators must implement technology strategically to avoid diminishing learning outcomes. Engineering education extends beyond technical tools to complex problem-solving, and poorly integrated technology may hinder progress. In diverse contexts like South Africa, where students have varying levels of technical exposure, careful adoption is crucial. While technology will inevitably reshape engineering education, its success depends on educators' ability to integrate it effectively.

2 Background (Lit Review)

The SDGs (United Nations, 2025) are playing a crucial role in shaping a more holistic approach to graduate development, particularly in the Global South. As industries and economies strive to meet sustainability targets, universities are recognizing the need to equip graduates with the skills to address complex, interconnected challenges. This shift emphasizes not only technical competencies but also broader considerations such as environmental responsibility, social equity, and ethical leadership. The need for graduates to think systemically and innovatively is particularly pressing in regions where socio-economic disparities persist, requiring education systems to integrate sustainable and inclusive development into their curricula.

At the same time, rapid technological advancements are reshaping industries at an exponential pace, placing immense pressure on educators to prepare graduates for an evolving workforce (Kruger et.al., 2022). Emerging technologies such as artificial intelligence, automation, and smart manufacturing demand new skill sets, necessitating continuous curriculum adaptation. However, in the Global South, this challenge is compounded by resource limitations, massification of education, and barriers to access. The high cost of advanced equipment and restricted opportunities for industrial site exposure make it difficult for institutions to provide students with the hands-on experience needed to bridge the gap between theory and practice. These constraints create disparities in the ability of graduates to compete in global job markets, despite their academic potential.

Amid these challenges, the principles of Industry 5.0 are gaining traction, blending Industry 4.0 technologies with human-centric considerations (Leng et al., 2022). This paradigm shift is evident in the latest competency frameworks from the International Engineering Alliance (IEA), which highlight the importance of inclusivity and sustainability in engineering education. By recognizing the significance of human factors alongside technological advancements, these frameworks reinforce the need for a more balanced and ethical approach to innovation. As educational institutions adapt to these evolving expectations, they must find ways to integrate sustainability, technological literacy, and socio-economic awareness into their teaching strategies, ensuring that graduates are equipped to drive meaningful progress in their respective fields.

Against this background, the broader objective of this research study is how to enable equitable access (for diverse cohorts) to industrial experiential learning opportunities (Kolb, 1984) through cost-effective, contextually-responsive, technology-supported strategies?

The growing student population in South African classrooms, coupled with logistical challenges, has made traditional site visits increasingly difficult to implement. Engineering and technical education, which rely heavily on hands-on learning and real-world exposure, are particularly affected by these constraints. Industrial site visits are essential for bridging the gap between theoretical knowledge and practical application, but factors such as cost, safety concerns, and limited industry access make them less feasible. As a result, educators are exploring alternative methods to ensure students still gain valuable industry insights, with virtual reality (VR) emerging as a promising solution to address these challenges (Steed et al, 2025).

VR technology offers an innovative way to create immersive, interactive learning experiences that allow students to explore industrial environments without physically being present. This approach not only overcomes logistical barriers but also promotes inclusivity by ensuring that all students, regardless of location or mobility constraints, have access to experiential learning. By simulating real-world scenarios, VR enables students to engage with

complex systems, practice problem-solving skills, and develop industry-relevant competencies in a controlled, repeatable environment. As South African universities and technical institutions strive to provide quality education amidst growing class sizes and resource limitations, VR presents an opportunity to democratize access to experiential learning.

le many of the earlier challenges associated with the cost and technological limitations of VR in education are increasingly being addressed (Ardiny & Khanmirza, 2018), new opportunities now emerge around understanding the pedagogical and dyadic potential of VR (Graeske & Sjöberg, 2021). A major enabler of this educationally responsive shift is the significant reduction in the cost of VR hardware. Once prohibitively expensive, headsets and supporting systems have become more affordable as a result of rapid advancements in manufacturing and growing market competition. This trend has made it feasible for institutions, including those in resource-constrained environments, to adopt VR-based learning. At the same time, issues such as low simulation realism, physical discomfort, and hardware limitations are being actively resolved. Improvements in graphics, ergonomic design, and sensor fidelity have enhanced immersion while reducing simulator sickness and user frustration. As these technical barriers diminish, attention turns toward VR's potential to enhance student engagement and better prepare learners for digitally transformed industries.

Importantly, this evolution underscores the role of affective learning in VR-based education and how immersive experiences can actively enhance student mood, creating emotionally supportive environments optimal for learning. Instruments like the Positive and Negative Affect Schedule (PANAS) offer a structured means to assess this dimension (Crawford & Henry, 2004). Studies have shown that VR environments—particularly those designed to induce calm or simulate nature—can significantly boost positive affect (Pallavicini et al., 2020). These findings suggest that beyond increasing engagement, VR can be used intentionally to create affective conditions conducive to learning, helping students feel more relaxed, focused, and emotionally prepared for challenging educational tasks. This paper focuses on the affective dimension of student support in two different cohort contexts (3rd and 4th years). The question is: ***What is the emotional impact (affective) of a virtual industrial experience designed to enhance student engagement (affective) and interest in Industry 4.0 concepts (cognitive)***?

The integration of virtual reality (VR) in education is not a new concept, with numerous studies exploring its potential applications. Tootell et al. (2024) advocate for the use of VR training as a valuable tool for Continuous Professional Development among medical practitioners, highlighting its ability to enhance skill acquisition and retention. Similarly, the EVRIM framework emphasizes the ethical employment of VR in education (Geriş, 2024). This framework consists of five stages: Discovery, Design, Development, Deployment, and Impact. The Impact stage evaluates critical aspects such as Educational Assessment, focusing on transparency, fairness, and privacy (Cao, 2023; Yu & Xu, 2022). Additionally, User Satisfaction is assessed in terms of objectivity and privacy (Alizadeh & Cowie, 2022; Sadek et al., 2023), while Continuous Improvement considers transparency and a user-centered approach (Chen, Fu, Liu, & Wang, 2024; Walker, 2022). In the field of engineering education, Chandramouli and Williams (2024) propose VR as a cost-effective solution for providing students with exposure to smart factory equipment and environments. While their study effectively demonstrates VR-based experiences, it does not assess their impact on learning outcomes. Collectively, these studies reinforce the potential of VR in education, spanning from professional training to ethical and practical considerations in its implementation.

3 Theoretical framing in context

Given the focus on holistic engineering student development, the research site for this paper is a research-intensive university in South Africa, in which the engineering faculty has adopted a formal ‘head-heart-hand' development approach to engineering education. This approach combines the theories of learning objectives (Bloom, 1956), curriculum framing (Barnett, 2000), and student support (Tait, 2000) into an overarching Cognitive-Affective-Systemic (CAS) model. The CAS model enables educators to unpack and analyse the different educational dimensions of student learning. (Gilmore et al., 2016; Kruger, 2021; Lewis et al., 2025)

This study was conducted within the industrial engineering department of a research-intensive university, which has a substantial student body of approximately 500 enrolled in the degree program across various academic years. Focusing specifically on the third and fourth-year cohorts, which each comprise around 150 students, the large class sizes present a significant challenge, particularly in facilitating industry visits that are crucial for practical learning in the field. Furthermore, student engagement has been notably low and has resulted in decreased class attendance, impacting the overall learning environment and necessitating innovative approaches to re-engage students and enhance their educational experience. The study forms part of an ongoing, faculty-wide, developmental programme renewal process with a continuous improvement ethic.

Production Management & Ergonomics modules cover key concepts like facility layouts and the effective placement of equipment for manual assemblies in factories – Initial observations revealed that lack of exposure to real-world environments influences student grasp (cognitive) and application of these key concepts. The focus on calculating inventory, production line capacity and material resource planning (MRP), for example, can be richly enhanced if the student actually sees and even physically engages with artefacts in a real-world environment. Ideally, the experiential learning cycle entails concrete experience, reflective observation, abstract conceptualisation and active experimentation. This kind of experiential learning (Kolb, 1984) reinforces psychomotor skill development within the context of a larger system. These are aspects entailed in the Systemic domain of the CAS model.

As a result of resource constraints, large class sizes and low student engagement, the students in these modules were effectively speaking only working at the abstract conceptual level when trying to implement (calculate and decide) their understanding in a system. The collaborating researchers decided to develop a VR experience in order to address the challenge by allowing students to experience the real-world/ factory environments in class. Figure 1 showcases the VR experience that build to model the physical learning factory at the university.

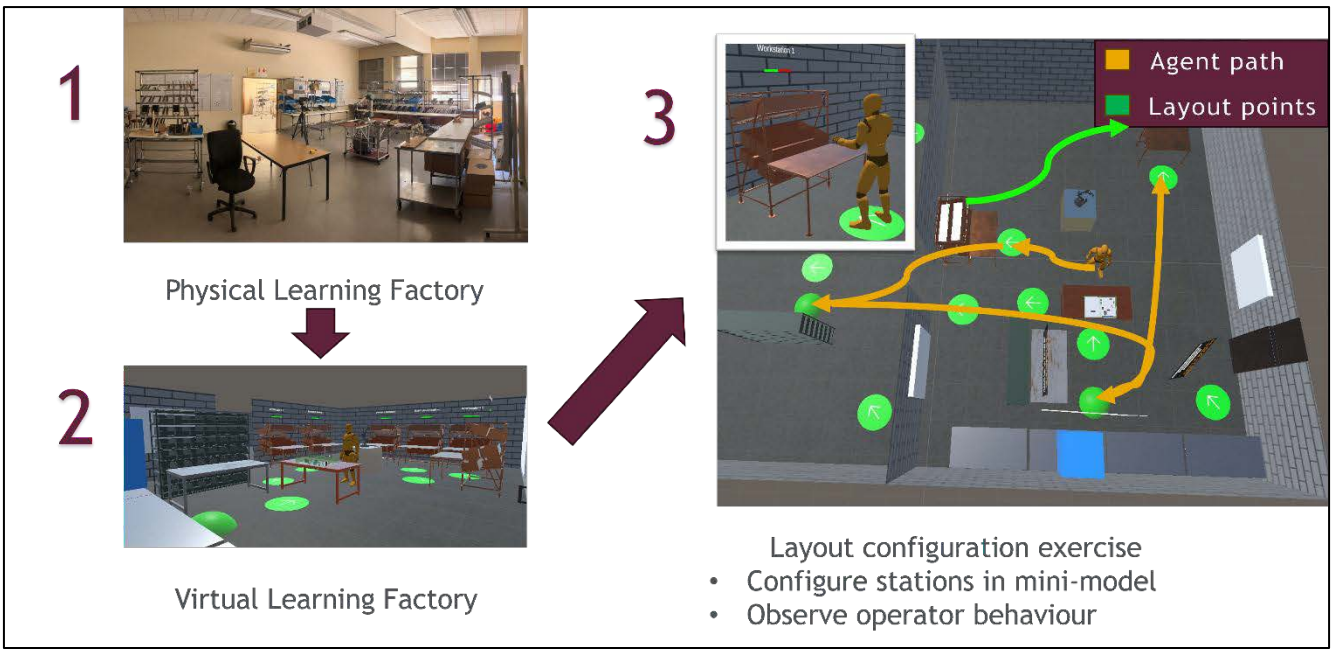

Figure 1: Progression from a physical learning factory (1) to a virtual representation (2), enabling a layout configuration exercise (3) in which users arrange stations and observe simulated operator behaviour along agent paths.

4 Research methodology and intervention design

To enhance experiential learning in a resource-constrained, large-class environment, this study implemented a Virtual Reality (VR) upgrade to a previously manual assembly exercise traditionally used in the classroom (figure 1). The original practical involved observing a single group assemble a skateboard in an unoptimized layout, followed by a demonstration of the improved layout's reduced lead time. This format limited student interaction and engagement. In contrast, the redesigned VR activity allowed students to actively reconfigure assembly station layouts within a virtual factory environment. They could manipulate workstation positions, observe simulated operator paths, and accelerate time to visualize the effects of their layout decisions more rapidly. This interactive and immersive approach aligned closely with Kolb's experiential learning cycle by enabling concrete experience, active experimentation, and reflective observation within the classroom setting.

The VR activity was made available voluntarily during class time. Students could choose between experiencing the VR scenario privately or projecting their interaction onto a shared screen for peer observation, allowing for varied engagement levels suited to different comfort zones. Following the activity, students completed an online feedback survey that included the Positive and Negative Affect Schedule (PANAS) and additional questions focused on their interest in digital technologies and manufacturing. This self-reporting data provided insight into students' emotional responses and interest levels. Data collection and interpretation were framed within the CAS model to account for the emotional (affective), reflective (cognitive), and practical (systemic) dimensions of learning. Comparative analysis between third- and fourth-year student responses indicated that senior students reported higher positive affect and lower negative affect, consistent with expectations of increased academic maturity and technological familiarity. Moreover, interest-related items showed that the activity contributed to greater curiosity about digital manufacturing technologies, even though enthusiasm for the manufacturing domain itself remained unchanged. These findings informed a continuous improvement cycle for refining VR content and instructional design.

5 Findings

A voluntary VR learning activity engaged 15 third-year (Group A) and 25 fourth-year students (Group B) from a cohort of over 100, with noticeably higher participation among the fourth-year group. This difference may be attributed to factors such as greater academic maturity and/or increased technological familiarity. These results suggest that senior students are more receptive to integrating emerging technologies into their learning processes.

Emotional responses, assessed using the PANAS survey (figure 2), revealed a generally positive experience across both groups, with positive affect (PA) scores averaging above 3.5 and negative affect (NA) scores below 2. While some discomfort persisted, particularly among third-year students, fourth-year participants reported greater emotional ease—indicating that repeated exposure to VR may enhance comfort and engagement. The most positively rated emotions were "enthusiastic," "proud," and "inspired," all of which align with Bandura's (1977) framework of self-efficacy development.

From a systemic and psychomotor perspective, both groups demonstrated strong interest in Industry 4.0 technologies, though fourth-year students reported higher levels of technological adaptability and comfort. While interest in digital technologies and active engagement were generally high for both cohorts, enthusiasm for manufacturing itself remained relatively static. This suggests that although VR boosts engagement with advanced technologies, additional refinement may be needed to increase interest in specific domains such as manufacturing.

The data also revealed a polarization in responses: some students embraced the VR experience enthusiastically, while others experienced discomfort or disengagement. This highlights the importance of a nuanced and student-centred approach to VR content design. Overall, the findings affirm the potential of VR to enhance

engagement in engineering education—especially among senior students—while emphasizing the need for ongoing content refinement. A continuous improvement framework will be essential to ensure that VR remains both effective and scalable in future iterations of the curriculum.

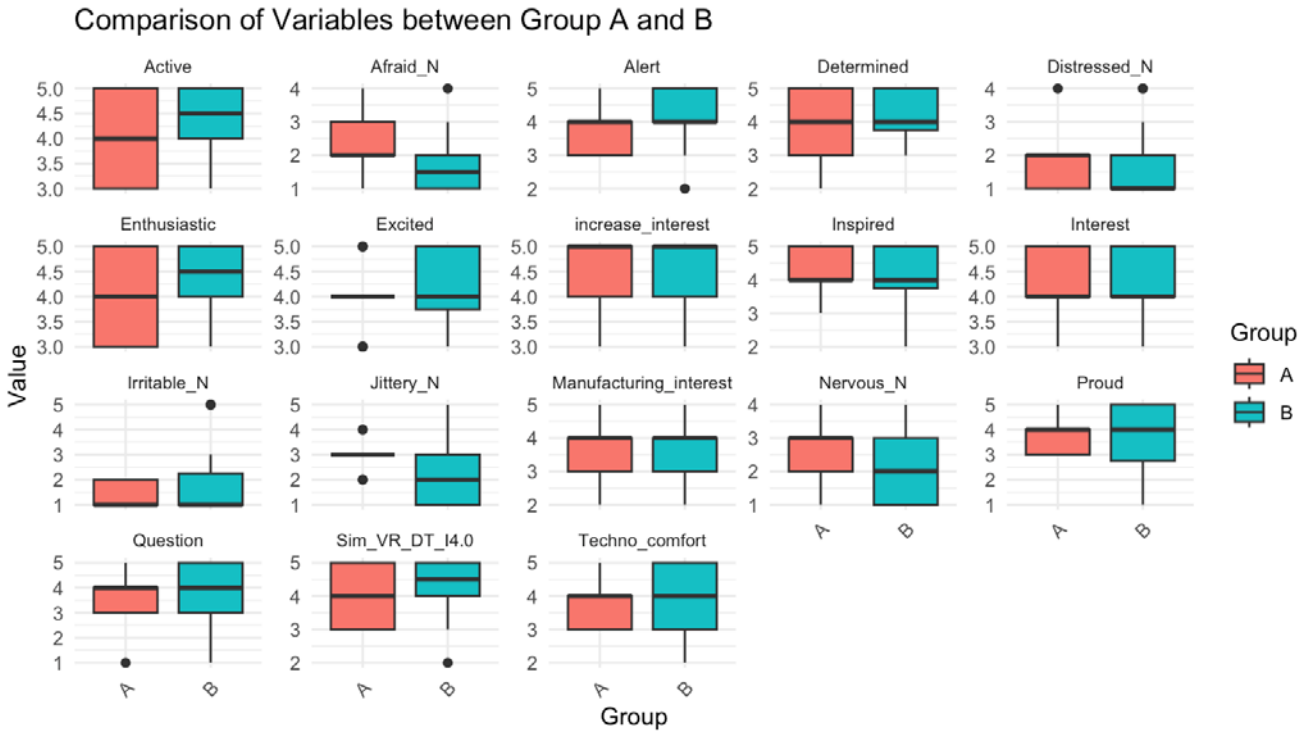

Figure 2: Boxplot comparison between group A (3rd years) and group B (4th years)

The boxplot comparison between Group A and Group B (figure 2) reveals notable differences in engagement, emotional responses, and interest in technology. Group B generally shows higher enthusiasm, excitement, and a greater sense of pride, suggesting a more positive emotional experience. They also demonstrate a slightly stronger interest in emerging technologies such as Simulation, VR, Digital Twins, and Industry 4.0, along with higher techno-comfort levels. Additionally, Group B appears more engaged, with higher median values for increased interest and questioning behaviour. In contrast, Group A exhibits slightly more variation in negative emotional responses, such as fear and distress. However, both groups share similar distributions in determination, inspiration, and comfort with technology. Overall, the results indicate that Group B may have found the experience more engaging and stimulating, while Group A displayed more variation in emotional responses.

Viewing comfort with the technology as a positive PANAS result, we see—as expected—that the fourth-year class is more comfortable with technology. This suggests that the technology may be more appropriate for that cohort and stands a higher chance of engaging students. For example, Group B self-reported significantly higher positive emotions such as techno-comfort, pride, and enthusiasm compared to Group A. Group B also reported lower levels of negative emotions (jitteriness, nervousness, distress, and fear) than Group A. Interestingly, both groups reported a significant increase in general interest, which was notably higher than the limited increase observed in interest in manufacturing. This suggests that while the technology itself may be engaging, it did not necessarily increase domain-specific interest and should therefore be examined more closely.

6 Conclusion and recommendations

6.1 Summary

This study demonstrates the potential of Virtual Reality (VR) to enhance engagement, emotional response, and interest in Industry 4.0 technologies within large-class engineering education. By integrating experiential learning principles and evaluating emotional feedback through the Cognitive-Affective-Systemic framework, the VR-based activity provided students with a more interactive and scalable alternative to traditional industrial exposure. Findings indicate that senior students show greater receptiveness and emotional ease, suggesting maturity and familiarity play key roles in technology adoption. Moving forward, the continuous improvement model and ecosystem-based development framework offer a sustainable path for refining and expanding VR integration in engineering curricula.

6.2 Future Work: Expanding the Ecosystem Design-Based Research Framework

A key avenue for future work involves further developing the collaborative framework underpinning this study through an Ecosystem Design-Based Research (DBR) (figure 3) strategy focused on continuous improvement. This approach is visualized as a layered ecosystem—akin to a pyramid—where each academic level contributes uniquely to the iterative development of VR-enhanced learning experiences.

At the strategic apex of the pyramid, academic staff act as principal investigators, introducing key learning objectives and theoretical foundations that guide the overall educational vision. At the tactical level, master's students take on the role of VR system developers, building and iterating on the technical infrastructure in alignment with these objectives. Honours students operate at the operational level, designing and customizing specific VR learning activities within the established system, supported by both lecturers and master's students.

At the base of the pyramid, third- and fourth-year undergraduate students engage directly with the VR content, serving as active participants and feedback providers. Their user experience data—emotional, cognitive, and systemic—is used to inform ongoing improvements in both content and pedagogy. This ecosystem structure promotes vertical integration of skills and knowledge across academic levels, enabling a sustainable model for continuous improvement and innovation in engineering education.

By structuring development and evaluation responsibilities across academic tiers, this framework not only offers the possibility of scalability and relevance, but may also create meaningful opportunities for mentorship, collaboration, and iterative refinement of both technology and teaching practice.

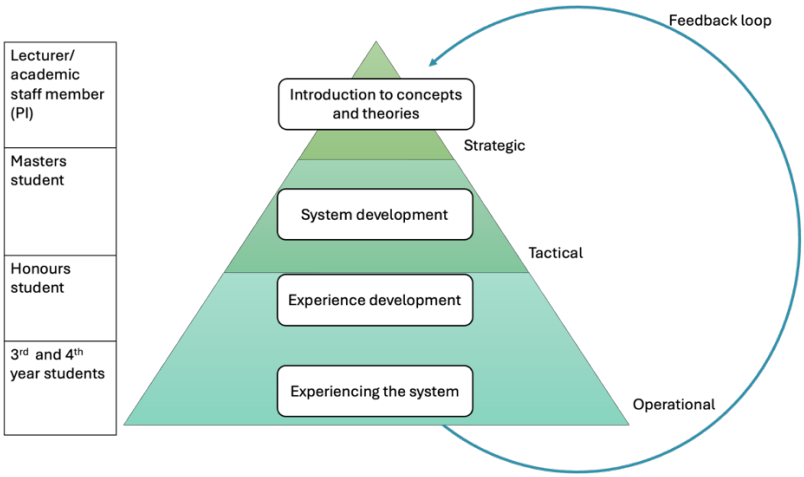

Figure 3: Ecosystem Design-Based Research Framework. A layered, collaborative model for continuous improvement in VR-enhanced learning. Each academic level—from staff to undergraduates—contributes

uniquely to system development, implementation, and feedback, enabling scalable, sustainable educational innovation

6.3 Future Interventions

Future research will investigate the impact of offering multiple, distinct educational experiences within the same 3D virtual factory environment. Currently, this virtual space supports various applications—such as a tablet-based interface for teaching industrial robot programming (van Dyk et al, 2025) via a Human-Machine Interface (HMI), and a VR-based facility layout exercise where students reconfigure workstations and observe simulated operator paths [Steed et al, 2025]. Figure 4 depicts these current applications. While this reuse is designed to enhance engagement and promote cognitive transfer through familiarity, the educational value and potential trade-offs of repeated exposure to the same virtual context across different learning activities remain underexplored. Understanding how familiarity affects learning, motivation, and performance will be central to refining the design of scalable VR-based curricula.

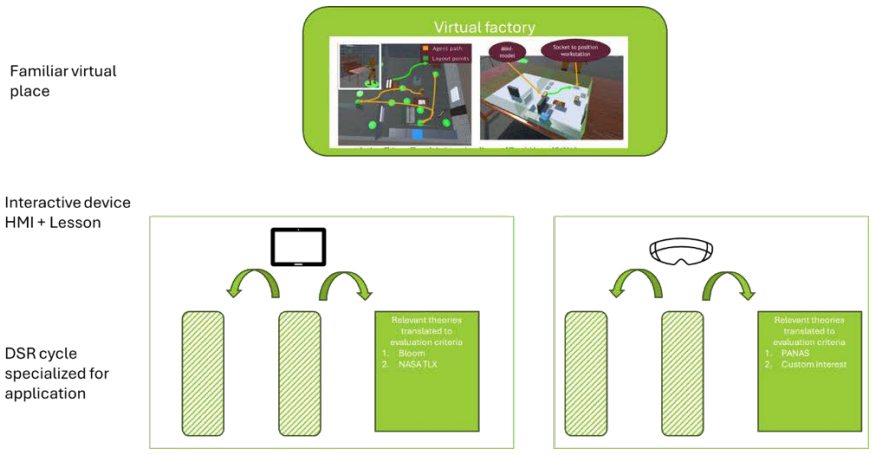

Figure 4 The virtual factory is reused across tablet- (Van Dyk et al., 2025) and VR-based lessons to support robot programming and layout design exercises. Familiarity from repeated use is intended but remains underexplored.

6.4 Limitations

As part of the faculty-wide continuous improvement strategy aimed at enhancing engagement in large classroom settings, future studies will address the following limitations:

- Expanded sample and statistical rigor: Future research will broaden the scope of qualitative approaches and increase the sample size to enable more meaningful statistical analysis and demonstrate significance. More granular data will also be collected to strengthen insights.
- Enhanced participant profiling: Higher-fidelity demographic data—including age, gender, and social background—will be gathered for focus group participants. These variables may influence results, especially given the small sample sizes used in earlier phases.
- Industry-Academia alignment: Incorporating feedback from industry stakeholders can further inform these studies. This will not only provide industry with insight into the current state of classroom technologies but also help bridge the gap between academic instruction and industry needs.

Acknowledgments

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8 Review

Reviewer	Comment	Actions	Response
Reviewer 3	Good research paper on an innovative learning process for students using VR.	N/A	
Reviewer 3	Literature review is well done and solid.	N/A	
Reviewer 3	The effect of COVID is contradictory – less engagement vs. more technological maturity.	Clarify the narrative around COVID's impact, ensuring consistency and nuance in how these two aspects are discussed.	I've removed reference to Covid. While it may be relevant, (1) we did not provide sufficient evidence (2) nor did we compare pre and post covid groups. My suggestion is that we remove the minor mentions of it.
Reviewer 3	Methodology is theoretically relevant, but small study groups (15 in Year 3, 25 in Year 4) make findings fragile.	Acknowledge the limitation; propose expansion of sample size in future work section.	Added section 6.4.
Reviewer 3	No profile data for focus group participants (age, gender, social background) – may affect results given small sample size.	Add a note on the lack of demographic data as a limitation and suggest its inclusion in future studies.	Added section 6.4.
Reviewer 3	Data in Figure 2 are not very self-explanatory for some indicators.	Improve the clarity of Figure 2; add detailed captions or explanations in the text.	Added a paragraph at the end of the section.
Reviewer 3	Overly positive tone on VR; lacks mention of drawbacks or weak points.	Include a paragraph discussing limitations or challenges associated with VR in education.	See comment.
Reviewer 3	Industry feedback is missing – would help assess the approach more fully.	Suggest the inclusion of industry feedback in future work or acknowledge its absence as a current limitation.	Added section 6.4.
Reviewer 4	Issue of active learning for large student groups is very relevant, especially in unequal contexts.	N/A	
Reviewer 4	VR strategy is viable; well-written document.	N/A	
Reviewer 4	Lacks clarity on importance of students' emotional response to the strategy.	Expand discussion to explicitly include emotional responses and their potential impact.	Refer to earlier addition for figure 2.
Reviewer 4	Problem definition should more clearly state the significance of emotional responses for effective implementation.	Revise the problem statement to emphasize emotional aspects of learning with VR and their implications.	

AI-Supported Tutoring and Cognitive Learning Styles in an Engineering Mathematics Refresher Course

Gustav Potgieter
Faculty of Engineering, North-West University, South Africa, gustav.potgieter@nwu.ac.za

Brandt Klopper
Faculty of Engineering, North-West University, South Africa, brandt.klopper@nwu.ac.za

Liezl van Dyk
Faculty of Engineering, North-West University, South Africa, liezl.vandyk@nwu.ac.za

Liandi van den Berg
TELIT-SA, Faculty of Economic and Management Sciences, North-West University, South Africa, Liandi.vandenBerg@nwu.ac.za

Abstract

Many second-year engineering students enter advanced mathematics courses with gaps in foundational knowledge, leading to high failure rates and limited progression in engineering studies. Artificial intelligence (AI)-driven tutoring has emerged as a potential intervention to address these gaps by providing structured support and real-time feedback. This study investigates the effectiveness of AI-supported tutoring in a one-week intensive refresher course, with a focus on how cognitive learning styles influence engagement.

Using Neethling Brain Instrument (NBI) cognitive profiling, Google Form surveys, and interaction data from the Mindjoy tutorbot, the analysis revealed that students with structured, analytical preferences (L1) engaged most frequently with the AI tutor, while creative (R1) and relational (R2) students engaged less. Students who made frequent use of the AI tutor reported increased confidence in problem-solving. These findings highlight the need for AI tutoring systems to adapt to diverse cognitive profiles to maximise engagement and learning outcomes.

Keywords: AI tutoring, engineering education, mathematics refresher course, cognitive profiles, student engagement

1 Introduction

Artificial intelligence (AI) tools are increasingly used in education to personalise learning, provide real-time feedback, and support complex problem-solving (Green & Carter, 2022). While AI has been applied successfully in adaptive learning platforms, automated grading, and intelligent tutoring systems, its role in short, intensive refresher courses remains underexplored.

Mathematics proficiency is essential for engineering students, yet many enter second-year courses with foundational gaps that hinder their ability to master advanced concepts (Bringula et al., 2021). At North-West University (NWU), high failure rates in early-year mathematics modules have prompted the introduction of a one-week pre-semester refresher course aimed at strengthening conceptual understanding before formal classes begin.

This study examines whether AI-supported tutoring can enhance engagement and learning outcomes in this setting. The Mindjoy large language model (LLM) tutorbot was integrated into the course to provide content review, guided problem-solving, and clarification of key concepts (Mindjoy, 2025). Unlike traditional instruction, the AI tutor offered instant, personalised feedback and self-paced learning opportunities.

The research addressed three questions:

1. How does student engagement with AI tutors vary across cognitive learning styles?
2. How effective is AI in addressing common misconceptions in mathematics?
3. To what extent does AI adapt to the learning needs of students with different cognitive profiles, as measured by the Neethling Brain Instrument (NBI)?

In alignment with the Southern African Society for Engineering Education's focus on student success, this study aims to inform the effective integration of AI with human-led instruction. The intensive five-day format compresses the learning cycle, potentially amplifying both the benefits and limitations of AI support, and may produce engagement and learning patterns that differ from those in longer interventions.

2 Methodology

2.1 Course Structure and Daily Schedule

This study was conducted at North-West University (NWU), South Africa, as part of a one-week intensive refresher course designed to reinforce key second-year engineering mathematics concepts before the

semester commenced. The programme targeted common learning gaps to strengthen students' conceptual foundations for advanced coursework.

Forty-nine students from various undergraduate engineering programmes participated voluntarily, all enrolled in core second-year mathematics modules and with prior exposure to the topics.

The five-day course covered four foundational modules: MTHS 211 (Advanced Calculus), MTHS 212 (Linear Algebra), APPM 211 (Dynamics I), and APPM 212 (Differential Equations). Each day was dedicated to a single module, with Friday reserved for review and integration across all topics.

Students had access to the Mindjoy AI tutorbot throughout the day for independent practice and review. Each day included two instructor-led sessions (09:00–11:00 and 11:30–13:30) covering key concepts and guided problem-solving. In the late afternoon (16:30–18:30), all students participated in a compulsory AI-assisted session, during which they completed a short test on the day's content using Mindjoy. This session ensured consistent engagement with the platform while providing immediate, tailored feedback.

The week concluded with a Friday integration session focused on consolidating knowledge across modules, revisiting challenging material, exploring links between topics, and reflecting on learning in relation to students' cognitive profiles. This structure supported both conceptual understanding and self-directed learning through interactive AI support.

2.2 Data Collection Approach

A multi-source data collection strategy was used to analyse student engagement, learning behaviours, and the effectiveness of AI-assisted tutoring. Data came from three primary sources:

(1) AI-based engagement metrics

Interaction data were logged automatically by the Mindjoy platform throughout the week. Metrics included:

- Number of interactions (complete query–response pairs).
- Common misconceptions flagged by the system.

Misconceptions were identified from AI error logs and manually reviewed by instructors for accuracy and relevance. The tutor usage score was defined as the total number of discrete interactions per student during the refresher week, regardless of the number of modules attended or the total time spent on the platform.

(2) Student self-reported data

Neethling Brain Instrument (NBI) profiles were collected voluntarily from all participants, classifying cognitive preferences into four quadrants: L1 (analytical thinking), L2 (logical organisation), R1 (creative thinking), and R2 (social/holistic thinking). The NBI is a cognitive preference profiling tool rather than a traditional learning styles instrument; it identifies thinking preferences in four quadrants without making prescriptive claims about fixed learning modalities. It was selected for this study because it provides a quantifiable measure of thinking preferences that can be correlated with observed engagement patterns.

(3) Engagement constructs and perceptions

Google Form surveys captured:

- **Engagement constructs:**
    - Emotional Engagement (EE): motivation and enthusiasm when using AI.
    - Behavioural Engagement (BE): active participation in AI-assisted tasks.
    - Cognitive Engagement (CE): ability to connect AI-assisted learning to broader mathematical concepts.

- **Perceptions of the AI platform:** measured with the System Usability Scale (SUS) and a custom Perceived Learning (PL) questionnaire, both administered at the end of the week. Full item lists for these instruments are provided in Appendix A.

2.3 Data Analysis Approach

The data analysis aligned with the study's three research objectives:

- **Engagement:** The number of discrete conversations (query–response pairs) recorded for each participant during the refresher week was used as the measure of AI engagement.
- **Misconceptions:** The total number of misconceptions identified by the Mindjoy platform was recorded for each module.
- **Cognitive profiles:** NBI results were used to classify participants into four cognitive quadrants (L1, L2, R1, R2) and compared with tutor usage counts to explore patterns in AI interaction.
- **Engagement constructs and perceptions:** Survey responses were used to calculate Emotional Engagement (EE), Behavioural Engagement (BE), and Cognitive Engagement (CE) scores. The same survey included the System Usability Scale (SUS) and a custom Perceived Learning (PL) questionnaire, which were summarised to evaluate usability and perceived learning benefits.

All analyses were descriptive and conducted in Microsoft Excel.

3 Results

Quantitative survey results are presented separately from qualitative findings. Quotations are drawn from open-ended survey responses or informal verbal feedback. Numerical trends are based on survey ratings and platform analytics.

3.1 Tutorbot Usage and Student Engagement Trends

A key objective of this study was to examine how frequently students engaged with the AI tutor and how these usage patterns varied across the cohort.

3.1.1 Engagement Classification Criteria

Student engagement was categorised descriptively based on the total number of discrete AI tutor interactions (query–response pairs) recorded for each participant during the refresher week. Three usage categories were defined:

- High engagement: $\geqslant$ 38 interactions
- Medium engagement: 19–37 interactions
- Low engagement: $\leqslant$ 18 interactions

Descriptive statistics for each category are shown in Table 1. High-engagement students recorded between 44 and 83 interactions (median = 57.5), medium-engagement students between 20 and 36 (median = 28), and low-engagement students between 0 and 18 (median = 4).

The boxplot in Figure 1 illustrates these distributions, showing that high-engagement students consistently interacted more with the AI tutor, with a narrower spread at higher usage levels compared to the other groups.

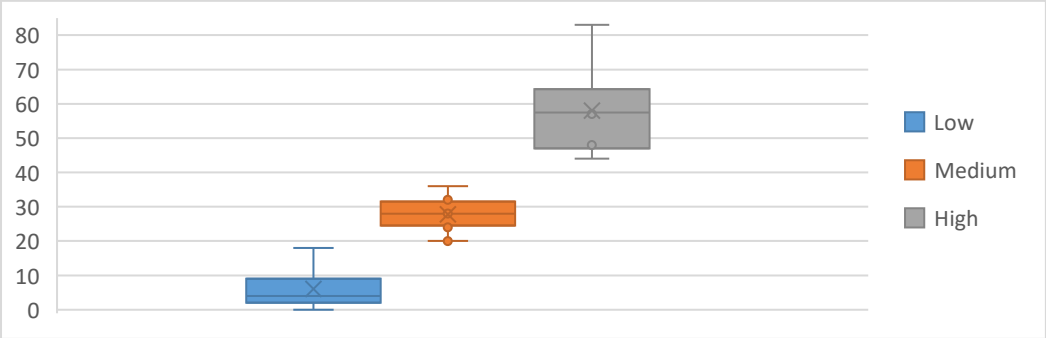

Figure 1: Tutorbot Usage vs. Engagement Level

3.2 Interpretation of Engagement Patterns

Highly engaged students ($\geqslant$ 38 interactions) frequently used the AI tutor for real-time problem-solving, feedback, and clarification, which indicates that they derived clear value from the structured, on-demand support it provided.

Medium-engagement students (19–37 interactions) tended to use the AI tutor selectively, often consulting it for specific problems rather than as a consistent study aid.

Low-engagement students ($\leqslant$ 18 interactions) showed minimal interaction with the AI tutor despite having full access throughout the week. In open-ended survey responses, these students reported barriers such as uncertainty about how to phrase questions, difficulty interpreting text-heavy responses, and a preference for face-to-face clarification.

Although daily tests were scheduled during the evening sessions, usage data indicate that students engaged with the AI tutor at various points during the day, including morning classes and independent study. Recorded usage therefore reflects a combination of scheduled and self-directed engagement.

Overall, these patterns reveal that AI tutors are most effective when students are already motivated and comfortable with text-based interaction. The variation in engagement levels highlights the potential benefit of expanding AI functionality to include more visual, collaborative, and adaptive features to better support different students' needs.

3.3 Misconceptions Across Modules and AI Effectiveness

Misconceptions were identified from AI tutorbot error logs generated during student interactions and manually reviewed by instructors to confirm accuracy and relevance to the course content. The highest number of misconceptions occurred in APPM 211 (20 cases), followed by APPM 212 (18) and MTHS 212 (15). MTHS 211 recorded 12 misconceptions, while 10 were general cross-module issues.

While Mindjoy analytics provided counts of misconceptions per module, these did not distinguish between procedural and conceptual types. The following two broad patterns are drawn from instructor observations and student comments, and are therefore qualitative rather than coded data categories.

Procedural misconceptions typically involved errors in applying known methods or executing calculation steps. Examples included:

- Numerical integration (APPM 211): Students applied Simpson's Rule without accounting for initial conditions, or confused it with unrelated numerical methods.
- Normal vector calculation (MTHS 212): Several students attempted to compute a normal vector from points without correctly using the vector product, or misread coefficients from a plane equation as the normal vector.

- Bernoulli's equation (APPM 212): Students omitted the substitution step needed to transform it into a linear equation, resulting in incorrect solutions.
- Row reduction (MTHS 212): Some students performed the basic operations but did not follow the logical sequence required for full reduction, leading to incorrect system solutions.

Conceptual misconceptions were linked to misunderstandings of underlying principles. Examples included:

- Rectilinear kinematics (APPM 211): Students struggled to relate position, velocity, and acceleration in continuous motion, often misapplying integration when deriving displacement.
- Geometric relationships between lines and planes (MTHS 212): Confusion over conditions for parallelism or skewness of lines/planes, and how vectors and planes interact geometrically.
- Exact differential equations (APPM 212): Misinterpreting the conditions for exactness, or confusing integrating factors with exact equations.
- Span and linear transformations (MTHS 212): Students conflated the meaning of "span" with generic combinations, or could not differentiate between definitions and applications of linear transformations.

These insights show that although the AI tutor was often effective in helping students correct procedural errors through step-by-step guidance, conceptual misunderstandings were more persistent, particularly when the explanations relied heavily on text. Addressing these would require incorporating interactive visual explanations, contextual hints, and follow-up questioning to encourage reflective thinking.

3.4 Cognitive Profiles and Tutorbot Engagement

This study examined how cognitive learning styles, as measured by the Neethling Brain Instrument (NBI), influenced engagement with AI tutoring. Students' dominant cognitive preferences were categorised into four quadrants: L1 (Analytical Thinking), L2 (Sequential Thinking), R1 (Creative Thinking), and R2 (Holistic/Relational Thinking).

Tutorbot usage was quantified as the total number of discrete AI–student interactions (complete query–response pairs) logged during the refresher week. Table 1 summarises the distribution of dominant NBI profiles across high, medium, and low engagement categories.

Table 1: Distribution of dominant NBI profiles across engagement categories

Engagement Category	**L1**	**L2**	**R1**	**R2**	**Total**
High (≥38)	4	2	0	0	6
Medium (19–37)	6	3	0	3	12
Low (≤18)	12	13	1	5	31
Total	22	18	1	8	49

Descriptive analysis showed that L1 (Analytical-Sequential) students recorded the highest median number of AI tutor interactions, followed by L2 (Organised-Practical) students, although L2 engagement varied more widely. R1 (Creative-Experimental) and R2 (Relational-Interpersonal) students tended to engage less frequently, and no R1 students appeared in the high-engagement group.

Figure 3 illustrates these patterns, showing that L1 students were more prevalent in the high- and medium-engagement categories, indicating that the AI tutorbot's structured, step-by-step explanations aligned closely with their preference for logical, sequential problem-solving. L2 students were present across all engagement levels but were most frequent in the low-engagement group, suggesting that while some adapted well to the AI format, others may have preferred more applied, hands-on approaches.

R1 students were absent from both high- and medium-engagement categories, with only a single low-engagement participant, indicating that the text-heavy format was less suited to their preference for exploratory, visually rich learning. R2 students appeared only in the medium- and low-engagement categories, consistent with a preference for collaborative, discussion-based learning over solitary AI interaction.

These findings highlight the need for AI tutors to integrate multimodal learning strategies (such as dynamic visualisations for R1 students, collaborative features for R2 students, and applied, context-based scenarios for L2 students) to ensure balanced engagement across diverse cognitive profiles.

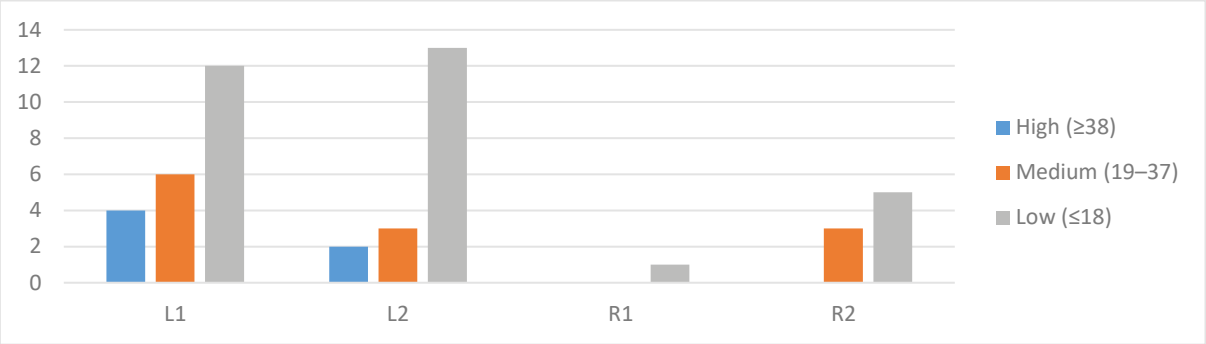

Figure 2: Engagement category vs. dominant NBI quadrant

3.5 Student Engagement Constructs and System Usability

Engagement constructs were measured using:

1. Survey-based self-reports (1–5 Likert-scale ratings capturing student perceptions of engagement),
2. Tutorbot usage analytics (total number of discrete student–AI interactions), and
3. Statistical summaries of survey ratings for Emotional Engagement (EE), Behavioural Engagement (BE), Cognitive Engagement (CE), System Usability (SUS), and Perceived Learning (PL).

Not all 49 students completed the survey items for these constructs; therefore, the results below are based only on respondents with complete data for each construct and a recorded NBI profile. Table 2 reports mean values (± standard deviation) for each construct by dominant cognitive profile.

Table 2: Mean Survey Ratings (Likert 1–5) for Engagement Constructs, System Usability, and Perceived Learning by Cognitive Profile

Dominant NBI Quadrant	Emotional Engagement (EE)	Behavioural Engagement (BE)	Cognitive Engagement (CE)	System Usability (SUS)	Perceived Learning (PL)
L1	3.45 ± 1.11	3.22 ± 1.15	3.92 ± 0.85	4.17 ± 0.84	3.89 ± 0.76
L2	3.60 ± 0.88	3.09 ± 1.15	4.20 ± 0.87	4.27 ± 0.92	4.10 ± 0.76
R2	3.90 ± 0.88	2.90 ± 0.99	2.60 ± 1.17	4.25 ± 0.64	4.00 ± 0.00

Note: Scores are based on 1–5 Likert ratings, reported as mean ± standard deviation.

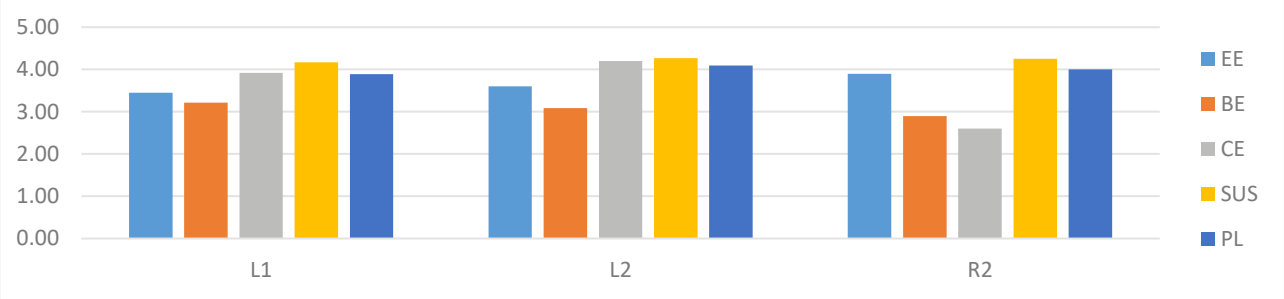

Figure 3: Mean ratings across the five constructs.

For emotional engagement (EE), R2 students reported the highest mean ratings (3.90), with L2 close behind (3.60), which implies that positive perceptions of the AI tutor were not limited to sequential thinkers. However, open-ended responses from R2 students indicated that these positive feelings did not always translate into sustained use, with some describing the AI as "impersonal" and preferring more collaborative interaction.

Behavioural engagement (BE) scores were moderate across all groups, with L1 slightly higher on average (3.22). This aligns with usage analytics showing that L1 students tended to complete more AI-assisted problem-solving sequences. R2 students recorded the lowest BE (2.90), often citing the "text-heavy interface" as discouraging for extended sessions.

In cognitive engagement (CE), L2 students reported the highest values (4.20), reflecting strong confidence in procedural problem-solving when using the AI tutor. L1 students followed closely (3.92), whereas R2 students had notably lower scores (2.60), consistent with their qualitative feedback that the AI "lacked conceptual depth" for complex reasoning tasks.

System usability (SUS) ratings were high for all profiles (4.17–4.27 range), indicating that students found the AI tutor generally easy to navigate and integrate into their learning routines. High SUS scores were moderately associated with higher usage, particularly among L1 and L2 students.

For perceived learning (PL), L2 students again led (4.10), followed by R2 (4.00) and L1 (3.89). Many L2 participants emphasised the value of step-by-step guidance for reinforcing key concepts, while R2 students stressed the need for more adaptive, context-rich explanations to support deeper understanding.

Overall, the data indicate that while the AI tutor was rated as usable and beneficial across cognitive profiles, its strengths were most evident for structured, sequential thinkers (L1 and L2). Creative and relational students (R2) engaged positively on an emotional level but showed lower behavioural and cognitive engagement, highlighting the importance of incorporating multimodal and collaborative features into AI-supported learning environments.

4 Discussions

As expected, students with a strong preference for structured, sequential learning (L1 profiles) engaged most readily with the AI tutorbot's text-based, step-by-step feedback. The value of this study lies in quantifying the strength of that alignment and contrasting it with the markedly different engagement patterns of other cognitive profiles. By combining NBI profiling with detailed usage analytics and engagement constructs, we were able to pinpoint not only who engaged more, but also why, highlighting the specific features of the AI tutor that supported or limited each profile. These insights go beyond simply confirming known learning preferences, offering clear, evidence-based directions for improvement, such as incorporating multimodal elements to better support R1 and R2 students in engineering education contexts.

4.1 Tutorbot Effectiveness and Cognitive Profiles

This study examined the effectiveness of an AI-powered tutorbot in supporting engineering students' mathematics learning across different cognitive profiles (NBI). As shown in the results, L1 students (Structured Thinkers) recorded the highest engagement across all metrics, reflecting a strong alignment between their preference for clear, rule-based learning and the tutorbot's structured, step-by-step feedback. In contrast, R1 (Creative) and R2 (Social) students engaged less consistently, with several noting in open-ended responses that the AI felt "impersonal." This perception, coupled with the text-heavy interaction style, may account for their lower usage. Taken together, these findings point to the possibility that current AI tutor designs may inherently privilege structured students, highlighting the need for adaptive, multimodal interfaces that accommodate a wider range of cognitive styles.

4.2 Engagement Constructs in Context

Engagement with the AI tutor varied notably across cognitive profiles, underscoring the need to tailor digital learning tools to diverse student preferences. L1 students consistently reported high emotional, behavioural, and cognitive engagement, completing AI tasks more regularly and describing the system as both stimulating and effective for step-by-step problem-solving. This alignment reflects their preference for structured, rule-based environments and indicates that sequential students can thrive when AI-assisted contexts mirror their cognitive tendencies.

In contrast, R2 (Social) students reported mixed or lower engagement across some constructs. Many perceived the AI as impersonal or lacking emotional presence, leading to reduced behavioural engagement and difficulty sustaining focus. Cognitively, they often struggled to apply AI-generated feedback to real-world problems, particularly in the absence of collaborative or visual scaffolding.

The evidence shows that while structured AI systems effectively support L1 students, they risk marginalising students who rely on social interaction, exploratory learning, or visual reasoning. Addressing this gap requires moving beyond a one-size-fits-all approach toward adaptive, multimodal strategies that align more closely with diverse cognitive styles.

4.3 Implications for AI Tutor Design

The engagement disparities across cognitive profiles point to the need for AI tutors that are both flexible and adaptive. While structured students (L1) benefited from the linear, text-based format of the Mindjoy tutorbot, this approach was less effective for students who favour conceptual, collaborative, or visually driven learning. To engage a wider range of students, AI systems must evolve from static feedback toward responsive, multimodal interaction.

For R1 students, who thrive on visual pattern recognition and creative problem-solving, features such as interactive diagrams, animations, and graphing tools could enhance conceptual clarity. R2 students, who value interpersonal and language-based learning, may respond better to conversational scaffolding, discussion prompts, and simulated peer dialogue. In both cases, adaptive branching logic (adjusting tone, strategy, or pacing based on user profile) could substantially improve engagement and learning outcomes.

Personalisation in AI learning should go beyond adjusting content level or delivery speed. Considering how students think and interact with information can shift AI tutors from rigid information providers to responsive, context-aware learning partners.

4.4 AI Usability and Learning Outcomes

The System Usability Scale (SUS) and Perceived Learning (PL) results offer valuable insights into how students experienced the AI tutorbot. Most participants rated the system as intuitive and easy to navigate, with a

mean SUS score of 4.21. This aligns with prior research showing consistently high usability ratings for AI-based learning tools, particularly when they provide structured, step-by-step interaction (Vlachogianni & Tselios, 2021; Wang et al., 2024). Students also reported that the tutorbot enhanced their learning, especially in consolidating procedures and supporting independent problem-solving.

However, these positive perceptions were not evenly distributed across cognitive styles. L1 students rated both usability and learning impact highly, whereas R2 students struggled with dense, text-heavy explanations and often disengaged due to limited interactivity or conceptual scaffolding. This indicates that strong usability in technical terms does not necessarily translate into high cognitive or emotional engagement for all students.

For broader adoption and greater impact, future AI systems should pair usability with adaptive learning features (such as progressive onboarding, multimodal feedback, and differentiated interaction modes) to better serve students who think and engage in different ways. High usability should be treated as a necessary starting point, not the ultimate measure of an inclusive AI learning tool.

4.5 Limitations

While this study offers valuable insights into AI-assisted mathematics learning, several limitations must be considered. First, the implementation was confined to the Mindjoy tutorbot within a structured refresher and intervention setting, meaning the results may not generalise to other AI systems or contexts without comparable scaffolding and instructor support.

Second, as noted in the Results section on Misconceptions Across Modules, the AI tutor displayed limited conceptual flexibility. Although effective in guiding students through procedural steps, it often struggled to address deeper conceptual misunderstandings or adapt explanations dynamically, particularly among students with R1 and R2 learning profiles.

Third, as highlighted in the Student Engagement Constructs and System Usability results, the absence of visual and interactive elements reduced engagement for some students, especially those with visual or kinaesthetic preferences. The lack of diagrams, simulations, or collaborative tools underscores the importance of multimodal support in future AI designs.

Fourth, certain students (particularly those less familiar with AI) experienced cognitive overload when presented with long, text-heavy feedback. Progressive scaffolding, beginning with simplified explanations and gradually increasing complexity, could mitigate this challenge.

Finally, the study's modest sample size (n = 49) and homogeneous participant profile (engineering undergraduates at a single institution) limit the generalisability of results. Future research should include a more diverse student base across disciplines and institutions, and employ longitudinal designs to assess the sustained impact of AI tutors on conceptual understanding and academic performance.

5 Conclusion

This study examined how engineering students with different cognitive profiles engaged with an AI tutorbot during an intensive mathematics refresher course. By combining NBI profiling with survey-based engagement constructs, usage analytics, and perceived learning measures, the analysis addressed three research questions.

First, student engagement varied markedly across cognitive profiles: L1 students recorded the highest levels of interaction, followed by L2 students, while R1 and R2 students engaged far less, no R1 students appeared in the high-engagement category.

Second, AI support proved more effective in addressing procedural misconceptions than conceptual ones. Step-by-step guidance often corrected calculation errors, but deeper conceptual misunderstandings persisted, particularly when explanations relied solely on text.

Third, the AI tutor displayed limited adaptability to diverse cognitive needs. Its structured, text-based format aligned well with sequential thinkers (L1), but creative (R1) and relational (R2) learners called for more visual, interactive, and discussion-oriented features.

These findings quantify the alignment between AI affordances and student preferences while offering targeted design directions (such as incorporating multimodal content, adaptive feedback, and collaborative features) to extend benefits across a broader range of learners. Advancing beyond confirmation of known learning tendencies, this work provides evidence-based recommendations for more inclusive, adaptive AI tutor design in engineering mathematics education.

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APPENDIX A – EE, BE, CE, SUS and PL Structured Questions

Emotional Engagement (EE)

(1) I feel excited when solving math problems with the AI tool.
(2) I enjoy learning math concepts using AI-based tools.
(3) I feel emotionally involved when solving problems with the AI tool.
(4) The use of AI tools makes learning enjoyable for me.
(5) I feel curious about what we are learning when using the Tutorbot.

Behavioural Engagement (BE)

(1) I try hard to engage actively with the AI tool during lessons.
(2) I complete all tasks provided through the AI tool.
(3) I participate fully in discussions or exercises involving AI-based tools.
(4) I actively explore how to use the AI tool to enhance my problem-solving.
(5) I work hard when engaging with the Tutorbot.

Cognitive Engagement (CE)

(1) I try to connect concepts I learn with the AI tool to my prior knowledge.
(2) I use the AI tool to help integrate various mathematical ideas.
(3) I reflect on how the AI tool supports my problem-solving skills.
(4) I apply critical thinking when interacting with the AI tool.
(5) I evaluate the effectiveness of the AI tool in helping me understand complex concepts.

System Usability Scale (SUS)

(1) I think that I would like to use the Tutorbot frequently.
(2) I found the Tutorbot to be simple.
(3) I thought the Tutorbot was easy to use.
(4) I think that I could use the Tutorbot without the support of a technical person.
(5) I found the various functions in the Tutorbot to be well integrated.
(6) I thought there was a lot of consistency in the Tutorbot.
(7) I would imagine that most people would learn to use the Tutorbot very quickly.
(8) I found the Tutorbot to be very intuitive.
(9) I felt very confident using the Tutorbot.
(10) I could use the Tutorbot without having to learn anything new.

Perceived Learning (PL)

(1) The Tutorbot provided me with an integrated knowledge of the mathematical concepts covered in the refresher course.
(2) The Tutorbot enhanced my ability to investigate, discuss, and critique mathematical problems more effectively.
(3) The Tutorbot enhanced my ability to apply mathematical techniques to solve problems.
(4) The Tutorbot helped me to develop a deeper understanding of mathematical principles and their applications.
(5) The Tutorbot improved my ability to analyse and solve complex mathematical problems.
(6) The Tutorbot developed my ability to apply problem-solving strategies in mathematics.

Open-Ended Questions

(1) How has the use of AI tools impacted your learning experience?
(2) What do you find most helpful about the AI tool?
(3) Are there any challenges you encountered while using the AI tool? Please elaborate.
(4) What suggestions do you have for improving the AI tool or its integration into learning?

Rethinking engineering education outcomes in the light of Artificial Intelligence

Anné H. Verhoef
AI Hub, North-West University, South Africa, Anne.Verhoef@nwu.ac.za

Willem van Niekerk
Faculty of Engineering, North-West University, South Africa, Willem.vanNiekerk@nwu.ac.za

Jean du Toit
School of Philosophy, South Africa, JduToit@ufh.ac.za

Liezl van Dyk
Faculty of Engineering, South Africa, Liezl.vanDyk@nwu.ac.za

Abstract:

The deployment of LLMs (large language models) in AI (artificial intelligence) has led to a wide-spread increase in the use of AI in contemporary society, which will impact how teaching and learning takes place in higher education in the future. Since constructive alignment – which suggests that in curriculum design there should be a close alignment of teaching and assessments with intended outcomes – plays a crucial role in higher education teaching and learning, this paper examines how burgeoning AI technology reshapes such alignment considering both human and AI capabilities. The current paper investigates an undergraduate engineering curriculum to determine which tasks specified in module outcomes, as presented in the yearbooks (program portfolio), can 1) be delegated to AI, 2) are uniquely human, and 3) require a combination of human and AI capabilities. This categorization of outcomes will, be compared to the ECSA prescribed graduate attributes of the South African engineering student. The aim will be to determine which module outcomes and graduate attributes remain relevant in an AI-dominated pedagogical environment, and which have been usurped by the increasing competence and accuracy of AI systems, to future proof students in a changing technological landscape. We recommend that the outcomes and graduate attributes should be reformulated to incorporate the potential and risks of AI from the beginning.

Keywords: Artificial Intelligence, Outcomes, Graduate Attributes, ECSA.

1 Introduction:

Artificial Intelligence (AI) can be described as the field of computer science that focuses on the simulation of human intelligence. AI includes mainly two categories. The first is machine learning (ML) where algorithms are used to train computers. This includes natural language processing (understanding and generating human language), deep learning (ML uses neural networks computer models as inspired by the human brain), and computer vision (ML that enables computers to see and act on visual information). The second category of AI is Generative AI (GenAI) which creates new text, images, audio and video. This category includes Large Language Models (LLMs) (trained to analyse prompts to generate human-like responses) which we see in AI apps like ChatGPT, Claude, CoPilot and others. GenAI includes productivity tools like design programmes and virtual assistants like Siri or Alexa. In an educational environment, GenAI can be defined as:

> The development and deployment of computer systems or sophisticated algorithms in teaching-learning or research with the capabilities to perform tasks that would typically require human intelligence. These systems can analyse large amounts of data, identify patterns, formulate predictions, learn from experience, and automate complex processes. Put differently: the development of computer systems that can copy human behaviour.

This definition was taken from the NWU Policy for Academic Integrity and it is expanded on in the NWU Guidelines on the Responsible and Ethical Use of Artificial Intelligence, where the following definition of AI as LLMs are given:

> AI, as Large Language Models (LLMs) or Generative AI, is primarily defined as "a type of artificial intelligence that can learn from and mimic large amounts of data to create content such as text, images, music, videos, code and more, based on inputs and prompts" (https://huit.harvard.edu/ai#block-boxes-1687273052). AI may also include other AI tools such as research summarising tools, automatic data analysis tools, and creation of synthetic data tools (https://sajs.co.za/article/view/17147). AI is not restricted to this definition and with new AI tools constantly being developed, the use of other or new forms of AI should not be excluded from this definition.

In this article we will work with the category of AI as GenAI, and then specifically how it is defined in the higher education context in the examples above. AI is understood as a tool students should learn to use effectively, and it is not seen as something that functions without human guidance and intervention. The relationship between AI and humans is thus crucial in any subject field. We argue therefore that GenAI will fundamentally reshape contemporary higher education landscapes, particularly in terms of (re)defining the desired graduate outcomes we pursue with our students. The impact of AI directly affects how constructive alignment between teaching and learning, but also assessments, takes place. Constructive alignment is an approach to curriculum design which places emphasis on closely aligning teaching and assessment to intended outcomes (Biggs & Tang, 2011).

In this paper we will investigate the effect of the burgeoning use of AI in higher education in terms of its impact on the relevance of module outcomes for an undergraduate engineering programme at a South African higher education institution. We argue that critical reflection is needed for ensuring the continuing validity and usefulness of module outcomes in an AI-integrated educational environment. A product of the paper is to suggest how we could integrate AI considerations into the module outcomes, graduate attributes, and engineering curriculum to future proof and prepare students.

We use AI, the free version of ChatGPT, to initially categorize the outcomes according to the framework, proposed by Cilliers (2024). He proposes six categories in which he categorizes module outcomes and engineering graduate attributes into the following domains: 1) those that can be delegated to AI, 2) those that remain uniquely human and cannot be delegated to AI, 3) those that require a combination of human and AI capabilities, 4) new outcomes that are now possible due to AI capabilities, 5) traditional outcomes that need to be approached differently in an AI-enabled world, and 6) outcomes that have become redundant in an AI enabled world. We only work with the first three, because the last three categories (especially category four and five) would require content knowledge and creative reformulation of the outcomes from a subject specialist. Furthermore, this is an initial exploratory study, and to limit the scope, the last three categories were not included. The categorization is then validated through double checking the results of AI. We argue that categorizing the modules and graduate outcomes within this framework will have distinct implications for engineering curricula of the future. It is clear that we need to rethink which outcomes should still be part of the intended outcomes, and which ones need to be reinterpreted and reformulated with the goal of optimal and efficient deployment of AI, while students are still learning the necessary skills to be an engineer. This is important for aligning the engineering curriculum with accreditation requirements, such as those set by the Engineering Council of South Africa (ECSA).

This paper therefore explores the continuing applicability of current module outcomes in terms of graduate attributes within the context of an AI-directed pedagogical space at an engineering faculty at a South African

university. Using sources such as the ECSA graduate attributes, yearbooks (program portfolio), and ECSA exit-level outcome maps, we will critically evaluate how alignment may take place between AI and higher educational outcomes.

2 Research question, method, and outcomes:

Research question: We will indicate that AI in higher education radically impacts the module outcomes in an undergraduate engineering program. We will investigate this to focus on the question: How should we rethink, reimagine, and reformulate engineering education outcomes in the light of Artificial Intelligence? What criteria should be considered when rethinking engineering education outcomes in the light of Artificial Intelligence?

Methodological approach: We will examine how AI can potentially fulfil and even replace certain outcomes and graduate attributes as listed within an engineering curriculum in SA. We will analyse the outcomes and graduate attributes by first prompting AI, specifically ChatGPT, to answer which engineering module outcomes and graduate attributes can 1) be delegated to AI, 2) which remain uniquely human, and 3) which require a combination of human and AI capabilities. The AI output on these questions will then be compared to the initial data to identify shortcomings in this analysis and to ensure its correctness. Lastly, we will interpret the analysis and the framework to propose some ways in which we should rethink and redevelop engineering outcomes in the future, especially keeping in mind the potential and risks AI poses.

Outcomes: We aim to develop a framework and recommendation to ensure that AI-integrated engineering curricula remain relevant, future-proof, and effectively prepare students for industry demands.

3 Research on outcomes and graduate attributes

We analysed two documents for this study:

1. The first was the learning outcomes of all the modules which forms part of all the undergraduate engineering programmes at North-West University in 2025. These outcomes are listed in the NWU Engineering Yearbook (17_FENG-UG-2025.pdf) and are attached as Annexure 1.
2. The second document were the graduate attributes as listed in the Engineering Council of South Africa's "Qualification Standard for Bachelor of Science in Engineering (BSc (Eng))/ Bachelors of Engineering (BEng): NQF Level 8, revision 7" (Annexure 2). Only the list of graduate attributes, as extracted from this ECSA document, is available in Annexure 3.

We uploaded Annexure 1 to ChatGPT (GPT-3.5 on OpenAI's free plan) and asked the following questions: to provide us, based on the module outcomes in the document, an analysis of which outcomes can be comfortably delegated to AI, which cannot be delegated, and which require a combination of human and AI capabilities. We used the following prompt: Based on the module outcomes in the document, make an analysis of which outcomes can be comfortably delegated to AI, which cannot be delegated, and which require a combination of human and AI capabilities.

We did the same with Annexure 3 but just changed 'modules outcomes' to 'graduate attributes'. The results of this question to ChatGPT about the outcomes, are available in Annexure 4, and the results about the graduate attributes are in Annexure 5. The prompts were: Provide me with a structured analysis of the graduate attributes based on their delegability to AI, human-only capabilities, and hybrid tasks. The further questions to ChatGPT in refining the analysis, and our answers, with the further analyses are all included in these annexures.

Our initial observations of the ChatGPT analysis were that the answers were vague, and we realised that not all modules were discussed. We did find that with the further prompts, the answers became more specific and clearer. The total number of modules listed in the yearbook is 174 and only 62 of those modules were discussed in the analysis. That is only one third of the modules. We repeated the exercise by providing a MS Word file (the first version was PDF) but the total modules analysed the second time were only 26. We decided to work with the initial analyses of 62 modules because that already provided enough data for our further analysis and discussion.

The analysis of the 11 graduate attributes were done much more efficiently and thoroughly by ChatGPT. The reason might be that this was a much shorter list (11 vs 174) with much less text to examine (only 3 pages). We only prompt once more on the answer of ChatGPT and then we had enough data to work with for the purpose of our research.

It is important to note that the descriptions of the module outcomes were the only data ChatGPT worked with and that more information and content of the modules were not provided. To verify the correctness of the analysis of ChatGPT, the lecturers for the specific modules need to be questioned. We did a control and verification of some of the modules' analysis with the lecturers of Industrial Engineering modules (INGB). Our finding was that ChatGPT gave an overall fair analysis and that we could proceed to the next step, namely, to interpret and discuss the findings in the context of our research question, namely how we should rethink and redevelop engineering outcomes in the wake of AI's increasing influence.

4 Discussion of analysis

We agreed with the key take-aways given by ChatGPT (page 11, Annexure 4) that regarding the role of AI and the lecture, we can think about outcomes in general:

- AI can automate repetitive, computational, and optimization-heavy tasks, such as simulations, numerical computations, and data analysis.
- AI cannot replace human intuition, ethical considerations, regulatory compliance, hands-on experimentation, and leadership roles.
- Best results come from AI-human collaboration in areas where AI can optimize performance, but final decisions require human expertise.

This is in line with the categorization of the module outcomes (page 8, Annexure 4):

Table 1: Expanded Categorization of Engineering Module Outcomes and AI Delegation

Module Name	AI Can Handle	Requires Human Expertise	Best Achieved Through AI-Human Collaboration
Statics and Mathematical Modelling (APPM121)	Solving force resultants, vector computations, dimensional analysis	Conceptualizing equilibrium, selecting appropriate models	Verifying AI-generated force systems for real-world accuracy
Dynamics I & II (APPM211, APPM221)	Computing displacement, velocity, acceleration, energy, and momentum	Understanding motion physics and interpreting unexpected results	Validating AI-assisted kinematics/kinetics predictions
Differential Equations (APPM212)	Solving ODEs/PDEs numerically, using Laplace transforms	Selecting the correct equation for specific engineering problems	Adjusting AI-driven solutions for real-world applications

The verbs used within the different categories are significant. The tasks AI can handle are described as "solving, computing" while human expertise is required to "conceptualise, understand, select" and for AI-human collaboration: "verifying, validating, adjusting". This gives a strong indication of the specific role of AI and the continuous needed role of humans, but also of the way they can strengthen each other.

The above description of the roles of AI and humans to reach the outcomes of the module should, in our view, be given to each lecturer, to rethink how the module outcome, the teaching and learning of it, and the assessment, could be rethought to keep the outcomes relevant. The question for the lecturer (subject specialist) should be what unique human skill should be focused on in this module to ensure that AI can be incorporated meaningfully and efficiently. In other words, the question is not which module outcomes should be dropped, but rather to take on the challenge to assess all outcomes in terms of what AI can do or not and reimagine and rethink them within this context.

Regarding the graduate attributes the same pattern were noticed as with the module outcomes, namely that there are certain roles AI can play in fulfilling these attributes, but some of them will remain exclusively human tasks, with some to be hybrid. The summary ChatGPT gave after the analysis (Annexure 5, pp 5-6) is one we agree with:

5 Key AI Roles Across Graduate Attributes:

Examples of tasks according to the three categories we analysed, are as follows. The first category are tasks that can be fully delegated to AI. These include:

- Data analysis, pattern recognition, numerical simulations.
- Automating calculations, document formatting, report generation.
- Process optimization, scheduling, and workflow automation.

The second category are tasks that require a combination of human and AI capabilities:

- Design optimization (AI proposes solutions, engineers validate and refine).

- Experimentation and research (AI processes data, engineers conduct and interpret findings).
- Sustainability assessments (AI models impact, engineers integrate ethical and societal concerns).
- Teamwork and management (AI manages logistics, engineers lead and strategize).

Tasks that remain uniquely human:

- Ethical decision-making and professional judgment.
- Leadership, interpersonal collaboration, and conflict resolution.
- Innovation, creativity, and strategic planning.

The discussion of the first three graduate attributes by Chat GPT is a good example how the same verbs and actions are linked to humans, AI and humans with AI. From Annexure 5, pp4-5:

Table 2: AI Delegability Analysis of Graduate Attributes with AI's Role in Each Category

Graduate Attribute	AI's Role (Delegated Tasks)	AI Limitations (Why Humans Are Needed)	AI + Human Collaboration (Hybrid Approach)
1. Problem Solving	AI can analyze large datasets, detect patterns, optimize engineering solutions, and run simulations to test hypotheses.	AI struggles with ambiguous, ill-defined, or ethical problems requiring creativity and judgment.	AI generates possible solutions; engineers validate feasibility, ethics, and applicability.
2. Application of Scientific & Engineering Knowledge	AI can perform numerical analysis, simulations, and predictive modelling.	AI lacks real-world experience and cannot determine which principles best apply in novel situations.	AI speeds up calculations; engineers select, refine, and interpret models for application.
3. Engineering Design	AI can generate design alternatives, optimize layouts, and simulate performance under different conditions.	AI lacks human creativity, intuition, and the ability to balance trade-offs between conflicting constraints.	AI proposes optimized designs; engineers evaluate feasibility, compliance, and user needs.
4. Investigations, Experiments, and Data Analysis	AI can process large datasets, automate experimental data collection, and identify trends in research findings.	AI cannot design experiments requiring deep domain knowledge and physical intuition.	AI assists with data processing; engineers design experiments, interpret results, and refine hypotheses.
5. Engineering Methods, Tools, and IT Use	AI can assist with CAD modelling, predictive analytics, and process automation.	AI lacks adaptability when working with novel or unstructured data.	AI provides rapid calculations and design iterations; engineers oversee

Graduate Attribute	AI's Role (Delegated Tasks)	AI Limitations (Why Humans Are Needed)	AI + Human Collaboration (Hybrid Approach)
			tool selection, modifications, and integrations.
6. Professional and Technical Communication	AI can generate reports, summarize technical documents, and provide automated translations.	AI struggles with context, intent, and audience-specific communication nuances.	AI drafts initial reports; engineers refine them for accuracy, clarity, and professional tone.
7. Impact of Engineering on Society and the Environment	AI can model environmental impacts, optimize resource use, and assess regulatory compliance.	AI lacks ethical reasoning and cannot fully understand long-term societal implications.	AI provides data-driven insights; engineers ensure ethical, sustainable, and socially responsible decision-making.
8. Ethics, Responsibilities, and Professionalism	AI can flag potential ethical concerns in engineering designs or projects based on predefined rules.	AI cannot make value-based ethical decisions or exercise professional judgment.	AI highlights possible issues; engineers apply ethical reasoning and professional responsibility.
9. Independent and Lifelong Learning	AI can provide personalized learning paths, recommend relevant literature, and facilitate knowledge retrieval.	AI lacks curiosity, self-reflection, and the ability to critically assess new information.	AI helps engineers stay updated; engineers critically engage with content and apply knowledge contextually.
10. Engineering Management	AI can optimize project schedules, forecast risks, and assist in budgeting through data analysis.	AI lacks leadership, strategic vision, and human-centered decision-making skills.	AI provides analytical support; engineers make strategic, team-oriented, and financial decisions.
11. Project Management and Finance	AI can track budgets, predict cost overruns, and optimize resource allocation.	AI does not understand human factors, organizational culture, or negotiation dynamics.	AI enhances efficiency; engineers handle stakeholder interactions, compliance, and decision-making.

The verbs used within the different categories are similar to those in the analysis of the module outcomes. The tasks AI can handle are describe as “analyse, identify patterns, optimise, mathematical modelling,

simulations, statistical analysis, simulate performance" while human expertise is required to "handle ambiguous, ethical, or novel problems; apply domain knowledge; ensure applicability; ensure feasibility and practicality" and for AI-human collaboration these two come together in various ways.

The interesting thing about the modules outcomes and the graduate attributes are that they are normally only thought of as human abilities and characteristics. With AI this mindset needs to change to incorporate, from the beginning, the combined abilities and characteristics to be developed within curricula and programs. It will always be a question of how AI and humans will together be able to fulfil certain tasks.

6 Findings and recommendations

This study has its limitations in the sense that it only analysed the modules outcomes of 62 of the 174 of the engineering curricula. It only used one AI tool, and that was the free version of ChatGPT because that is available to all lecturers. The stronger ChatGPT-4 version is however recommended for analysis of longer texts.

Another limitation was that the outcomes – as described in the Yearbook – do not include the unarticulated outcomes of the modules and programmes. The outcomes are just short descriptions of the main objects to achieve within the module, but there are always more that are achieved in the classroom, in discussions, in assessments, and in the curriculum, that is described by theses outcomes. To assess all these unarticulated outcomes is important but is beyond the scope of this study. We furthermore found that many outcomes are not well defined and that is it critical to evaluate and reformulate outcomes continuously, even if AI did not exist. As the rule is with most AI apps, 'garbage in, garbage out', we concur that the better the outcomes were formulated, the better analysis was given by ChatGPT.

Furthermore, we did not focus in our analysis on the powerful AI Bots that are available for engineers to use. One example is Leo AI: Revolutionary AI-Powered Engineering Design Copilot for Mechanical Engineers. This bot is trusted (see their website) by mechanical engineers in mega companies like Scania, HP, Phillips, Zutacore and by MIT. How these bots will play a role in rethinking outcomes and graduate attributes should be part of further research about AI and development of engineering curricula.

The data gathered in our module outcomes analysis by ChatGPT, with the analysis of the graduate attributes, were limited as mentioned above, but is still indicative of certain patterns. We can therefore list the following findings and make some recommendations based on the interpretation of the data from our analysis.

How should we rethink engineering education outcomes in the light of Artificial Intelligence? We found that:

1. It is important to critically evaluate and reformulate outcomes in the light of AI. An analysis of the outcomes should be done, not to phase them out, but to reinterpret and reformulate them within the possibilities AI poses.
2. Outcomes and graduate attributes remain crucial for developing curricula, but they should be reimagined and reformulated to think AI and humans as a team, and not only think about humans in isolation.
3. By rethinking outcomes and graduate attributes, it will become possible to rethink assessment in creative and alternative ways.

4. There are always opportunities and risks associated with AI, and it will become increasingly important to highlight these in rethinking module outcomes.
5. Proven educative principles in designing curricula and assessments, like those found in Bloom's taxonomy for example, should not be ignored or dropped in the face of AI, but they should also be rethought and redeveloped. We see some examples of this already in the work of the Vanderbilt University Centre for Teaching (see online article of Morgan (2024), and by Gonsalves (2024).

Our recommendations aim to ensure that an AI-integrated engineering curricula remain relevant, future-proof, and effectively prepare students for industry and society's demands. The following framework can be used in this regard:

1. Analyse all modules' outcomes of all programmes. This can initially be done through different AI tools, but it is crucial to get subject specialist and lecturers involved to analyse it further, in more detail, and in the context of the module's content and assessments
2. Further analysis of the module outcomes can be done by following the last three categories as proposed by Cilliers (2024), namely:
    a. Identifying and formulating new outcomes that are now possible due to AI capabilities.
    b. Reimagining traditional outcomes that need to be approached differently in an AI-enabled world.
    c. Identifying outcomes that have become obsolete or unnecessary in an AI enabled world.
3. Rethink and reformulate outcomes, and do not just change assessments. The problem is that many lecturers just change assessments because AI can do the assessments and students use AI then to complete the tasks, sometimes unethically.
4. The ethical and responsible use of AI is of course crucial and should be promoted in all possible ways (e.g. by forming a Community of Practice for academic integrity as indicated by Verhoef et al, 2022). We should however not get stuck at only changing assessments but rather rethink the outcomes. The new assessments should then be linked to the reimagined module outcomes that incorporate AI. Various AI Assessment Scales have been developed with AI incorporation, e.g. Furze, Perkins et al 2024, and provides excellent guidance in this regard.
5. Regarding the graduate attributes that are prescribed by ECSA to be part of the outcomes of the engineering curriculum, we would encourage a rethink of these to make them more specific and aligned with the capabilities of AI.
6. Some new skills will need to be developed in our students for our future that will be increasingly one influenced by AI. Some of the critical skills young people in the workplace (ECSA competencies) need in the era of AI are according to Verhoef (as quoted in Carew 2024:43), are the ability to:
    a. Always be willing to learn. Students must experiment, test, and play using different forms of AI. This is the fun part of AI. There is so much to explore, but it needs to be discovered, and this skill should be encouraged.
    b. Acknowledge and embrace their unique contributions. AI can do so much. In response, young people need to understand how they can complement AI's answers with their own creativity.
    c. Prioritise critical thinking. This is crucial in a world of AI everything. We should not just trust what AI presents as a true or good answer but question it.
    d. Not be too dependent on AI. We still need basic subject knowledge to judge whether AI gives a good answer.

e. Learn to work ethically and responsibly with AI, by being transparent in our use of it and by being honest if we have used it so that we can keep the integrity of our work intact.
f. Be mindful of issues regarding privacy, security and safety when using AI. The safeguarding of personal information and respect for user privacy will become an increasingly important skill.

To conclude, AI poses new challenges and opportunities for higher education. To constructively engage with these, we propose that we should start to rethink, reimagine, and reformulate the outcomes of modules, programs, graduate attributes and degrees. We examined how this might look in terms of engineering education at a South African university. We realised that outcomes should be carefully rethought and formulated. During the analysis of the outcomes by AI, some outcomes were identified as something AI can do, others were however outcomes that remain something only humans can achieve, or in AI-human combination. In general, we would recommend that all outcomes should be rethought and reformulated with the integration of AI part of it. The outcomes will then include what skills students will need to use AI as a tool to co-achieve higher levels of outcomes.

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Annexures

The annexures referred to in this research paper can be found in the following folder:

https://drive.google.com/drive/folders/1qa36Dbf-n2iZkTeNaA3SSuJsgqJXoI-e?usp=sharing

Same but not The Same: Describing and shaping meaning-making in engineering mathematics problems

Matheus O. de Andrade
UCL Centre for Engineering Education, UCL, United Kingdom

Bettina Dahl
Department of Planning, Aalborg University, Denmark

Karin Wolff
Faculty of Engineering, Stellenbosch University, South Africa

Abstract

Existing paradigms for mathematics education emphasise self-regulated learning, modelling competencies, and learning outcomes in all cognitive, psychomotor and affective domains of learning. However, there is a gap in the engineering education literature with regards to meaning making of mathematics concepts as applied to engineering problems. This paper is written as a configurative dialogue between two educators delivering and supporting teaching and learning of mathematics in two different European contexts and one supporting learning in a South African context. In sharing our practices, we realised that although an exhaustive list of frameworks for mathematics education exists, telling them apart in the context of engineering mathematics education can be difficult and often adds little actionable insights. This realisation motivates the title of this paper "Same but not The Same". We use the semantic plane of Legitimation Code Theory (LCT) to reflect on problem or scenario-based learning of abstract and/or complex mathematics topics such as linear algebra and differential equations through examples of their (engineering) applications. We argue that qualitative descriptions of meaning-making in open-ended, real-life mathematics problems, methods, and tasks are scarce, and that this can create significant challenges for educators to describe, share, and shape their practices.

Keywords: Engineering Mathematics, Applications, Abstraction, Real world problems, Semantics

1 Introduction

Engineering education change often envisions ambitious goals, such as rethinking what kind of engineer society needs (Guerra & Rodriguez-Mesa, 2021), what type of education best prepares students for dealing with open-ended, interdisciplinary and complex problems, and how curricula can be restructured to better reflect authentic engineering practice (Roach et al., 2018). Active learning approaches such as Problem-Based Learning (PBL) have become increasingly central to this vision, promising to develop students' academic achievement and transferrable skills such as social responsibility, communication, teamwork, and self-directed learning through engagement with real-world problems. However, there is a significant difference between envisioning educational change and operationalising and implementing it at the classroom level. Designing new curricula is one thing; designing actual activities, assessments, and learning environments that can operationalise any educational philosophy is another (Remillard & Heck, 2014).

In a review of the literature, Chen and coworkers (2020) identified a range of challenges faced by educators in the implementation of PBL, including the transformation in professional identity and acquisition of skills necessary for the transition from lecturers to facilitators, a lack of practical experience in multidisciplinary fields, the design and evaluation of materials and assessment, as well as limited institutional support or a lack practical resources in supporting the adoption of PBL. In mathematics-heavy disciplines such as engineering, these implementation challenges are particularly exacerbated.

Engineering and the natural sciences are fields with a "strong grammar" (Bernstein, 1999), where knowledge is built within a tightly regulated system of relational and methodological rules which might be out of scope for students to construct on their own. In adapting pedagogical approaches of such disciplines to contemporary educational paradigms, teachers must help students bridge abstract mathematical content via the naturalistic epistemologies of the applied sciences as well as the socio-constructive complexity and messiness of life in society (Sierpinska & Lerman, 1996). The practical implication is that educators seeking to transform their educational practices are not only required to rethink syllaba and classroom contents, but also how knowledge is presented, sequenced, transformed, and connected to other knowledges. In sum, there is a need to consider more carefully how mathematical meaning is made and how/whether meaning is construed in scenarios that are heavily bound by their context.

In this paper, we analyse meaning making in (engineering) mathematics by using the Semantics dimension of the Legitimation Code Theory (LCT) (Maton, 2014) to analyse educational practices within and across three different institutional contexts. In sharing our practices, we realised that although an exhaustive list of

frameworks for mathematics education exists, telling frameworks apart in the context of engineering mathematics can be difficult, and the similarities in learning objectives are often far more important than differences. Therefore, our main research question is:

RQ: *What are the organising principles of meaning-making in engineering mathematics PBL education across different institutional implementations?*

To answer this question, the paper is structured as follows: First, a brief description of institutional environments and objectives in mathematics teaching is provided, then artefacts used in our subsequent analyses are introduced. We move onto a brief introduction to LCT Semantics as a tool to conceptualise and reveal how meaning-making is organised within educational artefacts which is followed by individual and comparative an analysis of the three artefacts. We conclude by identifying organising principles behind different educational practices, such as Mathematics PBL, Integrated Engineering Mathematics, and cross-faculty Mathematics teaching to engineering students.

2 Three Institutional Contexts and Related Artefacts

In this section, three institutional contexts shaping the experiences of the authors of this paper are outlined and discussed. For each context, an artefact around the teaching and learning of mathematics is presented which is then analysed through the theoretical framework presented in Section 3. Following initial discussions around the theoretical framework and research objectives, each author selected an existing teaching artefact representative of their context which has been used within their institution.

2.1 Mathematics PBL at Aalborg University

Aalborg University (AAU) in Denmark has since its establishment in 1974 run a problem and project-based learning (PBL) curriculum at all faculties. Half of the students' time is typically used in traditional courses and the other half in PBL groups of up to eight students. Behind the curricula are shared PBL principles of, e.g., problem orientation, project organisation, students being responsible for their own learning as well as project planning, and feedback supervisors who act like facilitators.

The problems addressed in each study programme vary, but there is a tradition for contextualising disciplinary knowledge. Usually that students find a problem in society or within an application of mathematics in professional life fitting the thematic frames of a semester, then they analyse the problem in its context, formulate a more specific problem statement, and finally embark on a problem solution. In earlier semesters, students are often being given suggestions to problems in project catalogues as their level of subject knowledge is often not high enough to be able to formulate relevant problems from scratch by themselves (Kolmos et al. 2004, de Graaff and Kolmos 2007, Askehave et al. 2015).

AAU also has a study programme in Mathematics. Dahl (2018) argues that mathematics fits PBL as (1) The methods of working with mathematics are quite similar in PBL and in research, (2) The concept of society includes the society of researchers and professionals to whom (pure) mathematics is highly relevant, thus suitable for both the pure and applied part of mathematics. Dahl et al. (2023) further discuss different types of PBL-projects in mathematics ranging from projects that are solely driven by an external case, over projects where the concrete case more functions as an opportunity to learn the theory, to finally purely theoretical projects where the problem in internal to mathematics theory.

AAU Artefact

The artefact of analysis from AAU is taken from a 2nd semester group project with five students at Mathematics in 2018 (Simonsen, 2018). The project amounted to 15 ECTS, thus intending to take up have the semester (NB: In most of European countries, 60 ECTS is considered the workload of a full semester). A 5 ECTS course in Linear Algebra was provided at the semester as well as two other mathematics courses of each 5 ECTS. The overall thematic framework for this semester's project is linear programming, particularly

LPP (linear programming problems). With this framework, students chose their own specific angle. Author 2 acted as a co-supervisor of this project with the main supervisor being from the Department of Mathematical Sciences.

The group focused on the diet problem in linear programming. Here, the objective is to maximize or minimize for instance cost while finding the optimal amounts of foods satisfying various conditions of, e.g., nutrition, weight, etc. The specific problem the group worked on was to find the best foods to pack for a fictional one-week hike in the Swedish wilderness. This was a problem solely chosen by students themselves. The students took outset in discussing how heavy a backpack ideally can be considering the weight of a person, discussed limitations such as just putting an estimated weight on sleeping bags, tent, etc. They focus on the weight of the food, its nutrition in terms of proteins, carbohydrates, and fat and no other factors, to simplify the problem. The problem is solved using the simplex method.

2.2 Integrated Engineering Mathematics at UCL

UCL is a research-intensive university with a multi-faculty structure and a student cohort of over 6000 students in the Faculty of Engineering Science. In 2014, following a major curriculum review, the faculty introduced the Integrated Engineering Programme (IEP) as a shared programme framework across eight engineering departments (Mitchell et al., 2019). The establishment of the IEP resulted in a restructuring of mathematics education at UCL Engineering, where mathematics teaching was centralised under a new faculty-wide curriculum and delivered by engineering academics with expertise in modelling, simulation, and design. This was a move away from mathematics as a discipline-in-itself towards mathematics as a language and a tool, which was reflected in the name Mathematical Modelling and Analysis (MMA) for the main mathematics course undertaken by engineering students over their two first years of study.

In 2020, as a response to the migration to emergency teaching during the COVID-19 pandemic, MMA was redesigned to further align the teaching contents to disciplinary engineering practice. In each of the ten weeks of MMA1, over 900 students at UCL Engineering are introduced to a case-study that activates mathematical concepts and techniques and orients them toward a real-world problem or engineering application (Graham, 2022). For example, students learn about derivatives through modelling optimisation in family-run agriculture settings and integrals by designing non-invasive surgery protocols. The problems explored in the course are rooted in themes of social or environmental relevance (de Andrade & Makramalla, 2023), shaped by principles of critical mathematics literacy (Frankenstein, 1990) and critical mathematics education (Skovsmose, 2023).

UCL Artefact

The artefact of analysis from UCL is taken from MMA1's teaching resources introducing students to ordinary differential equations (ODEs) via energy balance on planet Earth through a zero-dimensional model (Marshall et al., 2007). The artefact is framed as a case-study explained via a series of videos recorded by a UCL academic. In the videos, the lecturer models Earth's average temperature in terms of incoming energy from solar radiation, outgoing energy due to light reflection, and energy trapped in the atmosphere caused by the presence of greenhouse gases. The videos outlining the case study are accompanied by content videos explaining the connections between ODEs and differential calculus, ODE terminology, notation and properties, as well as analytical and numerical solution techniques for ODEs which are connected to integration concepts and techniques. Videos explaining mathematical content are followed by automatically graded exercises implemented in the institution's Virtual Learning Environment (VLE) Moodle via the STACK plug-in which allows for personalised feedback and step-by-step solution guidance.

Later in the same week, students practice the contents learned through the asynchronous material in departmentally offered face-to-face workshops led by UCL Academics and facilitated by Teaching Assistants (TAs). The workshops are designed to provide students with opportunities to solve complex problems individually and in groups, where activities are scaffolded and facilitated by staff. In the workshops,

mathematical problems range from specific examples that extend or simplify the case-study as well as exercises in applying underlying modelling principles to different situations that are amenable to similar mathematical treatment.

2.3 Stellenbosch University's Mathematics in your Engine(ering)

South Africa (SA) faces significant challenges in the Higher Education (HE) sector, with consistently low throughput and retention, particularly in Science, Technology, Engineering and Mathematics (STEM) fields (CHE, 2022). Given the importance of these fields in addressing national and international Sustainable Development Goals (SDGs), the Department of Higher Education and Training (DHET) have invested significant funding to build educator capacity. All HE institutions have professional and academic support staff to assist lecturers in better understanding and implementing educational strategies across their curriculum, teaching, learning and assessment activities. The SA case study is based on an interdisciplinary group of engineering education researchers, along with science and engineering faculty academics at Stellenbosch University (SU), a research-intensive university in South Africa. Collaboratively, the group – around 10 key members - has been developing explanatory and foundational resources to better equip themselves and their students to integrate physics, chemistry and mathematics in engineering contexts.

SA has grappled with poor mathematics preparedness for HE for several years. Only 6% of the approximately one million school leavers have school mathematics eligible for application in STEM and Medical degrees (Nxasana, S., 2025). This means the available pool of students qualifying for Engineering is very small. The second challenge is that most SA HE institutions which offer engineering qualifications are reliant on science faculties to 'service' the required science and mathematics courses, particularly at first year level. 1st year engineering students are not, therefore, taught mathematics that explicitly links to their chosen degrees. Having conducted a 10-year cohort analysis on student performance and context in the engineering faculty, along with observational data from various academics and surveys, the collaborative research group targeted the first-year mathematics content. It became clear that students were not aware of why or how the mathematics they were learning was relevant to their chosen engineering degrees. The artefact analysed in this paper is a collaborative, multi-modal video demonstrating mathematical concepts such as vectors, differentiation and integration in the context of an internal combustion engine.

3 Theoretical Framework

We use Legitimation Code Theory (Maton, 2014) to analyse the organising principles within and across the different practices outlined in Section 2 in the teaching and learning of mathematics. LCT is a sociological toolkit based on Basil Bernstein's code theory. As a social realist framework, LCT is "theory agnostic" and can be used to analyse practice within and across diverse social ontologies. The basic premise of LCT is that actors in fields of practice simultaneously cooperate and struggle to align the field's language of legitimation closer to their own practice. In this sense, a language of legitimation is the compound system of values that define and measure achievement in a field, for example successfully applying abstract mathematical concepts in engineering practice.

3.1 LCT Semantics

Semantics is one of the dimensions of LCT that is employed to analyse meaning making in practices. LCT Semantics offers two analytical dimensions upon which meaning making is organised. The first dimension is semantic gravity (SG) which refers to the degree in which meanings depend on a specific context and is activated to analyse a continuum of possibilities between "abstract" and "pure" mathematics in engineering education. The second dimension is semantic density (SD), which refers to the degree in which meanings are condensed within a set of practices. LCT has been previously applied in the teaching of chemistry (Blackie, 2015), engineering (Wolff, Blaine & Lewis, 2021), and in defining semantic discontinuities in mathematics teaching (de Andrade et al., 2025). The two dimensions SG and SD exist theoretically within a continuum

ranging from strong (+) to weak (-) and can be topologically organised into a Semantic Plane, as shown in Figure 1.

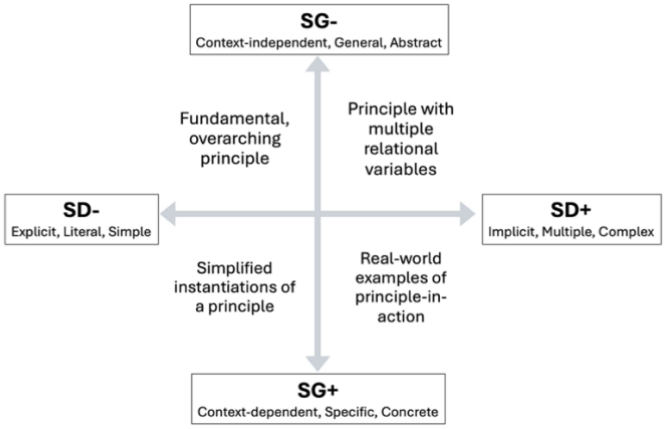

Figure 1: Semantic Plane, adapted from (Wolff et al., 2023).

4 Analysis and Discussion

Each author in this study individually coded the artefact related to their institution, and then all authors reconvened around the first author to discuss and compare coding.

4.1 AAU: Linear Programming Problems

This project is an Aalborg University project, where PBL is the overall educational framework. In PBL, the outset of work is usually an ill-structured problem, which through a problem analysis is then developed into a more narrow and concrete problem statement, which the project group then works on by applying elements from the general theory to find specific solutions. Hence, the *envisioned* semantic tour to be undertaken by students starts as concrete and complex problem (SG+, SD+), to be simplified as students choose boundary conditions and make choices and simplifying assumptions (SG+, SD-). Mathematics is activated via abstract and complex symbolic systems (SG-, SD+) which are used to solve break down the problem into simpler and general parts (SG-, SD-).

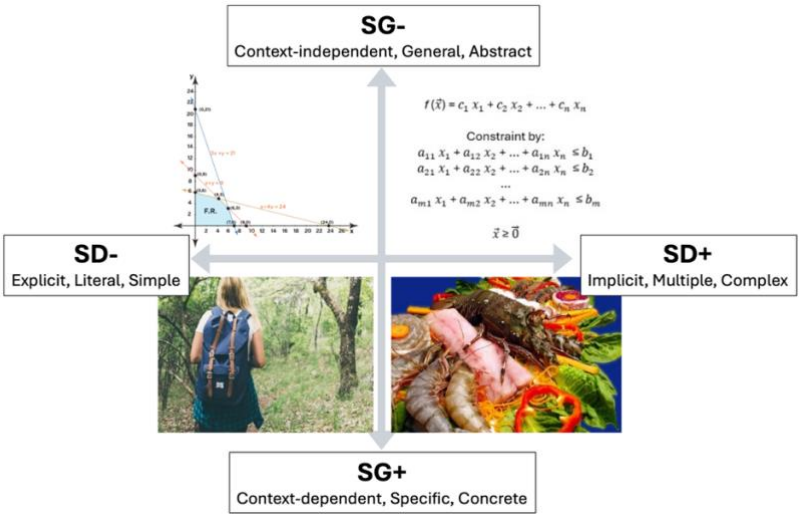

Figure 2: AAU Artefact on the Semantic Plane.

The final conclusions could, and should ideally, move the students back to the abstract world, both the concrete and the abstract to provide some insight into these, based on the group's work. However, often in practice, projects are what is termed Type 2 in (Dahl et al., 2023), where the case from practice often functions as an opportunity to learn a piece of theory. Therefore, the actual journey of the students might omit or skip the complex and concrete step (SG+, SD+), which in this case could be that humans in very different contexts need healthy food for reasonable prices, which naturally is subjective and context-dependent. This is only mentioned it in passing, as the real purpose of the project is to learn the theory with its multiple relational variables (SG-, SG+). In this case, the actual simple and concrete case (SG+, SD-) to some extent does drive the curiosity and motivation, but the case is not overly complex, as most students would instinctively know what to pack for a hike in the wilderness; or in practice they would never have asked mathematics for help.

4.2 UCL: Earth's Energy Balance

The MMA course has two main objectives: the first is to foster mathematical modelling competencies in students, and the second is to provide a solid knowledge foundation to aid students in carrying out complex algebraic manipulations and in implementing engineering problems in MATLAB (Nyamapfene et al., 2022). The case study of Earth's energy balance starts out with the presenter anchoring the concepts into real-world phenomena, such as incoming solar radiation, energy reflected from the Earth's surface, and energy trapped due to greenhouse gases (SG+, SD-). These components are then *conceptualised* as sources or sinks within an energy conservation system, where equilibrium is given by no change in energy.

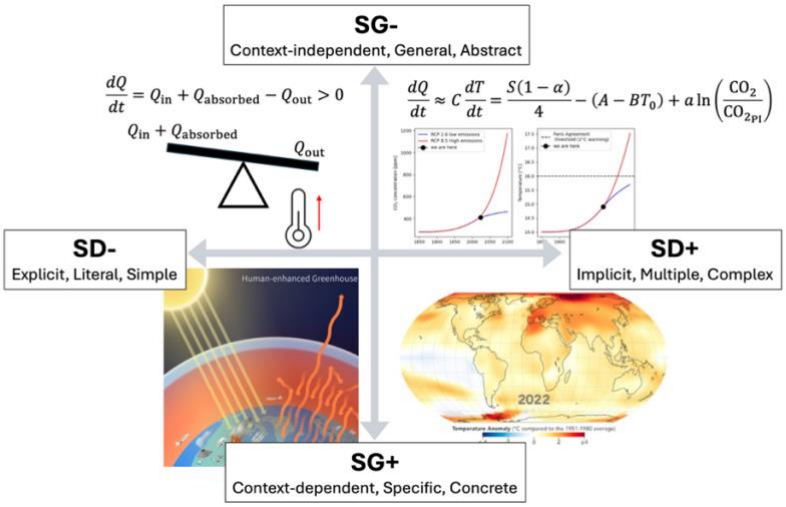

Figure 3: UCL Artefact on the Semantic Plane.

In natural language, this model is given as Change in Energy = Energy in - Energy out, which is then mathematised in canonical conservation law form (SD-, SG-). This movement towards abstraction serves to bridge concrete meaning into the abstract equation, which is then packed with more meanings via an exposition of the relational variables that compose it. For example, "Energy in" is given by solar radiation, but this radiation only reaches a part of Earth's surface at a time; or "Energy out" would be given by full reflection from the surface, but with changing areas of the polar cap this might need to be adjusted in the model on a yearly basis based on satellite data and must also deduce the energy that is trapped due to the presence of greenhouse gases in the atmosphere. This semantic heuristic that oscillates between complex and abstracts ideas and simple and concrete terms has been called a "semantic wave" elsewhere(SG-, SD+)⟷(SG+, SD-).

As a final step, the model denoting the principle of energy conservation and all its relational variables is linked back to the initial problem situation as a theoretical description of a real-world phenomenon. Later in the week, students have the opportunity to deal with this problem in a more concrete and complex form as they implement the model in MATLAB and retrospectively fit coefficients for energy trapped due to greenhouse gases from real-world average temperature on planet Earth (SG+, SD+).

4.3 SU: Mathematics in your Engine(ering)

The narrative in the SU artefact begins with "*Have you ever wondered where mathematics can be applied in engineering? Luckily, you don't have to look too far – If you've ever driven in a car (SG+, SD-), you've probably heard the noisy rumblings of the internal combustion engine (SG+, SD+)".* The narrator starts in the real world at a fairly simple level and quickly moves to the 'invisible' world of the internal combustion engine (ICE). Literally zooming into the ICE, she then isolates the slider crank mechanism, describes its sub-components (SG+, SD-). To understand how the mechanism works, she explains, we need "to understand some basic maths concepts", and she moves into the simple, abstract domain while providing an explanation of vectors (SG-, SD-). She keeps the explanation in the simple, abstract domain, including a graphic representation. As she unpacks vector basics, she adds layer upon layer of abstract explanations, such as the difference between 'dot' and 'cross' products, and then the role of differentiation and integration. These moves collaboratively increase the semantic density (SD ↑), but each time she adds a new element, she returns to the simple slider crank mechanism (SG+, SD-) to explain the relevance of the mathematics.

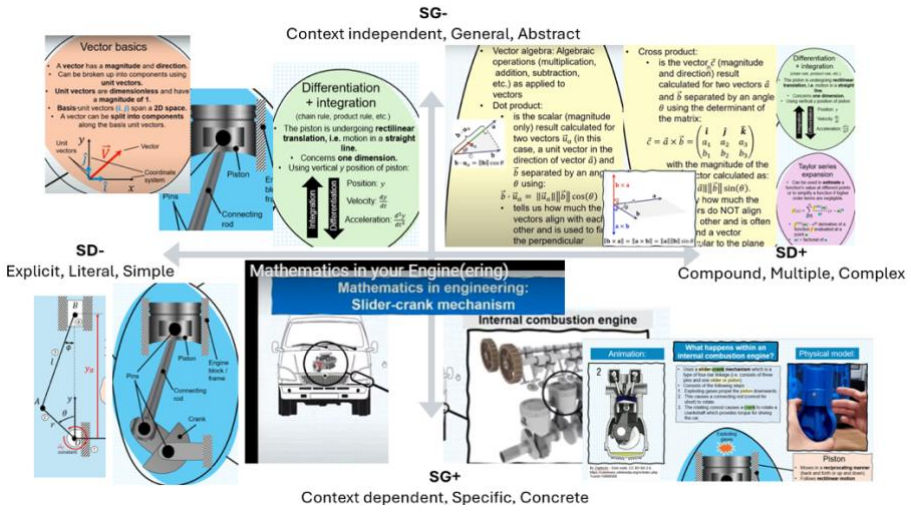

Figure 4: SU Artefact on the Semantic Plane.

The video resource demonstrates the continuous code-shifting along both axes as the narrator builds a picture of how mathematics is relevant in this particular engineering system. As a resource for students, it offers simple and increasingly complex guidance on each of the mathematical concepts using verbal, visual, symbolic and graphical modes of meaning-making. The team working on this particular resource report a significant development in understanding each other's disciplinary fields and how they can be combined to better aid students.

4.4 Revealing Organising Principles Within and Across Practices

In this paper, we have described three institutional practices aiming at bridging abstraction and concreteness in mathematics education. This description was followed by a configurative analysis through the lens of LCT Semantics, which analytically distinguishes between the degree of context dependence of meanings and the degree to which meanings are condensed within practices. By employing the Semantic Plane (Figure 1) we were able to outline a realist description of individual practices (Figures 2 – 4), revealing the principles that underpin meaning making in each of them.

The AAU artefact represented the semantic journey undertaken by students across a second semester project in Linear Algebra. Our analysis of this artefact revealed that student work in this project consisted of breaking down the complexity of a problem by setting boundary conditions and making simplifying assumptions (SD↓) as well as linking concrete simplified ideas to their abstract counterparts (SG↓). In this artefact, the (SG+, SD+) code is used as a motivator, but the life experiences of students supersede the intended socio-complexity of the problem and thus the (SG+, SD-) code serves as a relational anchor to access specialised mathematical objects and procedures (SD↑) that would have been otherwise counter-intuitive or difficult to construct individually.

The semantic journey in the AUU problem is thus based on a simple-concrete code (SG+, SD-) and focused on complex-abstract or simple-abstract codes (SG-, SD+) or (SG-, SD-). In discussing this artefact, we were able to identify that in Mathematics PBL there might be a distinction between *envisioned* and *enacted* semantic journeys. That is, ideally a Mathematics PBL project would start from a real-world problem (SG+, SD+), proceed to simplify it (SD↓) and then abstract and re-pack meaning into it (SG↓, SD↑). However, the *enacted* journey might mention the (SG+, SD+) code in passing such that students work mostly from the more relatable (SG+, SD-) code, defined as a Type 2 Project (Dahl et al., 2023).

One could discuss if this is a *weak* form of PBL practice since the main drive for student work is not based on the complex, ill-posed problem (SG+, SD+). However, using Skovsmose's (2001) framework of landscapes of investigation, we could argue that (PBL) investigation can also happen with reference to pure mathematics (as seen in SG-, SD+). Moreover, as discussed in Simonsen (2018) an investigation can occur in a *semi-reality* (SG+, SD-). Therefore, one could think of PBL as a way of working within the interplay of theory and practice, hence the actual "route" one takes is less important than the fact that one's work eventually embodies all semantic codes.

The UCL artefact represented a *scaffolded* journey presented to students in contextualising the importance and applications of ODEs, rooted in the urge to align engineering practices to Sustainable Development Goals (SDGs). In this practice, meaning is anchored in visual descriptions of planet Earth as a natural/engineered system so that modelling competencies of mathematising phenomena (SG↓) foreground formal mathematics. The semantic journey follows in waves towards "packing" real-world and algebraic meaning into the basic equation representing energy conservation principles, and each source or sink in the system receive a specific algebraic form that is rooted in close approximations to the real-life situation at hand (SD↑). The explanation ends back at the (SG+, SD-) code, where the initial visual representation of the problem is compared to the principle of energy balance with its relational variables.

The semantic journey in the UCL Artefact is then also based in a simple-concrete code (SG+, SD-), but focuses on preparing students to solve problems in a (SG+, SD+) code. That is, later in the week students implement the model of energy balance on planet Earth in MATLAB with the objective of calculating both Earth's equilibrium temperature (stationary approximation) and also parameterising coefficients the equation based on real-world data (SG+, SD+). Within this stage of learning, students face complex questions such as: "*what is the effect of a shrinking polar cap on the energy reflected from Earth's surface?*" or "*how could this model be improved toward modelling space-dependent reflections in areas of high concentration of greenhouse gases?*".

Similarly, the SU artefact is based on a (SG+, SD-) code which is an anchor to the complexity of an engine (SG+, SD+). Mathematical topics are introduced in the (SG-, SD-) code and the density of meanings is progressively strengthened in abstraction (SD↑), recurring to simple-concrete descriptions (SG+, SD-) in order to avoid losing practical relevance. Most interestingly, although this artefact cumulatively "packs" meaning into the ideas of vector and their products, as well as oscillations and their differential and integral forms, it avoids lingering in a (SG-, SD+) code. This absence points to the purpose to which the artefact has been designed which is to contextualise how mathematics is present in engineering design and practice, or in other words, to strengthen the semantic gravity of mathematics topics (SG↑). As mentioned in Section 2,

the SU artefact is different from the AAU and the UCL counterparts in that was designed collaboratively between engineers, physicists, chemists and mathematicians as a support resource to enrichen students' understanding of mathematics in practical engineering design. The semantic journey in the SU Artefact is then based on (SG+, SD-) codes but does not focus on a particular code, but rather on foregrounding semantic gravity shifts (SG↑↓) which naturally build up semantic density (SD↑).

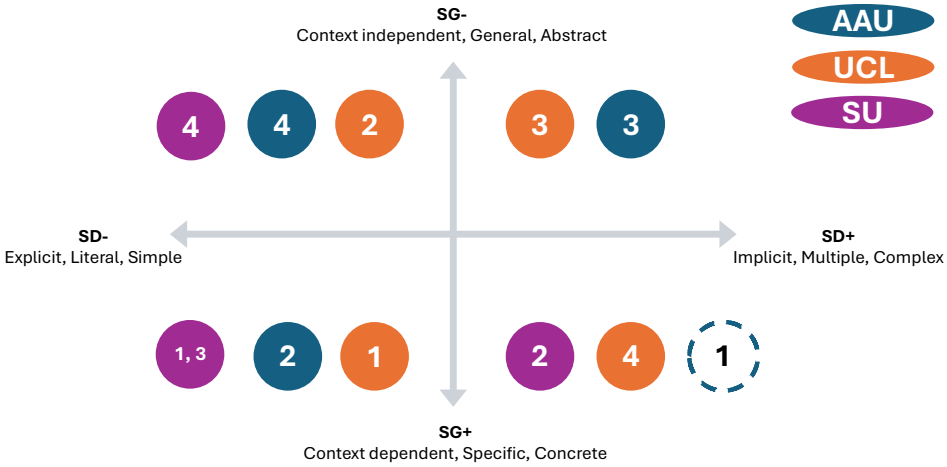

Figure 5: Comparison of semantic journeys across practices. Numbers within circles represent main semantic stages within practices. Blue circles are used to represent AAU, orange circles represent UCL, and purple circles represent SU. The dashed line in stage 1 for the AAU artefact accounts for a possible weakening of SD in this code in practice.

Figure 5 shows a two-dimensional visualisation of the three practices analysed in this paper mapped onto the semantic plane with respect to four of their main stages as coded individually by the authors of the study in their home institutions. The analysis shown in Figure 5 is then conceptualised as an analysis within, as opposed to across, practices to gain insight onto situated semantic journeys related to different ways of thinking about bridging the gap between mathematical abstraction and concrete applications.

The most important similarities between practices seemed to be an anchoring in (SG+, SD-) codes so that mathematical content is relatable, and the mathematical theory has an explicit equivalent in real-life that does not include complexity that is added from technical or socio-cultural aspects, which would result in (SD↑). Across practices, a (SG-, SD+) code was only present in instances where students were involved in solving a problem that involved a high degree of technicality and condensation of mathematical meaning, such as the Linear Programming Project or the Earth Energy Balance scenario.

In our analysis, a (SG+, SD+) code was strongly visible in two instances. First, when contextualising a problem that has both technical and socio-cultural aspects (AAU), and second when implementing complex models via computer programming (UCL). It is important to note that although within the SU artefact there were clear instances of (SG-, SD+), these were not highlighted by Author 3 as stages where the artefact "stayed" for too long. Rather, the objective of the artefact was not to guide students into a semantic context where complexity was required, but to contextualise the connections between mathematical objects and operations such as vectors and vector products and their real-life counterparts in an engine (SG↑↓). Another similarity between the AAU and the SU artefact was an emphasis in "packing" and "unpacking" meaning within (SG+), that is, both artefacts involved a shift from (SG+, SD+) to (SG+, SD-), where the SU artefact presented a "there and back again" tour with stages 1 through to 3 within (SG+).

5 Conclusions and Future Work

In this paper, we have used LCT Semantics to investigate the organising principles underpinning educational practice aimed at bridging the gap between mathematical abstraction and real-world engineering applications. We individually coded three separate artefacts from different institutional contexts in terms of semantic gravity (context dependence of meanings) and semantic density (condensation of meanings into a practice). These artefacts served different educational purposes, where one was undertaken as a semester-long project in a PBL course in linear algebra, the other was presented as a series of videos introducing the real-world significance of ODEs in engineering practice, and the last one aimed at connecting mathematical and engineering meanings in a combustion engine for engineering students and multidisciplinary faculty. Our analyses revealed three distinct semantic journeys shown in Figure 5, each related to the specific context of education and the learning objectives of the artefacts under analysis.

Across all three cases, LCT Semantics provided a configurative language for describing and comparing how mathematical meanings are introduced, transformed, and operationalised. This analysis makes visible the often-implicit pedagogical designs behind mathematics tasks and offers a conceptual toolkit for ensuring that design of mathematics education resources is intentional, inclusive, and connected to students' lived experiences. More importantly, LCT Semantics proved equally useful in mapping out practices across seemingly incompatible social ontologies such as socio-constructivism in PBL and the scientific realism of research-based educational case-studies.

Linking back to our motivating problem, which was the absence of clearer analyses of what characterises PBL teaching and learning in engineering mathematics, we could analytically distinguish three important components in contextualising mathematics in engineering mathematics which are useful for educators in designing problem-based learning of mathematics in engineering.

- Firstly, the presence of (SG+, SD-) codes in all artefacts pointed towards the use of simple everyday language as well as visual aids in grounding and anchoring the understanding of students in studying mathematics in engineering. This was a seemingly invariant code in all artefacts where all practices effectively started (note that the AAU artefact was classed as a Type 2 problem).
- Secondly, two main shifts in meaning-making were identified. The first comprised weaking semantic density within strong semantic gravity (simplifying problems), which involves breaking down a complex (SD+) and concrete (SG+) situation into constituent parts in everyday language (SD↓). The second included weakening semantic gravity (mathematising phenomena and their relationships), which consisted of using equations and symbolic variables to represent a concrete problem-situation via a mathematical model (SG↓). This second practice took place across SD+ and SD- instances.
- Finally, we have identified the possibility that semantic journeys in education might present both envisioned and enacted configurations, much similar to issues of alignment between intended and enacted curricula (Remillard & Heck, 2014).

As limitations to our study, we would like to highlight that the three artefacts coded were not one-to-one equivalent in that they were designed for different applications in different institutional settings. Furthermore, our LCT coding of the artefacts involved coding within artefacts, such that no comparisons between SG and SD across artefacts was made.

Future work in this area might involve research problems such as:

- Exploring intra- and inter-coder reliability when using LCT Semantics. Relevant research questions could be "To what degree different actors and their orientations change their coding of artefacts on the Semantic Plane?" as well as "To what degree the codes assigned by an actor change temporally or situationally?".

- Exploring student's perspectives on LCT Semantics. A relevant research question would be "To what extent do students perceive and conceptualise abstraction and complexity when solving real-world engineering problems and projects using mathematics?".

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Deploying Multidisciplinary AI-Personas to Enhance Critical Thinking and Communication Skills in STEM Education

Liezl van Dyk
Faculty of Engineering - North-West University, South Africa, Liezl.Vandyk@nwu.ac.za

Roelof Burger
Faculty of Natural and Agricultural Science - North-West University, South Africa, Roelof.Burger@nwu.ac.za

Jacoba H. Bührmann
School of Industrial Engineering - North-West University, South Africa, Joke.Buhrmann@nwu.ac.za

Abstract

This paper explores the integration of multidisciplinary AI personas as educational tools to enhance critical thinking, communication, and decision-making skills in STEM education. Drawing from two case studies at the North-West University, South Africa, students engaged with AI personas representing varied disciplinary perspectives in Decision Science and Environmental Science modules. In the first case, students applied the Analytic Hierarchy Process (AHP) to a business acquisition scenario, relying on AI personas to provide comparative input on decision criteria. The second case involved reflective essays on environmental worldviews, where students interacted with personas representing distinct ecological perspectives. It is concluded that AI personas across multiple disciplines can potentially enhance STEM students' critical thinking, engagement, and professional skills, provided their use is paired with structured methodological guidance and real-time instructional support. Keywords: AI personas, critical thinking, engineering education, decision-making, student engagement

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1 Introduction

Engineers operate in complex, multidisciplinary environments where effective communication and collaboration are essential for problem-solving and innovation. Engaging with professionals from diverse backgrounds—whether technical, managerial, or regulatory—demands the ability to convey complex engineering concepts clearly (GA 6: Professional & Technical Communication)(ECSA,2023). This responsibility includes the translation of technical findings for non-engineers, actively listening to stakeholders to grasp their needs, and synthesizing information from multiple sources to inform decision-making.Moreover, multidisciplinary collaboration is a cornerstone of modern engineering practice (GA 8: Individual, Teamwork & Multidisciplinary Collaboration). Engineers often work alongside experts in finance, environmental science, policy, and manufacturing, requiring not only technical expertise but also a deep appreciation for the broader social, economic, and environmental implications of their work (GA 7: Impact of Engineering on Society and the Environment)(ECSA,2023).

Social Role Theory offers a useful framework for understanding how learners adopt different roles during educational interactions. It suggests that behaviour is shaped by the expectations attached to social roles, which in turn influence communication patterns and engagement. Nguyen (2023) demonstrated that students interacting with AI conversational agents portraying peer roles—rather than authoritative expert roles—engaged in more meaningful, transactive dialogue. This indicates that simulating varied roles can foster empathy, critical thinking, and open communication, especially in multidisciplinary settings.

The incorporation of AI personas into STEM education provides a novel approach to cultivating these essential GAs among students. By simulating interactions with AI personas representing varied worldviews

and disciplinary backgrounds, students can practice and enhance their critical thinking and communication skills. This innovative methodology not only encourages empathy and understanding of diverse perspectives but also prepares students to navigate the complexities of their future professional environments. Despite growing interest in educational AI, the application of multidisciplinary AI personas in engineering education remains underexplored. This study addresses this gap by integrating AI personas into STEM modules to simulate realistic interactions with diverse stakeholders. In doing so, it aims to cultivate essential graduate attributes and prepare students for communication and decision-making challenges in professional practice.

2 Methodology

Two case studies were conducted at North-West University to implement AI personas in STEM modules: Decision Science for final-year Industrial Engineering students and Environmental Science for third-year Natural and Agricultural Sciences students.

In both case studies, a similar methodological approach was adopted:

First, A specific problem was defined, requiring students to gather information from multiple stakeholders. Then, AI personas were created through prompting techniques to emulate typical individuals with whom students would need to engage and students were provided opportunities to interact with these personas.

In both cases the Mindjoy platform was used (www.mindjoy.com). Mindjoy is an embedded AI system for STEM education, using prompting to create AI assistants and personas that enhance learning. By crafting structured prompts, users generate AI tutors or mentors that guide students, support inquiry-based learning, and adapt to individual needs. These AI personas provide expert knowledge, interactive problem-solving, and contextualized feedback, fostering engagement and deeper STEM understanding. For each of these two case studies the 1. Background and Assessment Outcome is described, followed by the rationale for 2. Selection and Creation of Personas. Then the 3. Engagement Process is described followed by 4. Reflection by the respective lecturer and 5. Conclusions. Findings and conclusion from respective case studies are culminated towards final conclusions and recommendation for future work.

3 Case Study 1: Decision Science

3.1 Background and Assessment Outcome

The assignment aimed to assess students' proficiency in applying the Analytic Hierarchy Process (AHP) (Vaidya & Kumar, 2006). Introduced by Thomas Saaty in 1977 (Saaty, 1977), AHP is a tool used in multi-criteria decision-making to evaluate alternatives and develop a weighted scoring model for selecting the best option (Vaidya & Kumar, 2006). In general, weighted scoring models involve first identifying the criteria for evaluating decision alternatives (Saaty, 2001b). Each alternative is then compared against the others for each criterion, resulting in a comparison matrix. Additionally, a separate matrix is created to compare the criteria themselves, determining their relative importance. After these matrices are established, a sum of products calculation is performed to derive the final weighted scores of the alternatives. The alternative with the highest score is recommended.

AHP differs from traditional weighted scoring methods in both how scores are assigned and in its built-in mechanism for detecting decision-maker bias, known as AHP consistency (Saaty, 1977). Instead of evaluating all alternatives simultaneously, AHP uses pairwise comparisons, with Saaty arguing that comparing two options at a time helps reduce bias and leads to more accurate evaluations. Scores are assigned using a logarithmic preference scale ranging from 1 to 9 (Saaty, 2001a; 2001b), with a variant of this scale introduced to students in their textbook (Taylor, 2013). Grounded in the Weber-Fechner law for response to a stimulus, the scale follows a logarithmic progression to more accurately capture differences in relative importance between alternatives. To further ensure rigor, AHP incorporates consistency checks that verify the logical coherence of pairwise comparison matrices (Saaty, 2008). These checks flag contradictions in scoring, such

as preferring A over B, B over C, but then C over A, prompting a review to correct inconsistencies and strengthen the decision-making process (Saaty, 2001b).

3.2 Selection and Creation of Personas

The assignment tasked students with determining the best location for Sunrise Cookies to acquire an existing bakery from a competitor. Sylvester Kodal, CEO of Sunrise Cookies, recently learned that Brokers Cookies, a rival brand, was downsizing and selling off some of its bakeries. He identified three potential locations within budget: Bloemfontein, Pietermaritzburg, and Nelspruit. To guide the selection, the CEO chose three evaluation criteria and specified how these criteria should be weighted relative to each other. Additionally, he designated key personnel to provide insights for comparing the locations based on each criterion:

- Expected monthly expenses – Kobus Marais, Financial Manager
- Marketplace potential of each location – Anya Shezi, Marketing Research Analyst
- Impact on logistics – Johnny Kosil, Distribution Manager
- The AI prompts for each of these personas can be provided by authors.

3.3 Engagement Process

Students were required to interview four AI personas representing the CEO and the three keypersons. Each persona provided the necessary information to construct a pairwise comparison matrix. To mimic real-world constraints, these AI personas were programmed as busy professionals, offering only limited time for interviews. This scenario was designed to challenge students to effectively gather essential information and apply their understanding of AHP to recommend the optimal decision. The AI personas were designed without any understanding of AHP or technical knowledge. Their role was solely to assist with comparisons within their specific areas of expertise. In preparation, students were provided with lecture material and attended two in-person lectures covering the concepts of AHP. Additionally, they were required to work through AHP consistency calculations. To support their learning, a separate AI tutor persona—familiar with the lecture content—was made available to answer questions related to theory and calculations.

The primary objective of the assignment was to assess students' ability to comprehend and apply the concept of pairwise comparisons within AHP. Students needed to understand how to conduct these comparisons, use the 1–9 preference scale provided in their textbook (Taylor, 2013), and effectively interview non-technical individuals to gather the necessary input for constructing comparison matrices. They also had to recognize the importance of performing AHP consistency checks on the scores obtained.

To ensure individual engagement, students were assigned randomly to different instances of the company, each featuring the same AI personas but with slightly varied comparison scores. This variation led to different recommended bakery locations across instances. Furthermore, in each instance, two of the AI personas—the CEO and either the marketing research analyst or the distribution manager—provided comparisons that resulted in AHP inconsistency scores. This design element was intended to challenge students to identify and address inconsistencies in their analyses.

Students were required to construct the comparison matrices, calculate the AHP consistency scores, and return to the individual AI personas whose input resulted in inconsistencies, requesting them to review and revise their choices. The AI personas were programmed to adjust one pairwise comparison—specifically the one causing inconsistency—when prompted by the student, thereby ensuring a consistent matrix. Any change made by the CEO in response to such a prompt would lead to a different location emerging as the top-scoring alternative. To minimize confusion, AI personas who initially provided consistent scores were not assigned alternative responses. This design choice emphasized the importance of students thoroughly completing their calculations before requesting score revisions, discouraging arbitrary re-interviews with all personas.

3.4 Reflection by Lecturer 1

Prior to the assignment, most students expressed enthusiasm and a positive outlook toward engaging with the AI personas to gather the required data. They were advised not to expect uniform responses from all personas, which successfully encouraged students to interact with all assigned personas in their individual company instances. The rate of plagiarism was low, indicating that most students completed the assignment independently and submitted original calculations. This also suggests that students felt confident in their understanding of the material. However, a significant portion of the cohort struggled with fully grasping the concept of pairwise comparisons. Rather than prompting the AI personas for step-by-step pairwise evaluations, many students requested general summaries or direct comparisons of all locations at once. This approach reflects a misunderstanding of Saaty's key principle of moving away from simultaneous weighted scoring of multiple alternatives, toward focused pairwise evaluations to reduce bias. Many students appeared eager to obtain quick answers, opting for summarised information rather than guiding the AI personas through proper pairwise comparison procedures.

Another common misconception among students was a lack of understanding regarding Saaty's non-linear 1–9 preference scale. Although the AI personas were programmed to provide preference descriptions aligned with the correct scale, many students bypassed these cues and instead asked the personas to assign a numerical value between 1 and 9 directly. In 26% of submissions, students failed to properly introduce the scale to the AI personas and neglected to verify the precise phrasing provided in double quotes. As a result, they accepted numeric values that did not align with Saaty's scale. In some instances, students insisted on receiving a numerical rating without considering the qualitative meaning behind the values, leading AI personas to respond with values based on a linear interpretation, thus distorting the intended scoring.

Additionally, in 15% of cases, students failed to perform AHP consistency checks on their pairwise comparison matrices. These students had minimal interaction with the AI personas—averaging only seven exchanges—and did not follow up to clarify or correct inconsistencies. While 21% of students correctly identified inconsistencies, 15% of them did not prompt the AI personas to revise their scores, even after inconsistencies were detected.

The use of AI personas was a valuable tool for teaching students how to engage with individuals to obtain information necessary for applying theoretical concepts. However, the results highlight the need for a shift in mindset. Many students approached the interactions with the AI personas as merely a different way to obtain data for calculations, rather than as an opportunity to develop real-world skills in information gathering and critical thinking. This could further enhance their skills in GA 6 (Professional & Technical Communication) as well as their skills to consult with experts and contribution to teamwork needed in GA 8 (Individual, Teamwork & Multidisciplinary Collaboration). For future assignments, additional emphasis may be needed to reinforce that the core learning outcome is not just about deriving the correct numerical result, but about effectively interacting, interpreting, and applying theoretical knowledge in a practical context.

4 Case Study 2: Environmental Science

4.1 Background and Assessment Outcome

The Applied Geography third-year module at North-West University (NWU) is specifically designed to cultivate a deep understanding of sustainable practices, environmental management, and policy frameworks, thereby significantly enhancing students' graduate attributes. One of the central learning outcomes of the module requires students to articulate and critically reflect upon their environmental worldview, particularly within the South African context. To achieve this, an assignment was created based on Shume's conceptual framework from the chapter "Mapping Conceptions of Wolf Hunting onto an Ecological Worldview Conceptual Framework" (Shume, 2017), which identifies four distinct ecological worldviews: technocentric, ecocentric, egocentric, and resiliocentric.

The assignment tasked students with writing a reflective essay mapping their personal stance on climate change within South Africa. Students were expected to clearly articulate their perspectives by referencing specific examples of climate change impacts or policies, such as droughts, floods, and energy transition initiatives. Through this process, the students were encouraged to deepen their critical thinking skills and clearly communicate their positions in a structured and informed manner. The explicit goal was for students to not only understand the conceptual underpinnings of these worldviews but also to clearly express how their own views aligned or differed from these theoretical constructs.

4.2 Selection and Creation of Personas

The four personas were carefully constructed based on Shume's (2017) adapted ecological worldview conceptual framework, reflecting distinct beliefs regarding the human-nature relationship. Each persona encapsulates one of the four ecological worldviews—Egocentric, Technocentric, Ecocentric, and Resiliocentric—providing diverse and realistic perspectives for students to engage with.

Egocentric (Us vs. Nature): In this worldview, nature is considered something that needs to be controlled or subdued to safeguard human livelihoods. Thabo van der Merwe, a farmer from a traditional farming family in Limpopo, personifies this perspective. His upbringing in rural farming has shaped his strong belief in managing wildlife, particularly predators, to protect agricultural interests.

Technocentric (Us over Nature): This dimension emphasises technological innovation and human ingenuity as solutions to environmental problems, prioritising human benefit and resource optimisation. Mandla Mthembu, a recent graduate in environmental engineering from Johannesburg, embodies this worldview. His approach involves developing advanced technologies to address major South African issues like water scarcity and energy shortages.

Ecocentric (Us in Nature): The ecocentric view recognises nature's intrinsic value, advocating for minimal human interference and preserving ecosystems for their own sake. Zandile Mkhize, an environmental science student from the Eastern Cape with deep ties to nature, represents this dimension. Her passion for biodiversity and conservation stems from her personal and cultural connection to the natural world.

Resiliocentric (Us within Nature): This perspective acknowledges the intertwined relationship between humans and ecosystems, advocating for resilience and adaptability to environmental changes. Sibongile Nkosi, studying environmental policy at the University of Cape Town, personifies this worldview. Her analytical approach focuses on creating adaptive systems to address climate change and ecological shifts sustainably.

Students interacted with these personas through prompts designed to foster engaging, realistic conversations about various topics, including scientific issues, environmental management, political considerations, and even entertainment. The AI-driven personas did not explicitly state their worldview but demonstrated their ecological perspective implicitly through their responses and interactions. This methodology provided students with a nuanced understanding of diverse environmental worldviews and promoted critical thinking and reflective dialogue.

The AI prompts for each of these personas can be provided by authors.

4.3 Engagement Process

The engagement process entailed structured interactions between students and the AI-driven personas, encouraging exploration and debate around various environmental and socio-political issues pertinent to South Africa. Students could freely interact with each persona, posing questions or engaging in discussions that revealed underlying worldview assumptions. Through iterative engagements, students contrasted the personas' responses, gaining firsthand insights into how these worldviews differently shaped attitudes towards sustainability, climate change responses, resource management, and environmental ethics.

This interactive method effectively prompted students to articulate their views clearly by comparing and contrasting their own thoughts with those expressed by the personas. For instance, a student exploring drought management might engage Mandla's technocentric solutions emphasising technological interventions like desalination, Zandile's ecocentric advocacy for ecosystem preservation, Thabo's egocentric focus on protecting agricultural interests, and Sibongile's resiliocentric emphasis on adaptive strategies integrating both ecological and social dimensions. By experiencing these differing perspectives, students were better positioned to reflect critically on their own beliefs, enriching their reflective essays with nuanced understanding and well-supported arguments. The dialogue with personas encouraged deeper, more holistic reflections, moving beyond superficial analysis to genuine introspection about environmental challenges and potential solutions in the South African context.

4.4 Reflection by Lecturer 2

The integration of AI personas profoundly enhanced student engagement and learning outcomes, as noted by the lecturer overseeing the module. Students demonstrated significantly increased enthusiasm and critical depth compared to previous iterations of the module without AI interaction. Observations revealed a marked improvement in both the quality and analytical depth of the essays submitted.Notably, conversations after the assignment revealed students' high levels of enjoyment and intellectual stimulation derived from persona interactions. Many students described these exchanges as transformative, expressing that their discussions with the personas helped them to remember the complex paradigms and apply these insights effectively during examinations. The interactive format provided students with a "safe space," enabling even those who identified as introverts to freely engage in debates without fearing judgment or ridicule. Several students explicitly noted that the personas allowed them to ask questions they might have otherwise hesitated to raise, deepening their understanding and appreciation of diverse environmental viewpoints.

From the lecturer's perspective, using AI personas represented a groundbreaking educational strategy, substantially enriching classroom dynamics and fostering an inclusive, participatory learning environment. The nuanced dialogue facilitated by AI allowed students to explore challenging concepts interactively, prompting richer reflection on the broader ethical, societal, and practical implications of their engineering decisions. The lecturer emphasised the value of quantifiable engagement metrics provided by the MindJoy platform, which supported the qualitative observations of enhanced student involvement and deeper critical reflection.

5 Conclusion

It is concluded that AI personas across multiple disciplines can potentially enhance STEM students' critical thinking, engagement, and professional skills, provided their use is paired with structured methodological guidance and real-time instructional support. The Decision Science case study revealed particular pedagogical areas that required further development despite the positive results. Students incorrectly understood AHP methodological principles by misunderstanding pairwise comparison procedures and Saaty's non-linear scale implementation. Educators should implement direct instructional guidance to present AI personas as practical tools for skill development instead of information sources. Students need structured guidance toward complete theoretical comprehension while learning methodical application methods to prevent shortcut behaviours. The Enivironmental Science case study conclude that, the AI persona strategy demonstrated a compelling potential to advance student learning outcomes significantly. It successfully promoted critical thinking, deeper engagement with complex sustainability issues, and clearer articulation of students' environmental worldviews, thus substantially fulfilling the module's educational objectives and contributing to the achievement.

The educational advantages of MindJoy are enhanced through its utilisation of an advanced platform. MindJoy enables lecturers to monitor student engagement levels and conceptual understanding through real-time metrics while helping detect learning difficulties and misconceptions. Educators gain actionable

insights that allow them to deliver targeted support to critical areas while refining their instructional methods dynamically and addressing learning gaps proactively. Real-time analytics enable lecturers to make immediate educational adjustments, which leads to better results for individual students and their entire class.

The deployment of AI personas from multiple disciplines stimulates substantial growth in critical thinking, reflective practice, and professional communication skills among STEM students. These interactive AI-driven experiences benefit students by connecting academic theory with real-world practice while preparing for complex multidisciplinary professional environments. Students showed remarkable progress in executing structured interviews and combining multiple perspectives while effectively explaining their analytical steps. The AI persona interactions significantly boosted student engagement, which became evident through both survey results and the enhanced quality of their assignment submissions. Students felt comfortable in the AI personas' virtual environment, enabling them to develop intellectual curiosity while openly engaging with advanced concepts even when introverted. Student engagement at this level proved transformative because it improved their understanding and retention of theoretical paradigms and led to academic benefits.

6 Future Work

As this was an exploratory study relying primarily on lecturer reflection, future research should explicitly incorporate student perspectives, assess long-term impacts on graduate attribute development, and test the approach across a broader range of disciplines to refine best practices for integrating AI personas into pedagogy.

The prompts used in the case studies are provided as addendums, and a valuable extension of this work would be to analyze the different approaches used in each case study to develop these prompts and compare them with best practices documented in the literature. Such an analysis could provide insights into optimizing prompt engineering for AI-driven tutoring in STEM education. A follow-up study could also gather student feedback to evaluate the effectiveness of the AI Persona and assess the extent to which it supports the development of the targeted Graduate Attributes. This could be achieved through surveys as well as by using the data analytics available within the Mindjoy platform, although ethical clearance would be required before such data could be collected and analyzed. Furthermore, the Mindjoy platform’s embedded AI-driven analytics offer potential for deeper insights into student engagement, learning patterns, and areas for improvement. Future work could explore how these analytics can be leveraged to enhance tutorbot interactions and refine AI-driven pedagogical strategies. These directions will contribute to refining the role of AI Personas in engineering education, ensuring alignment with pedagogical best practices and improving student learning outcomes.

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Investigating Student Engagement in Emerging Technology Career Pathways

Anthony Perry, Ph.D.
University of North Dakota, United States, anthony.m.perry@UND.edu

Jonathan Lee Montoya, Ph.D.
Kalmanovitz School of Education, Saint Mary's College of California, United States, *jlm53@stmarys-ca.edu*

Krista Steele
University of North Dakota, United States, k.steele@UND.edu

Abstract

This study asks the question: How do rural undergraduate engineering students perceive emerging technologies (ET) in relation to their educational and career goals? Conducting semi-structured interviews and using in vivo coding, results are grouped into three themes: defining emerging technology, choosing ET pathways in a sociocultural context, and academic and industry preparation. The findings highlight the complexity of aligning engineering education with evolving industry needs, especially as technologies like generative AI, advanced manufacturing, and biotechnology reshape the workforce. Students are drawn to ET for career aspirations, societal impact, or ethical and philosophical exploration, yet schools often lack opportunities to cultivate these interests. Out-of-school experiences, such as internships, play a key role in skill development. The study suggests that framing ET careers as a means to address societal challenges, rather than focusing solely on skill acquisition, could better align engineering programs with student aspirations. This research emphasizes the need to consider sociocultural factors when designing ET pathways and calls for a broader integration of ethical considerations into engineering curricula. Ultimately, this work challenges traditional engineering education models and advocates for more flexible, forward-thinking approaches to preparing students for an ever-changing technological landscape.

Keywords: Emerging Technologies, Engineering Education, Student perceptions, Career plans

1 Objectives

This study investigates how rural students in postsecondary STEM-related degree programs perceive emerging technologies relative to their college and career plans. We ask: **How do undergraduate engineering students perceive emerging technologies (ET) in relation to their educational and career goals?**

Historically, technology has altered the nature of work. In recent years, the usefulness of specific STEM skills in the labor market is rapidly decreasing (Deming & Noray, 2020). Newly emerging technologies (ET; e.g., generative AI, advanced manufacturing, and biotechnology) are likely to accelerate this trend. Given these changes, tightly coupling postsecondary education offerings with the technical skills-related needs of industry partners may not meet the long-term needs of students or the labor market.

Furthermore, students are drawn to ET-related educational pathways for many reasons. In addition to career interests, students may view ET as a problem-solving tool to address critical societal issues (Nazar et al., 2019) or see themselves as “philosophers of technology” (Vakil & McKinney De Royston, 2022) who critically examine the social, political, and ethical issues related to new and ETs. Framed this way, students may not be interested in applying technology skills in traditional STEM occupations but are still eager to engage with ET as part of their studies. Attracting students to technology-based college and career pathways already presents a challenge. Technology students are motivated by out-of-school experiences (Smit et al., 2020; Peppler and Warschauer, 2011) because schools provide few opportunities to develop technology-related interests, identities, and aptitudes (Puckett, 2019). Designing ET educational programs to meet the needs of prospective students and workforce stakeholders is a pressing and complex issue with little evidence about student perceptions of ET to draw from.

This exploratory, qualitative study investigates ET-related interests of students in postsecondary STEM or computing degree programs. Through preliminary analysis of in-depth interviews, we identified three major themes present in student interests: defining emerging technology concerning their future interests, choosing an ET pathway in sociocultural contexts, and preparation in academia and industry. The quality of educational programs to prepare students for ET in academia and industry. Future research can differentiate emerging technology careers from traditional STEM-related pathways by making visible the

multitude of sociocultural factors associated with emerging technology interests as it relates to workforce-related goals. Furthermore, practitioners can better attend to student interests by framing ET as a tool to address larger societal issues rather than context-free skills development.

2 Theoretical Framework

Selecting a program of study is an achievement-related choice shaped by an interplay of personal beliefs, perceived values, and socio-cultural context. **Situated Expectancy-Value Theory** (SEVT; Eccles & Wigfield, 2020) offers a lens for understanding such choices by emphasizing two proximal determinants: **Expectancy of Success (ES)**—the belief in one's ability to succeed in a specific task or program—and **Subjective Task Value (STV)**—the perceived worth or importance of that task. STV consists of four components:

- **Utility value** – the perceived usefulness of the activity for achieving current or future goals.
- **Intrinsic value** – the enjoyment or interest derived from the activity itself.
- **Attainment value** – the personal importance of doing well in the activity as it aligns with one's identity or core values.
- **Cost** – the perceived negatives, such as time, effort, stress, or the loss of alternative opportunities.

In STEM education, degree choices are frequently framed in terms of **utility value**—for example, selecting computer science as a pathway to a software engineering career (Jacob et al.,2021) However, research indicates that appealing solely to utility value may be insufficient for sustaining long-term engagement, particularly for students whose motivations are rooted in broader goals such as solving societal problems or engaging in ethical, political, or philosophical inquiry related to technology (Rosenzweig et al., 2022).

Traditional applications of SEVT in STEM tend to operationalize expectancy and value through quantitative measures focused on performance in academic math and science courses. While this has produced useful insights, such approaches have proven less effective when examining career aspirations in non-traditional or sub-baccalaureate pathways (Gottlieb, 2018) or in understanding why students pursue degrees in emerging technology fields (Perry, 2022). Furthermore, this quantitative orientation often overlooks the socio-cultural factors, informal learning experiences, and identity-based motivations that significantly influence decision-making.

To address these limitations, our study applies SEVT within a **qualitative, constructivist research design**. The constructivist perspective recognizes that students' perceptions and choices are formed through lived experiences, personal agency, and social context. We use SEVT not as a rigid measurement framework, but as a conceptual guide for interpreting how students weigh different forms of task value and assess their likelihood of success in ET pathways. This framing informed both our interview protocol—ensuring that questions probed multiple facets of task value—and our thematic analysis, allowing us to connect participants' narratives about identity, motivation, and socio-cultural context to the expectancy-value components.

By integrating SEVT with a constructivist approach, we aim to provide a richer, contextually grounded understanding of **how rural undergraduate engineering students perceive emerging technologies in relation to their educational and career goals**. This blended framework enables us to examine both the cognitive evaluations students make when selecting ET pathways and the socio-cultural environments that shape and sustain their engagement.

3 Methods

3.1 Participants

Three undergraduate engineering students from rural backgrounds in the midwestern United States participated in this study. "Rural" is defined here as residing in communities with fewer than 25,000 residents, located at least 50 miles from a major metropolitan area, and with a local economy primarily based on agriculture or resource-based industries. Participant demographics included: one mature-age student with a young family and prior work experience as a career and technical education (CTE) instructor; one traditional-age student with extensive family involvement in farming; and one homeschooled student with a strong interest in national security. All participants were enrolled in STEM-related degree programs at a public research-intensive university.

3.2 Recruitment

Participants were recruited via targeted emails to students in engineering and technology-related programs, using purposive sampling to identify individuals from rural backgrounds. Inclusion criteria required current enrolment in an undergraduate STEM-related program and residence in a rural area.

3.2 Data Collection and Analysis

Data were collected through semi-structured interviews conducted via Zoom. Each interview lasted approximately 45–60 minutes. The interview protocol included open-ended questions designed to elicit participants' definitions of emerging technology, motivations for pursuing ET pathways, perceptions of academic and industry preparation, and the socio-cultural factors influencing their educational and career choices.

Interviews were transcribed verbatim and analysed using in vivo coding (Saldaña, 2013) to capture participants' own language in describing their experiences. Initial codes were organized into thematic categories aligned with the research questions. Coding proceeded iteratively, with constant comparison across cases to refine categories. Themes were reviewed for coherence and were interpreted through the lens of Situated Expectancy-Value Theory (SEVT), focusing on expectancy of success and subjective task value components.

4 Results

Preliminary results from this coding process resulted in three main codes: defining emerging technology, choosing ET pathways in a sociocultural context, and preparation in academia and industry.

4.1 Defining ET

Study participants were asked to provide a definition of ET, including concrete examples. The participants defined ET in contrast to "existing" or "old" technology. From their vantage point, ET is often "technology or ideas that we already have… in theory. But it has not until now been practical." That is, when a technology is becoming widespread and useful, it becomes an emerging technology rather than a research and development project.

The specific examples of ET al. came from the participants' direct experiences, including artificial intelligence, additive manufacturing, biotechnology, and unmanned aerial systems. In their descriptions, participants described other key aspects of ET to provide efficiencies for end users, provide access to new scales of engineering (e.g., nanotechnology in medical applications), and its ability to "push the limits" of what is possible.

Additionally, each participant defined engineering as a tool to solve problems they were interested in. Participant #1 was very interested in using ET to improve his experiences as an outdoors enthusiast (a lifelong pastime and the industry he plans to work in). Participant #2 provided many examples of applying ET to real problems in his life running his family's farm and his rural community, and participant #3 was very interested in national security issues and saw ET as central to solving difficult problems in the industry.

4.2 Choosing ET pathways in a sociocultural context

Each student ascribed various factors associated with their choices to pursue a STEM-related degree program and to engage with emerging technologies. These factors, viewed through the lens of SEVT, include students drawing from multiple identities to bolster their attainment value in ET, seeing their postsecondary degree programs a merely a means to an end, and displaying a high degree of expectancy of success that they can be successful in ET-related pathways.

Identities

Each student described numerous identities contributing to their education choices and career aspirations. Participant #2 went as far as to declare, "I am emerging technology." Each participant described their identities in relation to being different from a standard student profile. Participant #1 was older, with a young family and a fourth-generation farmer. Participant #3 ascribed his identity as being a homeschooler which made him different from most of his classmates. The participants did not position themselves as "STEM people," generally, or in relation to any discipline. In fact, Participant #1 explained that being a "math person" was not needed to be proficient in the ET field he teaches, advanced manufacturing, and that math is a barrier for many students who might otherwise continue in ET pathways.

Postsecondary Education as Means to an End

Two of the three participants described their educational choices in terms of the external validity a STEM degree will provide (i.e., utility value). Participant #1 wants to remain in his current position as a two-year college CTE instructor and the other wants to work in the defense industry. They were all, "sick of being student[s]," as participant #2 put it, but acknowledged the importance of credentials to unlock career opportunities. The first participant felt the same way about his degree but also emphasized the intrinsic value of working with technology. He said, "for me it's a lot of my personal interest in the industries… that is where I enjoy spending my free time." While each participant acknowledged the utility value of their degree, it is not the most important factor driving their ET-related choices.

Self-efficacy through self-learning

Self-efficacy is the belief that one can be successful in a specific task (Bandura, 1977) and is very similar to expectancy of success in the SEVT model. Each participant described their self-efficacy with ET-related tasks deriving from their ability to work outside of formal contexts. Participant #1 described having 3-D printers in their dorm room and being self-taught through YouTube. Participant #2 feels like he's always had an aptitude for mechanical thinking developed through the encouragement of his family and access to tools at home. Participant #3 explained how the homeschooling environment helped him become a voracious reader and resourceful networker to facilitate "just-in-time" emerging technology learning. These examples all come from experiences outside of formal educational environments.

4.3 Preparation for academic and industry

Study participants described the role of emerging technology with respect to their views of academia and industry. Participant #2, who is heavily involved in research at the university, suggested that academia needs to focus on "the weird" because industry cannot take the risk to develop new technologies. Instead, what students learn in academic settings should transfer into industrial and consumer applications. Rather than being focused on learning technology, the participants described their interests as being driven to make a difference in a particular industry (outdoor sporting, healthcare, and national defense). Context-free, disciplinary learning was not of interest.

Without prompting from the interviewer, each student reflected on pedagogy in their classes and how it prepares them to engage with emerging technology. Universally, they found limited access to ET in coursework and within the university. As their confidence to be successful comes from their ability to self-teach, they prefer learning environments that foster this approach to learning. For example, one student chose a degree program because the department fully adopted an interest-driven, problem-based approach to learning even though the content area was not his first choice. Another suggests, "[ET]seems like it's easier to be picked up when it's not taught conventionally. When it's something you just have to want to use." Participants created ways to engage with and learn ETs despite little to no opportunity in their coursework or through university channels.

5 Discussion

This study set out to explore **how rural undergraduate engineering students perceive emerging technologies (ET) in relation to their educational and career goals**. The findings suggest that these perceptions are shaped by a combination of personal interests, local socio-cultural contexts, and self-directed learning experiences, rather than by the formal curriculum. Participants valued ET not only for its utility in securing a credential or career advancement but also for its potential to address issues they care about—such as improving agricultural processes, enhancing outdoor recreation, or contributing to national security.

Through the lens of Situated Expectancy-Value Theory (SEVT), these perceptions reflect both **expectancy of success**—often grounded in skills developed outside formal education—and varied forms of **subjective task value**. While utility value was acknowledged, intrinsic and attainment values appeared more central to participants' engagement. Notably, all participants described formative ET learning experiences occurring outside of coursework, indicating that formal programs are not fully meeting their needs for hands-on, interest-driven engagement.

This research also highlights the influence of rural contexts on how students form their perceptions of ET. Participants' understandings of ET were closely tied to technologies with clear relevance in their local communities. This local grounding served as a strong motivator, yet it also risked limiting awareness of the wider possibilities ET offers. Providing curricular opportunities to engage with a broader spectrum of technologies and their societal applications could help rural students imagine a wider range of potential roles and career pathways.

From a theoretical perspective, this study demonstrates that SEVT can be meaningfully applied to the study of ET in rural engineering education, but that a purely quantitative operationalization may overlook key socio-cultural influences. A constructivist approach allowed these influences to emerge, providing a richer understanding of how perceptions are formed and sustained.

5.1 Limitations

This preliminary work is based on three participants already engaged in STEM pathways; as such, the results may not generalize to rural students with different levels of exposure to ET. Further research should examine a larger, more diverse sample, including those not currently in STEM programs, to capture a broader range of perceptions.

6 Scholarly Significance

These preliminary results provide scholarly implications for applying SEVT in ill-defined domains (e.g., emerging technology) and revisiting the degree to which coupling postsecondary education programs and local labor market trends serves student needs. Students interested in emerging technology career pathways were largely interested in "traditional" technology-based postsecondary education and ascribed their trajectory into ET pathways as being largely unrelated to any formal school-based experiences. The

kinds of formal learning experiences students sought (pedagogically and technologically), were mostly absent at the university. While previous technology-based career studies find student interests are largely driven by out-of-school experiences (Smit et al., 2020), these students are similar and they also create ET-related learning experiences outside of formal learning environments.

Furthermore, the results from this study provide a framework to scope the domain of "emerging technology." As more student data is collected in the scope of the larger project from which this data is drawn, including from a more diverse group of students who may not already be pursuing ET-related pathways, a more coherent student-centered definition of ET can be generated. The definition could be tested in more traditional SEVT survey research to address the limitations of math- and science-centric approaches to STEM career pathways studies (Gottlieb, 2018; Perry et al., 2022).

Future research can also build from these results to consider two aspects of pedagogical change to create and sustain ET pathways. First providing youth access to ET during the school day, a known issue in technology-related pathways (Puckett, 2019) is a critical issue. Second, creating more problem-based learning experiences that focus on addressing community needs through ET (e.g., Nazar et al., 2019) would be appealing to many young people who may not choose traditional STEM programs but are engaged with ET.

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Design-Expert to Streamline Chemical Engineering Experimental Research and Development: Mixed-Method Perspectives

Rishen Roopchund*
Department of Chemical and Materials Engineering, University of South Africa, Johannesburg, 1709, South Africa
roopcr@unisa.ac.za

Naadhira Seedat
Department of Chemical Engineering, University of Pretoria, Pretoria, 0028, South Africa, naadhira.seedat@up.ac.za

Olawumi Oluwafolakemi Sadare
Energy and Bioproducts Research Institute, College of Engineering and Physical Sciences, Aston University, Birmingham B4 7ET, United Kingdom, wumisadare@gmail.com

Kapil Moothi
School of Chemical and Minerals Engineering, North-West University, Potchefstroom, 2250, South Africa, kapil.moothi@nwu.ac.za

Abstract

This paper presents an overview of Design-Expert, a statistical experimental design tool, in optimizing chemical engineering research and development. A mixed-method approach is adopted in the study by using quantitative literature findings of diverse experimental studies incorporating the use of Design-Expert and qualitative findings stemming from a focus group study with four cross-institutional chemical engineering research supervisors. While the quantitative literature studies demonstrate the effectiveness and capabilities of Design-Expert across multiple fields of study, the qualitative study is based on the perspectives, experiences and recommendations of the research supervisors concerning Design-Expert. The qualitative study was structured with five main sections: the integration of Design-Expert into research activities, the effectiveness and outcomes of Design-Expert, management of academic priorities incorporating the use of Design-Expert, research skills and development concerning the training of postgraduate students in applying Design-Expert into their research, and the broader impacts and collaborations facilitated by Design-Expert. Overall, the findings indicate substantial positive findings concerning the productivity and quality of research outcomes incorporating the use of Design-Expert.

Keywords: Design-Expert; Experimental Research; Statistical Experimental Design; Research Optimization; Research and Development

1 Introduction

Chemical engineering academics typically balance four core responsibilities: teaching, research and supervision, community engagement, and academic leadership. Of these, research often receives the greatest emphasis, as it directly influences a university's global ranking and annual government funding. Unlike many other engineering disciplines, chemical engineering research is largely experimental, requiring extensive laboratory or pilot-scale work to generate meaningful results. Supervising numerous experimental projects across undergraduate and postgraduate levels presents logistical challenges, including delays in equipment and materials procurement, scheduling bottlenecks for shared instruments, and prolonged

analysis times. These factors frequently hinder timely project completion. To address such challenges, this paper explores the potential of Design-Expert, a statistical software package widely used for experimental design (DoE), data analysis, and process optimization. The software's intuitive interface and detailed analytical outputs provide valuable insights that can enhance experimental research efficiency. As technological innovation continues to transform pedagogical practices in higher education (Roopchund, 2022; Roopchund & Seedat, 2023), similar innovations in research practice are equally vital. This paper therefore outlines the value of Design-Expert in chemical engineering research, drawing on recent literature and the authors' experiences as chemical engineering academics at a South African university. The discussion highlights specific cases where Design-Expert has supported research progress and completion.

2 Literature Review

2.1 Overview of Design-Expert Optimizations

According to Njoku and Otisi (2023), quadratic models are typically used when dealing with several response factors, while the experimental central composite design (CCD) forms part of the optimization process. Statistically, a CCD is helpful in response surface methodology (RSM), for creating a quadratic model without using a three-level factorial experiment (Bhattacharya, 2021). After performing the designed experiment, iterative linear regression is used to obtain results. Optimizations are done by identifying and improving the independent factors, before RSM can be used to establish relationships between the process variables and their responses.

Overall, design of experiment (DoE) is a statistical approach that involves planning, analyzing, conducting, and interpreting experimental data (Skartland et al., 2011). When dealing with a CCD, a response surface involves a dimensional plot of the experimental results. RSM describes the experimental designs through response surfaces (Skartland et al., 2011). A factor controls an outcome. The output change occurs by manipulating the input factor(s) and can be set at different levels depending on the experimental conditions. These levels could be high, mid, or low (three-level design) or only high and low (two-level design). A response is the result of the experiment's effect, caused by changing the values of the predictors. A model is an equation expressing the relationship between responses and the factors under investigation. The outcome can be represented as a function of the experimental factors.

Optimization design seeks to minimize undesired outputs or maximize desired outputs. Often, simple linear and interaction models inadequately represent the nuances of the process. Therefore, response surface designs are used for fitting quadratic models, of which the CCD and Box– Behnken designs (BBD) are most common.

2.2 Diverse Studies using Design-Expert

In the pharmaceutical study of Hooda et al. (2012), Design-Expert was used to optimize gastroretentive ranitidine HCl microspheres. Specifically, the study involved the development and optimization of drug entrapment and bio-adhesion of multi-unit chitosan-based floating system containing Ranitidine HCl by ionotropic gelation for gastroretentive delivery. In this study, the effect of various process variables, including the drug polymer ratio, sodium tripolyphosphate concentration and stirring speed on various physiochemical properties, such as drug entrapment efficiency, particle size and bio-adhesion was optimized using CCD and analyzed using RSM. The observed responses coincided well with the predicted values indicated by the optimization technique.

The chemistry study of Popoola (2019), aimed to investigate activated carbon prepared from walnut shell and rice husk wastes for Cd(II) removal from aqueous solution using artificial neural networks (ANN) and Design-Expert as the design and optimization tools. The results from the two-level factorial DoE indicated a 78.58% Cd(II) sorption efficiency at optimum calcination temperature, calcination time, snail shell-rice husk mixing ratio and magnetite loading of 859.20 ˚ C, 2.32 hours, 2.54 and 5.56 wt% respectively. The calcination

temperature was identified as the most influential factor in adsorbent preparation based on sensitivity analyses. The prepared adsorbent was found to effectively remove Cd(II) from solution to a greater extent than commercial activated carbon with economic viability.

The food technology study of Singh et al. (2020) aimed to optimize the drying of red grapes to raisins using Design-Expert. The grapes were dried using the independent variables of blended oil (1:1 ratio of olive and clove oil) and temperature, generating responses in terms of drying time, acidity, total sugars, ascorbic acid, and phenols. RSM optimization was undertaken in 13 runs. The optimum conditions were 11% blended oil concentration and 63.4°C drying temperature with drying time, acidity, total sugars, ascorbic acid, and phenols of 22.80 hours, 1.26%, 64.2%, 5.60 mg, and 924 mg, respectively. Considering the challenges of maintaining the nutritional quality and shelf stability of fresh harvest, the Design-Expert application in this study was beneficial. Furthermore, statistical modelling can maximise success rates, yielding shelf stable fruits (raisin) that explore the application of oil dehydration to other fruits and vegetables of immense nutrition and shelf stability concerns.

The water treatment study of Shokrollahi et al. (2020) aimed to apply computational fluid dynamics and Design-Expert to optimize potable (drinking) water desalination using membrane distillation. Membrane distillation causes steam to pass from the membrane due to temperature and vapor pressure differences. However, the technology requires development under different operating conditions. Hence, this study investigated the effects of flowrate, temperature, and module length on its performance. Statistical DoE was used to numerically model flux and thermal efficiency. The results showed that increasing flowrate, inlet feed temperature, and decreasing the membrane module's length increased the water flux and thermal efficiency. Numerical flux modelling showed that temperature, module length, and interaction module length-temperature parameters had the most influence on flux and module length, temperature and quadratic relation of module length parameters have the greatest effect on thermal efficiency, respectively.

The pharmaceutical study of Akram and Garud (2021) aimed to prepare a mesalamine nanocarrier system to treat colitis with increased efficacy and targeting. Optimization is critical for understanding nano formulation variables. Hence, statistical DoE using Design-Expert was used to determine the effect of the independent variables (concentrations of chitosan, carboxymethyl inulin, and the drug) on the response variables (particle size and entrapment efficiency of the mesalamine-loaded nanoparticle using BBD). The correlation between the independent and dependent variables was investigated using the generated mathematical equations, contour, and response surface designs. An optimized batch was developed using the ionotropic gel method with selected independent variables and the developed nanoparticles had a particle size of 184.18 nm, zeta potential 26.54 mV, and entrapment efficiency 88.58%. The observed responses were similar to the predicted values. The developed nanoparticles were likely to have a small particle size with positive zeta potential and large extent of drug entrapment. BBD was found to actively optimize the formulation of the drug.

According to the review of Sopyan et al. (2022), optimized formulation is crucial in pharmaceutical drug development and is completed through lengthy laboratory experiments. Design-Expert can be applied to streamline this process. The review's findings suggest that Design-Expert is widely utilized and effective at reducing the number of trials, time, and costs associated with pharmaceutical formulation development.

In the process optimization study of Njoku and Otisi (2023), CCD was used to optimize Biodiesel yield from the transesterification of methanol and vegetable oil using Design-Expert. This optimization involved conditions of reaction time, methanol to oil ratio, catalyst loading, and reaction temperature. For a randomized experiment at a 95% confidence level, all the factors were found to affect the product's output. A 91% yield was obtained, and operating parameters were optimized at a temperature of 61 ˚ C, methanol to oil ratio of 22.13, and catalyst loading of 3.7 wt%.

2.3 Conclusion of Literature Findings

It is noteworthy that Design-Expert has several diverse applications in pharmacy (Hooda et al., 2012; Akram and Garud, 2021; Sopyan et al., 2022), chemistry (Popoola, 2019), food technology (Singh et al., 2020), water treatment (Shokrollahi et al., 2020), and process optimization (Njoku and Otisi, 2023). Each of these studies reported positive application and optimization capabilities of Design-Expert. In certain studies, the capabilities of Design-Expert were combined with other tools, such as artificial intelligence (Popoola, 2019) and computational fluid dynamics (Shokrollahi et al., 2020). However, despite several experimental (quantitative) studies showcasing the positive features of Design-Expert in the literature, there is a lack of qualitative evidence supporting the use of Design-Expert in research and development. Therefore, this study aims to provide qualitative evidence based on the perspectives of chemical engineering higher education research supervisors.

3 Methodology

The first part of the methodology entailed obtaining quantitative information regarding the use of Design-Expert from the literature. A simple search strategy was employed, which favoured the perspectives of recent and diverse studies. These studies were identified and presented in the literature review to demonstrate a contextualised application basis for Design-Expert, and the way it was integrated into optimization procedures across a range of study areas. The authors' own studies were also included in the literature review. In the second part of the methodology, artificial intelligence was prompted to provide key questions to the research supervisors and authors of this study. The questions were prompted with the aim of identifying the key qualitative themes that enable the effectiveness of Design-Expert to be harnessed by research supervisors to ensure optimal completion of postgraduate research projects- especially against the backdrop of competing academic priorities.

AI-enabled Qualitative Analysis Setup

The following prompts were used to guide the AI software (ChatGPT) to output the qualitative questions used in the qualitative study.

Prompt 1: I am writing a conference paper, titled: "Design-Expert to streamline chemical engineering experimental research and development" are you familiar with the use of Design-Expert in relation to this title/topic?

Prompt 2: Please propose interview questions to ask research supervisors regarding the use and application of Design-Expert in their work/research. Specifically, please provide key questions to the research supervisors to identify the key qualitative themes that enable the effectiveness of Design-Expert to be harnessed by research supervisors to ensure optimal completion of postgraduate research projects- especially against the backdrop of competing academic priorities.

Prompt 3: Please provide a motivation for each section of the questions and indicate what type of themes can be drawn from the question sections.

Based on these prompts, the AI-generated qualitative questions are shown in Table 1.

Table 1. Qualitative Interview Questions

Question	Motivation	Themes
Section 1: Integration into Research		

1. How do you incorporate Design-Expert into the planning stages of postgraduate research projects? 2. What specific features of Design-Expert do you find most valuable for achieving research objectives?	Investigating how supervisors integrate Design-Expert into the early stages of research helps to understand the strategic role the software plays. This section also uncovers how it's embedded into the research planning process, which is crucial for aligning resources and timelines.	• Strategic Planning and Research Workflow • Integration into Experimental Design • Early-Stage Decision-Making and Tool Selection
Section 2: Effectiveness and Outcomes		
3. In your experience, how has Design-Expert contributed to optimizing experimental design and process efficiency? 4. Can you share examples where Design-Expert directly led to significant improvements in research outcomes?	Evaluating the effectiveness and tangible outcomes achieved using Design-Expert allows you to determine how impactful the software is in producing high-quality research. This section identifies both qualitative and quantitative benefits that the software brings.	• Optimization and Process Efficiency • Quality of Research Outcomes • Software's Role in Innovation
Section 3: Managing Academic Priorities		
5. How do you balance the time and effort needed to use Design-Expert effectively with other competing academic responsibilities? 6. What challenges have you encountered when guiding postgraduate students in using Design-Expert, especially when they are managing multiple research tasks?	Research supervisors often juggle multiple responsibilities, from teaching to administration. Understanding how they balance their use of Design-Expert amid competing demands highlights whether the software streamlines or complicates project management and supervision.	• Time Management and Prioritization • Academic Workload and Resource Allocation • Balancing Software Use with Broader Academic Roles
Section 4: Skills Development and Training		
7. What training or support do you provide to students to ensure they can fully harness the potential of Design-Expert? 8. How do you assess whether a student is ready to independently use Design-Expert for their research projects?	This section explores the learning curve associated with Design-Expert and how supervisors approach skill development among postgraduate students. Effective training can be crucial for maximizing the software's potential in postgraduate research.	• Training Approaches and Methods • Learning Curve and Usability • Student Competence and Autonomy in Software Use
Section 5: Broader Impact and Collaboration		
9. How does the use of Design-Expert influence collaboration between you, your students, and other research teams?	Understanding the role of Design-Expert in collaboration and communication among research teams provides insight into how it facilitates or hinders teamwork.	• Collaboration and Team Dynamics • Cross-Disciplinary and Cross-Departmental Research

	This section also touches on cross-functional usage and its influence on broader research outcomes.	• Communication and Data Sharing

According to the AI tool, these questions are designed to help uncover the qualitative themes related to the effective use of Design-Expert, including challenges, best practices, and the relationship between software use and academic pressures. Furthermore, the sections and themes provide a structured way to understand the current usage and impact of Design-Expert while offering qualitative insights into its role in balancing the demands of academic supervision with effective research project management.

4 Results and Discussion

Table 2: Qualitative Interview Results from the Supervisors/Researchers

	Supervisor			
	1	**2**	**3**	**4**
Section 1: Integration into Research				
1. How do you incorporate Design-Expert into the planning stages of postgraduate research projects?	When formulating postgraduate research projects, Design-Expert is used to optimize the number of experimental runs in the methodology protocol.	Students use Design-Expert during the conceptual stages in developing the methodology. Design-expert is used to guide the experimental conditions for each run to be conducted with the given variables.	Alignment of research goals and understanding of research constraints; validation of the design through modelling and simulations; experimental plan optimization to maximize data collection with fewer runs; to have a structured approach to data collection, data analysis and data interpretation.	Design-Expert was incorporated into the research by defining the research objectives and hypotheses, identifying the key variables, selecting the appropriate experimental design, and simulating and planning the experiments.
2. What specific features of Design-Expert do you find most valuable for achieving research objectives?	Design-Expert can reduce the number of experimental runs, reducing time and expenses, while outputting high-quality results used to optimize processes.	Composite design	Response Surface Methodology (RSM) allows for optimisation; ANOVA and Regression Analysis allows for statistical reliability and validation.	Design of experiment to systematically investigate the relationships between multiple factors and their effects on a response, optimizing processes or products efficiently.
Section 2: Effectiveness and Outcomes				
3. In your experience, how has Design-Expert contributed to optimizing experimental design and process efficiency?	Design-Expert can reduce the time and expenses needed to conduct laboratory trials, thus improving the overall efficiency of the experimental process.	Design-Expert provides a comprehensive experimental design appropriate for publication and covering all bases for the experimental work to be reliable.	Through optimal design selection, it minimizes the number of experimental runs needed, saving time and resources; optimization tools promptly identify best conditions for desired outcomes.	Design-Expert enables precise identification of key variables and interactions, reducing the number of experimental runs needed, and providing clear insights for process optimization, leading to more effective and resource-efficient research outcomes.

4. Can you share examples where Design-Expert directly led to significant improvements in research outcomes?	With limited time to complete my doctoral research during the COVID-19 pandemic, Design-Expert optimized the application of cellulose nanocrystals (CNCs) in green construction material reinforcement. The main publications include: (1) Using cellulose nanocrystals to improve the mechanical properties of fly ash-based geopolymer construction materials (Roopchund et al., 2022) and (2) Cellulose Nanocrystals: Plant Design for Up-scaled Production and Applications in Green Construction Materials (Roopchund, 2021).	An article was submitted to a journal in which Design-Expert or similar software was not used. The reviewers requested that Design-Expert/similar software be used to generate the experimental runs that should be conducted for the article to be considered.	As per the two studies listed: (1) Exploring students' responses to Design–expert in a Chemical Engineering laboratory module (Sadare et al., 2022a) and (2) Parametric optimization of the production of cellulose nanocrystals (CNCs) from South African corncobs via an empirical modelling approach. (Sadare et al., 2022b)	During the production of biodiesel and synthesis of cellulose nanocrystals.
Section 3: Managing Academic Priorities				
5. How do you balance the time and effort needed to use Design-Expert effectively with other competing academic responsibilities?	I integrate Design-Expert into the development of the experimental plan for students' research proposals. Through this integration, there is no separate endeavour/effort to incorporate Design-Expert into my research activities.	Once the principles behind Design-Expert are understood, it does not take much time to perform the simulations.	By focusing on using Design-Expert for key experiments that will significantly impact research outcomes; collaboration with others (working with colleagues or students familiar with the software) gradually enhance proficiency with the software over time.	Design-Expert was used by undergraduate students during the 'Chemical Engineering Laboratory' module. The students were taught how to use the software and were monitored.
6. What challenges have you encountered when guiding postgraduate students in using Design-Expert, especially when they are	Sometimes, it is difficult for postgraduate students to grasp the concept of statistical experimental design using Design-Expert. To alleviate this	The main challenge is providing students with the appropriate training to use Design-Expert. Without the training, students struggle to use the software and rather	Students experience a learning curve and often struggle with using the software while undertaking other research tasks; not completely understanding the	I've encountered challenges in helping postgraduate students grasp the complexity of selecting the appropriate experimental design amidst their multiple research tasks,

managing multiple research tasks?	problem, I developed a guide to help students.	spend time in research tasks they can do.	data interpretation with respect to the software's output and over-reliance on the software without fully grasping the underlying concepts.	and ensuring they fully understand the software's statistical outputs while balancing their time and resources. Additionally, students often struggle with integrating the software's advanced features into their broader research workflow without becoming overwhelmed by the technical details.
Section 4: Skills Development and Training				
7. What training or support do you provide to students to ensure they can fully harness the potential of Design-Expert?	I created a step-by-step guideline (with pictures of each step) to help my postgraduate students manage their statistical experimental designs using Design-Expert.	YouTube videos were provided to students to learn how to use the software. Additionally, an experienced colleague provided guidance to students.	Support via senior students and colleagues to help address individual challenges and materials such as online resources via YouTube and other similar websites.	The students were trained on how to use Design-Expert on the University's learning management system.
8. How do you assess whether a student is ready to independently use Design-Expert for their research projects?	I review the students' initial experimental designs to determine if they are competent in using Design-Expert. I also ensure that the selected factors, responses and ranges are sensical.	This is a difficult question to answer. I believe that every simulation a student runs on Design-Expert should be checked and further evaluated by the subject experts to ensure the results are appropriate.	By assessing the application of the software (observing students' application of Design-Expert in preliminary experiments) one can gauge how students are coping.	The students were given tasks to do to ensure they grasped the concept of Design-Expert. However, they were guided throughout the process of using it.
Section 5: Broader Impact and Collaboration				
9. How does the use of Design-Expert influence collaboration between you, your students, and other research teams?	I find that experimental research can progress at a quicker rate using Design-Expert, implying that more time is created to spend on research publications. Thus,	The collaboration between myself and the student is essential as we analyse the results from the simulations. Collaborations with senior colleagues and/or supervisors are also evident in finalising	Provides a common platform for planning and optimization of experiments.	The students worked in groups. Therefore, Design-Expert facilitates collaboration by providing a common platform for clearly defining experimental designs, sharing data, and analyzing results,

	collaborations can be made more fruitful.	the experimental design obtained from Design-Expert. However, I do not feel that it has led to collaborations with other research teams.		which enhances communication, ensures consistency across research teams, and accelerates the decision-making process, leading to more cohesive and coordinated research.
10. In your opinion, what qualitative factors determine the successful application of Design-Expert in completing research projects on time?	Firstly, students' overall confidence and command in undertaking their experimental trials. Secondly, the ease and pace of conducting experimental trials. Finally, students' ability to use the Design-Expert outputs (such as the three-dimensional response surface models) to create high-quality research outputs.	It refines the number of experimental runs that must be completed to produce valid and reliable data, including base and reference runs. Without the use of Design-Expert the number of experimental runs is not defined and may have to continually be added, which wastes time and resources.	It allows for effective planning by facilitating a clear experimental design with corresponding objectives.	Qualitative factors like the user's familiarity with the software, clarity of the research objectives, team members' ability to communicate and collaborate effectively, and the ability to incorporate software-generated insights into practical decision-making throughout the project, in my opinion, determine the successful application of Design-Expert in completing research projects on time.

Supervisors widely recognized Design-Expert as a valuable tool for optimizing research methodologies, particularly in planning and defining experimental conditions. It enables efficient data collection with fewer runs, saving time and resources. Its RSM and ANOVA features allow detailed analysis of factor–response relationships, supporting process optimization. Overall, the supervisors viewed Design-Expert as highly relevant to chemical engineering research. In reflecting on their experiences, supervisors noted that Design-Expert improved experimental efficiency, ensured reliable data, and increased the likelihood of publication. Its optimization capabilities helped identify optimal conditions and visualize variable interactions. For example, Supervisor 1 used Design-Expert during the COVID-19 pandemic to complete doctoral research on cellulose nanocrystals, resulting in a published article (Roopchund et al., 2022). Supervisor 2 applied it following reviewer feedback to refine experimental design, while Supervisors 3 and 4 published studies on biodiesel and CNC production using the software (Sadare et al., 2022a; 2022b). Collectively, these experiences demonstrate Design-Expert's effectiveness in streamlining experimental planning and execution.

Regarding integration, supervisors emphasized introducing Design-Expert early in postgraduate research to build proficiency. Supervisor 4 further recommended exposing undergraduates to the tool to reduce learning barriers later. Although students often struggle initially with interpreting outputs, supervisors agreed that Design-Expert enhances research quality and innovation. To support student learning, supervisors employed diverse strategies, including step-by-step guides, online tutorials, peer training, and institutional learning resources. Regular feedback and practical exercises reinforced

understanding and autonomy. While some supervisors felt Design-Expert mainly improved individual efficiency, others found it encouraged collaborative experimentation and shared problem-solving. Successful application depended on confidence, effective planning, clear objectives, and familiarity with the software. Overall, Design-Expert was viewed as a powerful enabler of efficient, collaborative, and high-quality research.

5 Conclusions

This study indicated the applicability and optimization abilities of Design-Expert in Chemical Engineering research, as qualitatively documented by cross-institutional research supervisors. While the underlying concepts and statistical terms comprising Design-Expert may not be easily grasped by first-time student users, research supervisors are encouraged to provide resources, tools, and training to their students, to guide them through the application of Design-Expert in their studies. Based on the qualitative findings, Design-Expert was found to optimize the time, resources, and costs associated with experimental research. Hence, the authors recommend the use and application of Design-Expert in engineering and related experimental research. Considering the workload of academic staff members, Design-Expert was found to be a valuable tool in streamlining experimental research.

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First-Year Engineering Students' Use of Digital Technology for Learning: The Role of Agency

Lilian Ganduri
Department of Mechanical Engineering, University of Cape Town, South Africa, Department of Industrial and Systems Engineering, Cape Peninsula University of Technology, South Africa, gndlil002@myuct.ac.za,

Corrinne Shaw
Department of Mechanical Engineering, University of Cape Town, South Africa, corrinne.shaw@uct.ac.za

Brandon Collier-Reed
Office of the Vice Chancellor, University of Cape Town, South Africa, brandon.collier-reed@uct.ac.za

Abstract

The use of digital technology has become integral for teaching and learning in engineering curricula at universities. However, in South Africa, many students enter their first year of study with limited prior access to and engagement with digital technologies for learning, which presents challenges for them and their educators. This paper is based on a PhD study that explores the student experience, specifically agency, when students use digital technologies for their coursework in first-year engineering. The key question posed in this study is "How do engineering students demonstrate agency when using digital technologies for their coursework?" The study drew on Cultural Historical Activity Theory as a systemic framing for analysing learning as a socially mediated, culturally situated activity, emphasizing the dynamic interactions between its tenets. An ethnographic approach, which entailed observations, focus groups, and individual interviews, was employed to collect data and answer the research question. By mapping the elements within activity systems, the study identifies contradictions such as mismatches between students' prior digital experiences and institutional expectations that catalyse learning. The findings show variation in agentic engagement and action by students as they developed their ability to use digital technologies for course activities. The study revealed how digital literacy is not merely acquired but co-constructed through participation in culturally and historically embedded practices where students took initiative to improve their digital skills, used adaptation strategies to sustain learning, and redefined the status quo in unfavourable circumstances.

Keywords: agency, digital technologies, first-year engineering student, contradictions

1 Introduction

Digital educational technologies have emerged as integral to the delivery of educational knowledge and skills in higher education. For engineering students, using digital technologies, including software applications, computing devices, and internet-based platforms, is no longer optional but essential. First-year engineering students are expected to engage with a range of digital technologies to access learning materials, participate in academic activities, and complete coursework. Central to this engagement is an institution's Learner Management System (LMS), which serves as the primary gateway for students to access course content, receive communication from lecturers, and access links to download discipline-specific software. The LMS thus functions not only as a repository of resources but also as a scaffold for students' initial encounters with the digital practices that underpin contemporary engineering education.

However, first-year engineering students in South Africa have different socio-economic backgrounds, varying levels of digital literacy, and prior access to technology and other digital skills (Naidoo & Raju, 2012). This is primarily due to the historical patterns of inequality created during the apartheid era (Jantjies, 2020; Mhlanga, 2020). South African institutions of higher learning adopted the use of digital technologies at a time when they were still emerging from the effects of apartheid. The legacy of apartheid education, marked by racially segregated access, limited resources, and exclusionary pedagogical practices, continues to shape the educational landscape (Mekoa, 2018). For the students transitioning from high school to South African universities, these challenges would have affected the quality of their digital skills, since many would not have had access to digital technologies (Jantjies, 2020; Khalid & Pedersen, 2016).

In addition, the challenges posed by the 'fees must fall' protests between 2015 and 2017 (Czerniewicz, 2020; Czerniewicz et al., 2019) as well as the COVID-19 pandemic (Lazar, 2021) accelerated the need for first-year engineering students to engage with digital technologies for online or blended learning. It has been argued that integrating activities that require the use of digital technologies in curricula may aid the development of these digital skills (Ganduri et al., 2021; Mian et al., 2020), however, many students still find themselves in learning environments without these skills.

Engineering students can benefit from digital technologies by gaining appropriate skills and competencies as an outcome of self-paced online and blended learning activities. However, these affordances do not emerge automatically but rather, rely on the agency of students who actively participate in them (Aagaard & Lund, 2020; Castro, 2019). This study drew on Cultural Historical Activity Theory as a systemic framing for analysing learning as a socially mediated, culturally situated activity, emphasizing the dynamic interactions between students (subjects), digital tools (mediating artifacts), institutional norms (rules), peer relationships (community), role of educators and support staff (division of labour) as well as the curricular expectations (object). It considers the relationality between technologies and student learning when considering how students mediate their learning with digital technologies and how they demonstrate agency throughout their first year of study.

2 Literature review

Agency refers to the capacity of individuals to act independently and make their own free choices (Archer, 1996). In the context of education, agency involves students' ability to influence their learning processes, make decisions about their educational paths, and engage actively in their academic environments. Students are said to have this kind of agency when they have gained the power to influence their learning, making choices about, and achieving their learning goals through the optimum use of digital technologies (Andresen, 2020)

Many researchers have carried out studies on agency where students learn face-to-face in classrooms including Archer and Archer (1996); Bandura (1989, 1999); Emirbayer and Mische (1998); and Giddens, (1984), while research on agency that is centred on digital educational technologies for learning is gaining traction (Bandura, 2002). Passey et al. (2018) introduced the term *digital agency* to describe an individual's capacity to navigate, control, and adapt within digital environments. They conceptualized digital agency as comprising three interrelated components: *digital competence*, *digital confidence*, and *digital accountability*. This framing of digital agency emphasizes not only the technical skills required to operate digital tools, but also the self-assurance to use them effectively, and the ethical responsibility associated with digital engagement. However, Stenalt (2021) critiques this conceptualization, arguing that it may oversimplify the complex socio-cultural dimensions of agency in digital learning contexts. Stenalt suggests that digital agency should be understood as a more fluid and context-dependent construct, emphasising relational, cultural, and technological dynamics (Stenalt, 2021) shaped by learners' interactions with institutional structures, pedagogical practices, and broader societal influences. She further suggests that the framework of agency should consist of "agentic possibility, digital self-representation, data uses, digital sociality, and digital temporality" (p.60) as critical domains. Aagaard and Lund (2020), also argued that agency is transformational as the usage of digital educational technologies is based on the culture of the users.

The study of agency in digital spaces must, according to Klemenčič (2017), be promoted because it has the potential to intervene in and influence engineering students' digital learning environments and learning skills. For example, Tamássy et al. (2023) examined how students and higher education institutions are portrayed in discourses at highly ranked business schools, and highlighted the roles and agency of students within these institutions, emphasizing how students navigated their educational environments and the influence of institutional practices on their agency. Similarly, Wong and Chiu (2021) explored the concept of the 'ideal' university student, focusing on the expectations and perceptions of students in higher education. The research discusses how these ideals shape student behaviour and agency, and the implications for educational practices and policies. Brod et al. (2023) provide an interdisciplinary review of agency in the use of educational technology, examining different perspectives on agency, including psychological, sociological, and technological frameworks, and discussing how these perspectives can inform learning design and improve educational outcomes by fostering student agency. Research on agency within digital learning environments is actively progressing at the University of Helsinki, focusing on transformative agency (Cornér, 2020; Kajamaa & Kumpulainen, 2019; Kumpulainen et al., 2018). Furthermore, scholars are examining the social dimensions of educational interactions as a means to foster student agency in digital education (Echenique et al., 2015; Jääskelä et al., 2017; Stenalt, 2020), where the research intersects with broader debates concerning the power embedded in the use of digital technologies, an area that remains highly contested. These ongoing debates include the question of whether technology controls the user, or whether the user shapes new technologies as they interact with them (la Cruz Paragas & Lin, 2016; Oliver, 2011; Selwyn, 2010).

Siddiq et al. (2023) highlight how a number of theoretical frameworks have been used to study agency. These include cultural-historical activity theory (CHAT) (Aagaard & Lund, 2020; Ganduri et al., 2023), studies building on Galperin's theory of orienting phases, and socio-cultural theory (Vygotsky, 1978b). Agency itself has been studied within CHAT through the principle of double stimulation (Sannino, 2015), transformative activist stance (Stetsenko, 2017) and relational agency (Edwards, 2005). However, this study approaches agency through the notion of contradictions (Engeström, 2001a).

3 Theoretical Framework

This study is framed by Cultural-Historical Activity Theory (CHAT or Activity Theory) (Engeström, 2001a; Vygotsky, 1978). CHAT provides the context for understanding human actions as an activity system (Leont'ev, 1978). An activity system is a unit of human activity composed of a subject, an object, mediating artifacts, community, rules, and the division of labour (Engeström, 1987). CHAT emphasizes the idea that the use of cultural tools and symbols, in this case, digital technologies, serves as a foundation for self-consciousness and is an unavoidable starting point in the process of becoming a human being. In other words, it suggests that people are not born as agentive beings; rather, they gain agency through participation in social activities such as education. Development that occurs amongst students is a result of the process of becoming a subject capable of agency, that is, capable of contributing to, influencing, and changing the environment as well as the social and material circumstances in which the person lives (Bozhovich, 2004; Holland & Lachicotte, 2007; Vygotsky, 1978a).

Vygotsky (1978) developed Cultural-Historical Activity Theory in the 1920s and early 1930s, and Leont'ev, Vygotsky's colleague, expanded on it from 1978 to 1981. The theory has since evolved over four generations of research (Engeström, 1996). Engeström (2001a) describes how it was the first-generation CHAT that developed Vygotsky's idea of human activity being mediated by tools. This idea of "cultural mediation" of actions is represented by a triad of subject, object, and mediating artifacts and is shown in Figure 1.

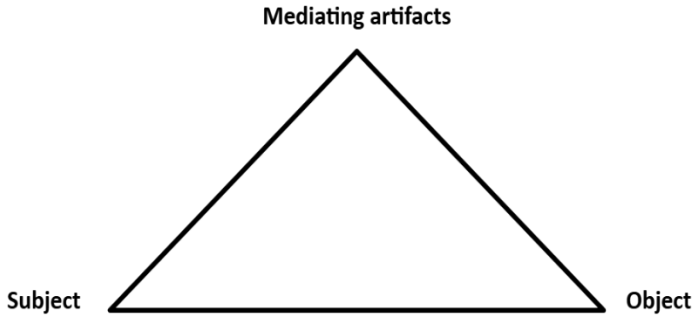

Figure 1 First Generation activity system (Engeström, 2001a)

The use of cultural mediating artifacts suggests that a society can no longer be described apart from its culture, and the study of its systems is hinged on the agency of the individuals involved. The second generation CHAT, shown in Figure 2, was introduced to highlight the relationships among subject, mediating artifacts, object, community, rules, and division of labour (Engeström, 2001a).

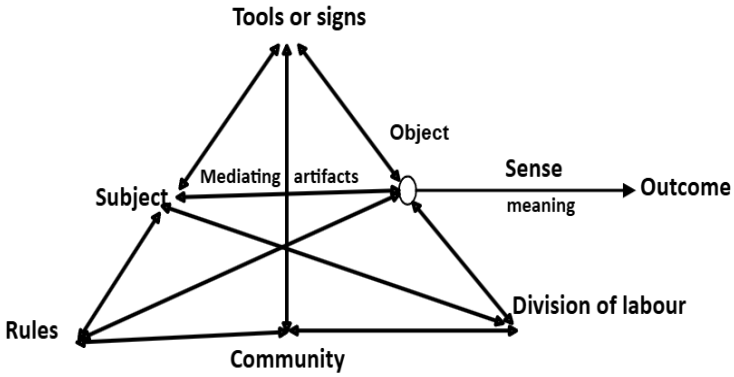

Figure 2 Second Generation activity system (Engeström, 2001b)

The third-generation CHAT was developed Engeström (2001) and includes the introduction of contradictions within and between interconnected activities. Here, the unit of analysis is the shared object (Engeström and Sannino, 2020). In the context of this study, agency is the recognition and negotiation of differences and complementarities. Researchers have recently developed a fourth generation of CHAT (Engeström & Sannino, 2020), which is different in that its unit of analysis is based on the coalescing cycles of expansive learning in a heterogeneous coalition of activities facing critical societal change. In this latest version of CHAT, Engeström and Sannino, (2020) argue that the object is a critical societal challenge or crisis demanding a multi-level and cross-sectional solution.

Second-generation CHAT was most appropriate for use in this study since it enables the conceptualisation of the use of digital technologies for learning as an activity system. In this framework, individual development

is understood as socially and historically constituted, occurring through participation in collective, goal-directed activities such as those found in engineering education (Rainio, 2010). Key components of the activity system, including the *community*, *division of labour*, and *rules* which encompass both formal policies and informal norms, shape how students engage with digital technologies and pursue learning outcomes (Engeström, 2001b). The identification of *contradictions* within the learning activity system is required for understanding both the challenges and opportunities for students to develop agency (Engeström, 1995). These contradictions, which may arise between institutional expectations and students' digital capabilities, can serve as catalysts for learning (Engeström, 1995). Furthermore, CHAT offers methodological tools for the identification and analysis of these contradictions (Engeström & Sannino, 2011).

3.1 Contradictions

Il'enkov (1977, 1982) introduced the concept of internal contradictions. These can be considered a driving force that causes constant change and development in activity systems (Engeström, 1999). According to (Engeström, 1987), these contradictions can arise within and between systems, and he distinguished four types: *primary*, which occurs within elements of an activity system; *secondary*, which occur between elements of an activity system; *tertiary*, which occur when the object of the central system clashes with that of a historically more advanced activity system; and *quaternary*, which occur between the central system and its neighbouring activity systems. The notion of contradictions have been widely used by researchers as a guiding principle of empirical research (Engeström, 1987, 2015) and have been applied to this study.

4 Methodology

This research explored student agency in a digital learning environment, employing ethnography as its core methodology due to its alignment with the interpretive paradigm (Hammersley & Atkinson, 2007, 2019). The interpretive paradigm, rooted in constructivism and relativism, acknowledges that reality is shaped through individual interpretations and social interactions (Denzin & Lincoln, 2011). Given its emphasis on understanding participants' lived experiences, ethnography enables the researcher to capture students' subjective meanings and interactions within the digital learning space (Hammersley, 2018). Through immersion in the natural setting, the use of this approach provides an improved perspective on the dynamic interplay between students, technology, and the broader social context.

The use of ethnographic methods also reveals tacit knowledge and implicit meanings that students might not have explicitly articulated, offering insights beyond what surveys or questionnaires can reveal (Alvesson & Sköldberg, 2017). However, despite its strengths, ethnography is time-intensive and carries a risk of subjectivity, requiring careful methodological considerations (Hammersley & Atkinson, 2007). To address these challenges, the research adhered to rigorous ethical guidelines, maintained reflexivity, and employed triangulation through multiple data collection methods to enhance credibility. By embedding researchers in students' daily academic lives, observing their actions, and conducting interviews, this study captured the nuanced manifestations of agency within the complexities of a digital learning environment.

4.1 Data collection

As the study employed an ethnographic approach for data collection, the use of observations, one-on-one and focus group interviews (Gobo & Marciniak, 2011; Hammersley & Atkinson, 2007, 2019) was appropriate.

Ten observation sessions were conducted, with five taking place in engineering drawing laboratories and five in computer engineering laboratories. To ensure comprehensive data capture, the sessions were both video recorded and documented in field notes. These field notes included detailed descriptions of observed activities along with the date of each session. Fifteen individual interviews and three focus groups were conducted face-to-face. This decision to prioritize face-to-face interaction was motivated by the ability to observe and capture participants' body language and non-verbal cues, which could offer valuable insights into their perspectives and experiences (Krueger & Casey, 2002). The data from individual interviews and focus groups were analysed and used in this paper.

4.2 Data analysis

Thematic analysis (Braun & Clarke, 2006) was the primary approach adopted for analysing the qualitative data collected. This widely used method involves identifying, analysing, and reporting recurring patterns called themes within the data (Creswell & Poth, 2018). Thematic analysis in this research involved a two-level coding process. The initial level made use of a combination of in vivo codes and descriptive codes (Saldaña, 2016). In vivo codes directly reflected participants' own words and phrases, capturing their unique perspectives and expressions without significant modification. Descriptive codes, on the other hand, summarized the underlying meaning of data segments using concise labels (Nowell et al., 2017; Saldaña, 2016). This initial coding served as the foundation for the second level, where themes were progressively identified by grouping and refining the initial codes based on their shared characteristics and relationships (Braun & Clarke, 2006).

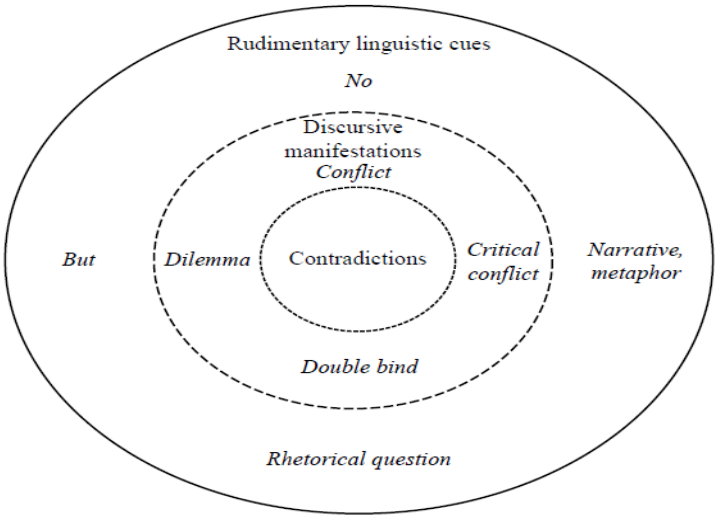

Figure 3 Methodological onion for analysing contradictions (Engeström & Sannino, 2011 p.375)

The identification of contradictions also started during the first level of open coding and involved iterative stages of thematic analysis to identify themes. Discursive manifestations of contradictions is a method within CHAT that identifies systemic tensions through the analysis of language, recognizing that contradictions are not immediately observable and cannot be discerned at face value (Engeström & Sannino, 2011). The linguistic cues for discursive manifestations of contradictions called *dilemmas* include "yes..but" which describes a form of doubt and/or hesitancy. *Conflict* is depicted by "no", "I disagree", whilst *critical conflicts* are characterized by "let us do that or we will make it". Lastly, *double binds* reflect situations where students

cannot help themselves and need others to assist them to get out of a difficult situation (Engeström & Sannino, 2011). Figure 3 shows the methodological onion for analysing contradictions as applied in this study.

5 Findings and discussion

The findings from the data analysis reveal that first-year engineering students encountered contradictions in the form of dilemmas, double binds, conflicts, and critical conflicts. Figure 4 shows various discursive manifestations of contradictions in the use of digital technology for learning.

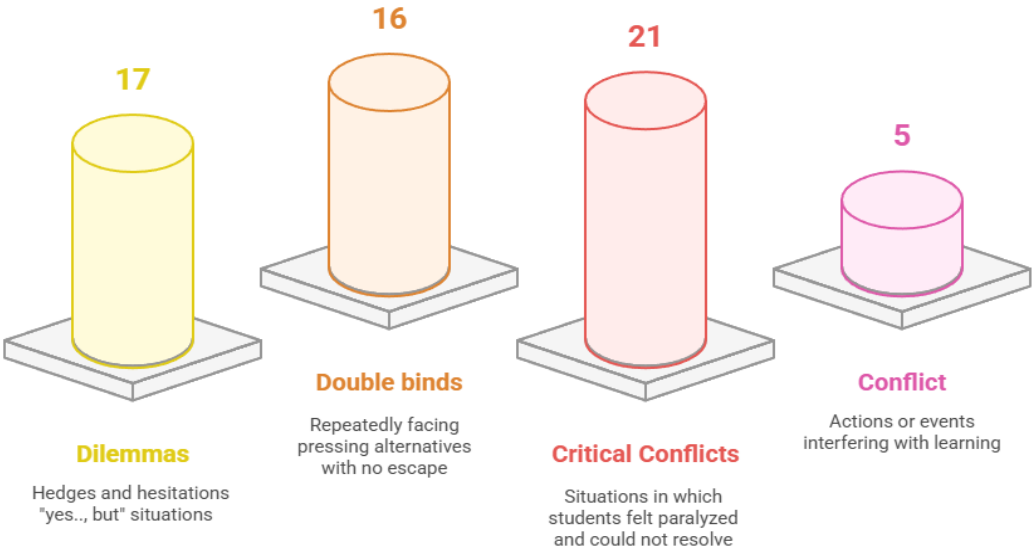

Figure 4 Discursive manifestations of contradictions among students

Four themes emerged from the seventeen dilemmas, whilst two and three themes were identified among the double binds and critical conflicts, respectively. There was also one theme that described the five conflicts that had been identified.

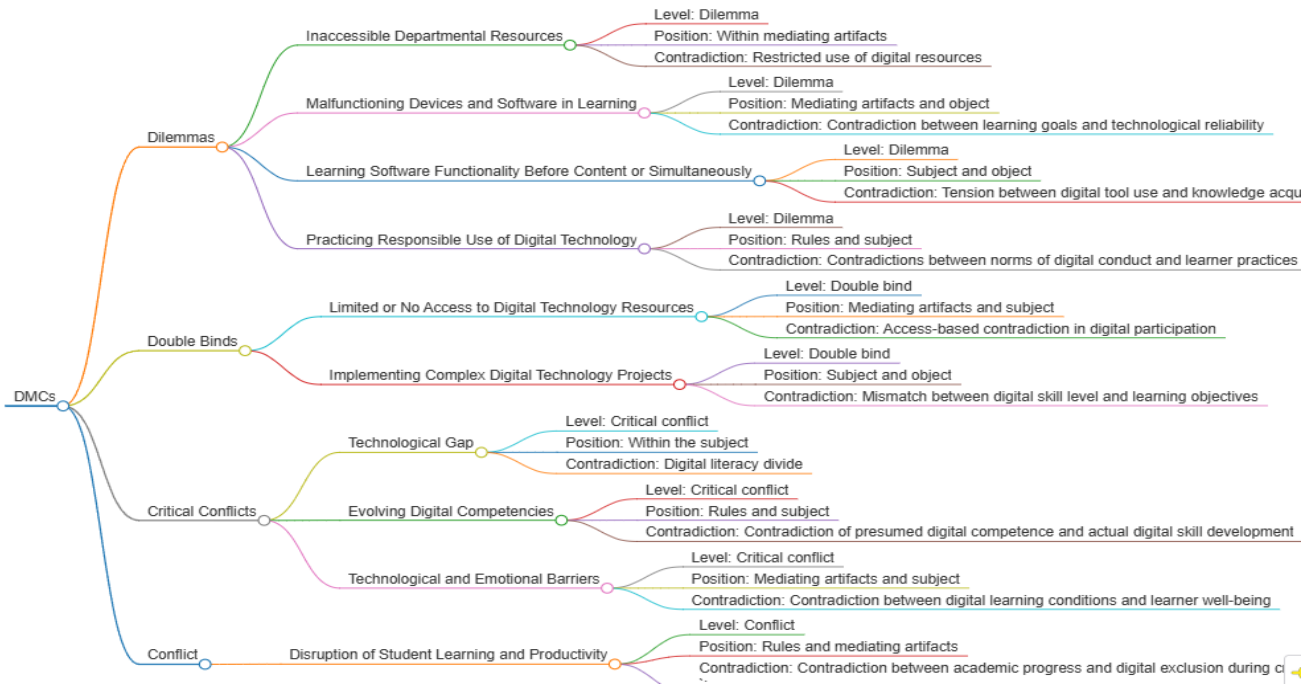

Figure 5 Categorised discursive manifestations of contradictions

The findings revealed that there were primary contradictions in the form of critical conflicts within the subject as an activity system tenet. The secondary contradictions were identified as dilemmas, double binds, conflict, and critical conflicts. Figure 5 shows the process of identifying contradictions from their discursive manifestations. Figure 6 shows the second-generation activity system in which first-year engineering students learn with digital technologies. The lightning bolts in the activity system indicate the positions of the primary and secondary contradictions.

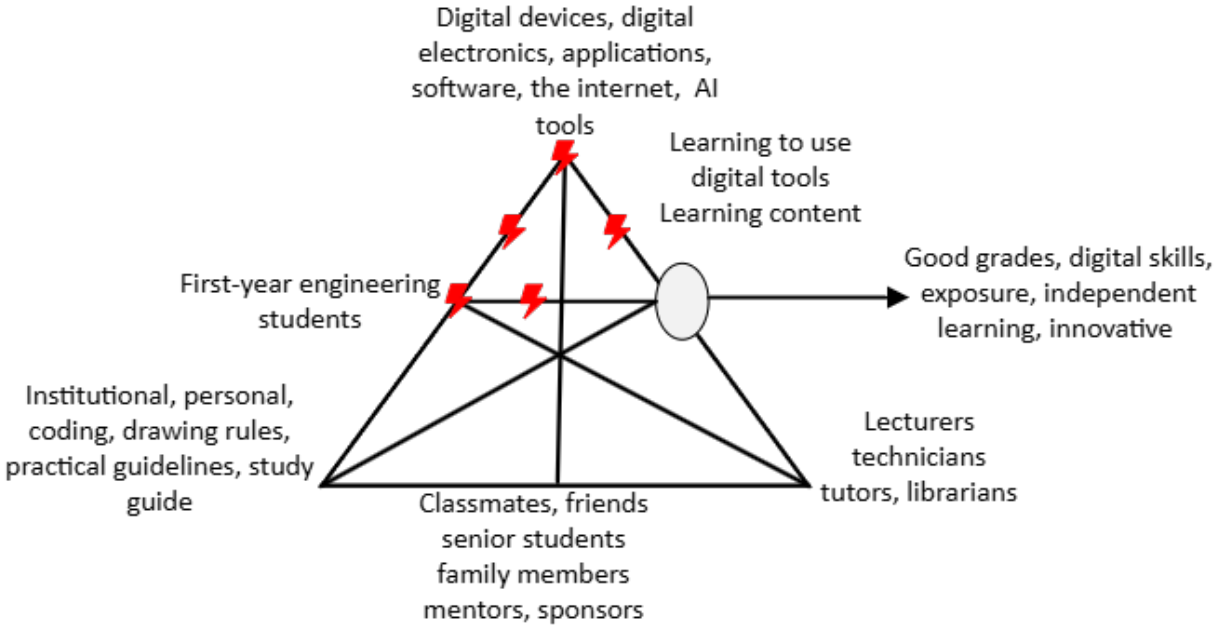

Figure 6 Students' learning activity system

The analysis showed various ways in which first-year engineering students exercised agency to overcome the contradictions. This paper focusses on three of the ways. Firstly, they exercised agency by investing time in constant practicing with software and hardware as a way to improve their digital skills. Secondly, they challenged the status quo and thirdly, they adapted to constraints to sustain learning throughout the year. These three ways that first-year engineering students exercised agency will be described in full in the sections to follow.

5.1 Practice as a key to understanding and applying digital tools

First-year engineering students were introduced to computer engineering and engineering drawing, subjects that required digital tools for their learning. The analysis indicated that students developed digital skills through constant practicing the application of digital technologies. They engaged in hands-on practice with the software, applying concepts that were either demonstrated through YouTube tutorials or documented through photographs taken during laboratory sessions. As an example, Spamandla commented: "*I'd go to YouTube, watch tutorials on YouTube, and then try to practice it on the software*" [FG3L411]. Protea believed that to understand technology, one must practice, and there is "nothing else". She stated: *"I think it was frequent practice on how to use it ...and also YouTube videos. It's frequent practice. Nothing else*" [I10L90]. Similarly, Beekay said: *"I actually try to practice more frequently so that I can actually get the glimpse of how*

to actually use the application that I have to actually use it into my advantage to get something out of it" [I4L142].

In addition, some engineering students were practicing on their own, whilst others collaborated with peers. They practiced how to use software such as Microsoft Office, AutoCAD, SolidWorks, MATLAB, Dev C++, and many others. Thumi is an example of a student who had to practice using Microsoft Word. She stated: "*I had to make sure that every day... I have to go into Word, do the exact thing again and again, take a break, and then go back in, try to figure out something else other than what I've learned*" [I15L90]. Swazi also attributed her success to practicing and gaining knowledge and familiarity with the tools. She asserted: *I remember the first few weeks I was just struggling with Blackboard, I didn't understand exactly how to use it and what it was for. But you know, the more you use it, the more you get used to it"* [I13L158]. Aphelele described that: "*me and my friends we meet up together maybe for computer engineering and try to practice codes and to write codes. So what we normally do, we send codes that we can practice to our WhatsApp group. And then we take it from there and then try to retype them to Dev C++ just for practice*" [I3L150].

Use of digital tools through repetitive practice was a primary pathway through which agency was developed and demonstrated. Agency among first-year engineering students manifested through their repeated engagement with digital tools as they sought to master both content and the technological instruments mediating that content. Rather than relying solely on formal instruction, students often turned to trial-and-error learning, self-paced experimentation, and peer collaboration to gain confidence with unfamiliar tools. Vygotsky's (1978) idea of mediated learning, where tools are internalised through use, explains this phenomenon. Luckin et al. (2011) extend this to technology use, showing that learners generate meaningful contexts for themselves when technologies are embedded in practice. This means that students' practice as a form of agentic learning is mediated by cultural tools. This notion aligns with Schubotz et al. (2023), who argue that tool mastering is not simply a matter of one-time use but a developmental process involving the integration of perceptual, motor, and cognitive competencies through repeated practice. In the context of digitally mediated learning, such repetition is not merely mechanical, it is an enactment of agency where students make intentional choices to build competence by actively shaping their interactions with technologies.

The engineering students' digital engagement, particularly through coding, Arduino circuits practicals, AutoCAD, and SolidWorks drawing, appeals to the three building blocks of tool mastering that Schubotz et al. (2023) describe as tool perception, selection, and handling. Ozturk et al. (2015) and Peng et al. (2014) also demonstrate that iterative modelling assignments allow students to customize their learning experiences, thereby improving both technical skills and epistemic engagement. Their recursive practice enabled the development of manipulation knowledge in how to use tools, functional knowledge concerning what tools are for, and means-end knowledge on how tools achieve specific learning goals.

Practicing engineering content as well as mastering digital tools unfolded within a community. Students shared resources, collaborated on Web 2.0 technologies, and consulted with one another. These social practices reinforced the affordances of tools and promoted a culture of peer-supported learning. As argued by Lund and Aagaard (2020), digital technologies only yield educational benefits when users actively

appropriate them in meaningful ways. Repetitive practice served as a mechanism of appropriation, transforming tools from obscure systems into familiar elements of students' cognitive repertoire.

5.2 Challenging and modifying the status quo

Engineering students consistently deviated from rigid curricular expectations and institutional constraints to explore ways of learning. This form of agency was marked by autonomous planning, critical evaluation of digital tools, and the willingness to cross temporal, institutional, and technological boundaries to access and engage with technology. One student, Khulekani, installed Linux instead of the recommended Windows operating system as he believed that it was faster in programming. He explained: "*So in computer engineering, ... I tend to go even beyond those rules to actually break those rules and write certain programs that don't make sense just to see how this program is going to react. And that's actually how I've enhanced my knowledge of how the language works, how the computer works, how the system reacts to such code*" [FG1L366]. Another student, Mbigu challenged the status quo by doing things outside his academics stating:

> "*So immediately when I saw that I was able to do the code, I gained confidence that I can even do it more. That's why I always even did practicals, like on my own practicals outside of academics, Google Arduino practicals that I can do with this and this and this component. Find them and then do it together. And the more I did that, the more I see coding, the more like I get interested in coding as well. Doing those tasks actually really boosted my confidence as well"* [FG3L580].

These actions represent a shift from compliance-based learning to actively reshaping the learning activity system, aligning closely with the concept of challenging and modifying the status quo within CHAT (Engeström, 2001a).

Another example where students challenged the status quo was during their first semester, where they were instructed to learn coding through ChatGPT. However, some students like Spamandla and Swazi did not rely on ChatGPT, while others checked the accuracy of ChatGPT using Google. Spamandla stated: "*I try to make myself less reliant on consulting ChatGPT for every hard code that we are tasked with"* [I12L380]. He proposed asking friends for help instead. Through innovation, critique, and boundary-pushing, students resisted being passive recipients of technology and instead asserted themselves as active agents in shaping how technology functions within their learning environments. Araos Moya and Damsa (2023), conceptualise such moves as critical engagement with the conditions of learning. Students questioned the fitness of existing digital structures and, in doing so, they enacted a reconfiguration of power and participation in learning spaces. These practices suggest that agency includes the capacity to critique, transform, and reimagine digital tools and practices, not merely to use or cope with them.

5.3 Adapting strategies to sustain learning

The third finding describes how students adapted to constraints through creative or improvised strategies. First-year engineering students encountered various obstacles during their studies but demonstrated agency by developing and applying strategies to overcome each one of them. For instance, instead of waiting for help, some students like Swazi, Mbigu, Kitso, and Aphelele would teach themselves how to code and do engineering drawings assignments. Other students like Spamandla and Khulekani tried to use ChatGPT correct their train of thought instead of directly writing their code. Spamandla explained: "*I always make sure that I first attempt the code, and then should I not be able to figure it out, I try to make ChatGPT correct my*

train of thought instead of it influencing my code" [FG3L50]. Engineering students in this study also found it easy to research solutions to their practical assignments, build a prototype, and test it to see if they got the required results. Aloha described how he would do "*a little research"* on what he was going to do, whereafter he tried to *"build it and then test it"* [I1L102]. Similarly, Beekay would use "*[Google] Chrome to get the information*" that he was looking for and "*analyze the data*" to "*select the most important information that he would need*" [I4L226].

In addition, agency was demonstrated through the use of online videos to learn to use software such as AutoCAD, a tool that is outside of the curriculum. Students such as Khulekani used software and applications that were outside the scope of the curriculum. Khukekani asserted: "*And for my personal experience, since I enjoy coding, I have a personal IDE that I love and I prefer, it's called Visual Studio Code. And I've been using it a lot*" [I6L30]. Similarly, to access resources like books and computers, engineering students would improvise by sourcing books beyond those recommended and also try to access computers at the library, IT centre, or borrow laptops from friends. During power outages, some students chose to submit their coding and drawing assignments ahead of the deadline. The adaptive strategies to sustain learning were a key expression of agency, especially under conditions of limited control. Czerniewicz and Brown (2014) show how students from disadvantaged backgrounds develop distinctive digital practices that reflect both constraint and initiative.

The adaptation of strategies to sustain learning is closely tied to the notion of boundary-crossing in digital engagement (Akkerman & Bakker, 2011). Possible boundary crossing was evident as students accessed and used digital technology for learning. The strategies demonstrate that boundary crossing is not merely about interaction across domains but is central to collective concept formation, an essential mechanism of learning in CHAT. As Suchman (1994) also notes, boundary crossing entails entering unfamiliar terrains and negotiating partial knowledges, making it a cognitively and relationally demanding process. In this study, this principle is crucial because it emphasizes how learning moved across curriculum boundaries and transformed the activity system, fostering horizontal development through collaboration, contradiction, and mediation.

Furthermore, whilst institutional systems were insufficient, students demonstrated agency by creating or identifying parallel networks of support, including friends, classmates, and senior students. For instance, Aloha commented: *"They are my friends. One of my friends is good with computers because in our friend group, one knows this thing, one knows this module. So one of my friends helped me to use Dev C++"* [I1L143]. Khulekani supported this by saying: *"Fellow classmates … contribute in helping you because we don't learn in the same way. We grasp things in different ways"* [FG1261]. This is consistent with Zhang et al. (2017), who also noted that when students are tasked with creating screencasts, their study found that students must first overcome initial discomfort and gaps in technical knowledge. The screencast process itself became a coping mechanism where students engaged deeply with the material to explain it to others, which requires internalising and structuring the knowledge meaningfully. Thus, the creation of learning artefacts becomes both a form of mastery and a strategy for managing initial uncertainty or lack of confidence. Johnson et al. (2014) showed that contextual exercises that accommodate varied student experience, for example, in CAD environments, encourage engagement by recognising that students use new technologies differently depending on their background and prior exposure. This conclusion is consistent with Engeström's (2001)

model, which puts emphasis on the role of community in influencing subjects such as engineering students to achieve their objectives.

6 Conclusion

First-year engineering students enter university from diverse socio-economic backgrounds that significantly influence their prior access to digital resources and, consequently, their development of digital skills. This study examined how a sample of these students engaged with digital technologies, using discursive manifestations of contradictions to identify areas of systemic tensions within the activity system. Despite facing structural disadvantages, students demonstrated agency by actively navigating and overcoming these contradictions. They did so through sustained engagement with digital tools, creative problem-solving, and by challenging and reshaping normative expectations within their learning environments.

These findings provide insights for engineering educators, showing that digital technologies can act as barriers to equitable student learning. Recognizing these challenges enables educators to design pedagogical interventions that support students in developing digital skills and competencies before engaging with complex engineering concepts. By addressing these barriers, educators can create more inclusive and effective learning environments for engineering students.

For engineering education researchers, this study highlights that exploring student agency in digitally mediated learning environments remains a productive area for research, given the pace of innovation in digital technology. As digital tools continue to shape learning experiences, further investigation is needed to understand how different technologies facilitate or hinder student agency. This research contributes to the growing body of engineering education knowledge and encourages continued exploration of student agency within diverse technological learning environments as an important area for future study. The research's limitation encompasses the reliance on a singular method for identifying contradictions within CHAT to study agency. The researcher advocates for the inclusion of Change Laboratory and other CHAT-based methodologies in future studies to facilitate a more thorough examination of agency.

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The ESP32 microcontroller as a low-cost teaching tool for mechatronics

Abrie J Oberholster
Department of Mechanical and Aeronautical Engineering, University of Pretoria, South Africa, abrie.oberholster@up.ac.za

Abstract

South African universities face unique challenges in teaching technology-intensive modules such as mechatronics. One such challenge is the variability in students' prior exposure to technology and programming. As such, not all students are equally confident in the technological skills required for the final year mechatronics and control module offered by the Department of Mechanical and Aeronautical Engineering at the University of Pretoria.

However, recent technological advancements have opened up new possibilities. The ESP32-WROOM microcontroller, in particular, offers a versatile platform for learning mechatronics. Its compatibility with multiple programming languages ensures that students can choose the language they are most comfortable with to explore the world of mechatronics. The ESP32-WROOM's built-in wireless capabilities further make it ideal for Internet of Things (IoT) applications.

This paper focuses on the selection of microcontrollers and their utilisation in the mechatronics course offered by the university.

Keywords: Microcontrollers, Mechatronics, Programming

1 Introduction

South African universities face unique challenges in teaching technology-intensive modules such as mechatronics. A major contributing factor is that students do not have equal prior exposure to technology and programming at the primary and secondary school levels (Faloye & Faniran, 2023). One of the drivers of this “digital divide” is inadequate information and communication technology (ICT) infrastructure at schools due to socio-economic factors, with learners from affected schools reported to constitute 66% of the total public schooling system in South Africa (Chisango & Marongwe, 2021; Sithomola, 2021). As such, these students are not sufficiently equipped with basic computer and data manipulation skills at the school level. Furthermore, most strategies universities adopt to accommodate these students involve a ‘one-size-fits-all’ approach, which often does not address the challenges of individual students (Faloye & Faniran, 2023). Subsequently, not all students are equally comfortable with the programming skills required for an undergraduate course in mechatronics.

One solution is block-based visual programming (BBVP) which, as a programming tool, has gained wide popularity globally and can be an effective environment for introducing learners with minimal ICT skills to programming (Stolpe & Hallström, 2023; Weintrop, 2019). What makes high-level BBVP tools (such as the Scratch software) powerful in this scenario is that they bypass the requirement for good typing skills and make it possible to use natural language in the description of the behaviour of a command. Several BBVP tools are available for free, making BBVP further accessible. BBVP is used to teach programming skills, ranging from robotics for children (Stolpe & Hallström, 2023) to industrial robotics for adult novices (Weintrop, 2019) to programming for university students (Harvard University, n.d.). For advanced

applications, MATLAB Simulink and National Instruments LabVIEW represent commercial BBVP tools typically used in industry and academic research for system and process control.

It is essential to recognise that BBVP utilises formal programming languages such as Python and C++, and acts as an intermediary between the user and these traditional languages. For advanced applications however, the user is required to be familiar with one or more of these formal programming languages.

Python and C++ are among the most popular programming languages available. While Python is considered a high-level programming language, C++ is classified as a mid-level language. Python is generally less complex than C++, but much slower than C++ for specific tasks. Since Python code does not require compilation as with C++, Python's readability and ease of use make it a valuable script prototyping and lecturing tool in mechatronics. Higher-speed computations are necessary for more advanced applications, such as controlling an inverted pendulum. In such instances, C++ outperforms Python (Balogun MO, 2022; Capaciteam, n.d.).

In 2022, the opportunity arose to transform the classical control systems module offered by the University of Pretoria into a more applied mechatronics and control course. The challenge of selecting an appropriate microcontroller for incorporation into the module was recognised at the beginning of this endeavour. The requirement to balance the need to accommodate students with varying programming proficiency levels while teaching more advanced mechatronics concepts was also identified. Additionally, it was important to consider long-term support, local availability, cost efficiency and the presence of an established user community. While the previous version of the control systems module utilised powerful microcontrollers, these became obsolete over time, and did not meet several of the abovementioned requirements. As such, it was necessary to identify a new suitable microcontroller to maximise the educational potential of the module.

2 Microcontroller selection

In line with the observations made in the previous section, it was important to take cognisance of available software options that interface with microcontrollers, to inform the choice of microcontroller. An internet search quickly reveals that there are several software options available. Conducting an extensive survey of all available software options, however, lies outside the scope of this contribution. Instead, the focus was on determining which software options were available for interfacing with the different microcontrollers under evaluation, while addressing a spectrum of needs stretching from basic introductory mechatronics to advanced mechatronics. Examples of suitable software options identified included Blockly (BBVP), Thonny IDE (Micropython), Arduino IDE (C++) and MATLAB Simulink.

Subsequently, the following microcontrollers were evaluated: Arduino Uno, ESP32-WROOM, M5Stack Core 2 and Raspberry Pi 5. Although many more microcontroller options are available, extending the evaluation to more microcontrollers was not possible due to time constraints in selecting a microcontroller for the 2024 rendition of the mechatronics module.

Arduino Uno and Raspberry Pi were considered, as these are legacy devices with excellent support and extensive user communities. At the same time, M5Stack presents a "plug-and-play" option, albeit with limited local availability. The ESP32 microcontroller utilised by M5Stack showed much potential; hence, the ESP32-WROOM microcontroller was also considered. The advantage of this approach is that the microcontroller can be bought separately, reducing initial costs and making it user-scalable.

In evaluating the different microcontrollers, cost-efficiency was considered, taking into account additional costs required for the Arduino Uno, ESP32-WROOM and Raspberry Pi to include sensors, etc., as part of a microcontroller kit to maximise educational value. This was done to compare these with the M5Stack Core2, which has several onboard sensors.

For each of the four microcontrollers, consideration was given to whether they can be programmed via BBVP, Python and C++. Additionally, consideration was given to whether MATLAB Simulink supports the said controller without requiring additional third-party software licenses.

A 6-point Likert scale was used to assign criterion weight, ranging from 0 (No Importance) to 5 (Critical importance). Likewise, a 4-point Likert scale was used to evaluate microcontroller compliance with the set criteria, ranging from 0 (No Compliance) to 3 (Full Compliance).

Table 1 summarises the evaluation of the identified microcontrollers, along with the criteria considered, the assigned weights and scores.

Table 1: Comparison of candidate microcontrollers

Criterion	Weight	Arduino Uno	ESP32-WROOM	M5Stack Core2	Raspberry Pi 5
Cost efficiency	5	3	2	2	1
Local availability	5	3	3	2	2
Programming language	5	2	3	3	3
MATLAB Simulink support	5	3	2	2	3
Processing power	5	1	2	2	3
Onboard connectivity	3	0	3	3	3
User community size	5	3	3	1	3
Low complexity	4	3	2	2	1
Score		87	97	77	88

From the table, it is observed that the ESP32-WROOM achieved the highest score for this particular application. Hence, it was selected for implementation in the specific mechatronics module.

3 Demonstration board development

Since no demonstration boards were available for the ESP32-WROOM at the time, a local company was approached to develop a customised board according to the needs of the university. The resulting board consists of a rotary potentiometer, 6-axis accelerometer, light-dependent resistor (LDR), temperature, humidity and barometric pressure sensor, IR receiver, 0.96" LED screen, RGB LED, red and blue LEDs, two switches, buzzer and an SD card slot. This allows classroom demonstrations and teaching on several digital communication protocols (including I^2C and SPI), pulse width modulation (PWM), analogue-to-digital conversion (ADC), digital-to-analogue conversion (DAC), sensor selection, aliasing, hardware and software interrupts, etc. The final product is shown in Figure 1, which is commercially available on the company's website with the ESP32-WROOM microcontroller for ZAR 895 (at the time of paper submission). Table 2 lists the different components on the board.

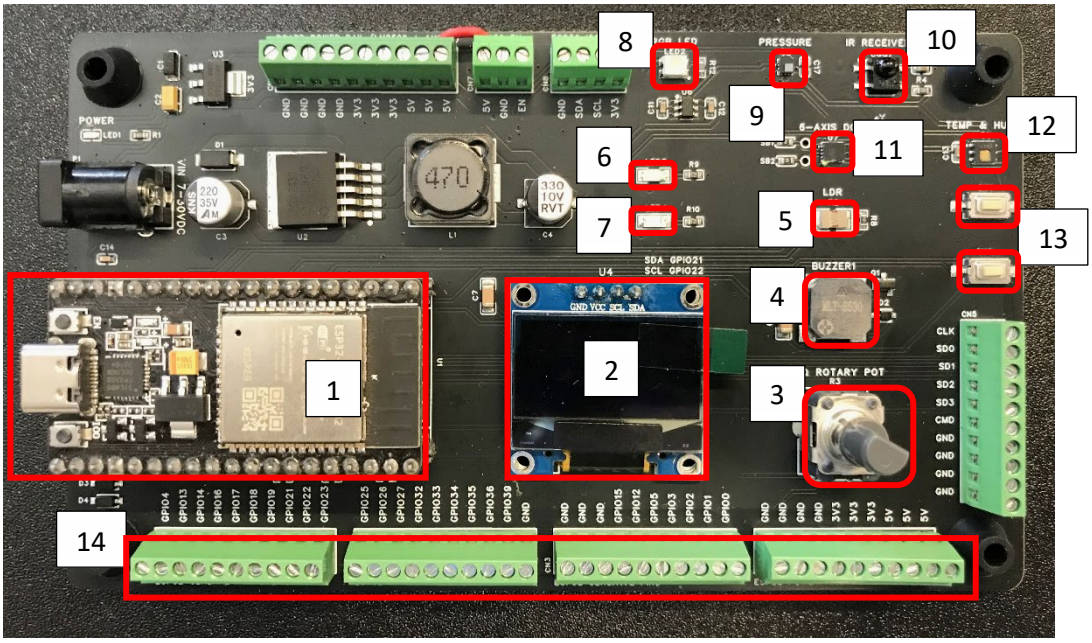

Figure 1: ESP32 Easy Proto V2 (Microrobotics, 2025)

Table 2: ESP32 Easy Proto V2 components

Item	Description
1	ESP32-WROOM (Dev Kit C)
2	0.96” LED screen
3	Rotary potentiometer
4	Buzzer
5	Light-dependent resistor
6	Red LED
7	Blue LED
8	RGB LED
9	Barometric pressure and temperature sensor
10	IR receiver
11	6-axis accelerometer
12	Temperature and humidity sensor
13	Push-button switches
14	Screw terminals

4 Implementation of the ESP32-WROOM

4.1 Practicalities around incorporation into the module

During the 2024 rendition of the mechatronics module presented by the University of Pretoria, the ESP32 Easy Proto V2 was introduced. With the onboard screw terminals, capacitating the measurement of sensor and communication signals with an oscilloscope, this made the unit ideal for teaching and demonstrating digital signal communication protocols and signal sampling theory. Thonny IDE was beneficial for class demonstrations with the board, as no compilation is required, saving time. In a practical session, students

had the opportunity to utilise the ESP32 Easy Proto V2, where they programmed the ESP32 to adjust the RGB LED colour according to the board's tilt using the onboard 6-axis accelerometer as the sensor.

Several final-year students were further tasked with designing and building a rotary inverted pendulum (RIP) using an ESP32 microcontroller as part of their final-year project. An important outcome was that although Thonny IDE was appropriate as a teaching tool, it was too slow to be used in higher-demand applications such as controlling RIPs. C++ was thus identified for higher-demand applications. While Arduino IDE presents an option for C++ programming, MATLAB Simulink combines the power of BBVP with C++. Although MATLAB Simulink does not yet have dedicated hardware support for ESP32, one can interface with ESP32 via the Arduino hardware support package.

While integrating MATLAB Simulink with the ESP32 necessitates a compilation step, it holds the advantage that the user can change parameters during runtime. This is particularly useful when doing live demonstrations in class of the effects of constant values in a PID control loop.

The widespread availability of low-cost, off-the-shelf electronics further enables students to experiment with mechatronics and control systems at home with a kit consisting of an ESP32 microcontroller, H-bridge motor controller and small DC motor with Hall encoder, from as little as ZAR 270 from local resellers.

4.2 Observations on learning efficiency

Students are given the opportunity to give anonymous feedback after each lecture of the mechatronics module, via a Google Form. Prior to incorporating the ESP32-WROOM microcontroller into the module, feedback was often received from students struggling to understand how different aspects of the module connected. This was further exacerbated by the requirement to use C++ (unfamiliar to the students) for low-level programming of the previous microcontroller used in the module.

With the ESP32 microcontroller, MATLAB Simulink was utilised to demonstrate the basic working principles of a quadrature rotary encoder, showing the analogue output signals of the encoder, and how these are used to measure the angle and direction of rotation. It further demonstrated the effects of sample frequency on the measured signal (such as aliasing) and how analogue voltage signals are converted to binary signals. This simple demonstration exposed students to a typical sensor, its operating principle, and basics around signal sampling theory, analogue-to-digital conversion and signal processing. Using MATLAB Simulink helped keep students focused on the learning outcomes of the demonstration, while minimising distractions from coding complexities.

Using the ESP32 Easy Proto V2 with a PicoScope USB oscilloscope, digital communication protocols could be demonstrated effectively in class. Students were observed to be much more engaged with the topic than when they were only shown static textbook figures. Of particular value was the demonstration of the IR receiver, where students became aware that they use a digital communication protocol every time they use an IR remote control.

Using the Thonny IDE as a Python programming interface for the ESP32 Easy Proto V2 helped reduce distractions from low-level coding complexities, which had been problematic in the past. This shift allowed for more in-depth student engagement with topics such as interrupt service routines, analogue-to-digital conversion, bitwise operations, and binary concatenation within the context of the ESP32-WROOM microcontroller.

5 Conclusions

The availability of various software options and low-cost, off-the-shelf electronic hardware, such as the ESP32-WROOM, creates an ideal situation for teaching technology-intensive modules such as mechatronics in an environment where students have a wide range of programming skills. Classroom observations show increased student engagement, allowing them to interact with mechatronics principles hands-on.

This also enables students to experiment with mechatronics in their own capacity at home, and at minimal cost. This teaching and learning approach ultimately aims to empower students to identify and solve everyday mechatronics-related problems innovatively, utilising the available technologies.

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Integrating Collaborative Technologies within a BIM Course for Ireland's AEC Sector: Overview and Proposed Research Directions

Shannon Chance
TU Dublin, Ireland, shannon.chance@tudublin.ie

Abstract

This paper examines the integration of collaborative Building Information Modelling (BIM) technologies within the Bachelor of Science (Honours) in BIM (Digital Construction) course at Technological University Dublin, a course designed to upskill professionals in Ireland's Architecture, Engineering, and Construction (AEC) sector. Recognising the inherently interdisciplinary nature of modern construction and the collaborative workflows enabled by BIM, the course strategically incorporates technologies such as Revit, ArchiCAD, and MagiCAD for discipline-specific modelling, as well as Navisworks and BIM360 for multidisciplinary coordination and clash detection. This practice paper details how these technologies facilitate active and immersive learning, mirroring real-world industry practices while fostering reflective practice and multi-disciplinary teamwork. The paper highlights the crucial importance of developing collaborative skills for the digital transformation of the Irish AEC sector. Building on the BIM course overview and the role of collaborative technologies, this paper concludes by proposing future research to enhance the understanding and practice of BIM education within engineering education research, which may inform the development of similar educational offerings.

Keywords: BIM Technologies, Engineering Education, Collaboration, Multidisciplinary, Digital Construction

1 Introduction

The surveying and construction innovation programs at Technological University Dublin (TU Dublin) are designed to support the digital transformation of Ireland's Architecture, Engineering, and Construction (AEC) sector by equipping students with critical skills in Building Information Modelling (BIM) and related collaborative technologies. The program is designed for mature students, employed or seeking employment in the AEC sector, who complete their studies within a 12-month timeframe. This practice paper describes our integration of advanced active learning methodologies and collaborative tools, such as BIM360, Navisworks, and Revit, to foster lifelong learning and innovation within the AEC sector (Bonde, 2023). Central to this approach is the incorporation of project- and problem-based pedagogies, which provide students with hands-on experience and support in solving real-world challenges (Chance & McAuley, 2023a). Research-driven learning further enhances this process by ensuring that students not only master technical tools but also engage critically with emerging trends and innovations within the industry (Chance & McAuley, 2023b).

Our course emphasises cloud-based collaboration, interdisciplinary teamwork, and the development of reflexive thinking and problem-solving skills, which are essential in a sector that increasingly relies on integrated digital workflows (Chance, 2024). Our blended learning model combines in-person instruction,

synchronous online sessions, and work-based learning, allowing students to engage in flexible, dynamic, and immersive educational experiences. Through this model, students also develop essential leadership, strategic thinking, and communication skills critical for managing the complexities of modern construction projects (Black & Gregersen, 2013; Fullan, 2007).

The outcomes of this pedagogical approach are multifaceted: students gain technical proficiency in digital construction platforms and develop improved competencies in teamwork and leadership, which are critical for driving innovation in a rapidly evolving industry. Moreover, the continuous iteration of pedagogy and technology has been key to refining our approach, enabling us to respond to industry shifts. The paper suggests directions for additional research to support the iterative improvement of the course and similar courses. We hope readers will gain insight into how such strategies can be adapted across various educational contexts to prepare students for leadership roles in a digitally transformed AEC sector, both within and beyond Ireland.

2 Overview of the course

This bachelor's level BIM course employs active and immersive learning approaches across all modules. The hands-on activities include projects tied to each student's employment in the sector, such as case studies, action research projects, modelling and clash detection, and project planning. The course also requires reflective journaling and peer-to-peer learning, fostering reflexivity, critical thinking, and collaboration skills. The modules are listed in Figure 1; every student completes one module from each row, for a total of 60 ECST (i.e., on the European Credit Transfer System).

credits	module name				contact
5	Digital Construction Principles & Standards				24
10	BIM Architectural Modelling & Review	BIM Civil & Structural Modelling & Review	BIM MEP Modelling & Review	BIM Construction Model Exploitation & Review	48
10	BIM Federation & Validation				48
15	Work-Based Learning		Special Collaborative Project		16
5	Research Methods				24
15	Dissertation with Agile Project Management				30

Figure 1: Module provided in this BIM course (Source: Chance, 2024)

The university is actively involved in research and education, supporting the digital transformation of Ireland's AEC sector, with a particular focus on BIM and BIM Management. These digital methodologies are crucial for fostering efficiency, minimizing errors, and driving innovation within the industry. Several key aspects of TU Dublin's work contribute to this digital transformation.

BIM Education and Upskilling: TU Dublin offers comprehensive BIM education programs, including this and research-intensive honours BSc in BIM (Digital Construction), launched in 2020. It complements an MSc offering in applied Building Information Modeling and Management (aBIMM), offered since 2015. These programs aim to upskill working professionals and inject new BIM knowledge and skills into the Irish construction sector. The curricula integrate active learning methods, such as group work and project assignments, to prepare students for the collaborative nature of modern AEC.

Student Research as a Driver of Innovation: A significant component of the BIM programs involves student research via dissertations and capstone projects. The research addresses real-world challenges in the Irish AEC context and encourages students to propose and evaluate solutions relevant to their organisations. The themes explored by past students have included implementing BIM, improving industry practices (especially

in SMEs), leveraging BIM for lean and efficient practices, and utilising BIM in areas like facilities management, heritage conservation (HBIM), and energy retrofits (Chance & McAuley, 2023a).

Scaffolded Approach to Research Skills: TU Dublin employs a stepped and scaffolded approach to support students in developing research skills (Chance & McAuley, 2023a). This equips graduates with the ability to critically analyse information, propose solutions, and contribute to the knowledge base of the Irish AEC sector. The BSc research typically involves synthesising existing literature on topics relevant to Ireland, often leading to the development of new models, workflows, or frameworks.

Alignment with Industry Needs: The BIM courses are designed to be highly applied and relevant to the needs of Irish industrial and governmental employers. The research undertaken by students often addresses specific challenges encountered within their workplaces, fostering a direct link between academic learning and practical application. The format of student theses often mirrors conference papers for industry-relevant events like the bi-annual Construction Information Technology Alliance (CitA) BIM Gathering.

Dissemination of Knowledge: Student and faculty research outputs, including conference papers, industry reports, and thesis documents, are often made available through the university's research repository, ARROW@TU Dublin. This facilitates the sharing of knowledge and best practices within the Irish AEC community and beyond. MSc capstone papers have been downloaded thousands of times internationally, indicating the broader relevance of this research (Chance & McAuley, 2023a).

Focus on National Context: There is a strong emphasis on applying BIM within the specific context of the Irish construction sector, with many student dissertations focusing on national-level issues and adapting international research to the Irish environment. This targeted approach aims to address the unique challenges and opportunities within Ireland's AEC landscape.

Overall, TU Dublin, through its BIM education programs and the research conducted by its students and faculty, plays a vital role in fostering the adoption and effective use of collaborative digital technologies, such as BIM, within the Irish AEC sector. This work contributes to the sector's digital transformation by upskilling professionals, generating relevant research, and disseminating knowledge to improve industry practices and drive innovation.

3 Overview of collaborative technologies

The BIM BSc course utilises several technologies to facilitate and promote collaboration among students and with industry practices. BIM software, such as Revit, ArchiCAD, and MagiCAD, is central, enabling students from different disciplines (Architecture; Civil & Structural, and Mechanical, Electrical, and Plumbing (MEP)) to create and share digital models of buildings. Collaboration is further enhanced using Navisworks (geared toward our Construction Management students, with engagement from students of all disciplines represented in the course). Navisworks allows students to federate these discipline-specific models, run clash detections in multidisciplinary teams, and analyse the integrated project information. The course also employs BIM360 as a platform for collaboration, supporting teamwork in the "Federation and Validation" module. The cloud-based nature of BIM facilitates blended learning, using both synchronous and asynchronous approaches for collaborative learning activities. Beyond specific BIM tools, students develop web-based e-portfolios (using Adobe Portfolio or Brightspace ePortfolio) with secure OneDrive file storage. These tools help students reflect on, cultivate, and showcase their learning. Finally (up until 2024), access to LinkedIn Learning (LIL) provided students with resources for self-directed exploration of various technologies relevant to collaborative BIM workflows and project management. These technologies collectively support the course's active and immersive learning approach, fostering hands-on experience and preparing students for the collaborative environment of the AEC sector.

Learning to collaborate is essential in the course and in the broader AEC sector. For one, the AEC sector is inherently interdisciplinary. Modern construction projects involve professionals from diverse fields, such as

architecture, structural engineering, MEP engineering, and construction management. BIM, as a digital project management tool, necessitates that these different disciplines work together seamlessly. The course mirrors this by having students break into discipline-specific streams for modelling but then come together in multidisciplinary teams in modules like "Federation and Validation" to integrate their models, run clash detections, and resolve errors. This experience in collaboration is vital for their future professional practice.

Secondly, BIM workflows are inherently collaborative. The technologies used in the course (such as Revit, ArchiCAD, MagiCAD for discipline-specific modelling and Navisworks and BIM360 for federating models and managing project information), are designed to facilitate shared access and collaborative work on project data. Understanding how to use these tools effectively in a collaborative setting is a core learning outcome, as it reflects how BIM is implemented in industry.

Thirdly, collaboration fosters better problem-solving and innovation. When individuals from diverse backgrounds and with varying expertise collaborate, they bring a range of perspectives to the table, leading to more comprehensive problem analysis and innovative solutions. The course design, with its emphasis on group work, field- or work-based activities, and project assignments, actively promotes this collaborative problem-solving process.

Moreover, research in BIM emphasises collaboration. By engaging in research projects related to BIM, students learn how to collaborate effectively across sub-disciplines. This is a key aim of the BSc course, which encourages students to address real-world challenges and implement proposed solutions within their organisations, via interaction with colleagues from different departments or specialisations.

Professional bodies and industry expectations also emphasise collaboration. Our course curriculum and learning outcomes are aligned with the frameworks of professional bodies, such as Engineers Ireland, the Society of Chartered Surveyors Ireland/Royal Institution of Chartered Surveyors, and the Chartered Institute of Building, all of which recognize the importance of collaboration in the modern AEC sector. The course explicitly aims to foster students as effective BIM collaborators, prepared to meet industry needs.

Challenges in PBL, as highlighted in the literature, often revolve around teamwork and collaboration. Recognising and addressing these challenges in a supportive academic environment prepares students for similar issues they might encounter professionally. The course's integration of reflective journaling and peer-to-peer learning allows students to process their collaborative experiences and learn from one another.

All in all, the complexity of modern AEC projects combined with the collaborative nature of BIM methodologies makes the ability to work effectively in teams an indispensable skill. This BIM course intentionally integrates various technologies and pedagogical approaches to cultivate these collaborative skills, to prepare graduates to contribute meaningfully to the digital transformation of the Irish AEC sector.

4 Evidence of Impact and Results

Regarding our students' research success and impact, three BSc dissertations from the course have achieved significant recognition, contributing to areas like energy-efficient design (Grego et al., 2023), structural design optimization (McLoughlin & McAuley, 2022), and enhancement of estate management within the healthcare sector (Martin et al., 2021). These specific examples provide strong evidence of the course's practical impact (Chance, 2024). Our students' research often focuses on national-level issues in the Irish AEC context, exploring new processes or tools, and addressing real-world challenges. The MSc capstone papers have been downloaded thousands of times internationally, indicating the broader relevance and successful dissemination of knowledge generated through TU Dublin's BIM programs.

Graduate Attribute Development: The curriculum aligns with TU Dublin's Graduate Attributes, fostering enterprising skills such as innovation, leadership, collaboration, and entrepreneurship. The course emphasizes global responsibility, ethical conduct, effective communication, critical thinking, problem-

solving, reflective practice, digital literacy, teamwork, emotional intelligence, strategic thinking, and resilience.

Demonstrated Learning Outcomes: Core learning outcomes include students' ability to create discipline-specific BIM models, utilize appropriate BIM standards, coordinate BIM models across disciplines, and exploit BIM models for various tasks (e.g., cost, energy, design).

5 Evaluation Methods and Quality Assurance

Our rigorous assessment involves formal procedures that include continual data collection, course-refinement activities, and twice-annual assessments by external examiners. The course was validated by Ireland's Higher Education Authority (HEA) in 2018 and is subject to continuous review. We use structured rubrics to assess student performance, thereby providing formative and summative feedback and helping ensure reliable reviews by multiple staff members. The Module Boards that we conduct each semester involve review by two external examiners (one from industry, one from another academic institution), to ensure validity, coverage, rigor, and fairness of grades. This follows meetings of the Program Review Committee, comprised of student representatives and teaching staff. The Committee meets each semester to consider student feedback, address concerns, and identify areas for improvement. The External Examiners have provided feedback such as: "The Project-based approach, both at individual and group level, is very practical and reflects industry situations" and the "Programme content is extensive and all modules are relevant to Industry needs [both present and future]". The examiners have also emphasized the program team's responsiveness and continuous improvement by noting positive developments within the Work-Based Learning (WBL) module following feedback examiners previously provided. We use an ongoing process of reflection and critique of current practices to enhance course design and delivery, as discussed by Chance (2024).

6 Proposal for future study

We have ideas for engineering education research projects that could expand our understanding of the BIM course. A study evaluating the effectiveness of the BIM/Digital Construction course in nurturing leaders who have made significant contributions to the Irish AEC sector could provide valuable insights. Such a study could involve surveying and/or interviewing graduates, in a research design underpinned by a leadership model such as Fullan's (2007) or Black and Gregerson's (2013). We aim to assess how well the BSc course equips graduates to contribute as leaders in the Irish AEC sector, describe graduates' career trajectories, and identify leadership roles they have assumed following their BIM education.

A second idea worthy of study involves further exploring the active learning pedagogies used in this course, as outlined in a study underpinned by the well-cited journal article by Chen et al. (2021). The research question for such a study could be:

> ***How do the design and implementation of the TU Dublin BSc (Honours) in BIM (Digital Construction) course align with the levels of PBL implementation identified by Chen et al. (2021), and what challenges encountered in the course resonate with the individual, institutional, and cultural level challenges reported in their review?***

By answering this research question, an applied research project could provide valuable insights into applying PBL in a specific digital construction context, using a well-established framework from the engineering education literature. This would contribute to understanding the implementation of PBL and the pedagogical approaches in BIM education. Here is how we could approach it:

Alignment with PBL Implementation Levels: We could analyse the course based on the four levels of PBL implementation identified by Chen et al. (2021):

- **Course Level:** Consider individual modules within the BIM program and how they incorporate PBL elements, e.g., the "Digital Principles and Standards" (DPS) module includes research activities.
- **Cross-Course Level:** Examine how different modules within the BIM program build upon each other and support project-based learning, particularly the link between the "Research Methods," "Work-Based Learning," and “Dissertation” modules.
- **Curriculum Level:** Evaluate how PBL principles are integrated as a key learning method across the entire one-year intensive BSc (Honours) BIM program.
- **Project Level:** Analyse the significant research dissertations and work-based learning components as substantial projects utilising PBL methods.

Resonance with PBL Challenges: The study could explore whether the challenges embedded in the design and delivery of the course, or experienced by its students and staff, align with Chen et al.'s categories:

- **Individual Level:** Consider the challenges students face as individuals working in BIM environments.
- **Institutional Level:** Investigate any lack of support from the institution (though the sources suggest strong institutional support at TU Dublin for BIM education and research) and challenges in designing an effective PBL curriculum.
- **Cultural Level:** Explore further how the Irish AEC sector's context and cultural factors influence the implementation and effectiveness of PBL in the BIM course.

7 Conclusions

To summarize, integrating collaborative technologies is central to this BSc course in BIM/Digital Construction, directly addressing the need for enhanced collaboration within Ireland's AEC sector. This course provides mature students with hands-on experience using tools such as Revit, Navisworks, and BIM360 to foster multidisciplinary teamwork and prepare them for the collaborative demands of digital construction. Building upon this foundation, future research is essential to evaluate the effectiveness of these pedagogical approaches and technologies in nurturing leaders and driving the ongoing digital transformation of the Irish AEC industry.

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Building towards better learning: Evolution of practical design, build and test activities in an introductory Mechanical Engineering Design course

Reuben Govender
Department of Mechanical Engineering, University of Cape Town, South Africa, reuben.govender@uct.ac.za

Adriaan de Villiers
Department of Mechanical Engineering, University of Cape Town, South Africa, Adriaan.devilliers@uct.ac.za

Abstract

We describe the iteration of a practical design and prototype testing activity in our 2nd year Mechanical Design course. The initial implementation was a low complexity, low risk design task where only FDM 3D printing was used for manufacturing a static structural part. Subsequent implementations involved more complex design tasks, where prototypes required moving machine elements, and the manufacturing "toolkit" expanded to include LASER cutting and carpentry tools. We discuss challenges encountered, either due to logistical difficulties or poor estimation of student preparedness for workshop tasks. Our students have embraced the experience and we intend to retain this activity, noting some logistical and scheduling improvements that will facilitate future iterations.

Keywords: Mechanical Design, Prototyping, Project Based Learning, Constructionism

1 Introduction

Our Mechanical Engineering undergraduate program currently includes a compulsory final (4th) year Product Design course, where students work in groups to design, manufacture and test a physical prototype for a stand-alone mechanical product, such as a motorised pipe bender or caulking tool. The 4th year Product Design Course (hereafter 4PDC) is considered "high stakes" by both students and lecturers as it includes the assessment of three Graduate Attributes at exit level for the qualification.

Previous versions of the 4PDC in our program were based on individual submissions of purely paper-based design, without any requirement for manufacturing a physical prototype. Hence not all students were exposed to a "design, build and test" learning activity, although a limited number of students did take individual capstone projects with a strong design and build component. The desire for all students in the program to have exposure to the manufacturing and testing of a design they created, motivated our curriculum change to the current final design project. Due to the inherent costs associated with manufacturing and our budget limitations, individual design & build projects were not feasible, leading to the implementation of a group design & build project. The group activity also has the benefit of more closely modelling workplace practices, where an engineer is more likely to design as part of a team with a broader scope, such as a component within a larger system.

Lecturers and workshop technicians observed final year students during the practical manufacturing tasks, noting that many struggled with basic practical activities, despite theoretical content for these manufacturing activities being presented in earlier courses. Informal conversation with students revealed that most students had limited prior hands-on experience in manufacturing. While students were required to spend time in manufacturing workshops, this happened during the vacation period and was not a requirement for the students' academic progression to final year.

These challenges motivated the inclusion of a design & build activity in the 2nd year Mechanical Design course, as a primer for the 4th year design course. The 2nd year activity would also be a group project that enabled students to develop professional competencies, such as peer communication and accountability for tasks within a team, at a more elementary level than required to succeed in the 4th year design course. The 2nd year Group Design Project (hereafter 2GDP) first ran in 2022 with further iterations in 2023 and 2024. This paper discusses the evolution of the 2GDP, which started with a small, low risk activity and has developed into a larger component of the module.

2 Project Framework and Context

Our implementation of the 2GDP as a Project Based Learning (PBL) experience largely follows the discipline project described by De Graaff & Kolmos (2003). We acknowledge that as these projects exist within a specific

2nd year course, and students take concurrent courses that don't subscribe to PBL approaches, the higher level curriculum aspects of PBL described by De Graaff & Kolmos have not been implemented. Our approach also incorporates themes of the Constructionist paradigm, as espoused by Seymour Papert (Harel & Papert, 1991), where building a physical prototype stimulates the connecting of prior or external learning to the task at hand.

All versions of the 2GDP thus far shared a common structure, which is similar to the approach of Denayer et al., (2003), though with less formal feedback given during the project. The project brief posed a problem, ideally with some familiar context, that the students should address. Each group was required to manufacture a physical prototype solution. The manufacturing resources and budget were limited and students were not permitted to buy their own materials or use tools outside the UCT Mechanical Engineering workshops. Due to the enormous variation in discretionary spending money across the UCT student population, this restriction was necessary to ensure that the wealthier students do not buy more materials (affording them more opportunities to iterate) or complete tasks at home workshops (where they could gain assistance that other students could not access). Exceeding the material allowance carried a (small) mark penalty. The first submission was a Bill of Materials (BOM), engineering drawings and 3D Computer Aided Design (CAD) files necessary for procuring materials and beginning manufacturing. Once students completed the manufacturing of their prototypes, each group's prototype would be physically tested against some criteria established in the project brief. Students could do preliminary testing within their group, but the final test and performance measurements needed to be supervised by a lecturer or teaching assistant. The final submission was primarily a presentation, in the form of a recorded 10 minute PowerPoint slide show, that documented the students' design decisions, the outcomes of their testing and some reflection on their learning during the project. Along with the presentation, each group needed to submit two written items: evidence of some group management in the form of meeting minutes; and calculations that informed sizing of components or material selection during the design phase.

Groups comprised of five students, with group composition chosen by the course convener. The class sizes ranged from 131 to 152 students. The 2GDP counted 10% of an individual student's final grade, with all students in a group receiving the same grade. It was expected that individual students would contribute 12 to 14 hours of work towards the group effort, recognising that the most successful groups would appropriately delegate tasks to suitably skilled members.

The initial submission of the BOM, drawings and CAD was screened to extract information for material purchasing, but the quality of the groups' designs was not assessed or corrected in any way before manufacturing began. We intended that problems in any group's design should arise organically during the manufacturing phase, with students needing to self-direct their learning and adjust their opinions based on observation and personal experience. This was in deliberate contrast to other learning activities, both within the course and in other courses, where design drawings are assessed and feedback on design quality is limited to what the marker writes. We intended to model the experience of design as practiced in industry, specifically so that students learned to process their emotional response to design shortcomings highlighted at the peer level, and to persevere through a problem even if they made a fundamental theoretical error at an earlier stage.

The final submission specifically avoided written reports, as students developed report writing skills in other activities. It was a requirement that all students participate in narrating part of the recorded presentation. Our intent here was to create a "paddling pool" experience for oral presentations as many of our students are not English first language and have limited exposure to public speaking training. In contrast to live presentations assessed in 3rd and 4th year courses, students could revise and refine their oral recordings. The written submissions of meeting minutes and calculations were intended as evidence to support claims made in the presentation and to guide students' reflection on their design experience, rather than items which were explicitly assessed in detail.

We did not conduct a formal survey or gather other quantitative data. Due to the students' deadlines overlapping with the end of semester and the preparation period for exams, we were sensitive to adding "yet another hand-in" to the students' workloads. Feedback on the students' experiences and challenges was based on informal conversations with students at various stages of the projects.

3 Iterations of 2GDP

3.1 Shelf Rack - 2022

Students were tasked with designing a rack that could hang on the window bars above a sink in a laboratory, capable of supporting a 2.5kg load – approximately the size of a detergent bottle. All parts had to be manufactured using FDM 3D printing, with a limit of 120g of PLA filament. Groups could use threaded fasteners or adhesives to join FDM parts. However, the attachment to the window bars had to be achieved without screws or other fasteners penetrating the window bars. The spacing of the window bars had loose tolerances – the designs had to accommodate the differences in dimensions. Performance testing consisted of hanging a dead load from a designated point on the rack, measured with a digital fishing scale and a dial gauge to determine the vertical deflection.

3.2 Jar Opener – 2023

The problem context moved from a university laboratory, to the students' homes. The groups needed to design a tool to assist in opening screw top jars, where the person's hands might not grip firmly or exert enough torque to remove a well sealed lid. In addition to 90g of PLA filament for FDM printing, groups could also use LASER cutting of acrylic polymer sheet (up to one A4 page, 3mm thick), and a limited range of threaded fasteners. We permitted the groups to request small quantities of additional materials (rubber sheet, rope etc) provided these could be sourced from local hardware stores. The performance test involved the same teaching assistant opening a jar of a given size using each group's designed jar opener. Following this, the torque that the Jar Opener could exert on a lid of given size, before either reaching a deflection limit or failing, was measured.

3.3 Bed Raising System – 2024

This project was suggested by an alumnus of the university, who sold hospital equipment to rural clinics in Botswana. They had observed that nurses often struggled with the mechanism for raising the backrest of hospital beds, that weren't equipped with electric motors. The groups were tasked with designing a mechanical system for elevating a hospital bed backrest, as electrical supply in this part of Africa can be unreliable, while keeping the load exerted by a nurse to below acceptable levels. We provided wooden bed frames with a hinged backrest, that were one quarter scale of a normal hospital bed. The use of 3D printing and LASER cutting was retained, but groups could request timber sections up to a length limit (2 m). The students had to cut, drill or shape timber themselves with access provided to table saws and drill presses, but not lathes or milling machines. Groups could also request threaded fasteners, bushings and rope within limits. The performance test involved placing a dead weight of 15 kg on the backrest and measuring the load exerted on the mechanism to raise this, using a digital tension scale. The designs were required to keep the input load below 4 kg and raise the bed rest to 36° within 60 seconds.

4 Discussion

Student groups took ownership of their projects with very little prompting from lecturers and tutors. It was pleasing to see this core tenet of PBL being realised with students' enthusiasm rather than lecturers imposing the requirement. This was most palpable in 2022, as our university had only returned to full in-person learning at the start of the semester, following the COVID pandemic – students were clearly hungry for socially interactive learning. However, this enthusiasm was sustained as the 2024 cohort regularly asked for the workshop's opening hours to be extended so they could keep working on their prototypes.

The complexity of the first 2GDP iteration in 2022 was deliberately kept low. We wanted to probe the unseen complexities and risks of the PBL experience without incurring substantive costs for material and staffing. As the major manufacturing work involved using our department's FDM 3D printers, which are managed by the lead author, we encountered very few logistical challenges. In 2023, we increased complexity by requiring designs that involved moving parts. We added LASER cutting to the "toolbox", as LASER cutting is faster than FDM 3DP. This introduced some logistical and scheduling challenges, as the students' CAD submissions for LASER cutting weren't always suitable for the workshop staff to process immediately. Delays incurred in scheduling additional workshop staff time to assist with correcting this caused some unhappiness for groups of students, who are understandably sensitive to delays. However, lecturers and postgraduate tutors could ameliorate this by pointing out that outsourced manufacturing in the workplace often requires this additional work, until relationships and communications between the design engineers and the manufacturing technicians matured. While the students received little formal instruction on the use of FDM 3D Printing and LASER Cutting, the class developed collective competence in these relatively quickly. For more than 95% of the class, this was the first time they saw one of their CAD models being realised physically, which they embraced enthusiastically.

The 2024 iteration of 2GDP required the use of powered carpentry tools. We anticipated needing more staff supervision, due to the inherent risks of powered cutting tools, but initially underestimated these demands. During the first carpentry workshop sessions, it became clear that most students lacked knowledge of how to work safely with table saws or drill presses. Less than half the class had completed their first year workshop training requirement, while many students expressed uncertainty as the tools were not identical to those they had trained on. We quizzed the few students who displayed sound judgement and workshop awareness, learning that many had gained carpentry skills at home workshops or during optional school projects. While the closer supervision was demanding for lecturers, it provided opportunities to discuss safety awareness and the role of engineers in risk management in a more organic setting than a lecture hall.

In all iterations of 2GDP from 2022 to 2024, the assembly and testing phases yielded significant surprises for students, that prompted learning and reflection on manufacturing and structural mechanics content taught in earlier courses. Students encountered the importance of allowing for manufacturing tolerances when parts needed to fit together, whether these were manufactured by 3D printing or being manually cut and drilled. During testing, we tried to gradually increase loads towards the target, which allowed students to observe structural response and how this affected the functioning. The more complex mechanisms applied for the Bed Raising System often revealed that a group had overlooked friction, parasitic loads or failure modes such as buckling. When quizzed about these, students often acknowledged that they had been taught about the concept in a prior course. Some students hadn't analysed the relevant behaviour at all due to time constraints, while others had made (incorrect) judgements that the phenomena would not be significant in their design's performance. There were rare cases where one group member had prior calculations that predicted an observed failure, but peers in their group did not include these in the final design decisions.

The cost of running the 2GDP was mitigated by the purchase of the FDM printers and LASER cutters being supported by a faculty teaching equipment CAPEX award, as this equipment would support work across the undergraduate curriculum and be available for postgraduate student usage. The cost of materials consumed was surprisingly low: < ZAR 3 000 in 2022 and < ZAR 6 000 in 2023. The inclusion of timber as a consumable and building several bed "test frames" in 2024 saw the costs climb to approximately ZAR 14 000. For a class of ~150 students, this is below ZAR 100 per student, representing positive value for money. The staffing costs are more significant; however, much can be achieved with well-trained postgraduate tutors when students are working with low-risk equipment. In 2024, the closer workshop supervision requirements resulted in lecturing and workshop staff accumulating just under 40 hours of contact time during the last two weeks of the project.

5 Concluding Remarks and Recommendations

The enthusiasm of the 2nd year students participating in the 2GDP is not sufficient on its own, as many undergraduate students would view workshop time as a welcome break from their typical calculation exercises. One of the 2024 final year undergraduate students, who completed the 2nd year Design course in 2021 before any practical projects were implemented, observed the 2GDP workshop sessions and had the following comments:

"*The current iteration of MEC2048S, which I had the pleasure of witnessing in 2024, is a much more holistic experience…. This hands-on approach is something that I deeply wish I had experienced during my time in the course. Not only would it have given me a much stronger foundation and understanding, but it would have also made me feel more like an engineer.* "

The tutors responsible for supervising the CAD sessions as well as the prototype assembly and testing shared similar sentiments, noting how this experience highlighted the importance of the thinking about manufacturing and assembly before one committed to a complex design "because it looked cool".

This feedback from more mature students gives us confidence in the longer-term value added by the 2GDP activity. We believe the 2GDP is stimulating the desired learning for the 2nd years. We will need to interrogate the performance of these cohorts as they reach the 4PDC stage in 2025 and 2026, to gather more robust evidence.

In our research-intensive university, the combination of theoretical and practical skills necessary to facilitate this design and build activity is not common. This poses a challenge should the current lecturers be rotated to teaching other courses. However, guidance on manufacturing and workshop supervision can also be provided by suitable technical workshop staff.

We have identified some key areas to improve the 2GDP activity in future:

- Providing short training sessions on the carpentry workshop equipment, well in advance of the project being released, would allow students to develop competence with less time pressure and relieve some demand for lecturer supervision.
- Scheduling the 2GDP to begin earlier in the semester would allow students more flexibility in scheduling their manufacturing and workshop activities, to avoid clashes with tests and assignments in other courses.
- Technicians from the workshop should be incorporated into planning and manufacturing supervision, including training for technicians not confident in working with undergraduate students.

Our future iterations of the 2GDP will likely involve less ambitious outputs than the Bed Raising System and the relative contribution towards the course mark should be increased to reflect the students' time on task. We believe the costs and challenges of running the 2GDP are far outweighed by its positive impact on the students' learning and attitude towards design and engineering practice.

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Developing Student Competency in Engineering Tools Using Open-Source Software in Undergraduate Engineering Education

Cila Botha
North-West University, Faculty of Engineering, School of Chemical & Minerals Engineering, South Africa, cila.botha@nwu.ac.za

Willem van Niekerk
North-West University, Faculty of Engineering, School of Mechanical Engineering, South Africa, willem.vanniekerk@nwu.ac.za

Abstract

Since the introduction of ECSA's revised Graduate Attributes in August 2023, engineering programmes have had to adapt teaching to meet new requirements. Graduate Attribute (GA) 5 emphasises competence in selecting, applying, and evaluating engineering and IT tools for complex problems, with a stronger focus on mathematical and computational foundations. Commercial CAD and CFD software, while effective, is costly and often inaccessible post-graduation, making open-source alternatives attractive. FreeCAD (for CAD) and OpenFOAM (for CFD) were integrated into a third-year heat and mass transfer module at a South African university to perform CFD analysis. These tools require students to engage directly with solver algorithms, numerical methods, and scripting, fostering deeper understanding of model development, computational efficiency, and tool limitations. Their accessibility also encourages collaborative, independent learning. The study assessed the potential of open-source tools to develop GA 5 competencies through a final assessment project. Students submitted self-reflective notes, which highlighted cost-effectiveness, improved proficiency, confidence in simulation tools, and enhanced problem-solving skills. One student noted, *"This assignment gave me a real sense of applying theory to practical engineering scenarios."* Findings indicate that open-source CAD and CFD tools can match the technical skill development of licensed software while adding accessibility and collaboration benefits.

Keywords: Undergraduate development, Open-source CAD software in education, Engineering education

1 Introduction

In August 2023 the Engineering Council of South Africa (ECSA) released their revised E-02-PE document containing changes to each graduate attribute (GA) (ECSA, 2023). The table below summarizes the key differences between the previous and latest elements of ECSA's GA 5.

Table 1: Concise summary comparing the previous (September 2020) and latest (August 2023) ECSA GA 5:

Aspect	Previous ECSA GA 5	Latest ECSA GA 5
Focus	Using appropriate engineering methods, skills, and tools, including IT.	Creating, selecting, applying, and recognizing the limitations of engineering and IT tools for solving complex engineering problems.
Key Requirements	Competence in discipline-specific tools, computational and simulation software, and IT for information management.	Emphasis on prediction and modeling, applying modern engineering tools, and understanding their constraints.
Knowledge Base	Practical use of engineering tools and IT for teamwork and productivity.	Stronger foundation in mathematics, numerical/data analysis, statistics, and computer science for detailed modeling and analysis.
Scope of Tools	Broad use of software and digital tools relevant to engineering practice.	More explicitly integrates analytical techniques, modern resources, and engineering technology.
Complexity	General application of tools for engineering practice.	A more critical approach, requiring graduates to assess tool limitations and suitability for complex problems.

Key Differences are therefore identified as:

- Increased emphasis on critical evaluation: The new GA 5 requires recognizing tool limitations, rather than just applying them.
- Stronger mathematical and computational foundation: The new GA 5 explicitly includes conceptual mathematics, statistics, and data analysis.
- Greater focus on complex problem-solving: The updated version ties engineering tools to solving complex problems rather than just using them effectively.

There is a strong emphasis on developing competency in discipline-specific software tools. While the use of open-source engineering tools is not new, this study's contribution lies in demonstrating their integration into a problem-based, collaborative learning framework aligned with the revised ECSA GA5 requirements. Previous studies confirm the computational reliability of open-source software, but literature showcasing its efficacy within undergraduate engineering education is limited. For example, (Najihah et al., 2021) showed FreeCAD and OpenFOAM produced results for a passenger ship hull simulation nearly identical to experimental data, while (Lee et al., 2020) successfully applied earlier versions to simulate an internal combustion engine and large trailer with high accuracy. In Chemical Engineering education, proficiency in CAD and CFD software is essential for modelling, simulation, and data analysis, especially under the revised GA 5. However, commercial software presents challenges: costly licenses often exceed institutional budgets, especially in the Global South, where limited IT infrastructure and support complicate maintenance and updates. Even with licenses, not all students have access to suitable computers, and installation or activation issues delay early use. Post-graduation access is also limited, particularly for graduates entering smaller firms without licensed software. Open-source alternatives like FreeCAD and OpenFOAM provide a sustainable, equitable solution. They promote self-driven learning through online tutorials and forums, fostering both technical and soft skills. This paper aims to demonstrate the potential of FreeCAD combined with OpenFOAM to develop ECSA GA 5 competencies in third-year Chemical Engineering students while addressing the cost and accessibility challenges of licensed software.

2 Educational approach and design

2.1 Pedagogical framework and learning principles

The intervention, which aimed to develop ECSA GA 5 competencies using open-source tools, was implemented in a third-year Chemical Engineering heat and mass transfer module. This module, taught by one of the authors, involved a cohort of 20 students in 2024 at a South African university, who had diverse backgrounds and varying prior exposure to engineering software. The module's design incorporated a blended learning approach that significantly emphasised industry-related problem-based learning (PBL). This framework was chosen to:

- Utilise realistic examples for problem-solving, aligning theory with practical application.
- Foster self-directed learning, allowing students to navigate challenges independently.
- Increase learning effectiveness, convenience, and accessibility for the student cohort.

Throughout the semester, students were prepared for a Final Assessment of Module Outcomes (FAMO) project, which served as the module's summative assessment, replacing a traditional examination. This individual heat exchanger design project was structured around a real-world industry design request, mirroring authentic engineering scenarios. Students were required to use FreeCAD and OpenFOAM to simulate, optimise, and critically assess their design choices. This approach ensured that the open-source

software was not just an add-on, but an integral tool for solving complex engineering problems within a practical, industry-aligned context. The module's assessment plan (summarised in Table 2) was designed to incrementally prepare students for the FAMO project, which explicitly utilised open-source software for ECSA GA 5 development.

Table 2: Assessment plan summary:

Participation mark		**60%**	**Notes & Comments**
Reading assignments	5%		Given to prompt students to prepare for in-person class sessions, laying the foundation of their module knowledge base.
Tutorials	15%		Given as assessment for learning aiding in applying the mathematics needed for CAD and CFD simulation.
Practical assignments	30%		Aimed at introducing student to FreeCAD and OpenFOAM. The executed practical fluid flow scenario has to simulated in FreeCAD in conjunction with OpenFOAM.
Class tests	50%		Given as assessment of learning of the fundamental principles governing fluid flow and heat and mass transfer.
FAMO Project		**40%**	Final assessment of module outcomes - Specific focus on ECSA GA 5 development, where a complex problem is presented which must be simulated and critically evaluated using the open-source software tool.
Individual Project	100%		
Module Mark		**100%**	60% Participation mark + 40% FAMO Project - Sub-minimum of 40% for both participation mark and FAMO Project

2.2 Integration of FreeCAD and OpenFOAM into module content

To effectively introduce and build student proficiency with FreeCAD and OpenFOAM, the following elements were implemented throughout the semester:

- Initial Orientation: Students received an overview of CAD and CFD software, its relevance, and the FAMO project requirements in the first class session of the semester.
- Theory-Practice Link: Theoretical concepts were continuously contextualised with practical applications in CAD and CFD software during lectures and tutorials.
- Resource Provision: A "How-To Guide" was provided, detailing software download, OpenFOAM add-in installation, and linking to relevant YouTube tutorials and mini-tutorials to aid familiarisation. Students had seven weeks for project completion.
- Group Practicum: A collaborative group session allowed students to familiarise themselves with the software through a less intensive simulation, receiving feedback to prepare for the FAMO project.
- Dedicated Support: A module assistant provided logistical and technical support for software installation and usage, minimising adoption barriers.
- FAMO Project Submission: The project required online submission of simulation details, source files, residual graphs, and output proof, along with a three-minute video defence and self-reflective notes for proficiency evaluation, and perceived learning.

3 Challenges faced and lessons learned

This section discusses the primary challenges encountered during the module's intervention, followed by key lessons learned from both the lecturer's observations and students' reflections, highlighting their relevance to fostering competency, collaboration, and critical engagement with engineering tools.

3.1 Challenges

The main challenge in implementing FreeCAD and OpenFOAM was human perception. As the software was free and open-source, many students and staff held a negative bias, presuming it was less capable than commercial packages for CFD analysis. This perception exacerbated frustrations over minor logistical issues, despite the open-source tools actually presenting fewer technical problems than commercial alternatives.

While formal developer support was absent, the availability of numerous informal online user forums proved crucial. Engaging with these forums not only aided problem resolution but also facilitated a richer learning experience. Students developed essential IT-related problem-solving skills by independently seeking solutions, rather than relying on predefined manuals available when using licenced software. This process inherently promoted 'connection' within a broader community of users. Furthermore, this self-driven approach to troubleshooting reinforced the updated ECSA GA 5's emphasis on critical evaluation and independent problem-solving.

3.2 Lessons learned

The integration of open-source software yielded significant educational benefits, as observed by the lecturer and corroborated by student reflections. From the lecturer's perspective, students demonstrated marked improvements in technical skills, problem-solving abilities, and adaptability, achieving similar proficiency levels to those using commercial software while also gaining a deeper understanding of underlying algorithms and modelling limitations, consistent with ECSA GA 5. The open-source nature specifically facilitated open, cloud-based collaboration due to the absence of license restrictions, fostering a more connected learning environment. Students' reflections underscored their increased confidence in applying theoretical knowledge to practical engineering scenarios, improved problem-solving skills, and enhanced resilience in navigating complex software challenges. Students also showcased a better theoretical basis of reasoning from which they critically evaluated the proficiency of the software. These comprehensive lessons, providing valuable insights into both technical and soft skill development, are detailed further in Tables A.1 and A.2 in the Appendix.

4 Critical reflections and conclusions

The integration of FreeCAD and OpenFOAM for CFD analysis at an undergraduate level in a South African university proved highly promising. The advantages observed significantly outweigh the challenges faced, demonstrating the suitability of these tools for engineering education.

A core takeaway is that open-source software effectively aided the development of ECSA GA 5 competencies, fostering critical evaluation of tools, a stronger mathematical and computational foundation, and enhanced complex problem-solving abilities. Students not only matched the technical proficiency typically seen with licensed software but also gained a deeper engagement with modelling limitations, and manual workflow setup, thereby 'co-creating' their computational understanding due to a lack of formal user manuals. Open-source tools uniquely support the themes of 'connection, collaboration, and co-creation'. Their unrestricted

accessibility directly addresses significant challenges associated with commercial software, such as high licensing costs and post-graduation inaccessibility. This is particularly pertinent in the Global South, where limited IT infrastructure and support often complicate the use of commercial packages. Furthermore, the reliance on numerous informal online user forums for troubleshooting provided a richer learning experience, equipping students with essential IT-related problem-solving skills and promoting self-directed learning and resilience, a form of personal 'co-creation' of their learning strategies.

In conclusion, the findings showcase FreeCAD and OpenFOAM as reliable and impactful tools for developing well-rounded engineering graduates. This approach offers a sustainable and equitable solution for engineering education, promoting continuous learning and skill development beyond the confines of university, and providing valuable insights for other engineering disciplines reliant on Computer-Aided Design (CAD), CFD, and similar computational packages that often face similar accessibility challenges.

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Appendix

Table A.1: Lessons learned: the lecturer's perspective.

Module outcome	Lessons Learned
Using FreeCAD and OpenFOAM	Students learned to navigate complex engineering tools despite initial steep learning curves. Confidence in using these tools grew as students practiced and completed tasks. Simulation errors prompted critical problem-solving and troubleshooting. Requires deeper understanding and manual setup, rather than using pre-built commercial solvers, aiding in reaching GA 5 outcomes. Students learn to assemble and troubleshoot their own workflows rather than relying on vendor support. No license restrictions; enables open, cloud-based collaboration with version control
Application of Theoretical Knowledge	Students connected classroom theory to real-world engineering problems, gaining insight into practical applications. FreeCAD enabled Students to engage with the computational results in such a way that they could vary system parameters to find the best solution via an inquisitive trial-and-error based approach helping them to understand how design parameters affect performance and the importance of optimization.
Problem-Solving and Adaptability	Challenges with simulations, designs, and calculations fostered resilience and adaptability. Students gained confidence in iteratively refining designs and finding creative solutions.
Time Management and Project Planning	Many students highlighted the importance of starting early and allocating time effectively. The project emphasized realistic planning and the consequences of underestimating task complexity.
Communication and Reporting	Developing reports and video presentations enhanced communication skills. Clear articulation of technical concepts to diverse audiences was a valuable takeaway.
Collaboration and Independence	Students balanced teamwork with independent problem-solving, learning to seek help when necessary. They developed the ability to work autonomously while meeting project goals. Open-source tools are freely available, allowing students to collaborate without license constraints and use version control systems for group work.

Table A.2: Lessons learned: the student voice.

Theme	Student Reflections
Gaining Practical Skills	**Student 1:** "I feel much more confident in my ability to design a heat exchanger from scratch... This experience has strengthened my technical skills and problem-solving abilities." **Student 6:** "I have significantly improved my problem-solving and time management skills... Overall, this assignment has been a transformative learning experience."
Overcoming Challenges	**Student 5:** "FreeCAD is not beginner-friendly... but by starting with simple designs, I was able to build my confidence and apply the same concepts to more complex designs." **Student 7:** "I struggled to simulate my complex design but learned the importance of flexibility by scaling my values to run a simpler model."
Importance of Standards and Accuracy	**Student 3:** "Managing the allowable pressure drop while ensuring efficient heat transfer was a significant challenge, but it helped me understand the importance of optimizing design parameters." **Student 10:** "It is crucial for a product to be safe, reliable, and effective, which adhering to industry prescribed standards, ensures."
Resilience and Adaptability	**Student 2:** "I overcomplicated everything at first but learned to focus on the outcomes and simplify the process." **Student 9:** "This project taught me how to teach myself, fight through difficulties, and better manage my time."
Personal Growth and Confidence	**Student 4:** "Through repetition and problem-solving, I gained a deeper understanding of the design process and its practical implications." **Student 11:** "This assignment gave me a real sense of applying theory to practical engineering scenarios and significantly improved my proficiency in simulation tools."

Open-ended Modelling Problems

Dr. Jessica Swenson
Department of Engineering Education, University at Buffalo, New York, United States of America, jswenson@buffalo.edu

Abstract

This Practice Paper conversation describes the intentions, learning objectives, guidelines for problem design, and best practices for implementing Open-ended Modelling problems (OEMPs). OEMPs are ill-defined mathematical modelling problems assigned in the technical core engineering courses with the goal of engaging students in the practice of engineering judgment. This collaborative project, started in 2018, includes engineering education researchers studying student learning and practices and instructors iterating on problem design and implementation. While a significant amount of our project work focuses on students' learning and thinking, this paper is designed for engineering faculty interested in implementing similar problems within their classes.

Keywords: engineering judgment, complex problems, problem solving

1 Introduction

Graduating engineers need to be able to solve complex, ill-defined problems that are measured by non-technical metrics (Jonassen, 2014; Jonassen et al., 2006). While many design courses in the engineering curriculum ask students to solve complex problems, few engineering science courses, or courses based around learning mathematical models, assign problems where there are many justifiable solutions. Instead, engineering science courses typically assign well-constrained problems that have one correct answer. While these types of homework problems build technical ability, they do not build ability to make justified decisions or practice engineering judgment.

Our project aims to better prepare students for industry engineering work by giving them the opportunity to engage in making judgments while modeling or designing an engineering system. Over the last six years we have worked with faculty teaching statics, mechanics of materials, dynamics, fluid mechanics, advanced aerospace structures, and road vehicle dynamics to implement Open-Ended Modeling Problems (OEMPs).

2 Background

Engineering judgment, or informed decision making in engineering (Davis, 2012; Marr, 2006; Peck, 1991; Vick, 2002), is used when analyzing or predicting the behavior of systems, designing components or structures, or deciding how and when to use theories or canonical models (Edmondson & Sherratt, 2022; Peck, 1991; Vick, 2002). In literature, judgment is equated to expertise; the more an engineer practices engineering the greater ability and skill they have in making judgments. Our project seeks to understand how the ability to make judgments within engineering begins as well as providing an opportunity for students to develop judgment and problem-solving skills. To study this, we developed OEMPs to give students the opportunity to make judgments.

Our project aims to understand what kinds of judgment students engage in when given an OEMP, and how professors design and scaffold problems and notice students' practices of engineering judgment. This paper aims to share our innovative problem type and provide an overview of how our research team designs, assigns, and facilitates these problems in engineering classrooms.

3 Learning Objectives

The project began with four intentions for student engagement. Our research team believes that student learning is built off of their prior experiences both inside and outside of the classroom (Belenky et al., 1986; Bransford, 2000; Piaget & Inhelder, 1969; Vygotsky, 1978). Therefore, our first learning objective is to build links between students' real-life experiences and the engineering science content that they are learning in the classroom. In my prior work (Swenson, 2018), mechanical engineering students reflecting about their

courses described wanting to see more connections between what they were learning in the classroom and the real-world, which became an inspiration and goal of this work.

Second, students needed practice solving problems that had no "correct" answer (Jonassen, 2014; Jonassen et al., 2006), meaning problems that did not have an answer in the back of the book for students to try to match. My dissertation research on fluid mechanics and controls homework problems showed that many students were engaged in task production when doing their homework problems, meaning they were focused on getting through the task and finding the answer that matched the back of the book instead of learning the content of the course (Koretsky et al., 2014; Swenson, 2018). In physics education, researchers have written about students playing the "classroom game" (Hutchison & Hammer, 2010; Lemke, 1990) and our objective was to reduce this behavior.

Third, it was important to my collaborator and myself that students would continue to use and practice the canonical mathematical models taught in the courses in which they were enrolled (Gainsburg, 2013; Johnson & Swenson, 2019). A significant part of the OEMP is deciding which mathematical model or series of equations to use to model the system assigned which gives students additional practice.

Lastly, we wanted students to practice engineering judgment (Gainsburg, 2007; Swenson et al., 2025). Students are not explicitly taught judgment as part of the OEMPs. Instead, our project aimed to understand the productive beginnings, or emergence of disciplinary practices, of judgment. Over the first four years of the project, we analyzed the interviews of 34 students solving OEMPs in mechanics of materials or statics courses. We identified four types of judgment and fifteen justifications (Swenson et al., 2019, 2022, 2025) that students self-reported engaging in while solving one or two OEMPs, shown below in Table 1. The four major types of judgment we found are: making assumptions, assessing reasonableness, overriding a calculated answer, and using technology tools.

Table 1. Engineering modeling judgment (EMJ) taxonomy (Swenson et al., 2025)

EMJ 1 Making Assumptions	
EMJ 1a	Making an assumption with no justification
EMJ 1b	Assumption considers the user, client, or manufacturer
EMJ 1c	Assumption makes the model more realistic, accurate, or typical based on the student's research or experimentation for the class
EMJ 1d	Assumption makes the model more realistic, accurate, representative, or typical based on the student's personal lived experience outside the classroom
EMJ 1e	Assumption makes the model solvable
EMJ 1f	Assumption makes the model easier to solve and/or simplifies the model
EMJ 1g	Assumption does not affect the output of the model
EMJ 1h	Assumption models what the student thinks is the worst-case scenario
EMJ 2 Assessing Reasonableness	
EMJ 2a	Assessing the reasonableness of assumptions that the student made
EMJ 2b	Assessing the reasonableness of the output of the model
EMJ 2c	Assessing the reasonableness of the model as provided by the instructor in the problem
EMJ 3 Overriding a calculated answer	
EMJ 3a	Overriding a calculated answer with no justification
EMJ 3b	Overriding a calculated answer considering the user, client, manufacturer, or safety
EMJ 4 Using Technology Tools	
EMJ 4a	Using a technology tool to help with analysis or computation
EMJ 4b	Assessing their use of the technology tool

In addition to these four objectives, our faculty collaborators aim for students to engage in the outcomes outlined in ABET, the United States organization that accredits engineering programs (ABET, 2023). Outcomes met by solving an assigned OEMP could include:

1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. An ability to communicate effectively with a range of audiences
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives

Our forthcoming article provides a more detailed explanation of how the Pool Lift OEMP satisfies the above outcomes (Charakos et al., in preparation).

In addition to the above learning objectives, the faculty who have designed OEMPs were interviewed and identified objectives that they had when designing their OEMP. Besides wanting their students to learn engineering science concepts, faculty also wanted their students to understand the nature of engineering problems and engineering problem solving, learn engineering reasoning, and build emotional skills to thrive in learning and doing engineering (Miel & Swenson, in review).

4 Problem Design

When designing an OEMP, the first two major considerations are choosing the canonical mathematical models you want your students to utilize and practice when solving the problem and the real-world object that they will design or analyse. In the past, our faculty have chosen objects that students may have encountered but not used every day. These include the iWalk hands free crutch (statics)(Treadway et al., 2021), a knee scooter (statics), a pool lift (statics)(Churakos et al., 2024), a hobby aircraft located in the main aerospace engineering building on campus (mechanics of materials)(Swenson et al., 2020), aircraft found in museums (advanced aerospace structures)(Merrett et al., 2023), a washing machine (dynamics)(Vitali et al., 2022), and a skating spin (dynamics)(Vitali et al., 2022). Other OEMP authors have created fictionalized scenarios such as a bridge between two buildings on campus (mechanics of materials) (Johnson & Swenson, 2019) or an underground pipe system connecting a lake with a greenhouse (fluid mechanics). Details about each of the problems can be found in the cited works.



Figure 1: Previously designed OEMP systems assigned to students in statics and dynamics.

When initially outlining the problem, faculty need to consider which pieces of the problem to leave open-ended and where students will have to make judgments. First- and second-year students may need more knowns or given assumptions than upper-level students who have more experience with ill-defined problems. For example, in the pool lift problem students are given a short list of assumptions in the

assignment. Yet, students have many decisions to make including the weight of the person, the material, and the dimensions (Churakos et al., 2024). This is where students need to make the most assumptions to move forward in the project and justify their decisions using research, personal experiences, and considering the user or manufacturer (Swenson et al., 2022, 2025).

Another decision the instructor must make is how many pieces of the problem will be completed individually or in groups. Allowing students to complete early pieces of the OEMP individually and then in a group has been found in some cases to build competence with the mathematical models, as the students complete the problem twice. Having students' complete pieces individually also demonstrates to students the many ways the problem can be solved, or decisions can be justified.

Naturally, instructors also need to decide the length of the assignment. Many of the instructors assign an OEMP towards the end of the semester when students have more conceptual knowledge in the course topic. These OEMPs are typically assigned over two or three weeks (Treadway et al., 2021; Vitali et al., 2022). The pool lift problem is assigned over the duration of the entire semester and builds throughout the semester alongside the content of the course (Churakos et al., 2024).

Lastly, we suggest having the OEMP reviewed by other faculty members who have created and assigned similar problems. We have created a community of practice (Lave & Wenger, 1991; Swenson, Rola, et al., 2021) to support other faculty designing and implementing the problems and have found that collaborative review has helped many faculty test and revise their assignment design.

5 Implementing an OEMP

Over the course of six years of designing, assigning, collecting data, and interviewing students about OEMPs, our team has determined several implementation best practices (Swenson, Rola, et al., 2021).

First, instructors have found it helpful to assign pieces of the OEMP very near to when the topic or skill is taught in the course. Many times, the OEMP provides a second avenue for practice with concepts after students complete more traditional homework.

Second, we have found that it is very important to break the problem into pieces and if there is time, allow students to get feedback (Treadway, et al., 2021). Breaking the problem into pieces is first and foremost helpful for procrastinating students, as successful learning from doing these problems does not happen the night before the assignment is due. Having students complete initial assumption making and allowing them to either get feedback from the professor or comparing with other students provides a check on some unreasonable assumptions. In some cases, faculty have created spreadsheets for students to compare their answers to each other, invited students to discuss their results in class, or provided ungraded professor feedback (Treadway et al., 2021). The iWalk problem is assessed in three parts: an individual assignment to create the free body diagram, an individual assessment of the frame analysis, and an assessment of the group assignment when the model is complete.

The instructor of the pool lift problem, which has five parts and a final report (Churakos et al., 2024), has a design review process where student groups are assessed every few weeks. The faculty member runs a prepared MatLab code to check the students' numbers and then provides feedback to students and helps them eliminate any poor assumptions or mathematical errors that may create a flawed design. These mini-check-ins function as student assessments and allow the faculty member to monitor where students are conceptually falling behind. Breaking into pieces and allowing for feedback can also take pressure off of students by knowing they don't have to have the "right" answer the first time and can fix any errors.

Third, students can be very uncomfortable that the problem does not have a single correct answer or that they must make justified decisions. Numerous faculty have reported students coming to them to seek validation or indication that their answer is correct. In retrospective interviews with students after they solved an OEMP, we noticed that the newness of making assumptions caused students to have numerous negative emotions due to the uncertainty of not having a correct answer but also pride and accomplishment from finishing these problems (Swenson, Treadway, et al., 2021; Swenson et al., 2024). Since then, we have further investigated student emotions, or epistemic affect, when solving OEMPs and how students regulated these negative emotions (Swenson et al., 2024). We suggest reminding students at the beginning and throughout the problem-solving process that negative emotions such as confusion and frustration are normal. Encourage emotional regulation strategies such as talking to or comparing answers with classmates or going to office hours (Swenson et al., 2024). Discuss with the students how the skills that they are developing by solving the problem will help them in their engineering careers so they can see value in the struggle. Recognize their accomplishment by building in course-wide celebrations (Maykish et al., 2024). In our examination of emotions, we also saw hints that the feelings of pride and accomplishment also contributed to students' engineering identity or feeling like an engineer (Swenson et al., 2023, 2024).

One way to lessen students' stress or anxiety is to provide rubrics to students that show how they will be graded. In most cases, our faculty grade OEMPs for well-designed and justified mathematical models. For example, the pool lift (Churakos et al., 2024) design reviews include check boxes in which students earn points for well-designed and justified answers. If students make errors, such as if their pool lift would tip into the water, the instructor allows them to revise their work and try again to earn the points.

6 Conclusions

This practice paper conversation detailed the learning objectives and best implementation practices as found by instructors and researchers who design and study OEMPs. Over the course of the six-year project, we have seen students successfully engage in engineering judgment, emotional regulation, mathematical modeling, and teamwork while creating a mathematical model of a real-world system. Currently, our team continues to work with faculty to study the ways in which instructors scaffold problems and notice and respond to students' use of judgment. We invite any interested faculty to join our community of practice and collaborate with our team.

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Traditional to transformative: Empowering education with computational thinking

Adri van Nieuwkerk
Opti-Num Solutions, South Africa, adri.vannieuwkerk@optinum.co.za

Prebantha Moodley
University of the Witwatersrand, South Africa, prebantha.moodley@wits.ac.za

Abstract

In 2020, the COVID-19 pandemic upended global routines, compelling a re-evaluation of established systems and daily life. Educational institutions faced the challenge of transitioning traditional teaching and learning practices to online platforms. This paper presents the continued collaboration, catalysed by COVID-19 lockdown, of industry partners, Opti-Num Solutions, MathWorks and the University of the Witwatersrand (School of Chemical and Metallurgical Engineering), on the second-year computing for process engineering course. The course lends itself favourably to online learning and assessments and is the ideal case study to explore the delivery of computational thinking-based coursework. We present findings from 5 years of this collaboration with purposeful interventions to enhance student learning and feature computational thinking relevant to the current climate. This includes the implementation of self-paced online courses and integration of an automated assessment tool. Results from a student survey show that approximately 95% of students had little to no experience in programming due to the absence of related courses in high school, limited opportunities, lack of resources, and no prior need or requirement to learn programming. However, after completing the self-paced online course, most students felt competent and empowered in their programming skills showing that these and future interventions impact computational learning.

Keywords: programming, COVID-19 interventions, digital tools, industry-academia collaboration

1 Introduction

1.1 Computational Thinking

It is now essential to include computational thinking skills in STEM courses, due to the need of these skills in industry, as expressed by the World Economic Forum, "Future of Jobs Report" in 2023 (World Economic Forum, 2023). The authors recognise that, at the time of delivering interventions for the computing for process engineering course (CHMT2011) and when writing this paper, definitions for computational thinking are fluid and continue to evolve. For the purpose of this paper, the authors have identified two definitions that encapsulate the approach for including certain course interventions.

First, computational thinking is "the conceptual foundation required to solve problems effectively and efficiently (i.e., algorithmically, with or without the assistance of computers) with solutions that are reusable in different contexts." (Valerie J. Shute, 2017). In addition to this, computational thinking vocabulary should include the second definition "CT encompasses the thought processes of abstraction, decomposition, algorithmic design, evaluation, and generalization." (Selby, 2013). In the case of CHMT2011, computational thinking is the fundamental stepping stone for students to achieve key learning outcomes.

1.2 Computing for process engineering: Course Overview

The computing for process engineering course (CHMT2011) is an introductory programming course taught at second year within the school of chemical and metallurgical engineering (CHMT) at the University of the Witwatersrand (Wits). The course aims to equip students with proficiency in computer programming to solve engineering problems, with the intention to develop a sense of importance for computers and programming in addressing realistic process engineering challenges (School of Chemical and Metallurgical Engineering, 2024). The course incorporates a computational thinking approach to teaching programming principles, i.e. enabling students to understand programming as a language for problem solving.

Key learning outcomes of the course: understand core programming principles, execute programs, understand data types, control flow, logic, functions, visualize data and create scripts. These were achieved through various learning tools, such as lectures, tutorials, assignments, tests and exams. MATLAB was the programming language of choice for this course. This decision was made based on (a) the availability of MATLAB via the Campus-Wide License (The MathWorks, Inc, 2025) (b) the ease of use of the integrated development environment and (c) the digital teaching resources and training made available to Wits.

MathWorks is a leading developer of mathematical computing software which engineers and scientists use and rely on to accelerate the pace of discovery and innovation. The campus license is a teaching and research license offering from MathWorks, providing open access to software and training for all faculty staff, researchers and students.

The course was previously taught in duplicate lessons to cover large groups of students (150 students average class size) where student submissions (often handwritten) were marked by the lecturer or tutors. This course was the first point of reference for computational thinking within the CHMT2011 curriculum; illustrating to students how to problem-solve using a programming language. It is important to note that computational thinking is still not considered a learning outcome or objective for this course, creating an incorrect perception of the value of the course.

2 Addressing Urgency

Wits, like many academic institutions around the world, was forced to re-evaluate the delivery of instruction while maintaining learning outcomes during the COVID-19 pandemic. In the case of CHMT2011, the course lent itself well to being taught online however an online transition proved a great challenge due to the immediacy of lockdown. There was little to no time for lecturers to mobilise online resources and foster an online mindset, thus ensuring motivation to learn for this course and meet learning outcomes became a driving a factor.

Opti-Num, the sole authorised distributors of MATLAB in southern Africa, have strong ties in academia due to their support for universities, enhancing instructional learning and innovative research. Additionally, they understood that a new approach was needed in this time. Collaborating with them presented an opportunity:

1. Intervention tools: Leveraging MathWorks resources and training to transition “classroom teaching” to self-paced learning in an online environment. This meant that learning about coding using the MATLAB interface was something students could learn independently.
2. Evaluation methods: Integration of an automated grading tool, MATLAB Grader, within the Wits learning management system (LMS), meant that students coding assignments and submissions were assessed timeously and with immediate feedback (unlike the tedious marking of handwritten coding assignments which result in delayed feedback).

3 Intervention Tools

Several tools, from the university and the campus license, were leveraged to address the transition of course lessons and assessments to online teaching and learning. The intervention tools are presented in this section and the implementation discussed in Section 4.

It is important to note that prior to 2020 none of the MATLAB related interventions presented here were used to deliver the course; tools that were used included MATLAB, MATLAB documentation and online videos and course notes developed and created by the previous lecturer. These notes are currently used.

3.1 Course Notes and Programming Documentation

CHMT2011 includes well-developed course notes with additional reference material, such as MathWorks Documentation (The MathWorks, Inc., 2025). Documentation pages are sources of help for learning about and working with MATLAB software.

3.2 Self-Paced Online Training Courses

The integration of MathWorks online courses (The MathWorks, Inc., 2025), with the Wits LMS, meant that an array of online courses were accessible to students. These courses covered programming topics such as,

core programming skills, data visualisation, artificial intelligence, modelling and simulation. Two courses from this suite were used:

MATLAB Onramp: A 2-hour introductory course focused on the basics of programming, commonly used functions and workflows, i.e., navigating the interface, saving, creating files in different formats.

Solving non-linear equations with MATLAB: A 3-hour course focused on the basics of solving non-linear equations within MATLAB. This includes root-finding methods to solve nonlinear equations thus preparing students for problems they will encounter in the engineering curriculum.

3.3 Automated Assessments

Automated marking of coding assessments ensures that students practice coding skills via a platform that provides instant feedback on their performance of the task. MathWorks offers an automated assessment tool, MATLAB Grader (The MathWorks, Inc., 2025) which was integrated into the Wits LMS, where students access assessments, submit their code, receive instant feedback on the correctness of their submissions, and are graded automatically. The coding assignments were provided by a MathWorks repository of existing ready-to-go problems and tests, known as Assessment Items (The MathWorks. Inc., 2025).

3.4 Online Videos and playlists

In previous years of instruction, Dr Ming included online videos, which he created, in the course notes. Following this, Dr Moodley created additional video playlists as supplementary material to classroom activities and tutorials. Students accessed videos via the course notes. Topic-specific videos were shared on a weekly basis.

4 Implementation of Interventions

4.1 Evaluation Methods

Table 1 (Section 8,Appendix) maps out a high-level view of a 5-year period of implementation; summarising the intervention tools used per year as well as the learning outcomes. The choice of intervention depended on (a) method of teaching e.g. lockdowns in COVID meant that all teaching was done online, (b) the size of the class e.g. average class size of 150 students meant that each year required slightly different approaches. (c) changes within the faculty and CHMT.

4.2 Evidence of Impact

A survey was sent out in 2021, to students who completed the CHMT2011 course in 2020 and 2021. The survey aimed to (1) collect anecdotal feedback of student's learning experience, (2) to determine the efficacy of interventions and (3) explored students' knowledge of graduate employability skills required for industry.

Since the survey in 2021, new cohorts of students have participated in the updated version of the course. Apart from University-Wide course evaluations, new student cohorts have not taken part in formal surveys for this particular course. The survey, distributed as a Microsoft Form, contained 14 questions, with an average completion time of 9 minutes. 22 students completed the survey and provided feedback.

The class of 2020 was the first to complete the MATLAB Onramp, where 82% of the 2nd year cohort had little to no experience in programming due to the absence of programming courses in first year or at high school. When asked about the use of the MATLAB Onramp course, some students reported it as "Challenging" or "Difficult", and 50% of students reported an "Exciting experience":

"The Onramp course was so helpful, and it wasn't pure video. The interactive part helped me understand what was being conveyed."

In 2021, when MATLAB Grader was integrated into the Wits LMS, students submitted coding assignments and received instant feedback on the correctness of their submissions. When asked about the experience of receiving instant feedback on coding assignments, students reported that they enjoyed the platform:

"The instant grading was really good as it did not give me the anxiety of waiting for results".

When asked about their opinion on employability skills needed upon graduation, and the usefulness of learning programming skills for solving engineering problems; all surveyed students answered that programming skills were vital for seeking jobs. A portion of students also commented that, upon further research there were many more programming languages that they should learn and that they feel confident in doing so now that they have *"covered the basics"*:

"I went for a job interview and was asked about my computer proficiency and the skills that I learnt, and this course was definitely a talking point and interested the interviewer. Thank you for the course as it truly equipped me with valuable skills and I've always procrastinating learning to code, but this course helped me start that journey!"

Overall, the sentiment from students was that the ability to program was important for problem solving, specifically when it comes to thinking about and solving engineering problems:

"It was quite interesting to use programming to solve engineering problems. And just developing the skill of programming, which I think is valuable in many different domains."

Upon completion of the CHMT course, students believed they were more competent in programming and felt empowered to expand their programming skills:

"Provided a good foundational understanding of MATLAB programming and an exposure to several scenarios in which MATLAB programming could be used to solve an interesting problem. It was beneficial for the CHMT2011 work and understanding the fundamental of programming as a skill in general."

5 Discussion

Navigating the transition from classroom to online teaching was a significant challenge during the COVID-19 lockdown. Student and staff access to resources was severely restricted and collaborative effort with industry partners slowed. Specifically for course CHMT2011, internet access and use of a personal computer was not possible for many students. While the university provided such resources for many students, peer-learning and engagement with lecturers remained an essential aspect of the university experience. From the perspective of the student, transitioning from the physical classroom to digital instruction was difficult and challenged their entire "way of learning".

To complicate matters further, students were faced with learning programming. In the case of MATLAB, the logic used in problem solving is similar to that of spoken English and the syntax is relatively easy to learn. However, English is typically a Wits student's second or third spoken language which meant they were faced with learning a new language as well as the ability to convert logic and problem solving into readable code. Having uncovered this, lecturers were encouraged to emphasize problem solving over the word "coding" so that students focus on the engineering problem and become syntax agnostic.

The intervention tools and their implementation presented in this paper focus on the resources available from MathWorks. It is possible to take a similar approach with any programming language within any engineering degree. In South Africa, other branches of engineering traditionally emphasise programming throughout a student's four-year degree. Historically, for chemical engineers this has not been the case. This must change for students to be better equipped for a working world that is valuing computational thinking and associated skills (World Economic Forum, 2023).

At this stage the student is aware of basic engineering principles, equations and formulae, and is able to solve specific problems without the use of code. By taking similar problems with similar engineering concepts, the student is able to use programming constructs to arrive at a solution that was previously iterated by hand. The challenge however is to efficiently combine and stagger concepts in engineering and programming, such that students can synthesis the information and engineering specific lecturers are not lecturing programming principles. This is still under consideration.

Given the success of the automated assessments and self-paced course interventions, we believe it is necessary for students in this discipline to be exposed to programming outside of this second-year course. By including 'programming for engineering problem solving' in other courses, students can solve course specific problems and build better computational thinking skills. Discussions with lecturers are ongoing to present a more coherent curriculum that creates continuity for computational thinking. This would involve re-introducing fundamental engineering problems in CHMT2011 but asking the student to solve it using a programming language.

6 Conclusion

This work presents industry-academia collaborations over a 5-year period. Whilst the COVID pandemic catalysed this shift, engineering faculties can benefit from reassessing delivery of courses and aligning learning content to better suit the current industry climate. We have shown that by leveraging existing and new digital tools, it is possible to meet and expand on learning outcomes in university courses that are tailored toward developing computational thinking, such as the second-year computers course in this practice paper. Including a computational thinking approach meant that the focus moved from 'learning to code' to 'problem solving using a programming language', thus reframing student's perspective of the course.

The results of the student survey show that these interventions have positively impacted students learning, and beyond this has encouraged them to leading their learning despite many challenges. Self-paced online courses, integrated LMS-assessments and instant feedback enhance student learning and support the computational thinking paradigm. Additionally, by approaching each student cohort differently, we are able to improve each year from lessons learnt the previous year. These improvements include adjusting the way assessments are conducted and the way new and existing tools are used as shown in this practice paper, all while still meeting course outcomes and university quality protocols regarding engineering courses.

To further support the work here, the authors are now involving other educators in the engineering curriculum to include a programming element in their course where students can solve specific engineering problems and enhance their computational thinking skills. This will create a steady thread for computational thinking that previously was broken across the years. An initiative of this scale however requires careful planning within the discipline curriculum and is currently still under consideration.

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8 Appendix

Note: Table 1 in Landscape on next page (pg 8).

Table 1: Timeline of the intervention tools

	Year 1: 2020	**Year 2: 2021**	**Year 3: 2022** *(Note 5)*	**Year 4: 2023** *(Note 5)*	**Year 5: 2024**
Course Notes	Yes	Yes	Yes	Yes	Yes
SELF-PACED ONLINE COURSES					
MATLAB Onramp *Learning Outcomes 1-3*	Used as an assignment (toward course mark)	Used as an assignment (toward course mark)	Used as an assignment (toward course mark)	Used as an assignment (toward course mark)	Used as a pre-requisite (does not count toward course mark) (*Note 1)*
Solving non-linear equations with MATLAB *(Note 6)* *Learning Outcomes 1,2*	Assignment	Assignment	Assignment	Assignment	Assignment
AUTOMATED ASSESSMENTS					
MATLAB Grader *Learning Outcomes 1-4*	No	Assignment	Assignment	Assignment	Tutorials, tests and exams
MATLAB Grader Assessments *Learning Outcomes 1-4*	No	No	Exams	Exams	Tutorials, tests and exams.
Online videos and playlists *(Note 2)* *Learning Outcomes 1-4*	Yes	Yes	Yes	Yes	Yes
COURSE MARK DISTRIBUTION (*Note 3)*					
MATLAB Tutorials *(Note 4)* *Learning Outcomes 1-4*	0	0	0	0	15 (10)
Assignments (%)	25 (2)	25 (2)	25	25	15 (1)
Tests (%)	25 (2)	25 (2)	25	25	30 (1)
Exam (%)	50 (1)	50 (1)	50 (1)	50 (1)	40 (1)

Continue to next page

Key learning outcomes:
(as per the course brief)

1. Understand the core principles underlying any programming language and understand how to execute a computer program.
2. Understand the basics of primitive data types, program control flow, program logic, and functions.
3. Plotting data and visualization using MATLAB.
4. Be able to apply these concepts and create MATLAB scripts that solve engineering problems.

Notes:
1. In 2023, the faculty introduced “Introduction to Programming with MATLAB”, a 6-week course for the first-year engineering students. This meant that students would have covered key learning outcomes before they entered CHMT2011. MATLAB onramp was encouraged to refresh skills, no marks were awarded.
2. These consisted of online videos and playlists, one of which was created by Dr Ming.
3. Total course marks add up to 100%. The number in parenthesis is the number of assessments within that category. The percentage shown is the total for that category.
4. MATLAB tutorials refer to a collection of engineering problems from MATLAB Grader. Students were given a defined number of attempts to solve the problem and submit within a given timeline. As the difficulty of the problems increased these parameters were adjusted. Consideration was given to special class circumstances.
5. In 2022 and 2023, the course was delivered by a part-time sessional lecturer. The data supplied is to the best of our knowledge.
6. The assignment consists of three parts, based on an engineering problem the student would have encountered in their first year. This includes mass balances with a reactor, separators and mixer components. Part 1 introduces the student to solving non-linear equations, part 2 asks the student to solve the problem using a flow chart and the 5-step engineering methodology (Etter, 1993). Part 3 is submitting code that solves for the mass balance and stream data across the process flow.

Grasping and shaping the emergence of GenAI in education: Insights from a workshop series with practitioners

Sofie Otto
Aalborg University, Denmark, sio@plan.aau.dk

Stine Ejsing-Duun
Aalborg University, Denmark, sed@plan.aau.dk

Lykke Brogaard Bertel
Aalborg University, Denmark, lykke@plan.aau.dk

Abstract

This practice paper reports on the iterative development, facilitation, and refinement of a workshop series with STEM educators centering on the role of Generative Artificial Intelligence (GenAI) in active and student-centered teaching and learning practices. A tentative deck of design lenses representing various types of GenAI interactions served as a point of departure for activating and inspiring dialogue and co-creation of teaching and learning designs that consider the role of GenAI-powered tools based on local contexts. We present key themes and ideas emerging from these dialogues and outline the iterative refinement of the design lens deck for future use in educational practice – in dialogue with both educators and students.

Keywords: Active learning, Problem-Based Learning, Generative artificial intelligence, STEM education

1 Introduction

In recent years, educational systems have undergone significant disruptions driven by technological advancements and global events. The sudden shift to emergency online instruction during the COVID-19 pandemic and the subsequent collective reflections it afforded regarding post-digital practices in a 'new normal' exemplify one such disruption (Otto et al., 2024). More recently, the arrival and public availability of sophisticated Generative Artificial Intelligence (GenAI) technologies have sparked polarized debates regarding their multifaceted dialogic affordances, ethical issues, and educational implications (Łodzikowski et al., 2024; Selwyn, 2024). Both events have prompted rapid adaptations in educational and pedagogical practices in arenas such as assessment practices and curriculum design. Very often, however, the responsibility of such adaptations has put educators as well as students at the forefront of navigating the complexity of an evolving educational landscape shaped by changing policies and emerging technologies (Driessens & Pischetola, 2024). In our prior research, we found that students experience several tensions related to navigating rules, norms, and social relations surrounding GenAI utilization in a group setting (Otto et al., 2025a). They missed dialogue with their peers and teachers when navigating these tensions. We believe that an important step toward addressing these uncertainties lies in equipping educators to initiate and sustain such conversations anchored in their local teaching and supervision practices. To this end, one meaningful approach builds on collective action, as noted by Mills et al. (2023):

> *In a moment of overwhelm, we can turn toward each other and toward students and share imperfect, incomplete insights and experiments.*

In this paper, we report on a workshop series designed to create a space for sharing and designing those insights and experiments among STEM education practitioners. Alongside the local insights contributed by

participants, we sought to activate initial and emerging insights reported in contemporary literature by materializing this knowledge into a deck of design lenses that served as catalysts for dialogue about the implications of GenAI in their local teaching environments as well as co-design new practices that consider those implications. Through this process, our aim was to support educators in becoming better equipped to support students in navigating the complexities of GenAI in education. In the following sections, we outline the workshop and lens design, including facilitation experiences that informed subsequent refinements alongside emerging insights from a parallel literature review (Otto et al., 2025b). We then highlight key themes that emerged from the discussions and outline the next steps.

2 Materials and methods

In the fall of 2024, we facilitated three workshops with STEM education practitioners and researchers across educational levels (Table 1). Workshops 1 (WS1) and 3 (WS3) followed a structured format revolving around the design lenses. Initially, participants were introduced to technical and ethical aspects of GenAI as well as frameworks for AI in Education (AIEd) (Molenaar, 2022; Mollick & Mollick, 2023; 2024). Subsequently, we used the lenses as both a structuring element as well as creative stimulation. The structure was adapted from Hansen's (2024) 'Creative collaboration' model as well as the think-pair-share model (Lyman, 1981) (Table 2).

Table 1: Workshops and participants

#	Participants	Arena	Duration
WS1	International engineering education researchers and educators (*N* = 38)	SEFI conference	60 minutes
WS2	Pre-university STEM teachers (*N* = 59)	LabSTEM-North conference	45 minutes
WS3	Scandinavian engineering education researchers and educators (*N* = 20)	ETALEE conference	60 minutes

Table 2: Workshop structure

Individual brainstorm	Participants draw a random design lens and reflect on its relevance to their current or past teaching practices
Same-lens exchange	Participants join others with the same lens to exchange ideas and discuss challenges grounded in their local contexts
Cross-lens exchange	Participants engage in discussions with participants who drew different lenses to share ideas, insights, and highlights from previous steps
Case work	In groups, participants apply multiple lenses to a shared case, co-designing approaches for integrating GenAI into teaching

Workshop 2 (WS2), designed for pre-university STEM teachers, was adapted to align with this audience's pedagogical needs and the session's shorter duration. Unlike the other two workshops, which were designed for a diverse audience of educators and educational researchers, WS2 was conducted exclusively for teachers attending the conference for competency development. Therefore, the introduction was expanded to include concrete, real-world examples of GenAI integration in STEM teaching as well as an overview of selected GenAI-powered tools and relevant characteristics (e.g., GDPR compliance). Additionally, the structured application of design lenses was replaced with a more flexible, discussion-based approach, where participants formed small groups and discussed one lens at a time. This ensured exposure to a broader variety of interaction types while allowing for in-depth discussion contextualized in similar local teaching practices.

2.1 Design lens development

Design is essentially a dialogue between ideas and the world, a dialogue that lies at the heart of inquiry (Rusmann & Ejsing-Duun, 2022). To nurture the dialogue on how to navigate tensions missed by students, the deck of design lenses served as a foundational element to provide a structure and language for dialogue as well as inspire new ideas. Originating from the field of gameful design, design lenses combine a clear statement of a design principle with a series of guiding questions to inspire perspective taking in design processes (Deterding, 2015). We adapted this concept to the context of active teaching and learning design in STEM education to provide educators and researchers with tangible and scoped representations of a multifaceted and unfamiliar topic (GenAI in education) and inspire thoughts on implications and ideas grounded in local practices. The content of these lenses was informed by an ongoing systematic literature review on interactions with GenAI-powered tools in the context of active and collaborative STEM learning environments (Otto et al., 2025b). From a synthesis of preliminary and evolving experiences reported in the literature, we identified a total of five overarching categories and 9 subcategories of human-GenAI interactions positioned to support student learning and higher-order thinking skills in both individual and collaborative learning spaces. Each category and subcategory were translated into a design lens encompassing a principle, guiding questions, and application examples.

The number and diversity of the lenses evolved in response to emerging insights from the ongoing review. Initially, based on 29 studies from 2023, the first five lenses were developed and tested in WS1. As the review expanded to 50 studies published between 2023 and July 2024, four additional lenses were developed, capturing a more nuanced variety of GenAI applications, which were tested in WS2 and WS3. This iterative process is depicted in Figure 1, while an overview of the latest iteration of design lenses designed for students can be seen in Figure 2.

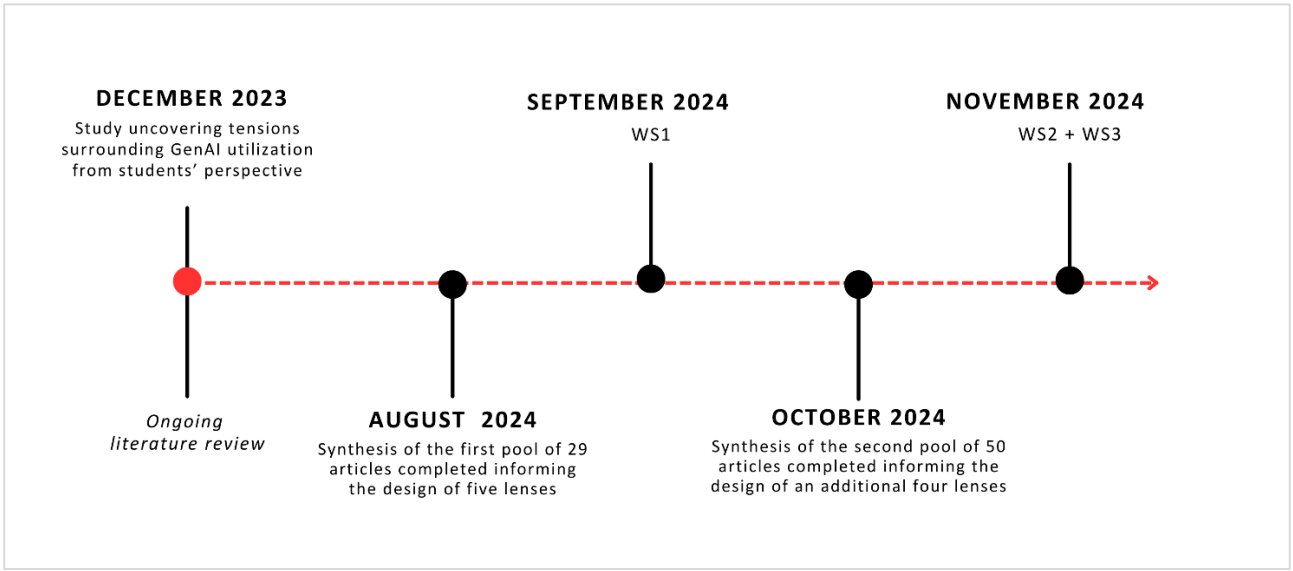

Figure 1: Process overview

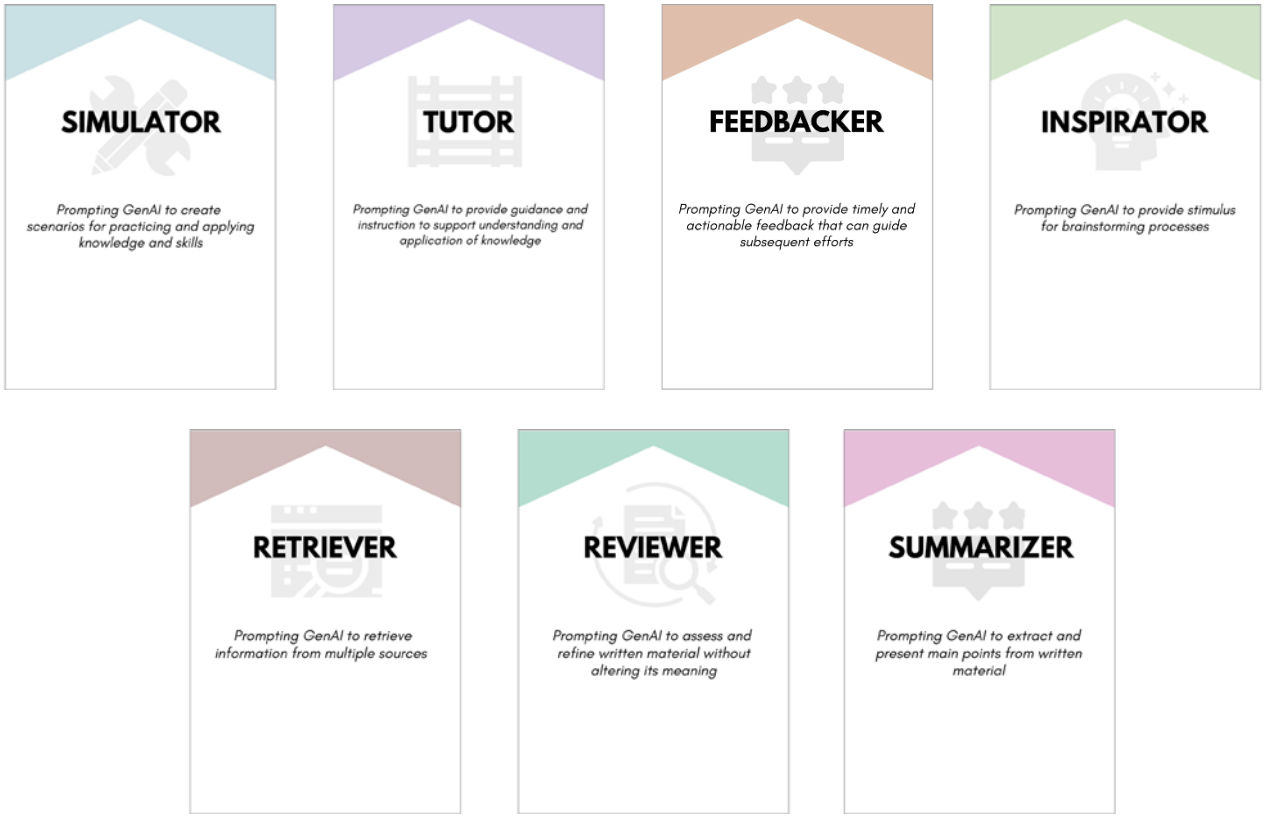

Figure 2: Design lens overview

2.2 Iterative test and refinement

Drawing on our experience facilitating and participating in the discussions at each workshop, subsequent reflections informed ongoing refinements to the workshop content and artifacts. Below, we share selected examples of these refinements implemented to enhance the operationalizability of the lenses for participants.

A key takeaway from the workshops was the value of using tangible cards to frame thinking and dialogue on a complex and unfamiliar topic. The lenses created a shared language that supported sense-making while enabling participants to engage hands-on with different application types. Combined with opportunities to externalize and refine ideas through peer discussion, this allowed participants to connect the lenses to their own practice and generate new insights. However, several barriers limited the full realization of these benefits. One major challenge concerned the complexity and cognitive load associated with interacting with the lenses. In the first iteration (Figure 3), the cards contained detailed background information grounded in research and theory. While this depth was intended to support and inform reflection, the effort required to process and apply the information to one's local practice within a limited timeframe created a high cognitive load. To address this, we revised the design of the cards. Lens descriptions were distilled into concise, single-sentence utilization principles. The guiding questions were refined, and multiple surface-level examples were replaced with a single, in-depth example (Figure 4). Additionally, we integrated a custom GenAI bot developed with schoolhub.ai. Participants could access the bot via a QR code, affording a more dynamic and interactive engagement with each lens.

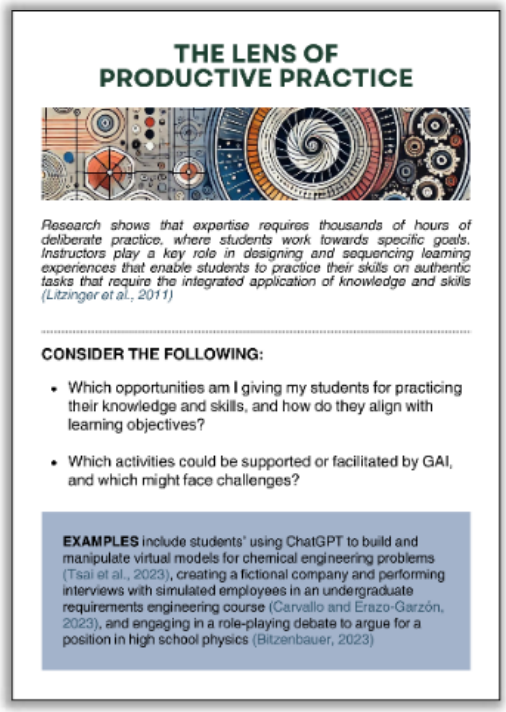

Figure 3: First iteration of design lens

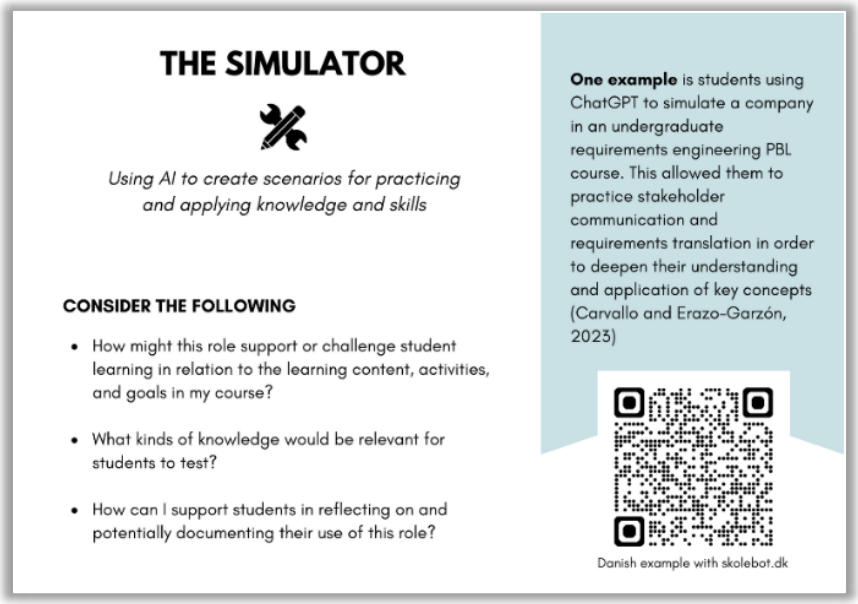

Figure 4: Second iteration of design lens

Another key revision emerged in response to challenges associated with the former *Offloader* lens. This interaction category, originally derived from the literature review and informed by Mollick and Mollick (2023), described scenarios in which tasks traditionally performed by students are delegated to GenAI. The underlying rationale is that offloading certain tasks can free cognitive resources for higher-order thinking (Lodge et al., 2023), provided it does not replace the thinking itself. However, during the workshops,

participants found the category too broad with limited practical value and post-workshop evaluations highlighted a need for greater disciplinary nuance. As one participant noted, the implications of offloading a coding task differ substantially from delegating the proof of a mathematical theorem or a reflective writing assignment. These distinctions highlight that the pedagogical consequences of offloading are highly context-dependent and shaped by both the task itself and the intended learning outcomes. At the same time, our ongoing analysis of an expanded pool of articles from the literature review revealed a more diverse range of GenAI roles than initially captured. This prompted a reorganization of the framework into main roles and sub-roles that afforded finer granularity. Consequently, the original *Offloader* lens was subdivided into several more specific sub-roles, informed by emerging literature and participant feedback.

3 Next steps

A recurring theme in WS1 and WS3 was the importance of incorporating student voices in shaping the role of GenAI in teaching and learning to ensure their perspectives are represented in decisions affecting their study practices and to better support them in navigating the complexities of an evolving landscape of GenAI in education. We try to nurture dialogue and thus facilitate change through two implementation strategies: 1) A sustainable implementation strategy engaging student and teacher voices in defining problems and practitioner involvement in testing the lenses and bringing them into their own contexts. 2) Workshops and lenses act as an expansive implementation strategy (Henriksen & Ejsing-Duun, 2022) allowing diffusion through these designs by dispersing the ideas of a broader use of GenAI reifying them into lenses and interactions among more teachers and students.

The call for student involvement manifested in several domains, including the development of use cases, course policies, and identification of inspiring practices. In WS1, for example, one group emphasized the need for exemplary use cases to guide students in using GenAI responsibly and purposefully. Rather than imposing predefined cases, participants advocated for a co-constructive approach in which students actively contribute to developing these cases to foster shared ownership (Otto et al., 2024). Similar concerns emerged in WS3, where participants discussed involving students in shaping formal course policies on GenAI utilization in PBL. Here, the emphasis was on aligning institutional guidelines with students' actual study practices to ensure that policies are both relevant and implementable.

Building on these discussions, particularly the emphasis on co-constructing use cases, policies, and practices, the next phase of our work involves developing a dedicated deck of lenses and an accompanying activity tailored for students. This resource will serve as the foundation for implementing a more reflective and purpose use of GenAI through a new workshop series aimed at supporting students in creating frameworks for responsible and purposeful GenAI use within both individual and collaborative study practices.

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Teaching Control Systems with Interactive MATLAB Live Scripts

Arnold Pretorius
University of Cape Town, South Africa, arnold.pretorius@uct.ac.za

Jamie Bok
University of Cape Town, South Africa, *jamie.bok@alumni.uct.ac.za*

Abstract

Control engineering, as with many other engineering courses, are commonly taught using static course notes and lecture slides. These methods, however, often fail to elicit adequate student interest and understanding of the advanced mathematical and theoretical concepts fundamental to the subject. As a result, many students experience a disconnect with the content early in the course, leading to disinterest and poor academic performance. This paper presents the development of an interactive "live" textbook using MATLAB Live Scripts, providing a dynamic and engaging learning experience. This resource allows students to interact with the theoretical material in real-time, run simulations, adjust parameters, and immediately visualise the impact of their changes — all in a single, unified environment. The integration of LaTeX typeset equations and text, code blocks, dynamic diagrams, and high-level controls such as sliders and buttons empowers students to explore the subject matter deeply at their own pace, fostering a stronger connection and understanding of the material. The effectiveness of the interactive course material is evaluated using anonymous course evaluations, which assess key performance indicators such as understanding of course material and overall course satisfaction. Furthermore, key course statistics, such as pass rate and average mark, are compared over the past four years, showing significant improvements across all areas following the intervention of the developed interactive textbook.

Keywords: MATLAB Live Scripts, interactive learning, engineering education, control systems education

1 Introduction

1.1 Background and problem statement

Modern control engineering is a field of engineering that encompasses a range of science, technology, engineering, and mathematics (STEM) sub-disciplines, which includes engineering sciences and programming. This subject is commonly found in several engineering programmes, such as mechanical engineering, electrical engineering, mechatronic engineering, and chemical engineering. Although control engineering is rooted in practicality, it is often received by students as being highly abstract and mathematically rigorous. The prevailing approach to teaching control engineering at university level is to make use of static course notes, in the form of a textbook, and/or lecture slides. Studies suggest that this non-dynamic approach fosters antiquated memorisation-and-regurgitation type learning in students, which leads to student disengagement in the course (Rossiter, 2020). The net result is commonly that lecture attendance drops significantly over time because of student detachment, leading to poorer academic performance. To remedy the stagnant nature of the learning material, zyBooks was investigated in 2022 as a non-static online learning resource. The service offers digitised online versions of popular textbooks, referred to as zyVersions, which include interactive tools, animations, and embedded learning questions (zyBooks, 2025). However, zyVersions offer moderate interactivity and limited customisation. Additionally, the service is charged based on a semester-based subscription per student, which meant that the cumulative cost over time was not financially viable.

1.2 Objective

The aim of this study is to showcase the development and application of interactive course notes in the context of a 3rd-year control engineering course. The interactive course notes take the form of multiple MATLAB Live Scripts, separated by chapter, with the intention of creating a dynamic and engaging learning environment for the students. This resource allows students to interact with the material in real-time, run simulations, adjust parameters, and instantaneously visualise the impact of their changes — all within a single, unified environment. The Live Script resources can facilitate a combination of typeset LaTeX equations, regular text, imagery, easily adjustable code blocks, and triggered visualisations of the code implementation, as shown in Figure 1. This experiential learning environment is intended to allow students

to explore the subject matter deeply at their own pace, fostering a stronger connection and understanding of the material.

1.3 Outcome and contributions

The effectiveness of the interactive course notes was evaluated through anonymous course evaluations, assessing student understanding and overall satisfaction of the course. Additionally, key course metrics of student pass rate and average mark were analysed over four years, demonstrating significant improvements in student performance and engagement. This study suggests that interactive course material enhance student understanding and satisfaction, as shown by course evaluations and performance data. While this study and teaching approach is applied to a particular course, the material preparation and presentation can be adopted by a wide range of STEM-based courses, both at high school and university level. The developed interactive textbook is freely available on MATLAB File Exchange and GitHub, and can be copied, modified, and repurposed without limitation. This allows for adoption and adaptation by educators globally. Literature review

1.4 Current teaching methods

Common pedagogical interventions in historically challenging STEM courses include project-based learning, lecture flipping, computer-aided assessment, and virtual laboratories. Project-based learning involves groups of students solving a complex, open-ended problem that aims to solidify understanding of the course content (Fernández-Samacá, Ramírez, & Orozco-Gutiérrez, 2012). Lecture flipping encourages students to cover the relevant course content prior to engaging in in-person activities with staff. The subsequent in-person activities are then used for more experiential activities, with the aim of facilitating a deeper understanding of the material (Seery, 2015). Computer-aided assessment and virtual laboratories work on the premise that interactive, multimedia environments that can offer instantaneous feedback on student understanding are essential for content assimilation (Rossiter, 2018).

1.5 Interactive learning tools

zyBooks offers digitised online versions of popular textbooks, referred to as zyVersions, which include interactive tools, animations, and embedded learning questions (zyBooks, 2025). The zyVersion most applicable to the field of control engineering is Control Systems Engineering, based on the static textbook by Norman Nise (Nise, 2020). The zyVersion offers moderate interactivity and limited customisation. The service is notably charged based on a time-limited subscription per student of $20, which means that the cumulative cost over time will grow approximately linearly, depending on the number of students in the class.

MATLAB Live Scripts provide an interactive and fully customisable environment for combining formatted text, equations, code, and visualizations in a single document. Unlike traditional scripts, they allow users to run code in sections, modify parameters dynamically, and instantly see results through embedded plots and simulations (MathWorks, 2025). Features such as LaTeX-rendered equations, sliders, buttons, and interactive figures make them particularly useful for educational purposes, enabling hands-on learning and real-time experimentation. Live Scripts are widely used in engineering and scientific fields to create self-contained, shareable documents that enhance engagement and understanding.

2 Methodology

2.1 Study design

This study made use of a quasi-experimental, retrospective analysis. There was no assignment of students to control and experimental groups, with data coming from real classroom settings, over multiple semesters. Past student data, including course evaluations and pass rates, were used to measure the impact of the intervention.

2.2 Participants

This study was applied to a 3rd-year control engineering course, named Control Systems (MEC3079S), in the Department of Mechanical Engineering at the University of Cape Town. The course has 12 NQF Level 8 credits, with three lectures a week. The entire course spans approximately 13 weeks and makes use of a combination of virtual labs, quizzes, a project, and a closed-book pen-on-paper test and exam. Data for the study was obtained and compared for the years 2021 to 2024, inclusive, with the introduction of the interactive course notes into MEC3079S taking place from 2023. No selection bias was present, as all students in each semester were exposed to the same teaching methods.

2.3 Intervention

The developed interactive course notes were used as the primary learning resource of the course and incorporated into certain lectures as a visual aid. Students had access to the interactive course notes chapter at the beginning of the relevant week and were encouraged to read through the notes prior to the associated lectures. The course notes were organised so that convenient sliders and buttons were present in the code blocks, allowing for easy adjustment of key system parameters that were highlighted as important for the particular section of work. The code blocks were configured so that any change in the slider or button state would automatically compile and run the code, and thereby instantaneously generate an associated visualisation of the code, such as a time-domain plot of a system's step response.

2.4 Data collection and analysis methods

Data collection comprised quantitative information, including pass rate and Likert-scale course evaluation questions, as well as qualitative information, such as student responses to open-ended questions and instructor observations on student engagement. The collected data was quantitatively compared over the years of 2021-2024 and considered the primary learning resource used for each year. A thematic analysis was performed to identify common themes in the student feedback.

2.5 Study limitations

No randomisation was included in this study. As a result, external factors, such as different instructors or exam difficulty changes may influence the results. Self-reported student feedback presented in the course evaluations can be subjective. The study was limited to a single control engineering course, and the results cannot be generalised to other control courses or institutions without appropriate adaptation. Data available for evaluation was limited for the years of interest and constrained the scope of evaluation methods that could be applied in this study.

3 Results and discussion

3.1 Quantitative metrics

Using student pass rates as a high level indicator of student understanding, we observed a clear upward trajectory over the past four years (2021-2024), as detailed in Table 1.

Table 1: MEC3079S pass rate and primary learning resource used for the period 2021 to 2024

	2021	**2022**	**2023**	**2024**
Pass rate (%)	73	80	92	91
Average mark (%)	55	64	84	72
Number of students	143	151	109	150
Primary learning resource	Textbook	zyBooks	Live Scripts	Live Scripts

In 2022, coinciding with the introduction of zyBooks as the primary learning resource, an increase of 7% in student pass rate was observed, elevating the pass rate to 80%. An even larger improvement in student pass rate was observed in 2023, where an impressive 92% pass rate was achieved — the average pass rate for all courses in the Mechanical Engineering department in 2023 was 85%, for reference. This 12% increase in pass rate notably coincides with the initial implementation of the MATLAB Live Scripts as a primary learning resource. The same MATLAB Live Scripts were used in 2024 by a new lecturer, and a similarly high level of student success was maintained, with 91% of students passing the course (the average pass rate of all Mechanical Engineering courses in 2024 was 84%). While these results cannot be directly attributed to the change in course material, the coincidence of such a marked improvement in student pass rate in 2023 with the debut of the MATLAB Live Script notes potentially hints at a positive correlation. The sustained success of students in 2024 under a new, and notably inexperienced lecturer, not only potentially supports the aforementioned correlation, but also suggests that the effectiveness of the developed course notes is not solely dependent on the original lecturer's teaching ability, and thereby underscores the potential for the interactive material to be adopted widely and successfully by other instructors.

We see a similar positive trend in grade average (Table 1, row 2) over the four year period under consideration. With the introduction of zyBooks in 2022, the grade average increased by 9% to reach 64%. In 2023, when Live Scripts were introduced, the grade average increased significantly by 20% to 84%. In 2024, the second year of using Live Scripts, the average grade was 72%. Although this was lower than in 2023, it coincided with the introduction of a new lecturer, and remained considerably higher than grade averages recorded in the years prior to the implementation of Live Scripts.

3.2 Qualitative student feedback

Student feedback, gathered through course evaluations between 2021 and 2024, reveals a largely positive trend in overall student satisfaction with the MEC3079S course and its content. This positive trajectory is particularly noticeable in the responses to the 'live' elements of the course, which students frequently highlighted as beneficial to their learning experience — see Figure 2.

In 2022, course evaluations were notably favourable, with 82% of students indicating 'Excellent' or 'Good' satisfaction with the course overall. This marked a substantial increase from the 67% positive response rate to the same question in the previous year — see Table 2.

Table 2: Overall level of student satisfaction (2021-2024)

	2021	**2022**	**2023**	**2024**
Excellent (%)	35	40	65	38
Good (%)	32	42.5	30	42
Average (%)	30	15	4.7	4
Below average (%)	3	2.5	0	4
Very poor (%)	0	0	2.3	8
Response rate (%)	37	40	43	24

The qualitative feedback also supported this positive trend. In 2022, when asked, "What aspect(s) of the course have you enjoyed?", 17 out of 40 students explicitly mentioned the interactive content, such as zyBooks and virtual labs, as being advantageous to their learning. Additionally, many students suggested that zyBooks, in particular, was a valuable tool in aiding their understanding of the course material.

The positive feedback continued into 2023, with an impressive 95% of students rating their satisfaction with the course as 'Excellent' or 'Good'. The qualitative comments in 2023 were overwhelmingly positive and focused on the interactive textbook used in the course. Students described the course notes as "exceptional", "extremely useful for understanding", and "too good".

In 2024, there was a slight decrease in student satisfaction, coinciding with the introduction of a new and inexperienced lecturer for MEC3079S. Despite this dip, the overall feedback remained positive, with 80% of students expressing satisfaction with the course. In response to the question about enjoyable aspects of the course, 3 out of 4 respondents specifically mentioned the MATLAB-based course notes as being particularly helpful.

Overall, student feedback from 2021-2024 shows that students were highly satisfied with the course. Interactive elements like zyBooks, virtual labs, and MATLAB course notes were repeatedly highlighted by students as valuable components that improved their learning. We note, however, that student participation in the course evaluations is entirely voluntary, and that the qualitative data obtained here only represents 36% of students on average (see Table 2, row 6). The quantitative data from the past four years, however, is available for all students, and shows a promising improvement in student performance. Key factors identified as potential drivers of this success were the temporary introduction of zyBooks in 2022, and the implementation of MATLAB Live Scripts course notes from 2023 and onwards.

4 Conclusion & future work

4.1 Summary of key findings

The above-mentioned results infer that the positive levels of student satisfaction are likely attributed to the implementation of interactive learning material. The interactive elements of the course notes were repeatedly highlighted within the course evaluations as components that improved student learning. Furthermore, data from 2021 to 2023 exhibit a monotonic improvement in student performance, with 2024 closely matching that of 2023, which coincides with when the course intervention took place. These findings emphasize the importance of continuing to explore and adopt innovative teaching methods and resources to enhance student learning outcomes. All content developed is freely available on MATLAB File Exchange and GitHub, with the invitation for other educators to copy, modify, and repurpose the content as required.

4.2 Implications for education

This teaching pedagogy has been applied to a particular control engineering course. However, the concepts can be abstracted to other STEM-based courses. MATLAB has an extensive list of well-written toolboxes, ranging from engineering and computer science to finance, which can be incorporated into bespoke teaching material for the course in mind.

4.3 Future work

The impact of the interactive course notes was evaluated using easily accessible quantitative data such as pass rates and student feedback from course evaluations that served as broad indicators of the effectiveness of the developed interactive notes. However, to gain a more nuanced and precise understanding of the developed material's utility, we propose the development of assessment indicators specifically tailored for this purpose. This may involve the creation of questionnaires designed to elicit detailed student opinions on how effectively the live script material supports their learning and comprehension. The next phase of this study is to strategically assess the 2025 course offering against an improved evaluation framework. In particular, the upcoming investigations, based on data from 2025, will seek to establish a robust evaluation design and assess causality between the intervention and performance improvements.

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6 Appendix

6.1 Interactive course notes

With reference to Figure 1, the developed MATLAB Live Script course notes contain a collection of sectioned text, LaTeX-rendered equations, customisable code blocks with convenient sliders, and associated information-rich visualisations. Adjusting one of the sliders automatically recompiles the code block and instantaneously generates the updated figure (see on the right). The interactive course notes can be accessed online using MATLAB Online here.

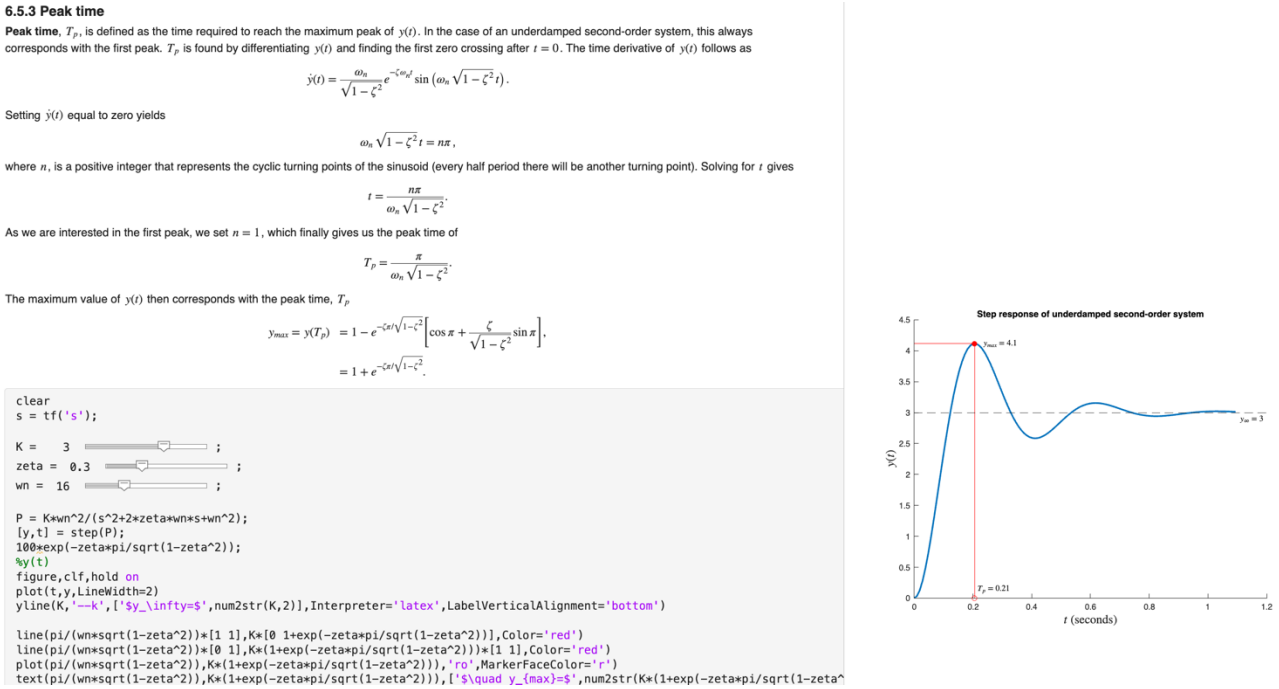

Figure 1: Example of information present in the developed MATLAB Live Script course notes

6.2 Word cloud of student responses

The word cloud shown in Figure 2 was generated from qualitative data obtained in the anonymous course evaluations. Students were asked to comment on elements of the course that they particularly enjoyed, and/or found useful.



Figure 2: Word cloud of free-written student responses



Sustainability, Professional Practice, and Global Transformation

Celebrating Refugee Innovation: Shifting from Deficit to Asset-Based Engineering Perspectives

Pelumi Abiola-Oseni
Civil Engineering, University of Calgary, Canada, pelumi.abiolaoseni@ucalgary.ca

Nada Alreyyes
Civil engineering, University of Calgary, Canada, and Gaza, Palestine.
el.rayyes.nada@gmail.com

Robyn Paul
Sustainable Systems Engineering, University of Calgary, Canada, robyn.paul@ucalgary.ca

Abstract

Refugee communities exhibit remarkable innovation as a means of survival, yet engineering's engagement with refugee communities often comes from a deficit-perspective, where we impose our technologies onto their communities. This research seeks to shift perspectives from a deficit-based view to an asset-based approach by highlighting and celebrating these communities' innovations and experiences (Gravel et al., 2021). Specifically, we interviewed student refugees to understand what engineers can learn from refugee innovation. Using qualitative methodology and engaging participants throughout in a co-design process, the data was analysed through qualitative content analysis (Elo & Kyngäs, 2008). These interviews offered valuable insights into refugees' daily lives, survival strategies, and engineering innovation. The stories shared illustrate how these existing skills can be cultivated within refugee camps, particularly when development opportunities are provided by organizations such as the UN. These opportunities contribute to the resilience of individuals and help strengthen the communities they are rebuilding. By exploring refugee experiences and innovations, this research promotes a broader perspective on community-driven engineering and asset-based understandings of refugee communities. Future work could be used in engineering classrooms, allowing students to engage with diverse perspectives and create more effective, culturally relevant engineering solutions for the communities they serve.

Keywords: Asset-based, Innovation, Refugee Community, Resilience, Community Engagement

1 Introduction

For many families across the world when civil war strikes, they seek refuge in neighbouring countries. Uprooting their lives and families, all for the sake of survival. However, in these foreign lands, refugees often find themselves innovating out of necessity by solving infrastructure problems, starting small businesses, and adapting to new environments (Oesch, 2020; Tomaszewski et al., 2016).

Frequently, the narrative surrounding these communities focuses on what they lack, framing them through a deficit-based lens (Cun, 2024; Lester et al., 2023). As a result, a asset-based perspective is helpful to bring when thinking about refugee communities and their need for aid, especially in technical solution-based fields like engineering. This research seeks to shift this perspective from a deficit-based approach to an asset-based one, where the innovative solutions that emerge within refugee communities, driven by resilience and necessity, are recognized.

This study catalyzes broader conversations in engineering education, encouraging future engineers to embrace the lessons learned from refugee innovations. This shift not only enriches engineering practice but also encourages greater social and cultural understanding, ultimately leading to more impactful and inclusive designs for communities worldwide. The guiding question for this study is: *What can we, as engineers, learn from refugee innovation to foster more collaborative and contextually informed approaches to community design?*

Myself, Pelumi, my engagement with refugee issues extends beyond the academic sphere. As an undergraduate student volunteer with the Student Refugee Program, I have worked alongside students in the student refugee program and formed close bonds and appreciation for their stories and journeys. These experiences have shaped my appreciation for the ingenuity and agency of refugee communities and have influenced my interest in asset-based approaches to engineering problems. While I do not share the lived experience of being a refugee, I have been mindful of how my background and values may shape the research process and approached interviews and literature analysis with an open mindset. My goal in this research

has been to centre the perspectives of refugees themselves, acknowledging that my role is to facilitate the amplification of their insights rather than to define them.

2 Background Literature

The background provides firstly an overview on research about refugee engineering infrastructure and innovation through a few case studies and reports outlining research and knowledge in these areas. Secondly, an overview of deficit vs. asset-based approaches are overviewed and their relation to the mindset used in this research project.

2.1 Refugee Innovation

Infrastructure

Host countries often enforce specific laws governing individuals with refugee status as they reside in the new environment. While some nations anticipate refugees' stay to be temporary, the reality is that many camp-based refugees reside in camps for extended periods, often exceeding a decade (Tomaszewski et al., 2016). As infrastructure and development needs grow within these camps, communities strive to address their requirements within the legal frameworks established by host countries. For instance, in Jordan's Al-Hussein camp, researchers have examined how residents navigate the delicate balance between state and non-state actors to maintain the camp's intended temporary nature.

The Al-Hussein Refugee Camp provides insight into the regulatory challenges associated with infrastructure development in refugee settings. Development usually refers to planning interventions aimed to generate improved standards of living in less developed parts of the world (Smith 2008 as cited in Oesch, 2020). Researchers have documented the urban development processes within the camp and the obstacles encountered when creating infrastructure. For example, the Community Infrastructure Program in Al-Hussein was not labelled as a comprehensive urban development initiative but rather as an "anti-poverty subsidized" approach, as a result, the approach to improvement isn't about longevity or thriving communities, but rather about meeting the minimum need (Oesch, 2020).

An architect for the corporation stated that in the camp, 'we were just allowed to put in infrastructure'. Hence, urban planning in its conventional form—that included architects, civil engineers, and social analysts—in the sense of programmed and displayed transformation had hardly existed in this space (Oesch, 2020). Yet, it was clear that the camp had undergone a process of urban development as canvas tents were long gone, and its materiality had blended with that of the city. Refugee communities and those assisting them had to find different ways to develop the area so that maintained the camp's "permanent temporary" status through unconventional urban planning approaches acceptable to residents and the broader refugee community.

Innovation

Upon arrival at refugee camps, individuals often receive initial assistance from organizations like the United Nations and various NGOs to help them settle. However, these camps are frequently situated in rural areas lacking essential resources such as electricity, water, and sustainable food sources. Even when basic infrastructure exists, services can be inconsistent, compounded by the "permanent temporariness" that characterizes many refugee camps (Tomaszewski et al., 2016). Studies utilizing satellite imagery have shown that refugees often relocate their shelters to be closer to relatives, markets, service offices, or areas with better electricity access (Tomaszewski et al., 2016).

Literature shows global instances where refugees created diverse and locally relevant innovative solutions to meet their needs. Innovation can identify ways in which external interventions can contribute to creating an environment where people are empowered to find solutions to their problems. It can allow us to consider

the types of facilitation and infrastructure required to allow people to help themselves in more sustainable ways (Betts et al., 2015). In Uganda, refugee-led organizations are actively engaged in creative problem-solving, developing or adapting products and processes to address daily challenges and create opportunities. This bottom-up innovation process often results in solutions that are better tailored to existing needs and more readily accepted within the community. For example, in a Ugandan refugee camp, Abdi founded the first computer games shop out of spare parts using skills in mechanics and electronics gained from his previous job in Somalia. In Uganda, Claude established a milling business and established other income-generating businesses, such as selling water from his milling plant (Betts et al., 2015).

In the Al-Hussein camp, the Jordanian government's policy of granting citizenship to Palestinian refugees facilitated their socioeconomic integration into Amman (Betts et al., 2015). This policy enabled refugees to buy and sell land and properties outside the camp and move freely, thereby influencing the camp's development and its relationship with the surrounding urban environment (Tomaszewski et al., 2016).

2.2 Asset-Based Framework

Engineering education researchers understand that diverse thinking and including different ways of thinking improve innovative ideas and design outcomes (Samuelson & Litzler, 2016). However, often in an attempt to be more inclusive to underrepresented groups and support their persistence in engineering, deficit-based approaches are used. For example, underrepresented students may be given information on how they can enhance their cultural or social capital to better succeed in engineering—the underlying assumption being that they are 'lesser' and need to change themselves in order to fit in and succeed. These approaches do not recognize or foster the brilliance that already exists in diverse learners (Martin & Wendell, 2021). Asset-based approaches instead aim to acknowledge "students' unique identities, backgrounds, and experiences, and leverage their assets for teaching and learning" (Budinoff & Subbian, 2021).

In the last decade or so, asset-based approaches have had increased attention and scholarship, with research showing how they benefit students' identity and achievement, acknowledge students' lived experiences and backgrounds, and aim to reduce marginalization (Budinoff & Subbian, 2021). In 2021, there was even a special issue on asset-based approaches in engineering education, outlining across multiple contexts, demographics, and methodologies (Martin & Wendell, 2021). Specifically, scholars in this area emphasize the importance of relationships and community being central to leveraging students' assets and unique skillsets.

Within refugee communities specifically, using asset-based approaches has been found to be valuable as it leverages existing networks to mobilize change and build on existing capacities and assets (Lester et al., 2023). Asset-based approaches have also been used for similar studies investigating the resettlement of refugee students in science, leveraging assets and cultural wealth to support their learning (Cun, 2024). Overall, an asset-based approach to this research was taken as it provided an opportunity to learn from experiences in refugee communities, leverage their wealth of knowledge in infrastructural and innovative engineering approaches.

3 Methodology

Interview data was collected in Summer 2024 from two participants, who agreed to be called Malith and Adol in research publications. A co-author of this paper has experiences as a Gazan refugee and brings insights to the innovation experienced in Gazan Communities. Both Malith and Adol, came from South Sudan and went to refugee communities in neighbouring African countries, Kenya and Uganda. They both came to University through the Student Refugee Program, where they are studying engineering. Interviews followed a semi-structured format, with some questions determined in advance but with flexibility in structure. Questions started with getting to know each other and acknowledging power differentials (based on trauma-informed research guidelines from (Edelman, 2023)), and then asked about engineering, innovation, and resilience. Specifically, a co-design interview process was followed where participants were encouraged to take an active role in the interview process, reframing questions and directing the flow of conversation. In practice,

this meant the interviewee helped clarify the kinds of questions to ask when approaching a community from an asset-based lens. For example, Adol said, *"but now it's okay, 'how can we make it better?' I think for me it would be 'how can we create more awareness' because people are less informed."* I responded, *"that's very true… it is more about how we can make it better, how can we bridge that gap,"* as her insight broadened my perspective on framing refugee innovation as also being about raising awareness.

Future work will continue to engage the participants in the co-design process to review the findings, correcting and validating results, and further adding their expertise and perspectives to the research. For example, the second interviews conducted in Summer 2025 used more open-ended, co-design-oriented questions, allowing participants to elaborate on earlier conversations and suggest ways their experiences could enhance the module. Where the modules aim is to help students understand the importance of designing *with* communities rather than *for* them. In the final stage, participants will each review the module individually, providing feedback and suggestions for improvement.

The interview data analysis following Elo and Kyngäs' qualitative content analysis process (Elo & Kyngäs, 2008). Qualitative content analysis was a valuable approach for the data, as well as given the scope and expertise of the researchers, with this work being conducted as part of a 4-month undergraduate student research project. Specifically, the first author transcribed the data manually to immerse herself into the data. Next, she did a first round of qualitative coding through NVivo software. From there, she did a second-round coding, finding common themes across the data and collecting them together in the results presented here in this paper. The second author acted as a validator throughout the process, where regular weekly meetings were used to reflect on the findings, explore different interpretations of the data, and iteratively review the themes that were emerging. This paper is the first publication of this data, and further research will continue to iterate and refine the results, including exploring more in depth qualitative analysis methods such as narrative analysis.

4 Findings and Discussion

4.1 The Need to Survive: Challenges and Background Stories

To truly understand the refugee experience, we must hear firsthand accounts of survival and resilience in the face of immense challenges.

Malith shares his story:

"Umm...My story is that I'm from a country that experienced civil war, not all of it, but for some part of my life I lived as a refugee. And part of that life is having to figure out a way to live in the camp comfortably and how to get things done with the limited resources that we had... you just had to do it."

His account reveals the hardship of displacement caused by civil war and the necessity of adapting to life as a refugee. Survival was not a choice but a requirement, shaping every aspect of daily existence.

Adol describes her abrupt transition to becoming a refugee:

"Never at, and one point, was I expecting to be a refugee it just happened abruptly (…) There was a conflict in the government. Just one night we woke up at three AM, guns were everywhere… If you were not strong enough—or if you were not a soldier, then you had to seek refuge."

In an instant, Adol's life changed. One moment, her family was resting at home, and the next, they were fleeing for their lives. The familiar world she had known became unsafe overnight. There was little time to prepare, and families could only carry the essentials, "*You get one saucepan, salt, a little bit of food, what you would cook, you get a matchbox."*

A sense of strength in numbers emerged as families moved together in search of safety. Adol recounts, *"You would just move with the people who were moving because people would know what the safest place is to move to. And that time we went to the Nile [River] Bank."*

For Adol, this was a new and uncertain experience, but for her mother, it was a repetition of history. Having lived through civil war before, her mother shared her wisdom:

"So, my mom said this [the civil war] is not going to stop so soon, because she had had that experience before. So we are going to go somewhere near the border. So that if something happens in the country we can go to the neighboring country because that's what happens when a country is in war, you can seek refuge in the neighboring country." Her mother's words highlight the unspoken solidarity among nations that take in refugees during times of conflict.

Adol's journey ultimately led her to Uganda:

"So we went to the border and from there it was just a lot of chaos, people were fighting and killing people a lot. So we went to Uganda and that's how I became a refugee, the war continued and we never went back home. And we did not want to go back home. So that was my journey."

Adol's story, like Malith's, illustrates the resilience required to survive and the reality of not returning to the home they once knew.

4.2 Survival and Necessity Catalyses Innovation

The greatest innovations are born out of a need for survival. In refugee camps, constant survival becomes normalized. As Adol explains, *"We just tried to fit into the environment. Like survival of the fittest, we had to survive."*

The word "survival" suggests an individual or community has faced a life-threatening situation and found a way to overcome it. Humans have an innate ability to adapt to their environment in order to survive. In refugee camps, limited resources force individuals to maximize what little they have. As a result, those who think outside the box stand the best chance of survival—this is where adaptation through innovation begins.

Malith reflects on this process:

"I think living in a refugee camp and seeing the innovations that came through actually gives you perspective on how modern civilization came to be. Because these things were not always there. But someone had to be creative with what they had. Sometimes, where there is need, people tend to be creative…"

His words capture the essence of innovation born out of necessity—making the most of limited resources to meet essential needs. Throughout history, societies have faced similar challenges. When confronted with scarcity, people responded by creating solutions: shelter to escape the elements, hunting and farming to acquire food. Necessity drives problem-solving, and survival often becomes the catalyst for invention. Innovation is rooted in identifying a need and finding a way to meet it. This principle also exists in engineering and problem-solving. In refugee camps, as individuals develop solutions to their daily struggles, a sense of independence emerges. What begins as a means of survival gradually evolves into a system that not only meets basic needs but also improves upon them. This transformation is what allows communities to move from merely surviving to truly thriving.

Gazans have shown remarkable ingenuity in adapting to scarcity. Farmers have found ways to grow food in limited spaces. Even under siege, people find creative ways to repair homes and restore. Although sometimes there is a conflicted feeling, for example Nada describes, "Air and water pollution from relentless bombings and the burning of waste make the environment toxic, and some people, out of desperation, burn tires and garbage to extract fuel, worsening the pollution even more." Here, the necessity of survival fosters innovation sometimes at the expense of personal values (such as that of sustainability).

4.3 The Independence Required to Survive

When refugees first arrive at a camp, the United Nations High Commissioner for Refugees (UNHCR) provides essential resources, including land, shelter materials, and food. However, these resources are meant for short-term living conditions, requiring refugees to innovate and adapt for long-term sustenance. This necessity-driven problem-solving process directly connects to engineering, innovation, and resilience.

Engineering and Innovation Through Necessity

Engineering is fundamentally about designing solutions to meet human needs using available resources. In refugee camps, where resources are scarce, innovation becomes a survival mechanism. Malith highlights this when he describes the basic materials provided:

"And that free land usually comes with things like poles, some iron sheets, some canvas that was supposed to be used as tents for the camp. But most of the time you realize that those tents are not convenient for all weather, say for example in rain it's not as convenient, rain, cold season, it's not as convenient."

This statement depicts the ability for structural problem-solving; how can individuals create durable, weather-resistant shelters with limited materials? Communities think critically and apply engineering principles such as material optimization and environmental adaptability. Additionally, Adol explains how resources are sometimes repurposed or traded to meet emerging needs:

"They [the UNHCR] know you don't have anything, and they give you everything for you to be a bit comfortable. So, we started selling some things to the residents (…) For people to get money, buy iron sheets, or if you wanted anything else you would just sell what you had."

This reflects the entrepreneurial mindset essential to engineering innovation by identifying problems, finding solutions, and reallocating resources effectively.

Skill Development as a Path to Innovation

Beyond immediate survival, the transition from reliance on aid to self-sufficiency requires education and skill development. To address this, the UN supports training programs that provide refugees with technical skills, Malith describes this opportunity:

"There was a tertiary institution called Don Bosco. Don Bosco is a school sponsored with the UN to teach technical skills, from plumbing, electrician work, the basic computer skills, and masonry, so those guys were able to get those skills from there. As much as everyone built their own houses there were bigger places like shops where... a little bit of expertise was needed, and that's where these people came in and for pay they would do what they do best."

This initiative is a clear example of engineering education at work. By equipping refugees with skills in construction, infrastructure development, and technology, these programs foster independence and create opportunities for long-term sustainability.

Nada Explains that, "Despite the destruction of schools and universities, the pursuit of education continues. Makeshift classrooms are created in tents, homes, or online where possible. Teachers and students show incredible dedication, using any available means to keep learning alive. Education is not only a right but also an act of resistance and hope for a better future."

A common theme amongst many refugee communities is a desire for the right to education and to grow beyond the current circumstance. Malith and Nada both explore the importance of growth and progress towards independence through skills and education to lead to a thriving community.

Resilience and Resource Management

Resilience is the ability to adapt to adversity, and in refugee communities, this is evident in their ability to rebuild their lives despite hardships. The UN's gradual shift from direct aid to skill-building reinforces this principle as refugees develop resource management skills.

Nada gives insight that "The people of Gaza are not simply victims of war; they are agents of resilience and change. Through solidarity, creativity, and unwavering spirit, they continue to find ways to live, solve problems, and hope for a peaceful tomorrow."

The refugee experience demonstrates that engineering and innovation are driven by necessity, and resilience is built through adaptation. By developing technical skills and applying creative problem-solving, refugees engineer solutions that transform their communities. This mirrors how engineering functions in broader society, identifying problems, maximizing limited resources, and continuously improving solutions for a better future.

As Adol explains:

"Now they are reducing what they are giving people. Because they are providing people with skills, they are supporting people in so many ways, so you can be able to support yourself and not lean on the UN, because the UN has a lot of responsibilities."

This shift highlights the importance of self-sufficiency and long-term development. Instead of relying solely on external aid, refugees gain the ability to sustain themselves and contribute to their new communities. This is where engineering and innovation come full circle, by applying learned skills, individuals create businesses, build infrastructure, and strengthen economic resilience.

In refugee contexts, skills development and resource management are highly intentional, guided by a clear understanding of needs and how effectively applied skills and resources can address them. This deliberate approach promotes continuous skill improvement and innovative resource use. Ultimately, the ability to innovate and adapt in the face of hardship is what allows refugee communities to transition from mere survival to thriving and rebuilding their lives.

There is a clear understanding of the balance between asking for help and asking for self sufficiency. Nada demonstrates this through her plea: "I call on the world […] to see us as human beings who can make a difference if given the chance. Please do not let this dream die in the rubble of war. Help us build a future where our children can thrive in peace, with knowledge, dignity, and dreams that no war can destroy."

4.4 Cross Cultural Adaptation:

When refugees move from the country of their nationality to a neighboring country, they are faced with learning how to navigate a new culture in their laws and way of life. When coming to a host country, there are a set of rules and regulations outlining the rights and expectations of refugee communities. Because refugees are considered temporary residents of the land, refugee camps are intentionally kept separated and confined from the host country and do not allow refugees to seek legal employment.

Successfully integrating into a new country involves a delicate balance between adaptation, innovation, and compliance with legal and cultural frameworks. Refugees also have set rules and regulations in the countries they seek refuge in, as their status of residence is often considered temporary. As a result, understand the balance between innovation and creating a life in this new environment while still abiding by the rules and regulations, and customs of their new environment.

Adol explains her experience in Uganda:

"Absolutely, I think Ugandans are really nice people (…) but there are those few individuals that are not happy you are there, because they think you are taking your resources, their land(…)But in terms of safety, it was the same for everyone. Also, because we were protected people, we had the UN."

Adol's words depict a duality that exists when integrating into new cultures that is often experienced by many: Knowing that one is welcome into a country yet feeling the tension of navigating resource use. By having security and safety provided by the UN whilst understanding the laws and regulations of the host country, it brings into consideration this idea of context-centered innovation where refugee communities can thrive in innovation and growth while respecting the citizens of the land they reside on.

Adol further explained:

"We needed to have houses, but you couldn't go to the nearby forest or bush and just get trees because that is not your land, and it's for the government. And people started making bricks, that's when the idea of—I would say Mini technology because we weren't using concrete, but people started making bricks out of mud."

The understanding of ownership of land depicts a respect for the land that communities have and a recognition of being a guest in a new environment. From an engineering perspective, projects in refugee communities must account for the legal, cultural, and social dynamics of the host country. Engineers working in humanitarian settings must design solutions that align with local regulations, available resources, and environmental constraints. For instance, sustainable construction methods, like those employed by Adol's community, can inspire engineers to develop alternative building materials that do not rely on deforestation or costly imports. By integrating engineering principles with cultural awareness and legal considerations, infrastructure can be developed that supports refugee resilience, fosters economic opportunities, and strengthens relationships between displaced populations and host communities. This intersection of engineering and social responsibility is essential for creating lasting, ethical, and practical solutions in humanitarian settings.

4.5 The Balance of Improvement and Community Empowerment:

Imagine a thriving city filled with professionals—doctors, lawyers, engineers, and scientists—who have spent years building their careers, homes, and lives. Now, imagine a crisis forcing them to leave everything behind, abandoning not only their material possessions but also their professional identities. However, their knowledge and expertise do not vanish; instead, they carry these skills with them into the places where they seek refuge. In this new environment, there is an opportunity to reimagine how their abilities can be applied to rebuild their lives and support their families.

This reality reflects the experience of many displaced people. Before becoming refugees, they developed knowledge and skills in areas such as agriculture, infrastructure, and mechanics—expertise that once served their daily lives. Nada sheds light on the ways in which community expertise is used to provide solutions in the communities. She explains that ,"Additionally, due to the shortage of electricity and cooking gas, many families have turned to solar panels for heating, cooking, and lighting. However, since solar energy relies heavily on sunlight, power interruptions still occur on cloudy days, which are common in Gaza across various seasons. To address this issue, electrical engineers have proposed a programmed device that connects to the solar panels and reduces energy consumption based on sunlight and cloud conditions."

Adol and Malith's stories illustrate how these existing skills can be further cultivated within refugee camps, particularly when development opportunities are provided by organizations like the UN. These abilities not only contribute to the resilience of individuals but also help strengthen the communities they are rebuilding.

Merging Outside Expertise with Local Insight

When experts and problem solvers engage with developing areas, there is often a risk of misjudging community needs—either by underestimating or overestimating them—when there is insufficient understanding of the people they aim to support. While documentation can provide some context, the most meaningful insights come through direct engagement with the culture and community itself. By building connections and listening to those affected, communities can articulate their needs, ensuring that assistance leads to improvements and innovations that have a genuinely positive impact.

Adol provides insight into this balance through an analogy:

"Okay, what does it mean to be structurally sound? It doesn't just have to be beautiful. Now, this is where the civil engineers come in. These people could have helped us—maybe we could have made better houses. Because it was a lot of work. You would construct a house, then it collapses, and you have to redo it. And that's hard, right?"

Her words highlight the balance between external expertise and local ingenuity. Refugee communities have demonstrated remarkable innovation by building their own shelters with limited resources, yet there remains an opportunity to enhance these methods with engineering principles. Rather than imposing foreign solutions, engineers can collaborate with communities, equipping them with foundational knowledge to refine and strengthen their existing innovations.

This approach mirrors the function of tertiary institutions, where individuals acquire fundamental skills that they later expand upon to create businesses and improve their communities. By applying this principle to humanitarian settings, knowledge-sharing fosters sustainable development, allowing displaced communities to transition from makeshift survival strategies to long-term, self-sustaining solutions.

Empathy and Understanding in Humanitarian Efforts

Malith offers important advice on working with refugee communities:

"I would advise anyone who goes to a refugee camp to actually know that these are people with different backgrounds. These are people who will actually appreciate any little help that they receive; they are very grateful people. And no matter how small the help that comes, they will still take it. Also, some of them have traumatic pasts—having seen war happen, having seen people die with their own eyes, having seen their parents or their relatives get murdered. Those traumatic experiences stay with them. So when you approach them, approach them from a place of understanding. Because sometimes, they might react in a way you didn't expect."

Malith's words emphasize the importance of empathy in humanitarian efforts. Assisting is not just about offering resources; it is about understanding the people behind the need. A trauma-informed approach fosters genuine connections and ensures that the help given is both meaningful and respectful.

A Sustainable Approach to Support

Ultimately, the most effective form of support does not replace or overshadow the skills and knowledge that already exist within a community—it enhances and amplifies them. When assistance is provided with cultural awareness and collaboration, it fosters long-term sustainability rather than dependence.

Innovation, engineering, and resilience thrive when local knowledge and external expertise work together. The goal is not to impose pre-existing solutions but to empower communities to refine and expand upon their strengths. In this way, displaced individuals can move beyond survival and towards self-sufficiency, rebuilding their lives.

5 Conclusion

These preliminary results from this research project highlight refugee community resilience, ingenuity, and innovative skillsets. Refugee communities typically exist within scarcity, meaning community members quickly learning resource management and creative problem solving, two skills essential in engineering education. These stories of management of limited resources in refugee communities can be shared to support learning of students in engineering classrooms, to showcase and celebrate innovative solutions and emphasize the importance of asset-based approaches to working with communities.

Many of the findings talk about balance: providing assistance that's not too much and not too little. This balance is best achieved through collaboration with communities, ensuring we are leveraging both our

expertise as external partners, and the community ingenuity as experts of their own local context. When working with communities, engineers must understand how to avoid imposing foreign solutions and instead leveraging local assets to strengthen existing innovations.

The stories shared in this paper provide incredible insight into refugee experiences and innovative mindsets in refugee communities. Themes and findings emerging from this analysis will inform future work that aims to develop engineering modules that integrates participants' insights to authentically represent innovation in refugee environments. Ultimately, this project seeks to enrich engineering education by broadening students' perspectives on what innovation is and encouraging them to approach design with greater inclusivity; showing that engineers can empower and partner with the communities they serve, resulting in more equitable and innovative outcomes. Following the initial research, in Summer 2025 the work continued by applying the lessons learned to develop a first-year engineering module which will be piloted in Winter 2026. Students, as future engineers, need to understand how to work with communities, to support and nourish the innovation and resilience that exist within these communities. We need to foster skills in our students where they truly value the local, community knowledge that refugees hold. We will close with a quote from Nada that represents this incredible knowledge that exists within the people of Gaza:

"The people of Gaza are not only victims of war, they are people of resilience and strength. Palestinians have an unyielding spirit and a deep will to build a better, peaceful future. Living through hardship and repeated conflicts has shaped them into people with remarkable creativity, ingenuity, and skills that are rare to find elsewhere. We deserve the chance to live, to learn, and to contribute."

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Work-based learning: integrating academia, industry, and community

Cody Mann
Iron Range Engineering, U.S.A., cody.mann@ire.minnstate.edu

Bart Johnson
Minnesota North College, U.S.A., bart.johnson@minnesotanorth.edu

Ron Ulseth
Iron Range Engineering, U.S.A., ron.ulseth@ire.minnstate.edu

Katherine Ulseth
Minnesota North College, U.S.A., katherine.ulseth@minnesotanorth.edu

Abstract

This research paper presents a comprehensive analysis of a work-based learning model based on the principles of PBL and its positive synergistic effect on students, industries, and communities. The model is active in multiple communities in the United States. This paper will focus on the synergistic effect in a rural region of the upper Midwest. The model integrates academic instruction with hands-on industry experience, cultivating a collaborative environment that prepares future engineers to address complex challenges.

The paper explores how the model's partnerships with local and regional industries provide students with immersive, real-world learning experiences that enhance technical competencies, boost employability, and foster a mindset of lifelong learning. The paper also explores how industry partnerships drive innovation and generate social and economic benefits for the region, contributing to its resilience and growth. By supplying a skilled workforce to local industries, the model plays a critical role in community development, addressing both immediate industry needs and long-term sustainability. Additionally, the paper underscores the importance of community engagement, demonstrating how an integrated approach between academia, industry, and local stakeholders can yield significant advancements in engineering education and societal progress.

The findings offer insights into the transformative potential of work-based learning models linking education, industry, and community engagement, advancing engineering education and broader societal development.

Keywords: work-based learning, industry partnerships, community engagement

1 Introduction and background

Engineering Education has seen periods of evolution, innovation, and growth to meet the changing needs of society. A significant step was in 1989 when professional organizations from Australia, Canada, Ireland, New Zealand, the United Kingdom, and the United States formed what became the Washington Accord (Beanland & Hadgraft, 2013). It sought to establish standards for professional competencies and a competency focus for engineering students graduating from an accredited institution. Within the U.S. engineering education community, ABET, the non-governmental accrediting body for engineering education in the U.S., introduced in 1996 a new set of engineering accreditation criteria, the ABET Engineering Criteria 2000. Throughout the past quarter century, conferences, research, and scholarly activities have continued to focus on the need for engineering education to evolve, innovate, and grow at a rate that matches the accelerated rate of change being experienced in society (Sorby & Fortenberry, 2021).

One model recognized (Graham, 2018) for its exploration and innovation is the Iron Range Engineering (IRE) program. Developed as a project-based learning (PBL) model to address the growing gap between the skills and knowledge needed for professional practice and what was being acquired by graduation (Ulseth et al., 2011), it was adapted (Bates et al., 2024) from the Aalborg University PBL model (Kolmos et al., 2007). Student learning is focused on the development of the "whole student" through professional, design, and technical learning at workplace-ready levels by graduation. This contrasts with the traditional curriculum's primary focus on the technical learning domain (Sheppard, 2009).

The *design domain* focuses on developing the skills necessary to scope, manage, evaluate, and present engineering projects, emphasizing program graduates' ability to directly contribute to project management while fostering an innovative and creative mindset. The *professional domain* focuses on the professional skills of communication, the ability to work on teams, and understanding the professional and ethical

responsibilities of an engineer being developed to a workplace-ready level by the time they graduate. The *technical domain* focuses both on developing the traditional technical knowledge that engineers need for practicing in their discipline and, equally important, the ability to identify and develop the technical knowledge when they need it.

The initial PBL curriculum began in 2009 with a focus on industry-sponsored academic projects that were completed within the physical and operational structures of the institution, with interaction with professionals at the sponsoring company. By 2016, it was becoming clear that further development of the IRE model was needed (Ulseth & Johnson, 2023). It came both from the learning experiences of some students utilizing co-op or work-based learning experiences instead of the on-campus industry-sponsored projects and from the desire to 1) empower students to use employment to help fund their education while gaining recognizable experience, 2) utilize the emerging technologies for online learning, and 3) increase access to the engineering profession by designing it specifically for community college students bringing a wider student demographic diversity than the university counterparts to the profession of engineering. (Johnson et al., 2018). In 2019, the curriculum was reinvented by merging the original IRE model with the co-op placement model from the engineering program at Charles Sturt University (CSU) (Lindsay & Morgan, 2021).

In the new IRE Bell model, the lower-division (the first two years of a bachelor's degree) courses are completed at a community college anywhere in the U.S. This is followed by a one-semester, on-ground, intensive session called the Bell Academy, where participants began taking their upper-division technical courses, acquire the professional and design skills needed for their co-op experience, and develop the job-search skills to acquire the co-ops. After the Bell Academy, students spend 24 months doing full-time co-op work paired with 10-12 hours per week of continued coursework in the domains of technical, professional, and design learning. Integral parts of the learning experience are the students' learning coach (mentor), reflection, and being evaluated on their learning (Bates et al., 2020; Ulseth et al., 2021).

The program features of the IRE Bell Model align with the four modern learning principles behind PBL, as identified by Maastricht University (Dolmans et al., 2005): 1) Constructive learning, 2) Learning in a relevant context, 3) Collaborative learning, and 4) Self-directed learning.

Constructive learning

Learning in the IRE model is an active process where students gain knowledge from their experiences and interactions within the work environment. On projects, students are encouraged to think about what they know already, learn new information, and then learn to integrate new information with their prior knowledge to complete the project at hand. Facilitators, engineers with experience who return to mentor students in the program (Johnson et al., 2018), serve as learning coaches and work one-on-one with students through weekly conversations. These conversations focus on the student's short-term and long-term goals regarding the development of their design, professional, and technical domains. These relationships start in the academy and continue through the two years of co-op work placements. This process helps students to truly understand the subject matter and form well-founded opinions about what is and what isn't valuable and how to acquire new knowledge; all of this contrasts with the traditional engineering education model of just learning things by rote. Student retention of knowledge is higher.

Learning in a relevant context

Student projects are the current projects that a company is actively working on with all of the unique challenges, making solutions work in a current and rapidly evolving society and in an environment not

based on academic peer or faculty approval but on the approval of the market and society the project solution serves which have direct meaning as an engineer for today's society. The project timing is based on the company's timeline vs an academic timeline; therefore, students will find themselves joining project teams to finish a project, start a project, and occasionally for the entirety of the project. The authenticity of these industry projects and the timing piques students' motivation as they see the actual value and impact of their work as they are directly involved with practicing engineers and multi-functional teams.

In addition to the "on the job" development during the day of their professional, design, and technical skills, students additionally spend approximately 15 hours documenting their design/professional learning and taking evening technical courses while visiting and evaluating their learning with their mentor (i.e., learning coach) on a regular basis. Being confronted with the complexities and intricacies of work-based projects, IRE Bell graduates have spent two years tackling a wide variety of societal and technically relevant topics and developing their ability to make the all-important knowledge transfer from theory to practice.

Collaborative learning

The entire IRE Bell learning model encourages students to learn from and discuss their learning with peers, mentors, and industry colleagues. This begins during the academy, where the proximity of students to one another builds a strong sense of community both in the social aspect and also in their learning. At the end of each academy, students who are one or two years into their co-op placement return for exams and professional development weeks, during which students develop peer relationships with those who are a few steps ahead and build a better understanding of what their learning progression will look like. By exchanging ideas and providing feedback with their peers, mentors, and work colleagues, IRE Bell graduates understand the professional, design, and technical learning domains better. They realize that the learning process is not an individual one; it is developed in a social construct where the responsibility is for both the group and the individual to develop their domain knowledge.

Self-directed education

The learning process of IRE Bell is something students manage themselves by planning, monitoring, reflecting, and evaluating (Ulseth, 2016). The faculty and mentors are there to assist, but from the start of the program application process, through the Bell Academy, while finding co-op placements, and throughout the 24 months of learning in industry, the students remain the driving force of their learning.

Student learning initially takes place in the academy through a core set of one-credit modules that focus on two to six fundamental principles for a given topic versus attempting to teach "everything". These modules build on the information from the student prerequisite courses from their lower-division studies. Students are held accountable for carrying the fundamental principles to future courses, academy projects, and during their industry placements. Students then select future courses during their industry placements that directly support what is needed in their industry applications and are relevant to their engineering discipline.

As students progress through the program, they continuously build on the ability to direct their learning in a motivating and effective way that reflects the Sheppard (2009) helical learning cycle (Sheppard, 2009). The experience builds the lifelong learning ability and desire of students.

Importance of community engagement

Given the social construct of PBL, engagement in a peer community is necessary to build and cultivate strong social connections between student-to-student and faculty-to-students (Christensen et al., 2023).

These connections are fundamental to building a culture that builds relationships and fosters the student and professional development necessary in both the program, supporting retention, persistence, and identity building (Bates et al., 2024) in their future professional practices. Community is developed through three activities during the Bell Academy: 1) students live in a dormitory community environment, building the overall community for that cohort; 2) students have project rooms for their projects to build community within their project team; and 3) through student-life activities to further build a student's connections with both faculty and students. The relationships built continue to support students as they individually go into industry through continued, albeit remote, shared learning experiences and networking activities to both support their learning and project work.

Student participants identify this culture (Johnson & Ulseth, 2017) as strengthening the project and learning activity experiences in their development, especially in their professional competency development. The culture reinforces the practice of students conducting themselves in a professional manner on a continuous ongoing basis and not on a "just when they have to" basis.

2 Fostering a life-long mindset

2.1 Fostering a life-long learning mindset -methods

Student engineers use reflection as an essential part of their overall development. Called "learning journals," the students are given approximately 25 prompts during each of their five learning semesters. They respond to these prompts with ½ to 1 page of written reflective analysis. Some prompts are given once during the 2.5 years, while others are repeated from 1 to 4 times throughout the student experience. Data to analyze the lifelong learning mindset came from a 1-time prompt in the fifth semester called "Lifelong Learning" and from a prompt given both in their first semester (Bell Academy) and again in the fifth and final semester before graduation called the "Metacognition Memo."

Research Question: In what ways do the graduating students of the work-based learning program demonstrate the development of lifelong learning skills?

Data was gathered from the one-time Lifelong Learning journal entry and then paired before and after Metacognition Memos. The 10 graduates highlighted in this study were selected at random, and all data was accessed and analyzed after the students had graduated. The three sets of data are all connected to the same 10 students.

The Lifelong Learning journal entry asked the following questions of the graduates: 1) What does it mean to be a lifelong learner? 2) In what ways do you anticipate the field will change during your career? 3) Do you feel you embrace the concept of lifelong learning? Why or why not? 4) Discuss two ways you can demonstrate lifelong learning (within engineering or parallel to it).

The prompts from the Metacognition Memo start with this statement: **One of the important elements of learning is "regulating for the future." This takes place at the end of a learning cycle. The learner takes a step back and evaluates their learning processes, then identifies actions that can be taken to make future learning more effective and efficient.** The prompts that follow are: 1) In 1-2 paragraphs, describe your learning process. 2) How have your learning processes changed over the last 6 months? 3) What actions can you take now to make your learning more efficient and effective in the future?

After removing all identifying information for graduates, two authors conducted thematic coding to identify the lifelong learning attributes. Once they reached a consensus on the identified themes, each theme, and its combinations were further refined through data interpretation and supported with quotes that captured the unique perspectives of the graduating students.

2.2 Fostering a life-long learning mindset - results

The analysis identifies common themes of lifelong learning: curiosity and a growth mindset, adaptability to industry changes, seeking out new knowledge and experiences, multidisciplinary learning and broad skill development, reflective practice and self-improvement, collaborative learning and mentorship, and taking action toward learning.

- Curiosity and a growth mindset: Students emphasize that lifelong learning is driven by curiosity, a desire to improve, and a recognition that learning never stops. Quote 1: "To be a life-long learner means that as you continue in your career, hobbies, and life, you are always absorbing new information." Quote 2: "If you think you're already an expert in something, you will never progress beyond your current level of understanding."
- Adaptability to industry changes: Students acknowledge the need to stay current with evolving technologies, industry trends, and engineering practices. Quote 1: “Being a lifelong learner is about two key factors: Adapting to industry's inevitable changes and your own curiosity.” Quote 2: “As technology becomes more advanced, what we learn now will become less useful. In order to be a successful engineer, it is important to invest time into learning over your career.”
- Seeking out new knowledge and experiences: Students actively pursue learning beyond formal education, engaging in independent study, attending conferences, and exploring different disciplines. Quote 1: “Attending different conferences and presentations is often where people share their experiences that are different than yours and you can learn from them.” Quote 2: “I genuinely enjoy learning new skills, so I always make time to watch videos or read about a new topic.”
- Multidisciplinary learning and broad skill development: Many students wrote about how they embrace learning outside their primary engineering focus, valuing a well-rounded knowledge base. Quote 1: "I am a lifelong learner because I think it's better to be a jack of all trades." Quote 2: "I have learned about engineering, crochet, knitting, a little about chemistry, and a little about the medical field."
- Reflective practice and self-improvement: Students emphasize self-reflection as a tool for learning and improving their approach to problem-solving. Quote 1: “Even in the cases where I arrived at the incorrect answer, it helped me learn because I was able to see how the steps I took went wrong and how it needs to change.” Quote 2: “The opposite of a lifelong learner is someone who thinks they know it all, so they don’t learn new things and only try to protect their ego.”
- Collaborative learning and mentorship: Students emphasize the importance of learning from peers, mentors, and professionals. Quote 1: “Continuing to gain wisdom from the mentor that I have now and eventually making myself available for mentorship in the future.” Quote 2: “While some students mention mentorship and collaboration, there is relatively little discussion of networking and professional relationship-building.”
- Taking action toward learning: Lifelong learning emerges as an active process that requires continuous engagement rather than passive knowledge absorption. Quote 1: “Not allowing yourself to become stagnant and having an open mindset to conversations and experiences outside your comfort zone.” Quote 2: “Being a lifelong learner means continuing to pursue opportunities to gain new knowledge and skills even after ‘finishing’ a formal education.”

2.3 Fostering a life-long learning mindset - discussion

The results of this analysis show the essential role of lifelong learning as seen through the eyes of graduates in a work-based learning model. From the discussion above on the Maastricht model, the student quotes demonstrate deep understanding through constructive learning, collaborative learning, and self-directed learning growth.

- Deep understanding through constructive learning - One of the most compelling insights from the student reflections is the emphasis on curiosity and a growth mindset, which drives a deeper understanding of subject matter beyond memorization. These findings suggest that when students engage in lifelong learning, they take an active role in knowledge acquisition, forming well-founded opinions on what is valuable and how to seek out new knowledge. Students expressed that seeking out new knowledge and experiences—whether through conferences, independent research, or cross-disciplinary exploration—helped them understand concepts at a fundamental level rather than merely recalling information for exams. This aligns with the idea that lifelong learning enhances retention and application of knowledge, as students are continuously reinforcing and contextualizing what they learn.
- Learning as a social and collaborative process - A recurring theme in student reflections was the importance of collaborative learning and mentorship, reinforcing the idea that engineering knowledge is shared in a professional environment. Students' discussions of mentorship and collaboration show how they appreciate how exchanging ideas and receiving feedback helps them refine their technical, design, and professional learning domains. The quote, "Continuing to gain wisdom from the mentor that I have now and eventually making myself available for mentorship in the future," demonstrates an awareness that learning is a continuous process driven by community engagement. Additionally, students acknowledge the value of interdisciplinary knowledge exchange, recognizing that engineers benefit from understanding perspectives beyond their immediate technical discipline. However, a notable gap emerged in student reflections regarding networking and professional relationship-building. While many students engaged in mentorship and collaborative learning, fewer explicitly mentioned active efforts to develop professional networks. This should be studied further and used as input to the continuous improvement process of the program. Ultimately, these findings support the claim that engineering learning extends beyond the classroom, with students benefiting significantly from social, collaborative knowledge construction.
- Building lifelong learning ability through self-directed growth - The theme of taking action toward learning aligns strongly with Sheppard's (2009) helical learning cycle, which emphasizes the progressive development of self-directed learning abilities. The results illustrate this progression well. The students recognize that learning does not end with graduation and that they must take active steps to seek out new knowledge, skills, and experiences. Furthermore, students demonstrate multidisciplinary curiosity, with some expressing an interest in fields beyond engineering, such as business, medical science, and even creative disciplines. However, an area for potential improvement is ensuring that students not only develop motivation for self-directed learning but also structured habits and strategies to sustain it. Some reflections suggest that without external guidance, students may struggle to maintain consistency in their learning efforts. These findings reinforce the claim from above that lifelong learning is a developmental process, with students continuously refining their ability to direct their own learning in meaningful and effective ways.

3 Impact on industries – workforce skills development

3.1 Impact on industries – workforce skills development - methods

The research in this section aims to discover the impact of graduating students' workforce skills development in this work-based learning program. Research Question: In what ways do graduating

students of the work-based learning program add value to industry partners as perceived by graduating students and co-op supervisors?

Data was gathered from a written reflection assignment from graduating senior students and from co-op supervisor feedback that was provided directly to the program. All data was accessed and analyzed after the students had graduated. The two sets of data are separated from one another as supervisors did not have access to the student reflections, and the students were expected to turn in their reflection assignments prior to accessing the comments and feedback provided by their co-op supervisors.

The reflection assignment focused on the professional identity of students and recognized that their identity may shift throughout their education and life. They were asked to respond to multiple prompts that described their professional identity and how it has recently changed. One of the prompts had students respond to the following question: What are the top three assets you possess that allow you to bring value to a company? The responses to this prompt were used for this study.

Co-op supervisors were asked to respond to the following prompts for the supervisor's feedback. What are some of this student's strengths? What are some areas this student could improve in? What kind of value does this student add to the company? What comments do you have about the student's ability to work collaboratively with others? Is there anything else that you would like to add? Lastly, supervisors were asked to rate the student's overall performance on a scale of 1-5; 1 – not acceptable, 2 – needs improvement, 3 – acceptable, 4 – desired, and 5 – exceeding expectations.

Once the identifying information for all graduates and co-op supervisors was removed, two of the authors thematically coded all data to identify all value-added assets and skillsets that the graduates possess. The authors assigned “G#” as pseudonyms to each graduate to be able to cross-reference their reflection responses and their respective supervisor’s comments. Once a consensus was reached for all identified themes, each theme and combination of themes were further defined through the interpretation of data and by using quotes from the unique perspectives of the graduating students on co-op and their co-op supervisors.

3.2 Impact on industries – workforce skills development - results

The total list of unique themes from graduating students' responses to the written prompt includes strong communication, willingness to learn, hands-on work, problem-solving, adaptability, curiosity, strong engineering knowledge, networking, learning from others, work experience, professional attitude, understanding, persistence, empathy, willingness to take on all types of work, ability to ask good questions, ability to seek feedback from others to improve, work ethic, teamwork, resourcefulness, idea generation, resilience, and quick to learn. Although many graduating students simply created a list of items in response to the prompt, there were three who provided further context for a total of seven themes. These quotes help to further define the following seven themes, while the rest are connected to the results from the supervisors’ perspectives.

- Willingness to learn: “I am a learner. I have always had a strong desire to be challenged and learn from new things and experiences which means I will constantly be growing and learning from people and experiences” (G3).
- Problem-solving: “I have developed this through working on long term projects where I have been able to see the design process through” (G2).

- Adaptability: “I don’t always have work to do on my projects, so I have learned to converse with other engineers and have developed a wide range of skills to be able to work on a variety of different project to remain billable” (G2).
- Curiosity: “I have learned to develop questions in a way that enables me to conduct research on my own to find solutions. Instead of going to another engineer right away, I can research and develop my own thinking on a problem, and then converse with another engineer to find the correct solution” (G2).
- Willingness to take on all types of work: “Willingness to help and assist with any project no matter the task, and willing to learn what it takes to complete it” (G6).
- Ability to ask good questions: “Anytime something looks off on a plan I raise a question and ask about it because it could look off because of my lack of experience or perhaps there may be something wrong with it” (G6).
- Ability to seek feedback from others to improve: “Before I show a finished product to a supervisor I try to ensure that I did not miss any parts and it is completed to the best of my abilities. I then ask to see if there is anything I should improve and be mindful of the next time I perform a similar task” (G6).

The results from the co-op supervisors' feedback provide a unique industry perspective on students' workforce skills development. Supervisor responses were first categorized by each graduate and then categorized by each identified theme. The themes were identified by the authors and were used in combination to summarize the findings. The combinations of themes include innovation & problem-solving, operational improvements & efficiency, workforce skill levels & preparedness, work ethic & initiative, collaboration & teamwork, and company integration & long-term impact. The final theme is professional growth & development, and it is regarding the answer to the prompt about student improvement areas.

- Innovation & problem-solving: The comments within this theme highlight the student’s ability to identify problems and potential improvements, provide solutions to problems, and an ability to bring a fresh perspective to engineering problem-solving. One supervisor stated that one of the students on co-op was “amazing at figuring out things to improve and then figuring out how to make it happen” (G8’s Supervisor). Another stated that a co-op student “provides fresh thinking/perspective and a positive attitude towards work and engineering problem-solving” (G1’s Supervisor).
- Operational improvements & efficiency: Productivity, efficiency, and company workflow were all captured by the comments from supervisors and are used as words to help describe this theme. One supervisor stated that “[G4] has been able to quickly learn [Company E] practices and put them to work” (G4's Supervisor), while another stated that their co-op student "was always ready to work across the business, with operations, assembly, manufacturing engineering, and more” (G1’s Supervisor). A third supervisor stated that “with [G7] as an added resource being able to setup and run the various engineering tests we have on our prototypes and designs allows for faster turnaround in the validations. This also allows the other engineers to focus on other project deliverables while she is gathering the data” (G7’s Supervisor).
- Workforce skill levels & preparedness: Students on their engineering co-ops show up equipped with the skills to deliver valuable work from early on in their time at the company. One supervisor stated that the student on co-op for them is “willing to take on any tasks and take ownership of them” (G10’s Supervisor). Another said that “after [G4’s] training period, I was able to trust her to perform work with minimal oversight, and I was certain that she was doing it with integrity and accuracy” (G4’s Supervisor). Another provides evidence of preparedness through the form of technical competence as “[G2]’s strengths include his ability to understand new concepts and apply them to tasks and overall

knowledge of his work. He is motivated and great at communicating his needs, questions, and progress" (G2's Supervisor).

- Work ethic & initiative: Students show up in their co-ops ready to make an impact. They are motivated to make a good impression and are willing to put in extra work to show others around them that they care about their work. One supervisor stated that the student on co-op is "hard-working and motivated to make the team and client successful" (G2's Supervisor), and another stated that their student on co-op is "able to take on a wide variety of tasks, puts in the work to understand the project and get it to completion" (G10's Supervisor).
- Collaboration & teamwork: Students arrive on the job ready to work alongside all kinds of people in the engineering field. They have experience leading and contributing to teams of various sizes. This was the most discussed theme for graduating student supervisors, as it included 12 feedback comments for the 10 randomly selected students. Some made claims that the graduating student they work with is a "great addition to the team" (G3's Supervisor; G6's Supervisor). Others stated that they are "easy to work with" (G5's Supervisor) and they "work well with others" (G7's Supervisor; G8's Supervisor). An ability to seek feedback is also highlighted as a part of their collaborative work. One supervisor said, "[G3] continues to work with other employees and manufacturing engineers. She is earning the respect of her peers and supervisors. She listens to her peers when advice is given and applies it when needed" (G3's Supervisor). Value and effective communication skills are addressed in this theme. One supervisor said that "[G8] has added a great deal of value on a personal level with almost everyone and also on a company-wide level" (G8's Supervisor); another stated that [G10] "doesn't have an issue reaching out to people and getting the information he needs" (G10's Supervisor), and another said "[G6] works well with everyone and has very good communication skills" (G6's Supervisor).
- Company integration & long-term impact: Various students have made a positive impression on their company and will continue to make a long-term impact as companies look to hire them full-time upon graduation. As one supervisor stated, "We are fortunate to have had [G6] as part of the team these past few semesters and are happy he has chosen to start his career with [company A]" (G6's Supervisor). Another said, "[G4] has been very pleasant to have as a co-op, and I am excited to be adding her to our team as a full-time engineer" (G4's Supervisor). Many students have also made significant contributions to the co-op programs that companies offer. One supervisor said, "[G3] has been a great addition to the [company B] team. Her feedback during the training process has been invaluable, improving the program" (G3's Supervisor).
- Professional growth & development: One of the prompts specifically asked supervisors to provide areas where students could improve. As a result, a few of the areas that were identified were related to boosting confidence, developing relationships, and furthering knowledge of specific company processes or products. One supervisor said that "she does need to start being a bit more confident in the work she's doing, to trust her knowledge and experience. There is a bit of hesitancy sometimes in explaining what is occurring, but I think a lot of that will come with experience as well" (G7's Supervisor). Another said, "[G4] could work on furthering her knowledge in medical device packing. We are working to get her enrolled in further training seminars" (G4's Supervisor).

The remaining results stem from the supervisors rating the performance of students on the job. Two of the ten students received a rating of 4 – desired, and the remaining eight of the ten students received a rating of 5 – exceeds expectations. The ratings were found to be reflective of the overall written feedback provided to each student.

4 Summary – insights on the transformative potential of work-based learning

This study provides a comprehensive analysis of the IRE Bell work-based learning model, which integrates academia, industry, and community engagement to enhance engineering education, support workforce development, and contribute to regional economic resilience. Focusing on its synergistic effects in a rural region of the upper Midwest of the United States, the study examines how immersive, real-world learning experiences prepare future engineers to address complex industry challenges while also benefiting local industries and communities.

As shown above, the findings indicate that students in the program develop key lifelong learning attributes, including curiosity, adaptability, multidisciplinary learning, reflective practice, and collaboration. These qualities align with the Maastricht PBL principles and Sheppard's (2009) helical learning cycle, showing that work-based learning fosters deeper understanding, improved retention, and active knowledge application. The model places students in a social and professional learning ecosystem where they gain hands-on experience, work alongside mentors, and apply theoretical knowledge in practical contexts, reinforcing learning as an active, socially constructed process.

Beyond personal and academic growth, the model demonstrates significant industry impact. Co-op supervisors consistently highlight that students contribute meaningfully in problem-solving, operational efficiency, teamwork, and innovation, with most graduates exceeding performance expectations and many transitioning into full-time roles. Employers also emphasize the value of students' initiative, adaptability, and willingness to take on complex engineering tasks, reinforcing that work-based learning not only prepares students for industry demands but enables them to make immediate contributions to their organizations.

A defining feature of the IRE Bell model is its emphasis on community engagement and the development of professional networks. By embedding students within a network of mentors, peers, and local industry partners, the program fosters a collaborative learning environment that supports both individual and collective growth. The program extends beyond the workplace—students actively contribute to local industry needs, reinforcing their role in regional development and creating a sustainable talent pipeline that strengthens the community. This integration between students, industry, and local stakeholders ensures that learning remains relevant, impactful, and mutually beneficial.

The alignment between student reflections and employer feedback provides strong validation for the effectiveness of the work-based learning model. Students recognize their growth in problem-solving, adaptability, and teamwork, and supervisors confirm that they excel in real-world engineering roles, integrating seamlessly into teams and taking initiative in projects. Many employers express confidence in students' abilities to continue growing professionally, contribute fresh ideas, and enhance company operations. This convergence between student perception and industry validation demonstrates that work-based learning is not just beneficial for students but an asset for industry as well.

The IRE Bell work-based learning model exemplifies the transformative power of integrating education with professional practice and community engagement. By placing students in real-world learning environments, fostering mentorship, and encouraging collaboration, the model cultivates engineers who are not only technically proficient but also adaptable, reflective, and self-directed learners. The strong alignment between student learning experiences and employer feedback reinforces that this approach produces workforce-ready engineers who make meaningful contributions to industry and community development.

Moving forward, the authors intend future research to explore ways to further enhance professional networking, assess the long-term career trajectories of graduates, and expand the model's scalability to diverse regions.

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The importance of diverse economic contexts in African student success

Helen Inglis
University of Pretoria, South Africa, helen.inglis@up.ac.za

Esther Matemba
Curtin University, Australia, esthersayula@gmail.com

Disaapele Mogashana
University of Pretoria, South Africa, disaapele.mogashana@up.ac.za

Abstract

Existing research into student success may not be useful to develop interventions which can improve outcomes for engineering students in Africa, since they fail to account for diversity in local contexts. In our larger project we are using Grounded Theory Methodology (GTM) to investigate student success in African engineering education, interpreted through the experiences of educators. This phase of the project aims to understand better what is meant by "student success" in African engineering education, and to articulate the contexts which impact student success. We recruited participants who had at least five years' experience in engineering education in African institutions. We conducted a focus group with three participants, and individual semi-structured interviews with four participants. The seven participants are from six African countries and include lecturers as well as academic leaders. Our findings in this paper focus on national and institutional economic contexts. National policies governing funding of university studies, as well as historic funding strategies, contribute significantly to contextual diversity. Institutional contexts include the physical and staffing resources available, whether the institution is private or state-funded, and the socio-economic status distribution of the student body. Based on our analysis of the data, we propose a model in which economic factors are understood as emerging from interactions between national, institutional and personal context.

Keywords: Student success, Grounded Theory, Economic context

1. Introduction

Student success has been a key concern in higher education research for decades, and encompasses a range of diverse conceptualisations, including academic outcomes; retention, persistence and graduation; acquisition of knowledge and skills; and the holistic development and thriving of the student (Inglis & Matemba, 2021; Gesun et al., 2021). It is understood as the outcome of multi-dimensional interactions between individual students, classroom teaching, institutions, and the broader societal context. Different researchers have focused on one or more of these factors, and Tinto (2014) argues that effective interventions must be sensitive to the interplay between them. For instance, strategies that achieve positive results on residential campuses may fail for students who must commute daily, balance work responsibilities, or lack familial support (Tinto, 2014, p.9).

The classroom experience as well as the curriculum remain foundational to student success (Tinto, 2014; Boles & Whelan, 2017; Mashiyane et al., 2023). However, the literature also points to factors outside of both classroom and curriculum. These include financial hardship, under-resourced secondary schooling, lack of career guidance, large class sizes, and psycho-social challenges (Ahmed et al., 2015; Mogashana, 2015; van der Merwe & Maharaj, 2018). Additionally, mental health is increasingly recognised as an issue that affects student success (Masuku & Sebiya, 2025; Asghar et al., 2024). In contrast to studies in developed economies, where these challenges may affect a minority of students, at African universities they affect the majority of students. Further, many universities in the region lack the institutional resources to adequately address these needs (Bolu et al., 2020).

The importance of social, historical, and institutional conditions in shaping student success has been clearly demonstrated for engineering students in Africa. Mlambo (2022), for example, shows how apartheid-era legacies continue to influence the experience of Black African women in engineering in South Africa, making the educational journey one of both academic and socio-political navigation. Reinforcing the importance of context, Zakharov et al. (2016) argue that what is effective in one university or country may be inappropriate in another. In our earlier work with African engineering educators across three countries (Inglis & Matemba, 2021) participants identified institutional resourcing and students' socio-educational backgrounds as critical elements that impact student success. These factors are in turn shaped by country-specific realities, such as

national funding models, historical patterns of exclusion and inequality, and national accreditation requirements (Minalla, 2021; Naidoo & McKay, 2018; Mohamedbhai, 2015). As a result, understanding student success in African engineering education requires sensitivity to both national policies and local institutional dynamics.

This work is situated within a larger project that uses a Grounded Theory Methodology (GTM) (Bryant & Charmaz, 2019) to formulate theories for engineering student success based on the perspectives and experiences of African engineering educators. In GTM the analysis is grounded in the words of the participants, and theory is developed by interaction of the researchers with the data. Trustworthiness and rigour are developed through repeated cycles of interviews and analysis until theoretical saturation is reached. The long-term aim of the project is to develop contextually appropriate interventions to improve student outcomes.

The iterative and evolving process of theory generation is illustrated in Figure 1. In this phase of the project (Phase 1) we begin to better articulate the nuanced contexts surrounding student success in African engineering education. The development of contextual sensitivity is a recommended first stage in GTM (Nunes et al., 2010). It is necessary to understand the contextual details which interact with student success so that we can capture all relevant information when we collect data in Phase 2.

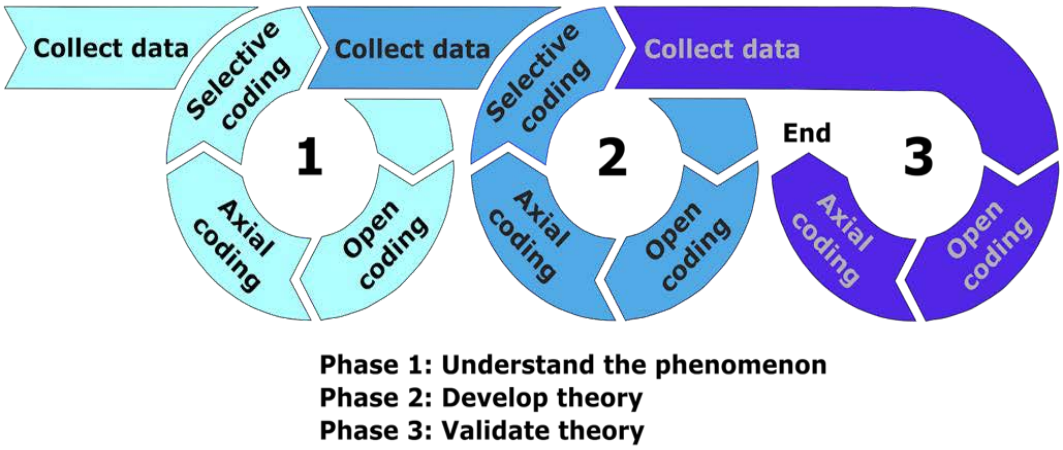

Figure 1: Sequential cyclical Grounded Theory process, as reported in (Inglis, Mogashana & Matemba, 2023)

In this paper we focus our attention on the economic dimensions of national and institutional contexts. We ask the research question: “In what ways do economic contexts interact with student success in African engineering institutions?”

2. Methods

2.1. Participants

We recruited participants who had at least five years’ experience in engineering education in African institutions. For this first phase of the study, participants were recruited via personal connections. We aimed for a heterogeneous sample in terms of academic rank, country and type of institution. Our seven initial participants are from six African countries and include lecturers and academic leaders, listed in Table 1.

Ethical clearance was obtained from the University of Pretoria, and each participant gave informed consent to participate in the interview and for the interview to be recorded. The participants confirmed that they were in compliance with their own university’s ethical requirements.

Table 1: Details of participants

Participant	Country	Role	Mode of interview
P1	Sudan	Academic Leader	Individual
P2	Nigeria	Academic Leader	Individual
P3	Zimbabwe	Academic Leader	Individual
P4	Nigeria	Lecturer	Individual
FG1	South Africa	Lecturer	Focus Group
FG2	Tanzania	Lecturer	Focus Group
FG3	Uganda	Lecturer	Focus Group

2.2. Data gathering

We conducted a focus group with three participants, and individual semi-structured interviews with four participants. The interviews and focus groups were conducted using Zoom, and the recordings were then transcribed by an independent contractor or by the researchers.

We asked participants to introduce themselves, including their academic history and the ways in which they interact with students. We invited participants to give an overview of their institution, giving information about the engineering faculty in the larger university, the size of the university, and the diversities in the student population. We then asked them for their definition of student success, and the factors and interventions that have an impact on student outcomes. We deliberately did not provide a definition of student success, as the goal of the project is to develop this from the participants' responses.

2.3. Data Analysis

The data was coded according to Grounded Theory Methodology (Glaser & Strauss, 1967; Clark, 2019), beginning with open codes, using the words of the participants as much as possible, and proceeding to develop axial codes or categories (Stough & Lee, 2021). In this first phase of our larger GTM study, we were looking for contextual detail that will affect student success.

The three researchers completed open coding separately, and then collaboratively used mind maps to visualise the interconnections between the data (Inglis, Mogashana & Matemba, 2023). The contextual factors developing from the data were categorized into national, institutional, and personal contexts. In this paper, we have chosen to focus on the economic dimension of the national and institutional contexts.

National contexts include government policies, funding of university studies, as well as historic funding strategies. Institutional contexts include the physical and staffing resources available, whether the institution is private or state-funded, and the socio-economic status distribution of the student body.

3. Results

3.1. National economic contexts

The data illustrates the impact of national contexts on the environments in which students study engineering. The most significant way in which national economic policies impact student success is through the provision of funding for students. Participant 1 says of Sudan, "We don't have this kind of support unfortunately."

In a discussion of funding in Zimbabwe, Participant 3 discusses the reduction of funding sources over the years. One source of funding for engineering students is industry scholarships: "when I was a student almost everyone had a scholarship, at the moment you will be lucky to get five to ten percent of the students being on scholarships". Those students who did not have scholarships relied on government funding:

> The government provided 100% grant, and their grant meant that they would pay your fees. Your parents would not contribute anything. [The government] would pay your fees, on the assumption that when you finish, you're working for the country, and then you can slowly give back. (P3)

As resources began dwindling in the early 1990s, the government funding was split, with half of the funding being offered as a grant, and half as a loan that must be paid back after graduation. The funding situation has now deteriorated further: "Government was not able to pay any loan, government was not able to pay any grant, so everything was expected to come from the parents from 2000."

In Nigeria, the government has historically sponsored tuition for students at public universities. According to Participant 2: "the government is responsible for almost 90 percent of the tuition. So the parents are just responsible for less [than] 10 percent." Participant 4 notes that this does not include "accommodation and maybe some manuals and things like that", and this may still impose a burden on lower-income students:

> … your subsistence fee lies with you, daily feeding is by you. For example, if your family is only on one dollar per day bill or income, and you have about two, three, or four of you in a higher institution at the same time, it affects the amount of fee that you have for your subsistence. (P2)

In 2023 Nigerian government funding for tuition was removed, requiring students to cover the cost of tuition:

> All federal universities … the tuition was free, so you only needed to pay for I think maybe the accommodation … But when the new government came in … and because of the economic situation of the country, tuition has been introduced. (P4)

Participant 2 notes that, "the government is trying to introduce scholarships to assist most of the indigent or what you call financially disadvantaged students", but Participant 4 is concerned, "we would know how that works when this new session [begins] because it's all new, it's entirely new."

The economic and political stability of countries also impacts higher education. For example, Participant 1, talking about the ability of Sudanese students and staff to interact with the international engineering community comments that, "Sudan is under sanction for more than 20 years and this has really affected everything in Sudan, especially universities." Participant 1 also notes that "in Sudan the instability is a little bit high, economic instability and even political instability." In Nigeria, Participant 4, discussing lecturer motivation, says, "economically it is a bit tough, and the government's not really been so fair. We had some couple of strikes that didn't yield anything."

Some other economic issues are similar for all countries. For example, Participant 1 mentions the cost of access to online teaching in the Covid era: "sometimes they have no way to download the lecture because it is a little bit expensive to download that lecture and they cannot attend that lecture because of this."

3.2. Institutional economic contexts

The economic contexts of individual institutions are explored indirectly through data on staffing resources, the physical spaces and equipment at the university, the availability of accommodation, the institutional support systems provided to students, and the range of socio-economic status of the students at the institution. Key data from the eight institutions in the study are presented in Table 2.

3.2.1. Staffing resources

Staffing resources contribute to the institutional context, and are shaped by the interaction between national funding and institutional resources. A lack of financial resources lends itself to staff shortages. For example, in Tanzania, FG2 reported that the staff-to-student ratio in most universities is insufficient for effective teaching. This experience is shared across multiple contexts, and it is often indicated by staff members serving various roles at the same time. In Uganda, FG3 discusses working as a lecturer, supporting the learning management system, assisting with library resources, being a student mentor and being responsible for industrial training and coordination. In Sudan, P1 indicated holding different work functions; in Nigeria, P4 shared their experience of holding multiple roles. The only two participants that did not report challenges

with staffing resources were FG1 from a medium old university in South Africa and P2 who is at a new private university in Nigeria.

Table 2: Institutional information

	Country	Size [a]	Age [b]	Public / Private	Urban / Rural	International profile [c]
P1	Sudan	Large	Old	Public	Urban	Low
P2	Nigeria	Medium	Established	Public	Urban	Low
		Small	New	Private	Rural	Medium
P3	Zimbabwe	Medium	Old	Public	Urban	Medium
P4	Nigeria	Large	Old	Public	Urban	Medium
FG1	South Africa	Medium	Old	Public	Urban	High
FG2	Tanzania	Large	Old	Public	Urban	Medium
FG3	Uganda	Small	Established	Public	Rural	Low

[a] Large: more than 30 000 students; Medium 10 000 to 30 000; Small: fewer than 10 000 students
[b] New: less than 10 years; Established: Less than 50 years; Old: Greater than 50 years
[c] International profile: Based on THE World university rankings (Times Higher Education, 2025). Unranked universities are indicated as having a "low" international profile.

Staff qualifications vary across contexts. Among the participants in this study, five hold PhDs, with three already at the professorship level. Two participants had not yet obtained their PhDs at the time the study was conducted. However, the participants' qualifications do not necessarily reflect the overall qualification levels within their respective institutions, as many reported generally low qualification levels among staff. Participant 3 describes the situation at their institution in Zimbabwe:

> The first issue is that only 25% of our academics at the university are trained up to the PhD level—just 25%. The remaining 75% hold only master's degrees. That is a problem. If you are in academia, you will understand what I mean. This means we have people who are still in the process of obtaining their qualifications training the future engineers. (P3)

Gender diversity also contributes significantly to the institutional contexts, particularly in engineering. At a large public university in Nigeria, Participant 4 highlights that the percentage of female academics remains below 10%: "Of the entire faculty, with a staff establishment of approximately 100, you will find only five to ten females. Unfortunately... Yes, so it is still mostly dominated by males." Similarly, P3, speaking about an institution in Zimbabwe, noted that many of the academic staff are still male. The male-dominated nature of engineering education in these institutions often results in female staff members taking on more nurturing and pastoral roles. Three of our female participants reported that they have increasingly assumed "emotional labour" roles for their students.

Participant 2 describes efforts to support female academic staff financially at their medium-sized public university in Nigeria: "we deliberately included what is called a female monthly bonus … because there are some needs that are peculiar to females, so we paid 10% more to the females."

3.2.2. Physical resources

Physical resources for studying engineering are an important contextual factor, partially defined by Participant 4 as "the environment and the way the classroom is organised." Participant 3, who is a lecturer at an old public university in Zimbabwe, noted that their institution had outdated laboratory equipment:

> The equipment has not been replenished. You'll be amazed, I mean if you were here, if I take you to the workshops and show you some of the machine tools that are still being used for training, these are the same machine tools that I used as a student. (P3)

There is also an issue of the laboratory resources not being expanded to accommodate the increasing number of students: "The numbers continue to increase year in, year out, but the infrastructure in terms of buildings,

in terms of equipment in the laboratories, in terms of staffing, expertise and so on, that is not matched" (P3). The issue of overcrowding is evidenced by an example:

> At one point I was just passing through and the lecture room was so full that some students were actually sitting in the corridor, purporting to be attending a lecture in a lecture room, you understand what I mean? (P3)

Participant 3 concludes that the shortcomings in physical space as well as equipment "translates to … a decline in the quality and decline in the standards."

In Tanzania at an old public university, FG2 says: "another challenge is on technology… access to technology". Participant 4 comments on the impact of unreliable power supply on learning:

> For example, sometimes we have issues with power ... We've been experiencing that for a long time in Nigeria. So the students kind of feel that their learning experience is being interrupted. If maybe you are projecting a particular slide or materials and [students] are … working on it and suddenly they start load shedding or power outage. (P4)

3.2.3. Institutional support structures

At points in their journeys, many students will require support of different kinds: academic support, support with coping strategies such as time management and self-regulation, emotional support and financial support. The data in this study show that the provision of this support differs between institutions. We will discuss formal institutional support mechanisms, support provided by a lecturer who acts as a mentor or advisor, and informal support through student organisations.

FG1, working at an old university in South Africa, reports on a range of formal institutional support structures, noting that "our faculty is blessed with […] dedicated psychologists, [...] a team of 4 psychologists" and also has "academic development / extended curricular programmes that then look into, you know, academic interventions". In addition to these structures which address academic and emotional needs directly, there is also support from a coach for "psycho-social challenges, which involved [...] other things – life issues, … the challenges that students bring, whether it's from their background, family background, financial, health, well-being."

FG3, at a small university in Uganda, implies that there are some institutional support structures, saying "then you have to direct them to the right office" but is not specific about what support is provided. At many universities it seems that the formal institutional support is concentrated into the role of a particular individual, for example "registrar" (FG3) or "Dean of Students" (P3).

In the case of Sudan, P1 reports that their institution has organised financial support from a private company for students who meet specific academic performance standards. The institution is stepping in to fill a need since there is no government funding available.

Six of the seven institutions covered in this data expect academic staff members to fill the role of mentor or advisor:

> We also have what we call mentorship in the faculty, and every lecturer is given a number of students in the first year when they enrol, maybe about 8 students. So, as the years go by, you accumulate a number of students under your mentorship. (FG3)

Participant 3 reports that "on average each lecturer is given about 10, 15 students to mentor throughout their student life at the University", while Participant 1 says, "I have 40 students from the first-year, I'm responsible for them. […] I will be the same advisor for them until they graduate." Participant 2, discussing their experience at a public university in Nigeria, comments that "At year one, you only have one person looking after the whole of the class, and that's the level advisor" while from year three, "there is normally a ratio between five and one so that you can have that personal interaction. The standard is 1 to 35 or 1 to 30 in the first year."

The kind of support provided by the advisors includes guidance for academic problems, “these are the do's and these are the don'ts” (P3), “‘Have you been able to come to class?’, “What are your challenges?’” (FG3); financial issues, including problems with tuition as well as with daily living, “‘Do you have your basics?’” (FG3); and social problems. We note that some academic staff will invest more time and effort into the advising role than others, and this is confirmed by one author who remembers that, although she was assigned an advisor in her undergraduate studies, she seldom saw him.

Students also access support through informal and extra-curricular structures. In some cases this might be a local chapter of a larger organisation, for example “a student chapter for Industrial Engineering and Operation Management Society – this is an international society” (P1) or a local student body “this is a student association that’s helping to build leadership skills and other skills way outside of the classroom area” (FG3). These societies foster student interactions within and between universities, and students “work very hard in soft skills” (P1). P2 gives a vivid example of how informal societies assist students and contribute to “the democratisation of learning”:

> Let's assume that I am a Muslim, I belong to the Muslim Students Society club, and let's assume that I know how to ride a bicycle, and I belong to the Bicycle Club … so those clubs … provide necessary support like tutorials … ‘that same course that I've taken … are you going to take it?’ (P2)

3.2.4. Accommodation

There is variation in accommodation provisions across different contexts, with a general sentiment that universities cannot accommodate all their students. In many cases, students must find their own accommodation, which may often be unaffordable. In South Africa, students who qualify for government funding receive an allowance for student accommodation both on and off-campus. In Nigeria the government subsidises only on-campus accommodation, leaving off-campus housing unsubsidised.

At a medium public university in Nigeria, Participant 2 reported that accommodation is insufficient for the entire student population. They indicated that the university can house only 30 to 50% of students, while the remaining 50% live off-campus. Some commute daily, while non-local students must find private, unsubsidized accommodation near campus:

> Normally, we have accommodation providers very close to campus, so those who cannot be accommodated on campus are accommodated by those, but they pay. But those hostels on campus are still subsidised by the government, but those ones by the private providers are not subsidised by the government... (P2)

The lack of sufficient university accommodation in different contexts also raises student safety concerns. In Sudan, for example, Participant 1 reported that diploma-level students are not allowed to stay on campus due to limited housing availability. As a result, many must travel long distances home each day. Additionally, female students face further safety challenges:

> If a class is too late, some females, they cannot attend it. They said because they cannot find any transportation to go back to their home at night. It will not be safe for them, so they just dismiss that course. (P1)

3.2.5. Student socio-economic status

Participants have reported that their student bodies are distributed across a wide range of socioeconomic status (SES) and the different types of financial support that is available. P4, who is in a large public university in Nigeria, claims “we have … students from low-income, middle-income and high-income families.” The issue of diversity in students’ socioeconomic status was also reported by P2 at a medium public university in rural Nigeria, stating that the student population falls mainly between low to medium-income earners, and that “The percentage of children from the high-income earning family is very low.” P2 estimated the ratio of high income, middle income and low income at their institution to be about “10:50:40”.

Financial difficulties were reported to be a contributor to student success. P1, who is a lecturer at an urban public university in Sudan, explained that when students cannot pay university registration fees, they are unable to attend classes for a significant period, or are unable to do their examinations, this results in low performance on their academic records. P1 further notes that students from rural areas with low economic background may be disadvantaged "because they don't have money to come to the capital of Sudan, to stay in the capital, or even to pay for the tuition fees … there are some fees to pay even at the public university and [there are] many students who cannot pay."

P4 reports on having a group of students that struggle financially, but adds that those students can acquire support through industry scholarships, "because they could apply for scholarships if they obtain some certain grades. We have scholarships being sponsored by industries that students could apply for." (P4)

FG2, who lectures in a large urban public institution in Tanzania, where government loans exist to cover student loans and bursary, also reports on similar challenges that a number of students from low economic backgrounds face. FG2 recalled their experience as a registrar where students failed to pay registration fees, saying "sometimes they are late to register because of failing to fulfil some mandatory fees – they have to pay some fees for registration."

Apart from school fees, some students lack money for basic necessities like food and shelter that affect their academic performance:

> Or some lack the basics in terms of, "I didn't have lunch", "I don't have money to buy my basics like soap," "I can't pay rent." So, that area, that social economic area as well really affects it and success. That's why we find ourselves having to support. (FG3)

Data also shows that despite a common account of students that have low socioeconomic status, there are some exceptions where students are relatively advantaged compared to the rest of the student population at the institution. FG3, who is in a rural university in Uganda, gives an example of an undergraduate student at their institution "who actually drives – so he even has to bring his fellow classmates to class." FG3 explains that this is "way out of the bracket for the biggest group here at undergrad level, to be able to drive – you have a car, you go home, you find everything ready for you."

Family backgrounds determine the extent to which the cultural capital which students bring to their studies is aligned to university or professional expectations (Setlogelo, 2008). FG1 compares their children's position with their own position at a similar age:

> So, for them, you know… they already have parents who are engineers. You know? ... So their starting point, it's different. They already have engineering conversations with us. They already are introduced to a whole lot of games and stuff that they play, they go to a private school. (FG1)

According to FG1 the alignment of cultural capital depends on "types of schools attended, educational level of parents (first generation, etc), exposure to resources."

FG2, at an old public university in Tanzania, commented on the impact of students' academic backgrounds on their understanding of the engineering profession and on how they learn:

> those who are coming from the urban area, have that privilege of being ready, or at least they know what they are going for … Most of them do know what they are going for, unlike those who are coming from rural areas. (FG2)

This is a challenge especially since their university does not have a structured way to introduce students to the engineering courses. "So, we are not preparing them, and this leads to another challenge, which is, it now leads the students towards studying to pass exams only and not acquiring knowledge and skills." While most urban students' cultural capital is aligned with institutional expectations, those who come from poorly resourced rural schools do not have aligned cultural capital.

4. Developing a model for economic context

In this paper we have investigated the ways that economic contexts interact with student success in African engineering institutions. In reporting our results, we disaggregated the data between national and institutional contexts, and identified the economic aspects of each.

In this section we begin to develop a theory based on our interaction with this data. Key economic factors originate in one or more of three contexts: the national, the institutional, and the personal. The personal context captures those aspects which are unique for each individual student. Our model groups factors thematically across contexts, to enable a richer engagement with the data. This is presented in Figure 2.

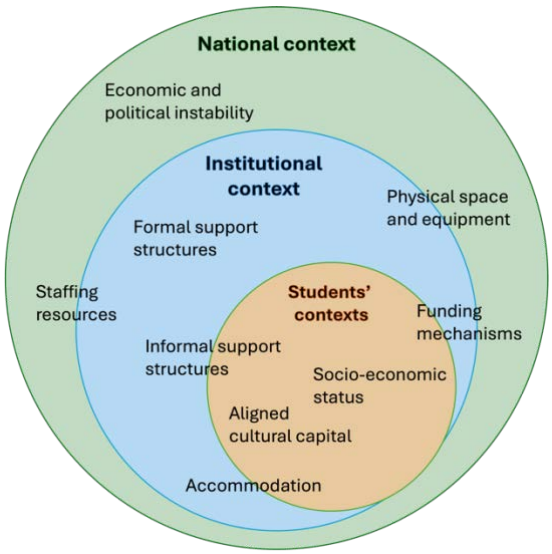

Figure 2: Economic factors originate in one or more domains

As an example, accommodation factors originate in both institutional and student contexts, since some students are accommodated in university residences, while others make use of private accommodation. Formal support structures originate within the institution, in contrast to informal support, which is a partnership between the institution and students.

The contribution of this model is illustrated by considering funding mechanisms. At the national level, governments determine funding policies and budgets, which may include student grants and scholarships. Similarly, institutions may make funding opportunities available to students based on various criteria. Students' diverse economic circumstances likewise contribute to the availability of funding. Without considering the interacting contributions of all three contexts, aspects of student experience are missing from our understanding.

By understanding the complex sources of various factors, the model allows us to interrogate the influence of actions from different domains on student outcomes. For example, the decline in government funding for tuition, reported in Nigeria and Zimbabwe, affects the maintenance of physical resources and the recruitment and retention of qualified lecturers. Loss of funding also impacts the pool of students who can afford to go to university, limiting opportunities and reducing diversity.

In contrast, the provision of institutional support mechanisms for students changes their ability to meaningfully access university, mitigating the challenges which students face if their cultural capital is not aligned with the institution.

This model demonstrates the complexities of context. Similar institutions exposed to different national contexts will result in different experiences for their students. Equally, resilient institutions can promote

student success despite a challenging national context. Understanding economic contexts in this way influences the framing of the larger study on student success.

5. Conclusions and Implications

Across the contexts that we surveyed, we can see that African universities deal with similar problems, particularly related to limited resources and differential preparedness of the students entering the university. However, national policies, mandates and funding have a significant impact on the conditions for success.

When we asked participants about factors that impact student success, an emphasis on economic contexts stood out in their responses. In this study we have separated national and institutional economic contexts, and, based on interview data, we have identified core components of economic context at each level.

At a national level, the provision of funding was the most important factor identified. This includes an understanding of the historical trajectory of tuition support from the government, and how this has affected institutions and students. The national political and economic environment is also significant, with political and economic instability and factors such as economic sanctions disrupting studies.

Considering institutional economic contexts, the availability of sufficient well-qualified academic staff members was identified, along with the physical environment, including classrooms, laboratory facilities and equipment, and accommodation. Support mechanisms can promote student resilience and agency, and range from formal support from dedicated staff to mentoring by academic staff to informal support via clubs or societies. The diversity of the student population in terms of socioeconomic status, as well as the ability of students to afford their studies have a significant impact on student outcomes.

We have proposed a model which identifies key economic contextual factors as originating across national, institutional and personal contexts. The model has not yet been validated. As we proceed with iterative data collection and coding according to Grounded Theory Methodology, the model will be modified and extended until theoretical saturation is reached.

This model provides a contextual basis to inform our research on the phenomenon of engineering student success in Africa. Developing contextually-responsive theories about student success will impact engineering education by providing a basis for designing and implementing effective interventions in classrooms, institutions and educational policy.

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Empathy and Education for Sustainable Development: An overview of key publications and implications for engineering education

Inês Direito
TEMA, Department of Mechanical Engineering, University of Aveiro, Portugal *ines.direito@ua.pt*
UCL Centre for Engineering Education, University College London, United Kingdom *i.direito@ucl.uk*
University of Johannesburg, South Africa

Aida Guerra
Aalborg University, Denmark, *ag@plan.aau.dk*

Carla Ferreira
TEMA, Department of Mechanical Engineering, University of Aveiro, Portugal, carlasusana@ua.pt

Diana Bairaktarova
Virginia Tech, USA, dibairak@vt.edu

Bárbara Gabriel
TEMA, Department of Mechanical Engineering, University of Aveiro, Portugal, barbara.gabriel@ua.pt

Robertt Valente
TEMA, Department of Mechanical Engineering, University of Aveiro, Portugal, robertt@ua.pt

Abstract

The engineering skills required for the 21st century and the green transition go beyond technical knowledge. Sustainability problems are multidimensional and require consideration of multiple perspectives. Empathy plays a fundamental role in enabling the development of more humanistic and socially constructed skills required to act for sustainability. It is an essential element of human-centred design and ethical behaviour, as well as engineering teamwork, engagement with diverse stakeholders, and ability to work in intercultural settings. Engineers must relate to the needs of the primary user and empathise with those (in)directly affected by their decisions. This highlights the importance of helping engineering students cultivate and apply empathy. However, little research has explored the influence of students' empathy on education outcomes for sustainable development.

The paper presents an overview of key publications in education for sustainable development (ESD) - the first step of a state-of-the-art review which is part of a larger study on empathic engineering education for sustainable development. The overview is guided by the research question "How is empathy described and framed in current sustainable education policies and frameworks?". The paper provides a time-framed overview of the current policies and educational frameworks and identifies directions for future work on embedding empathy in engineering education for sustainable development.

Keywords: sustainable development, empathy, engineering education, review

1 Introduction

The United Nations' Sustainable Development Goals (SDGs) were established in 2015 as a response to the urgent and global environmental, social, and economic challenges and built on the lessons learned from the Millennium Development Goals (MDGs), which were in place from 2000 to 2015. The SDGs have important implications for engineering and engineering education, as engineering plays a critical role in addressing many of the complex global challenges the world is currently facing. Engineers are essential in developing sustainable solutions for issues such as clean energy, water and sanitation, infrastructure, and climate change. Consequently, engineering education must equip future engineers with the knowledge, skills, and ethical grounding necessary to contribute effectively to sustainable development. This education goes beyond providing technical expertise – integrating the SDGs into engineering education involves embedding principles of sustainability, ethics, and social responsibility into the curriculum. This includes fostering interdisciplinary collaboration, promoting a holistic understanding of the societal impacts of engineering decisions, and encouraging empathy and engagement with diverse stakeholders. It requires an appreciation of various perspectives and an understanding of individuals' backgrounds and experiences.

The competences required for the 21st century and the green transition go beyond technical knowledge (Beagon et al. 2022). They span across different disciplines and bring to the fore the ability to collaborate with multiple stakeholders, consider different perspectives, and understand people with diverse backgrounds and experiences (Segal, 2018). In this sense, empathy plays a fundamental role in enabling the development of more humanistic and socially constructed competences required to act for sustainability.

In engineering education, the focus on sustainability has led to a body of initiatives focused on tackling global challenges. However, most of the engineering programs focus exclusively on technical solutions and tend to overlook the interpersonal and social dimensions of sustainable development (Andrade & Tomblin, 2018). Today, more than ever, engineers need empathy to address the 21st-century global challenges. Empathy – the ability to understand a person from his or her frame of reference rather than one's own, their feelings,

perceptions, and thoughts – is an essential element of human-centred design and ethical behaviour, as well as of effective work in teams, engagement with diverse stakeholders, and ability to work in intercultural settings. Alarmingly, studies show a decrease in engineering students' interest in public welfare over the course of their education (Cech, 2014), with students being less 'person-oriented' compared to practicing engineers (Bairaktarova & Pilotte, 2020). Empathy, which involves understanding others from their viewpoint, is essential for cultivating the humanistic and socially constructed skills necessary for sustainability. It is integral to human-centred design, ethical conduct, teamwork, stakeholder engagement, and working in intercultural environments. In sustainable design, engineers must empathize with both the primary users and those indirectly impacted by their decisions, as sustainability challenges are complex and require consideration of multiple viewpoints. However, despite the importance of empathy, little research has explored the influence of students' empathy on education outcomes for sustainable development. The current paper describes a study that is part of a larger research project on empathic engineering education for sustainable development. It presents an initial overview of empathy and sustainable education. This overview will inform a larger state-of-the-art review guided by two research questions: RQ1. "How is empathy described and framed in current sustainable education policies and frameworks?" and RQ2. "What empathy approaches and interventions are used in engineering education?". This state-of-the-art review will provide a time-framed review of the current policies, educational frameworks, and identifies to inform directions for future work on embedding empathy in engineering education for sustainable development. The overview presented in this paper addresses RQ1.

2 Literature review

2.1 Education for Sustainable Development (ESD)

Education for Sustainable Development (ESD) is an educational approach that aims to empower learners with knowledge, skills, values and attitudes to address interconnected global issues such as climate change, biodiversity loss, poverty and inequality (UNESCO, 2024a). It has been led by UNESCO (United Nations Educational, Scientific and Cultural Organization) since the United Nations Decade of Education for Sustainable Development (from 2005 to 2014), and then followed by the Global Action Programme (from 2015 to 2019). In 2019, UNESCO proposed a new framework for ESD, covering the period between 2020 to 2030 – the ESD for 2030 (UNESCO, 2020).

ESD is focused on the integration of sustainability principles throughout learning processes. As an educational approach, ESD encompasses three learning domains - cognitive, socio-emotional, and behavioural. Climate change education, and a broader approach encapsulated in the concept of greening education, are important elements of ESD. ESD is an element of SDG 4, Quality Education, target 4.7, "By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development" (United Nations, n.d.) with the following indicators "Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (*a*) national education policies; (*b*) curricula; (*c*) teacher education and (*d*) student assessment".

These frameworks emphasize the importance of equipping future engineers with the skills and knowledge necessary to address complex global challenges related to sustainability. For example, engineering programs now embed sustainability principles through innovative teaching approaches like challenge-based learning (CBL) and interdisciplinary collaboration. This includes teaching students about sustainable design, renewable energy, resource management, and the social and environmental impacts of engineering

decisions. Moreover, accreditation bodies such as EUR-ACE and ABET have revised their requirements to include sustainability competencies. Engineering programs are now required to demonstrate how they prepare students to contribute to sustainable development. This has prompted institutions to align their educational objectives with sustainability goals, ensuring that graduates possess the necessary skills to address sustainability challenges.

Education for sustainable development in engineering education has benefited from interdisciplinary collaborations that focus on ethical and social responsibility. Sustainability issues are multifaceted and require input from different disciplines to understand the interconnectedness of social, economic and environmental factors better. At the same time, considering the needs and perspectives of multiple stakeholders is essential for understanding how engineering decisions could have direct or indirect impacts on them (Bairaktarova et al., 2024). This requires a human-centred approach for developing sustainable solutions.

Empathy plays a pivotal role in these human-centred approaches, enabling engineers to genuinely understand the needs, concerns, and perspectives of diverse stakeholders affected by their work. By developing empathic capabilities, engineers can better anticipate the social and environmental impacts of their designs, identify potential unintended consequences, and create solutions that truly serve community needs rather than merely technical requirements. This empathic foundation facilitates more inclusive decision-making processes and ultimately leads to more equitable, contextually appropriate, and sustainable outcomes.

2.2 Empathy

In engineering education, empathy has emerged as a critical component of professional development, particularly in its connection to ethical decision-making and responsible practice (Hess et al. 2021; Strobel et al., 2013). While engineering has traditionally emphasized technical competence, growing recognition of the social impacts of engineering work has led to increased attention to empathy as a core professional skill (Walther et al, 2017). Notably, most studies have relied upon definitions of interpersonal empathy, as suggested by the frameworks which have been mostly used for empathy measurement in EER (Baligar, et al., 2024).

In the context of sustainable design, engineering students must not only relate to the needs of the primary user but also empathize with those indirectly affected by their decisions (Lehtonen et al., 2019). Sustainability problems are multidimensional and require consideration of multiple perspectives (Lönngren et al., 2016). Empathy is the foundational ‘people skill’ needed more than ever in engineering education for sustainable development. However, to date, little research has explored the influence of students’ empathy on the outcomes of sustainable education.

The larger study, of which this overview is one of the foundational steps, will use Elizabeth Segal's concept of Social Empathy, which extends beyond interpersonal empathy (which includes affective response, affective mentalizing, self-other awareness, perspective-taking, and emotion regulation) to include contextual understanding and macro-perspective taking (Segal, 2018—two components essential for sustainability education). Social empathy involves understanding the lived experiences of people and communities different from our own, recognizing the impact of historical, structural and systemic factors. This broader perspective taking, applied to larger social groups and communities, can help build positive engagement (Segal, 2018). Segal's social empathy framework provides a more comprehensive approach to understanding the broader social, economic, and environmental systems, making it particularly relevant for addressing complex sustainability challenges.

3 Methodology

State-of-the-art reviews aim to present a comprehensive coverage of the existing literature on more current matters and are usually presented in a narrative format but can also make use of tables. They are particularly useful for identifying potential new avenues for research (Booth et al., 2012; Grant & Booth, 2009). In this overview, and to identify relevant and current frameworks and policies in education for sustainable development, we searched the publication databases of two main organisations: The European Union, as the research project involves two European universities; and the United Nations. We considered documents that were explicit about frameworks, competencies and skills required for ESD 2020-2030, and that were published after 2019. The following documents and reports were included in this stage:

3.1 UNESCO Greening curriculum guidance

This guidance was designed to help individuals, institutions and organizations promote a holistic approach to climate change and sustainability education, for different age groups. It draws on the Education for Sustainable Development (ESD) for 2030 framework and offers guidance on how to integrate climate change into the educational curriculum at all levels of education and across all subjects – it's a foundational tool for greening education. The main part of this document includes key concepts, topics and learning outcomes for different age groups, ranging from K-12 to 18+. Despite its focus on climate change, the document "follows a holistic approach with climate change as the entry point to addressing environmental, social and economic aspects of sustainable development (UNESCO, 2024b, p.21). Greening education is organised in six key concepts with respective topics and learning outcomes, as listed in Table 1.

Table 1. Greening education key concepts

Key concept	Topics
1. Climate science	1.1. Weather, climate and climate change 1.2. Greenhouse gases 1.3. The carbon cycle 1.4. The water cycle 1.5. Avoiding pollution and conserving resources 1.6. Renewable energy
2. Ecosystems and biodiversity	2.1. Natural environment: ecosystems and biodiversity 2.2. The evolution of biodiversity over time and in the future 2.3. Ecosystems, biodiversity and ecosystem services 2.4. Human relation to nature: domestication and agriculture 2.5. Human-induced biodiversity loss and its consequences 2.6. Reconnecting to nature and protecting it
3. Climate justice	3.1. Contemporary manifestations 3.2. Social determinants 3.3. Historical economic and political processes 3.4. Transformed futures
4. Resilience-building	4.1. Social impacts of climate change 4.2. Navigating climate impacts: strategies for safety and resilience 4.3. Climate anxiety and constructive coping 4.4. Strength and interconnectedness 4.5. Urgency and community action 4.6. Tacking climate mis/disinformation
5. Post-carbon economies	5.1. Economic growth and development 5.2. The circular economy and everyday life

		5.3. Climate change and our economies 5.4. Energy consumption and carbon emissions 5.5. Our roles in a post-carbon economy
6.	Sustainability lifestyles	6.1. Engagement with nature 6.2. Renewable energy use 6.3. Responsible consumption 6.4. Sustainable living spaces 6.5. Sustainable mobility 6.6. Sustainable diets 6.7. Sustainable waste practices

3.2 The Inner Development Goals

The Inner Development Goals framework was launched in 2022 to address the slow progress towards achieving the Sustainable Development Goals (SDGs). While the SDGs offer a comprehensive framework for tackling global sustainability issues, the IDGs recognize that achieving these goals requires more than just technical or policy solutions. It requires a different mindset focusing on attitudes, values and skills of human growth and development that lead to change effectively. The framework includes five dimensions (Being, Thinking, Relating, Collaborating, Acting) with a total of 23 skills (IDG, 2021).

3.3 GreenComp – the European sustainability competence framework

To help promote learning on environmental sustainability, the European Union (EU) published the GreenComp – a framework that identifies a set of sustainability competences. It aims "to help learners develop knowledge, skills and attitudes that promote ways to think, plan and act with empathy, responsibility, and care" for the planet and public health (Bianchi et al, 2022). The GreenComp is organized in 4 areas, which one with 3 competences:

1. Embodying sustainability values: 1.1. Valuing sustainability; 1.2. Supporting fairness; 1.3. Promoting nature
2. Embracing complexity in sustainability: 2.1. Systems thinking; 2.2. Critical thinking; 2.3. Problem framing
3. Envisioning sustainable futures: 3.1. Futures literacy; 3.2. Adaptability; 3.3. Exploratory thinking
4. Acting for sustainability: 4.1. Political agency; 4.2. Collective action; 4.3. Individual initiative

3.4 UNESCO Education for Sustainable Development – a roadmap

This publication builds on the previous roadmap for 2015-2019 (Global Action Programme), and outlines UNESCO's steps in addressing sustainable development challenges through education in five main areas: advancing policy, transforming learning environments, building capacities of educators, empowering and mobilizing youth, and accelerating local level actions. In this document, ESD is considered to be critical to address SD4 (Quality Education), in particular of target 4.7, "By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development" (UNESCO, 2020, p.14).

4 Findings

4.1 UNESCO Greening curriculum guidance

In this document, empathy is clearly stated as a key competence for sustainability, part of a broader *collaboration competency*, "the abilities to learn from other; to understand and respect the needs, perspectives and actions of others (empathy); to understand, relate to and be sensitive to others (empathic leadership); to deal with conflicts in a group; and to facilitate collaborative and participatory problem-solving" (UNESCO, 2024b, p.182). Empathy as social and emotional learning was referenced multiple types for education of pre-18 individuals. For 18+ it was mentioned in two specific suggested activities:

- Topic 4.2. Navigating climate impacts: strategies for safety and resilience. "Key idea: there are specific activities than we can undertake for emergency responses risk reduction, mitigation and adaptation". At a social and emotional dimension, "learners should be able to enhance empathy for communities especially vulnerable to climate impacts and understand the importance of collective action in keeping everyone safe" (UNESCO, 2024b, p.109).
- Topic 4.3. Climate anxiety and constructive coping. "Key Idea: It is important to work together in addressing climate anxiety". At a social and emotional dimension, "learners should be able to demonstrate qualities like resilience, hope, empathy and assertiveness, essential for leadership in the face of climate challenges" (UNESCO, 2024b, p. 111).

4.2 The Inner Development Goals

The skill *empathy and compassion* is placed under *Relating – Caring for Other and the World*, as is defined as the "ability to relate to others, oneself and nature with kindness, empathy and compassion and the intention to address related suffering (…) Empathy here is understood to be the capacity to relatively accurately understand and feel into what other people feel, whereas compassion adds the quality of wanting to relate to other people with benevolence." (IDG, 2021, p.19). The framework includes other skills related to definitions of empathy, such as *perspective skills* (*Thinking – Cognitive Skills*), "skills in seeking, understanding and actively making use of insights from contrasting perspectives" (IDG, 2021, p.16), and *self-awareness* (*Being – Relationship to Self*), "ability to be in reflective contact with own thoughts, feelings and desires; having a realistic self-image and ability to regulate oneself" (IDG, 2021, p.14). Other skills were suggested to be associated with empathy and compassion in the framework, namely *connectedness* (*Relating*) "having a keen sense of being connected with and/or being a part of a larger whole, such as a community, humanity or global ecosystem" (IDG, 2021, p.18), *humility* (*Relating*), "being able to act in accordance with the needs of the situation, without concern for one's own importance" (IDG, 2021, p.19).

4.3 GreenComp – the European sustainability competence framework

'Empathy' is mentioned explicitly in competence *promoting nature* (1.3), which "is about developing empathy towards the planet and showing care for other species" (Bianchi et al, 2022, p.18), and as an attitude "shows empathy with all life forms" (Bianchi et al, 2022, p.42).It was also mentioned in competence problem framing (2.3) as a key attitude, "listens actively and shows empathy when collaborating with others to frame current and potential sustainability challenges" (Bianchi et al, 2022,p.22 and p.45). Moreover, Empathy is one of the 9 lifelong learning skills and is defined as one of the attitudes to develop 'Problem framing': "listens actively and shows empathy when collaborating with others to frame current and potential sustainability challenges" (Bianchi et al, 2022, p.22).

4.4 UNESCO Education for Sustainable Development – a roadmap

Empathy, along with solidarity and action-taking, is identified as a key competence in ESD, "Its (ESD) particular emphasis on competencies related to empathy, solidarity and action-taking can help advance SDG 4 towards the future where education contributes not only to the successes of individuals, but also to the collective survival and prosperity of the global community" (UNESCO, 2020, p.14). In the roadmap, empathy

is placed under the *social and emotional learning dimension* of ESD, with the other dimensions being cognitive learning and behavioural learning. The social and emotional learning dimension is defined as "build core values and attitudes for sustainability, cultivate empathy and compassion for other people and the planet, and motivate to lead the change" (UNESCO, 2020, p. 17). One of the reflections of the framework for the implementation of ESD is the need for transformative action, "An experiential exposure to the realities provides them (learners) with a deeper connection with the issue, which can also lead to an empathic connection to those affected by the said realities. Empathy can turn into compassion if the exposed realities bear relevance to the learners' own lives and their sense of identity" (UNESCO, 2020, p.57).

5 Discussion

Our analysis underscores the critical role of empathy in addressing the multifaceted challenges of sustainable development. Existing frameworks often provide a narrow understanding and conceptualization of empathy, focusing predominantly on its emotional and relational aspects. However, empathy encompasses significant cognitive, social, emotional and behavioural dimensions that are essential for a comprehensive approach to ESD. This perspective aligns with Segal's multi-component definition of social empathy – a transformative framework that expands interpersonal empathy into social justice. According to Segal (2011, 2018), empathy must include structural awareness, recognizing how history, culture, public policies, political attitudes, and social structure shape our capacity for empathy. Moreover, social empathy is associated with pro-social behaviour, political reform and collective action aimed at reducing inequality, positionings it as a powerful tool (Segal, 2011, 2018; Sochacka et al., 2021; Howcroft & Mercer, 2022, 2024; Howcroft et al., 2025).

UNESCO (2020) emphasises that education should: (i) equip learners with values, attitudes and behaviours for sustainability; (ii) promote transformative learning, including empathy and systems thinking; and (iii) cultivate interpersonal skills to collaboratively address global challenges. Empathy is increasingly recognized as a core competency in engineering education for sustainable development (ESD), especially when aligned with global frameworks like UNESCO's ESD Roadmap and the IDGs**.** Their emphasis on empathy-related skills can help promote SDG 4, in which education contributes not only to individual success but also to collective survival and prosperity. At the same time, there is a shift from a narrow focus on access and quality—often measured through learning outcomes—toward a broader emphasis on learning content and its contribution to social and planetary sustainability. In this way, ESD connects SDG 4 with all other SDGs (UNESCO, 2020).

According to Segal's framework (2011, 2018) and UNESCO's Agenda (2019, 2020, 2024a, 2024b), empathy is crucial to address the global education agenda envisioned by SDG 4, in which ESD occupies a prominent place. It is aligned with UNESCO's priority areas for action, as suggested in Table 2.

Table 2. Empathy and UNESCO's priority areas

Priority Area	Role of Social Empathy
Advancing Policy	Empathy informs inclusive, human-centred policies
Transforming Learning	Enables participatory, experiential education
Empowering and Mobilization of Youth	Build interpersonal networks through understanding others and their social-historical contexts

Engineering solutions inevitably have an impact on people and ecosystems. By incorporating empathy into engineering education, we can ensure that future engineers are better equipped to understand the diverse

needs of stakeholders; design inclusive, ethical, and sustainable technologies; and consider the long-term social and environmental implications of their work. Empathy is a critical skill for the 21st century engineers, as it enhances a deeper understanding of users' needs, foster creativity, and supports the development of ethical reasoning (Howcroft & Mercer, 2024; De Zoysa et al., 2024; Howcroft et al., 2025). Despite its importance, empathy-based pedagogies remain an underexplored area within engineering education research (Howcroft & Mercer, 2024).

While a few initiatives have embedded empathy within engineering curricula (e.g., Walther et al., 2017; Sochacka et al., 2021; Howcroft & Mercer, 2022, 2024), further opportunities exist to integrate *social empathy*—a deeper and more nuanced understanding of systemic inequalities and diverse lived experiences—into pedagogical frameworks. Such integration is essential for cultivating engineers as socially responsible change agents. Adopting definitions of social empathy, as proposed by Segal (2018), can enhance our understanding and application of empathy in educational contexts. This approach aligns with the *Greening Curriculum Guidance*, which emphasizes the importance of exploring the "sociopolitical and psychosocial dimensions of climate change is crucial for cultivating green life skills such as empathy" (UNESCO, 2024b, p.28).

For engineering education, this implies a need for more research on theories and models of empathy towards the planet. Understanding how empathy can be integrated into engineering curricula will help future engineers develop the skills necessary to address global sustainability challenges. Researchers and practitioners must examine their own institutions' experiences and practices to identify knowledge gaps and opportunities for improvement. Collaborative and cooperative studies are essential for advancing the field of engineering education. By sharing insights and strategies, the broader community can work together to foster a more holistic and empathic approach to sustainable development. This collective effort will not only enhance educational outcomes but also contribute to a more sustainable and equitable future.

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Who are the professional engineers participating in Continuing Engineering Education?

Understanding motivations and characteristics

Bente Nørgaard
Aalborg University, Denmark, bente@plan.aau.dk

Ellen Sjoer
The Hague University of Applied Sciences, Netherlands, e.sjoer@hhs.nl

Christopher J. M. Smith
Glasgow Caledonian University, United Kingdom, christopher.smith@gcu.ac.uk

Patricia Caratozzolo
Institute for the Future of Education, Tecnológico de Monterrey, Mexico, pcaratozzolo@tec.mx

Sonia Gómez Puente
Eindhoven University of Technology, Netherlands, s.m.gomez.puente@tue.nl

Katriina Schrey-Niemenmaa
Academic Engineers and Architects in Finland, TEK, Finland, katriina.schrey-niemenmaa@aalto.fi

Anna Overgaard Markman
Aalborg University, Denmark, Annaom@plan.aau.dk

Nicolaj Riise Clausen
Aalborg University, Denmark, Nclausen@plan.aau.dk

Abstract

The importance of Continuing Engineering Education (CEE) has increased significantly in response to rapid technological change, shifting industry standards, and the growing need for engineers to maintain up-to-date skills and competencies. Despite this, limited attention has been paid to understanding the profiles, career trajectories, motivations, and beliefs of the engineers who actively engage in CEE.

This study explores the motivations and characteristics of professional engineers participating in CEE across various European countries. It seeks to answer the research question: Who are the professional engineers participating in CEE, and what factors influence their decision to engage? Given the limited existing literature, an exploratory qualitative research design was employed. Semi-structured interviews were conducted with a diverse group of mid-career engineers from different disciplines, employment sectors, and national contexts. This approach enabled a deeper exploration of individual experiences and perspectives while allowing for flexibility in probing emerging themes. A total of eight interviews were conducted, focusing on participants' educational and professional backgrounds, their engagement with CEE, and their views on learning and professional development.

The study's findings provide valuable insights into how and why engineers engage in CEE, highlighting the importance of personal relevance, career alignment, and organizational context. The results can support CEE providers in developing more targeted and responsive learning opportunities that reflect engineers' aspirations, preferences, and professional realities. Ultimately, the study contributes to the broader dialogue on lifelong learning in engineering by emphasizing the diverse and evolving nature of CEE participation across Europe.

Keywords: Continuing Engineering Education (CEE); Continuing education; Professional engineers; Qualitative study; Motivation; Lifelong learning; professional development; Engineering education; Adult learning.

1 Introduction

The field of engineering is evolving at an exceptional pace, driven by rapid advancements in artificial intelligence (AI), Industry 4.0, and digitalization more broadly. These technological transformations are reshaping engineering practices, creating both significant opportunities and complex challenges. Among these challenges, the urgent demand for sustainability has become a central concern, positioning engineers as key actors in addressing the global environmental crisis (Chakrabarti et al., 2021). In this dynamic context, the need for Continuing Engineering Education (CEE) has become more critical than ever.

In this study, CEE is explicitly defined as the upskilling, reskilling, and ongoing development of competencies within the technical domain of engineering, explicitly excluding managerial or general leadership training. This definition reflects the study's focus on engineers' continued development of core technical expertise in response to a rapidly changing professional landscape.

CEE plays a vital role in equipping engineers with the skills and knowledge required to adapt to these evolving demands. However, despite growing recognition of its importance, current research in the field has primarily focused on the content, delivery formats, or effectiveness of CEE programs. Much less attention has been given to "who" participates in CEE and "why" they choose to engage. Yet, understanding the characteristics and motivations of the engineers themselves is essential. Such insights can support educational institutions, employers, and policymakers in designing more relevant and targeted learning experiences.

For engineers with over seven years of professional experience, typically considered mid-career, CEE is particularly important (Villanueva Alarcón, 2023). These professionals often face increasing expectations to keep up with technological developments while also balancing responsibilities in project management, mentoring, or leadership. Yet, many engineers in this demographic do not engage sufficiently in formal continuing education. A persistent disconnect between academic institutions and industry exacerbates this gap. While universities may lack current insight into industry demands, practicing engineers may have limited access to up-to-date academic knowledge that could inform their work (Villanueva Alarcón, 2023). Additionally, many small and medium-sized enterprises (SMEs) lack clear strategies for ongoing competence development among their engineering staff (Harper, 2021).

Another relevant dynamic is the trend among engineers to pursue management-focused education, often at the expense of continued technical specialization (Srour et al., 2013). This shift reflects broader career planning strategies, in which engineers are increasingly seeking to integrate technical expertise with leadership responsibilities. Furthermore, in many European countries, including the UK and Ireland, professional recognition through chartership requires ongoing engagement in CEE, underscoring its significance as a marker of professional development and commitment.

By gaining a clearer understanding of who participates in CEE and what drives them, educational providers can better tailor their offerings, both in terms of content and delivery, while industry stakeholders can be more effectively engaged in supporting professional development. To date, limited research has offered detailed insight into the profiles, motivations, and decision-making processes of engineers actively participating in technical CEE. Key questions remain underexplored: Who are these engineers? What motivates them to pursue further education in such a rapidly evolving field? What factors (personal, professional, or structural) influence their participation?

This study aims to contribute to the existing knowledge gap by providing an understanding of the engineers who engage in CEE and the factors that shape their participation. These insights can support

the creation of more targeted, responsive, and sustainable learning ecosystems that can adapt to the evolving demands of the engineering profession. This study addresses the following research questions:

What are the characteristics of the professional engineers participating in Continuing Engineering Education (CEE) in Europe?

What are the factors that influence the decision of the professional engineers to engage in CEE activities?

By addressing these questions, the research seeks to inform policy, guide educational practice, and support the development of a more integrated and future-ready system for lifelong learning in engineering.

2 Theoretical Framework and Methodology

This study is anchored in adult learning theory, which provides a comprehensive lens for understanding how professional engineers engage with continuing education. Adult learning theory involves a range of perspectives that underline the unique characteristics, motivations, and contexts of adult learners. A central belief in adult learning theory is the recognition of adults as self-directed learners (Knowles: 2005, Clausen: 2023), who are often driven by internal motivations and where the learning is typically experience-based (Kolb, 2014), with adults drawing on prior knowledge to contextualize and integrate new knowledge. The theory also stresses the importance of being goal-oriented, where educational activities are closely aligned with real-life challenges and professional demands.

Within this broader framework, Knowles' concept of andragogy highlights key principles such as autonomy, experiential learning, and the immediate applicability of knowledge (Knowles 1980). These principles are particularly relevant in the context of engineering professionals, who often seek learning opportunities that are tailored to their specific roles and responsibilities. Moreover, Illeris underscores the role of motivation as a driving force in adult learning (Illeris, 2004), aligning with broader theories such as self-determination theory (Ryan & Deci), which view motivation as essential to sustained engagement and meaningful learning outcomes.

These theoretical perspectives directly inform the three key areas of analysis in this study: motivations; experiences and perceptions and future expectations and recommendations. Knowles' emphasis on autonomy and goal-orientation helps illuminate why engineers choose to engage in continuing education, while Illeris' focus on cognitive, emotional, and motivational dimensions provides a framework for understanding how they experience and make sense of that learning. Furthermore, both theories support a forward-looking view of adult learning that is adaptive and learner-centered, offering valuable insight into participants' expectations for future CEE programs and their recommendations for improving relevance, flexibility, and impact.

This study employs a qualitative, exploratory research design to investigate the motivations and characteristics of professional engineers who participate in Continuing Engineering Education (CEE) across various European countries. The qualitative approach is well-suited to explore the nuanced, personal, and career-related factors that influence engineers' decisions to participate in CEE, as well as to gain a deeper understanding of their professional profiles (Creswell, 2009). Data were collected through semi-structured interviews, which allowed for in-depth exploration of individual experiences, perspectives, and motivations (Iii & Hagstrom-Schmidt, 2022). This format provided the flexibility to adjust the line of questioning based on participants' responses, enabling the interviewer to probe deeper into emerging themes while maintaining a consistent focus on the core research questions related to CEE participation (Buys et al., 2022). The interview guide was developed drawing on findings from the Nordic Engineering

Hub project (2018–2021) and the authors' extensive experience within the field of CEE. The guide included open-ended questions that addressed factors influencing participation, personal and professional motivations, experiences, and perceptions of CEE, as well as participants' expectations and recommendations for future development.

A total of eight mid-career professional engineers from various engineering disciplines, employment sectors, and geographical regions (Denmark, Finland, the Netherlands, and the United Kingdom) were purposively selected to participate in the study. Participants were included based on the criteria of being mid-career professionals, defined as having more than seven years of work experience, and actively engaged in engineering-specific Continuing Engineering Education (CEE), excluding management or leadership training. The participant's background characteristics are listed in Table 1.

Table 1: Participants' background characteristics

Respondent	1	2	3	4	5	6	7	8
Age	46	35	38	38	35	40-49	44	47
Gender	F	M	M	F	F	M	M	M
Nationality	DK	NL	NL	FI	FI	UK	NL	NL
SME/LE	LE	LE	LE	LE	LE	LE	LE	SME

Interviews were conducted in early spring 2025 by the authors. Interviews were conducted both in-person and online, with each lasting between 20 and 60 minutes. All interviews were recorded with participants' consent and subsequently transcribed. To comply with data protection protocols and institutional legislation, the authors who conducted the interviews also carried out the initial data analysis using a shared analysis template. The template was designed to reflect the structure of the interview guide, organizing the data according to major thematic areas. Through iterative analysis and cross-comparison, key themes were refined and substantiated with representative excerpts from the data.

The analysis is structured around three overarching themes:

- Motivations for participation in CEE
- Experiences and perceptions of CEE
- Future expectations and recommendations

Ethical approval for the study was obtained from each author's institution. All participants provided informed consent before their involvement and were assured of the confidentiality and anonymity of their responses. Audio recordings were securely stored and were accessible only to the researchers. Participants were informed of their right to withdraw from the study at any point without consequences.

3 Analysis and Findings

This section presents the initial thematic analysis of insights from eight semi-structured interviews conducted with mid-career professional engineers across Europe. The study explores common patterns and contrasts in how these individuals perceive, approach, and experience continuing education (CEE). The following five overarching themes emerged in the exploratory analysis.

3.1 Structured planning to organic growth: Diverse motivations for CEE participation

All participants in the study considered CEE a meaningful component of their professional lives; however, their approaches to engaging in learning varied significantly. For some, CEE was deeply embedded within structured annual planning processes. One respondent (P1), for instance, routinely assessed upcoming skill gaps, both her own and those of her team, and actively sought relevant courses to address them pre-

emptively. This forward-looking strategy was part of a broader organizational practice of aligning learning objectives with anticipated project responsibilities and competence demands.

Others (P5, P6, P7, P8) adopted a more emergent or interest-driven approach, responding flexibly to evolving work contexts or intrinsic curiosity. One (P1) engineer described her learning trajectory as an ongoing process of adaptation, where decisions to participate in CEE were often made informally in response to new challenges or areas of intrigue. For her, CEE functioned less as a strategic instrument for career progression and more as a tool for staying mentally engaged and intellectually stimulated.

These differences highlight two somewhat distinct orientations toward CEE: a careerist, goal-driven mode of engagement and a more organic, interest-led model. Some (P1, P3, P7) viewed CEE as essential to positioning themselves for managerial roles and broader responsibilities, while others emphasized deepening existing knowledge or maintaining technical fluency in rapidly evolving fields.

In addition, some participants holding supervisory or integrative roles (P1, P4) often described CEE as a necessity for maintaining a broad, systems-level understanding of emerging technologies. One such respondent (P4) emphasized the importance of grasping the "big picture" to assess whether team solutions were technically relevant. At the same time, another (P1) discussed her role as a translator between state-of-the-art research and practical implementations. These insights suggest that while CEE is widely valued, the motivations for pursuing it are multifaceted and shaped by role, responsibility, and personal orientation.

3.2 Organizational support: A spectrum from empowerment to self-advocacy

All respondents indicated that their employers supported CEE to some extent, but the nature, extent, and effectiveness of this support varied considerably. In several of the organizational settings (P1, P2, P3, P6), CEE was integrated into annual review processes, supported by structured planning tools such as development plans or collective competency matrices. These environments enabled participants to engage in learning with relative ease, often during work hours and with costs covered. One (P2) participant noted that participation in CEE was expected and facilitated, with a wide array of internal and external courses made available by their HR department.

In other (P5) cases, however, support mechanisms were more loosely defined, requiring individual initiative and negotiation instigated by the participant. One (P3) participant described having to advocate for learning opportunities and make strategic decisions about which courses to prioritize due to time constraints. Even in organizations where CEE was theoretically encouraged, work demands sometimes overshadowed learning intentions. One (P6) respondent highlighted this tension, stating that while he was technically allowed to attend courses during work hours, the pressure of ongoing responsibilities often made it challenging.

Notably, these differences were not necessarily tied to industry or geography. Still, they appeared to stem from variations in local management cultures and the degree to which CEE was seen as a legitimate and prioritized component of professional work. For example, while one participant (P1) described a workplace culture where CEE was seamlessly woven into the rhythms of everyday activity, another (P3) felt that participation required justification and compromise despite formal policies suggesting otherwise. Another (P6) participant reported that management was unsupportive to the point where he thought he was being sabotaged in his CEE efforts at one stage in his career. However, this individual felt so strongly about self-development that he made it work.

These accounts reveal a spectrum of organizational experiences, ranging from highly supportive ecosystems to more contingent arrangements where engineers must strategically navigate learning amid competing demands. They also underscore the importance of not just providing access to and time for

CEE but ensuring that the organizational culture meaningfully values and integrates it into the professional workflow.

3.3 Juggling priorities: Balancing time, family, and learning

Time, not surprisingly, emerged as a near-universal constraint on CEE engagement for all participants, yet how participants managed this constraint varied in accordance with their responsibilities, job roles, and obligations from their personal lives. Several (P3, P4, P5) engineers with young children pointed to the challenge of balancing family obligations with the demands of both work and CEE. In these accounts, time was not just a scarce resource; instead, it was a source of tension that required continuous negotiation and adjustment.

For some (P1, P2, P3), supportive employers and flexible work arrangements provided room to engage in CEE during working hours. One participant (P4) described a well-integrated schedule that allowed her to attend courses without significant disruption to her work or family responsibilities. For others (P3), even when the employer nominally supported CEE, the practical realities of project deadlines or team obligations made it almost impossible to dedicate sufficient time to CEE. These participants often found themselves studying during evenings or weekends, a compromise that, while manageable for some, added additional stress.

The contrast between those who viewed CEE as smoothly integrated into their weekly routines and yearly planning and those who experienced it as a burden to be absorbed outside regular hours illustrates how work-life context significantly impacts learning behavior. Some (P7, P8) engineers described that while they participate in both internal and external training requested for their jobs, they also engage in more sporadic additional CEE, participating when time allowed, while others (P1, P2, P3, P6) maintained a more consistent rhythm, enabled by personal time management strategies and organizational support. Interestingly, several participants (P1, P3, P7, P8) reported developing informal strategies to cope with time pressures, such as embedding learning into project workflows, utilizing CEE activities as a platform for reflection, or incorporating reading and self-study during commute times. These adaptive strategies highlight the ingenuity with which mid-career professionals reconcile learning with other responsibilities. Still, they also underscore the need for CEE offerings that accommodate the lived realities of adult learners. Another (P6) participant reported that their priority of CEE and the lack of company support to participate in it during work hours at one point in their career played a significant role in their decision to seek other employment, even though all other aspects of their work were agreeable.

3.4 Personalized learning preferences: Collaborative engagement and solitary study

A consistent theme across the interviews was the participants' preference for CEE formats that aligned with their learning behaviors. However, there was considerable variation in what their preferences entailed. While most of the engineers (P1, P2, P3, P4, P6, P7) favored interactive, group-based learning formats, such as in-person workshops, coaching sessions, or university partnerships, others (P4, P5, P8) found more excellent value in solitary, text-based study and individual reflection.

Most of the participants expressed a strong preference for face-to-face engagement, citing the value of discussion, feedback, and peer interaction as essential to the learning process. One participant (P1) suggested that the physical presence of others created a productive learning environment that could not be replicated online, while another (P6) pointed to the physical shift in location as paramount in avoiding disturbances from colleagues and other daily routines. A (P1) participant also mentioned hybrid approaches that blended short face-to-face seminars with more extended online modules or self-study. Flexible combinations were particularly appreciated by engineers navigating complex schedules, as they allowed for both in-depth exploration and pragmatic integration into daily routines. Another (P4)

respondent emphasized her aversion to audio or video-based materials and favored reading PDFs or handbooks that could be directly applied to the technical challenges of her daily work.

This divergence in format preference reflects broader differences in how participants positioned CEE in their professional lives. Those who viewed learning as a collaborative endeavor tended to value dialogue and exchange, often situating CEE within broader communities of practice and as part of an ongoing learning process. Others, especially those who described high workloads or limited time, gravitated toward more focused, efficient formats that could be tailored to their immediate needs.

Overall, these differences point to a key implication for CEE providers: engineers do not share a singular learning profile. Instead, their preferences are shaped by several factors, including personality, time constraints, learning goals, and prior experiences, which must be taken into account in the design and delivery of compelling CEE offerings.

3.5 Accessing state-of-the-art: Contrasting experiences with CEE content

A common motivation among participants was the desire to stay professionally updated, especially in areas characterized by rapid innovation, such as fiber composites, hydrogen technologies, and advanced simulations. However, the extent to which this desire could be fulfilled through the available continuing education offerings varied greatly among respondents.

Some (P1, P2) engineers reported difficulties in finding offerings that were both relevant and sufficiently up-to-date. One participant (P1) expressed frustration over the slow response of continuing education programs to technological advancements, arguing that many courses lag behind industry and field developments and fail to integrate new research. She (P1) emphasized the need for academic institutions to play a more proactive role in translating pioneering knowledge into accessible and practical learning opportunities for working professionals. In contrast, others (P3, P4, P5, P8) were more satisfied with the existing continuing education ecosystems, especially in countries with well-functioning frameworks for collaboration between universities and industry. For example, one (P5) engineer praised national initiatives that offered modular and stackable courses tailored to new industry needs. These offerings, often facilitated through university networks, enabled participants to acquire micro-competencies and gradually build specialized knowledge.

It is also significant that participants differed in their approach to navigating the landscape of continuing education opportunities. Some adopted a highly self-directed approach, utilizing personal networks, professional associations, and online platforms to identify relevant learning opportunities. Others were more dependent on institutional channels such as internal course catalogs or recommendations from managers. While the former group (P1, P4, P5, P7, P8) seemed better at managing their learning journey, the latter (P2, P3) more often aligned their interests with the needs of their employers in choosing CE opportunities.

These accounts reflect a dual challenge for providers of continuing education for engineers: They must not only ensure that content aligns with technological developments but also support participants in finding and accessing relevant opportunities.

4 Discussion

All participants in the study considered Continuing Engineering Education (CEE) a meaningful part of their professional lives. This is an overall positive response, as research and future studies consistently highlight the need for skills and competence development within all areas of engineering. However, as seen from the analysis, these positive attitudes are challenged by factors such as organizational structure, motivation, learning preferences, and the provision of CEE.

To synthesize these findings, Table 2 highlights the main dimensions, participant experiences, and implications for practice:

Table 2: Dimensions and implications for practice.

Dimension	Findings	Implications for practice
Motivations for CEE	Engineers are engaged either through structured, career-driven planning (often in larger firms with competence strategies) or through emergent, interest-driven learning (common in medium-sized enterprises (SMEs)). Participation was shaped by personal relevance, intrinsic motivation, and the need to remain qualified (e.g., chartered engineer requirements).	CEE must accommodate both strategic, career-oriented learners and flexible, interest-driven participants. Policies should account for SME contexts where formal structures are rare.
Organizational Support	Experiences vary widely: some participants had access to fully integrated CEE with company funding and time allocated during work hours; others relied on personal initiative and negotiation. In regions with charter systems, unions and institutions play a stronger role in provision.	Companies should embed CEE into strategic planning and organizational culture to ensure accessibility and sustainability.
Time & Work–Life Balance	Time was a universal constraint; engineers often studied outside work hours, creating stress and family conflicts.	CEE should be integrated into workflows (e.g., PBL and work-based learning) to reduce additional burden on professionals and enhance relevance.
Learning Preferences	Preferences were diverse: many favored interactive, group-based formats such as in-person workshops, coaching, or university partnerships. Others preferred a solitary, text-based study. Face-to-face engagement and peer interaction were strongly prioritized, with online courses and micro-credentials attracting little interest despite their availability.	Providers should offer a mix of formats, interactivity, and opportunities for peer learning. Over-reliance on generic online modules risks disengagement.

Access to Relevant & Updated Content	Some participants reported outdated offerings that lag behind industry developments. Others highlighted positive experiences with modular and stackable courses, often developed through strong university-industry collaboration.	Faster translation of emerging knowledge into practice is needed. Expanding modular, industry-aligned, and collaborative course design will help ensure engineers remain competitive in rapidly evolving fields.
Theoretical Alignment	Findings resonate with adult learning principles: Knowles' andragogy (self-directed, goal-oriented learners), Illeris' emphasis on motivation and meaning, and Kolb's experiential learning through problem-solving.	CEE design should foreground adult learning theory by ensuring content is relevant, flexible, situated in practice, and meaningful to learners.

A forward-looking strategy, where skill and competence needs are aligned with company strategic development and learning activities are integrated into work processes, represents a highly organized and structured approach. This method is often applied in larger companies with well-defined competence strategies and the resources to implement such an approach. However, in the EU, where more than 99% of companies are small and medium-sized enterprises (SMEs), this is not the typical experience of the average engineer. For many, CEE is more likely to be emergent or interest-driven, as 50% of the EU's workforce is employed in SMEs (Eurostat, 2022).

How individual engineers navigate, structure, and plan their CEE is highly influenced by their employment context. Whether it involves structured planning or more ad hoc, organic growth likely depends on the extent of strategic competence development and who bears the costs. However, regardless of the opening, there are fundamental characteristics that define how adults approach learning. As Illeris (2006) states, "Adults learn what they want to learn and what is meaningful for them to learn." This highlights a crucial point: participation in CEE is rarely about compliance or obligation alone. Instead, it is influenced by personal relevance, intrinsic motivation, and the perceived value of the learning experience.

Learning preferences among participants were diverse. There was a strong preference for face-to-face engagement and peer interaction, with some engineers emphasizing the importance of a physical shift in location to avoid disturbances from colleagues and daily routines. Those who view learning as a collaborative endeavor value dialogue and peer feedback. In contrast, engineers with high workloads or limited time prefer more focused and efficient formats tailored to their direct needs. Surprisingly, in-person learning activities are highly prioritized, with little interest in online courses or micro-credentials despite their prevalence in the current CEE landscape.

Several respondents reported significant challenges in finding CEE offerings that are both relevant and sufficiently up to date. Participants emphasized the need to translate pioneering knowledge into accessible and practical learning opportunities for working professionals. This is particularly evident in countries with well-functioning frameworks for collaboration between universities and industry, which facilitate the development of courses aligned with current industry needs.

These findings show that CEE is shaped not only by individual motivation but also by structural opportunities and constraints within organizations, and they are well aligned with adult learning theory, which emphasizes the self-directed and goal-oriented nature of adult learners (Knowles, 2005), as well as

the importance of internal motivation and meaningful application (Illeris, 2006, Ryan & Deci, 2000). The challenges engineers face in balancing time, family, and learning further reinforce Knowles' and Illeris' emphasis on the need for education that is relevant, flexible, and situated within real-life contexts. Additionally, the diversity of learning preferences observed in this study reflects Kolb's (2014) experiential learning theory, which underscores the value of accommodating different learning styles through varied instructional approaches.

5 Conclusion

This study highlights the importance of Continuing Engineering Education (CEE) as a vital component of professional development for engineers. Despite the widespread recognition of its value, approaches to engaging in CEE vary significantly, shaped by organizational support, personal motivations, and individual learning preferences. As such, CEE providers must offer a range of learning formats - from interactive, group-based sessions to individualized study options - to support sustained engagement. Addressing these challenges and aligning offerings with adult learning principles will help ensure that engineers remain competitive and well-equipped to navigate the evolving technological landscape.

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Exploring the Policy Landscape in Alignment to Outcome Based Education in Four East African Countries: Uganda, Kenya, Tanzania and Rwanda

Esther Matemba
Curtin University, Australia, esthersayula@gmail.com

Shamim Nassar
Strathmore University, Kenya, snassar@strathmore.edu

Irene Magara
University of Nebraska-Lincoln, USA, imagara2@huskers.unl.edu

Cecile Uwimana
Institution of Engineers Rwanda, Rwanda, ucecile01@gmail.com

Yashin Brijmohan
Utah State University, USA, yashin.brijmohan@usu.edu

Abstract

Proposals to enhance the quality of engineering education in Africa strongly suggest a transition to Outcome-Based Education (OBE). OBE offers several advantages over traditional educational systems and also addresses challenges related to employability and international recognition of qualifications between countries. Transitioning to OBE requires a supportive policy framework and environment, as it demands a new approach to curriculum design and development, supported by multiple stakeholders. Therefore, understanding the policy landscape that enables OBE during the transition is crucial. This paper explores how the national policies, systems and context surrounding curriculum in Africa align or support the implementation of OBE. This exploratory study analyses national policies obtained from publicly available information and documents from four East African countries: Kenya, Tanzania, Uganda, and Rwanda. The study explored institutions accountable for regulation of engineering education curriculum, the alignment between higher education bodies and professional societies regarding curriculum and accreditation processes, and existing higher education policies around curriculum design advocating OBE. This study highlights the similarities and differences in the policies and guidelines for curriculum development in these countries and helps in characterising the existing policy landscape and its alignment with OBE. The study provides a baseline for OBE implementation amongst the four countries, and can assist with understanding other countries with similar contexts.

Keywords: Outcome-Based Education, Engineering Education, East Africa, Curriculum development, Higher Education policy

1 Introduction

There has been a paradigm shift in educational practice from a focus on what teachers teach to what learners actually learn, leading to a move towards Outcome-Based Education (OBE) (Bigg & Tang, 2011). OBE is an approach defined by its focus on clearly defined outcomes, alignment of learning and assessment to the stated outcomes with the most distinctive aspect of OBE being alignment (Spady, 1994). This aligns with the student-centred approach to teaching and learning that emphasizes the development of technical as well as professional competencies and skills (Ervado, 2020; Manzoor, 2018).

OBE provides a unique platform with several advantages over traditional teaching and learning. It offers flexibility in teaching strategies and establishes a framework for assessing whether the curriculum and teaching practices facilitate desired student learning while enhancing clarity in both learning outcomes and assessments (Arize, 2017: Badkar, 2017). This enables regulatory institutions across geographical borders to agree on program outcomes, allowing for mutual recognition of qualifications with substantial equivalence. Moreover, clarity in outcomes creates a learner-centered approach, allowing students to be more self-directed learners, increasing their motivation and engagement with the program (Li & Rohayati, 2024).

Proposals to improve the quality of engineering education in Africa strongly suggest transition from traditional education to OBE, partially in response to challenges of employability. OBE is attributed to increasing graduate employability by improving the quality of education to better prepare students for the job market (Manzoor, 2017; Mohammad et al 2012; Oyebode 2021; Rao 2013). Globally, various countries have adopted OBE in engineering education to varying degrees, with different levels of implementation. International agreements such as the Washington Accord influence OBE adoption, and accreditation standards often reflect a shift towards OBE. In Africa, only South Africa is a signatory with full rights of participation in the accord. Nigeria and Mauritius are provisional signatories working towards becoming full signatories. More African countries aspire to become signatories, but in the interim, accreditation standards are guided either by national institutions mandated with the role of regulating and/or accrediting academic programmes.

Whilst transitioning to the OBE curriculum seems ideal for transforming engineering education in African countries, this requires a supportive policy framework and environment. OBE demands a new approach to

designing or developing curricula, with support from multiple stakeholders (Almuhaideb & Saeed 2020, Oyebode 2021). This transition requires intensive efforts by academic staff with associated training in aligning curriculum, teaching methods, and assessments to facilitate key outcomes for the students (Syed et al 2022). It is, therefore, important that the contextual landscape surrounding curriculum design and implementation is understood and considered in the transition. This paper explores the question:

"In what ways do the existing national and institutional policies and systems around curriculum in Africa align with the Outcome based Education concept?"

The study is based on the engineering higher education context, specifically in four selected African countries: Tanzania, Kenya, Rwanda, Uganda.

2 Transitioning to OBE in Engineering Education

1.1 Motivation for transitioning

Although OBE has been embraced by several countries across the globe, there is no comprehensive report about its global implementation in engineering. The Washington Accord (WA), an international agreement between national regulatory bodies, adopted outcomes principles related to OBE upon its inception in 1989 (Anwar & Richards, 2015). Some of its signatories like Accreditation Board for Engineering and Technology (ABET), and Engineering Council of South Africa, (ECSA) adopted the transition from input to output-based education, as reflected in their websites (ABET, n.d.; Engineering Council of South Africa, n.d.). Since then, accreditation standards among the full members of the WA have shifted from an Input-Based to an Outcomes-Based Education (OBE) system, (Laquador, 2014).

Literature indicates that developing countries seek international recognition by joining the Washington Accord and fulfilling accreditation requirements (International Engineering Alliance, n.d.; National Board of Accreditation, n.d.). The benefits of OBE include enhanced employability for graduates and improved industry performance (Obeyede, 2021). According to the Washington Accord website (International Engineering Alliance, n.d.), 25 countries are full signatories, committed to implementing OBE in their engineering programs. Developed countries such as the USA, UK, and Australia have long utilized OBE in higher education, with Australia's adoption occurring in the early 1990s and the US in the late 1990s (Froyd et al., 2012).

Other countries began implementing OBE around 2000, with more joining between 2010 and 2020 (Allais, 2007; Kennedy, 2011; Mohayidin et al., 2008; Jain et al., 2011; Nguyen & Nguyen, 2020; Akramy, 2021). Asian countries such as Malaysia, Indonesia (Handayani & Wibowo 2021), India (Jakhale and Attar 2015), Pakistan, the Philippines (Laguador, 2014), and Bangladesh (Syeed et al., 2022) are adopting OBE to meet national and international accreditation standards. In Malaysia, engineering degrees are required to quantify learning outcomes (Engineering Accreditation Council Malaysia, 2020). Philippine institutions implement OBE to comply with the Commission on Higher Education (CHED) standards and to align with international university standards (Lagoador, 2014; Borsoto et al., 2014; Evardo, 2020).

OBE adoption in Africa is largely unreported, although South Africa has been the sole full signatory of the WA since 1999, while Mauritius and Nigeria have recently gained provisional membership. Nigeria, a provisional member since 2023, sees OBE as essential for addressing globalization, technological development, labor needs, and alignment with the Washington Accord, leading their national regulatory body COREN to develop a framework for OBE in Nigerian engineering programs (Oyebode, 2021). Kenya had also made significant strides towards achieving provisional signatory status with external assessments by international nominators from the Board of Engineers Malaysia and the Pakistan Engineering Council determining Kenya's readiness for provisional signatory status (Accreditation.org, 2025).

The motivation for transitioning to OBE is driven by higher education regulatory bodies in collaboration with professional organizations. A literature review demonstrates that alignment between higher education

policies and engineering professional bodies is crucial for the effective implementation of OBE. Studies, such as those by Syeed et al. (2022) in Bangladesh and Philippines by Lagoador (2014) and Borsoto (2014) highlight significant collaboration among stakeholders in curriculum and accreditation processes.

Institutional preparedness for the transition to OBE, as examined by Evardo (2020), reveals, among other things, a need for faculty training to comprehend OBE principles. While previous studies focussed on readiness from an institutional perspective, they often overlook the importance of national and institutional policies in curriculum design and development. Hence the purpose of this study is to assess the policy landscape and how it is supportive to transitioning to the OBE in the selected East African countries - Tanzania, Kenya, Rwanda, Nigeria, Uganda. The study focuses on African tertiary Engineering education contexts.

1.2 Key aspects/features of OBE

A review of literature on OBE has identified the following important aspects of OBE: 1) Focus on learning outcomes that students need to display at the end of their course, or degree program (Ervardo, 2020; Almuhaideb & Saeed, 2020); 2) Emphasis on equipping students with skills and competencies, technical and soft, required for the job market (Almuhaideb & Saeed, 2020; Manzoor, 2017); 3) Curriculum design that begins with identifying the outcomes, beginning with program learning outcomes (PLO) then course learning outcomes (CLO) then design course content, learning activities and assessments to align with the CLO and eventually the PLO (Deivasigamani & Ragurama, 2022; Lagoador, 2014); 4) Student-centered teaching and learning that encourages active learning, critical thinking and problem solving activities that are essential for engineering practice, with teachers as facilitators of learning (Evardo, 2020; Oyebode, 2021); and 5) having the explicit learning outcomes that will enable learners to self-assess their progress (Gurukkal, 2018; Nguyen et al., 2024).

In addition to the teaching and learning aspect, OBE requires different assessment approaches in order to gauge the types and levels of outcomes gained by students. OBE endorses approaches such as formative and summative assessment; and self-assessment (Syeed et al 2022). OBE requires continuous quality improvement, whereby educational programs are regularly assessed and evaluated, identifying weaknesses and addressing them (Oyebode, 2021; Almuhaideb & Saeed, 2020) to ensure continuous improvement in curriculum, teaching methods and the quality of education in general. In addition, involvement of multiple stakeholders such as faculty, alumni, current students, employers, and government representatives ensures that programs are relevant to industry and that students are well prepared for the workforce (Almuhaideb & Saeed, 2020; Oyebode, 2021).

3 Methodology

1.3 Context and Scope

This exploratory study involves analysis of data from four African countries where the authors originate: Kenya, Tanzania, Uganda and Rwanda. The choice of these countries comes from the authors' in-depth understanding of their educational systems, policies, and the challenges they face in implementing Outcome-Based Education (OBE). With strong connections in these regions, the study offers valuable insights into how well national policies and institutional practices align with OBE frameworks across the different East African contexts.

To address the overarching research question "In what ways do the existing national and institutional policies and systems around curriculum in Africa align with the Outcome-Based Education concept?" we answer the following questions for each country's context:

Q1. Who is responsible for regulation of engineering education curriculums in higher education?

Q2. Are the programme accreditation processes by the higher education quality assurance body/agency and the engineering professional body aligned?

Q3. Are the existing higher education policies around curriculum design advocating OBE? What is the evidence?

1.4 Sources of Data and Method

Two data collection methods were used: a) Anecdotal evidence from the authors' experiences and knowledge regarding policy contexts in their countries b) Documentary analysis of the national policies that guide curriculum development in the respective countries. The documents were sourced from publicly available information and documents obtained with permission from institutions and relevant agencies, such as Accreditation bodies, Engineering Professional Bodies or Universities.

1.5 Developing a Framework for document assessment for OBE

Drawing from the aspects of OBE established from review of previous studies (Almuhaideb & Saeed, 2020; Deivasigamani & Ragurama, 2022; Ervardo, 2020; Manzoor, 2017; Oyebode, 2021) we derived six indicators/features of OBE to look for in the collected documents. These are: Clear Articulation of Learning Outcomes, Curriculum Design Alignment with OBE, Outcome-Based Assessment Strategies, National Policy Support for OBE Present, Stakeholder Engagement, Policy Alignment (within regulatory bodies).

4 Results

Here we present the results addressing the three questions in the methodology section (Q1, Q2, and Q3). To strengthen our argument based on the anecdotal evidence from the authors, we conducted a document analysis to assess policy preparedness across the different countries. In our next paper, we will delve deeper into each country's context by conducting interviews with key experts in the field. These interviews will help us assess policy alignment, identify the causes, challenges, and strengths for each country.

1.6 Who is responsible for regulation of engineering education curriculums in higher education?

Table 1 presents a National Accreditation /Quality Assurance Body and Engineering professional body that is linked to engineering education in each of the four countries being explored in this study.

In Uganda, the National Council for Higher Education (NCHE) regulates higher education through its Quality Assurance Framework, which was first published in October 2006. NCHE was established in 2001 through the Universities and Other Tertiary Institutions Act, with the aim of regulating and overseeing higher education institutions in the country. A revised version, the Quality Assurance Framework for Universities and the Licensing Process for Higher Education Institutions, was introduced in May 2011, and the most recent version was released in 2014. This Quality Assurance Framework has two main components: a) The regulatory component sets national standards for higher education and ensures that universities meet these standards through accreditation, regular audits, and external reviews, b) The institutional component, which focuses on universities' internal processes. Each university is expected to have a quality assurance unit that reviews programs, teaching methods, and assessments to ensure they align with NCHE's guidelines and contribute to maintaining high educational standards (NCHE, 2014).

Table 1: Engineering Education in Uganda, Kenya, Tanzania and Rwanda

	Uganda	Kenya	Tanzania	Rwanda
National Accreditation /Quality Assurance Body in HE	National Council of Higher Education (NCHE)	Commission for University Education (CUE)	Tanzania Commission of Universities (TCU)	Higher Education Council under the Ministry of Education (HEC)
Engineering professional Body	Uganda Institute of Professional Engineers (UIPE) and Engineering Registration Board (ERB)	Previously Engineers' Board of Kenya (EBK) now the Engineering Accreditation Council (EAC).	Engineering Registration Body (ERB)	Institution of Engineers Rwanda (IER)

In Kenya, university education is regulated by the Commission for University Education (CUE) whare the Commission's accreditation process emphasizes quality assurance. The CUE is mandated, in the Universities Act of Kenya No. 42 of 2012 (Government of Kenya, 2012), 'to provide for the development of university education, the establishment, accreditation and governance of universities ….'. Accreditation of engineering programmes is done in collaboration with the Engineer's Board of Kenya (EBK). In 2023/2024, the EBK established the Engineering Accreditation Committee (EAC), as 'an independent institution that oversees and carries out the recognition and accreditation of engineering programs within its mandated jurisdiction'. The EAC which reports to the EBK is responsible for implementation and maintenance of accreditation standards, evaluation and accreditation of engineering programmes, accreditation decision-making and; international benchmarking and standards alignment.

In Tanzania, university education is regulated by the Tanzania Commission of Universities (TCU) (https://www.tcu.go.tz/). TCU is a government agency established 2005, under the Universities Act, Cap. 346 with the mandate to recognise, register and accredit universities in Tanzania. TCU succeeded the Higher Education Accreditation Council (HEAC) established in 1995 which was established to regulate the establishment and accreditation of private universities. TCU is also mandated to regulate local or foreign university-level programmes, coordinate the proper functioning of universities and ensure a harmonised higher education system in the country. "TCU is a member of an Inter-University Council of East Africa IUCEA and AfriQAN (https://www.tcu.go.tz/) and therefore conforms to the standards stipulated by IUCEA. "

TCU has two levels of accreditation in Tanzania, institutional level and program accreditation level. At institutional level, they recognize, approve, register all universities operating in Tanzania, and at the program level TCU evaluates all curricula offered by registered higher institutions in Tanzania (Matemba 2020). At program level, accreditation is done during the process of curriculum review and TCU sets requirements for curriculum review and development in Tanzania i.e. the general framework to be followed and procedure for curriculum accreditation to be observed by university institutions (TCU 2021). and the procedure for curriculum accreditation (TCU n.d.).

The Engineers Registration Board (ERB) is a statutory body established by an Act of Parliament, Tanzania Engineers Registration Act No. 15 of 1997 (http://www.erb.go.tz) to regulate the engineering profession in Tanzania, and it also holds the authority to "accredit engineering programs and register engineers into different levels."

In Rwanda, university is regulated by the Higher Education Council (HEC) which was founded under Law No. 20/2017, enacted on April 28, 2017. HEC's mandate includes advising the government on educational policies

and strategies for higher learning institutions by offering general education programs, setting accreditation standards, monitoring compliance with those standards, approving academic curricula, disseminating policies and decisions, and ensuring the effective implementation of these initiatives.

The Institution of Engineers Rwanda (IER) was established as a professional regulatory body under Law No. 26/2012, enacted on June 29, 2012. Its primary mandate is to regulate, develop, and oversee the activities of those practicing engineering in Rwanda, ensuring adherence to established engineering standards and best practices in service delivery.

1.7 Are the programme accreditation processes by the higher education quality assurance body/agency and the engineering professional body aligned?

We established that alignment between professional bodies and higher education accreditation agencies varied between the East African countries as explained in the results below:

While the NCHE plays a critical role in regulating and ensuring the quality of higher education in Uganda, it also works with professional bodies like the Engineers Registration Board (ERB) and the Uganda Institution of Professional Engineers (UIPE) to ensure that engineering programs align with industry needs. The Quality Assurance Framework (NCHE, 2014) indicates one of NCHE's functions stipulated under Section 5 of the Act as:

"To receive, consider and process applications for the accreditation of the academic and professional programmes of those institutions in consultation with Professional Associations and Regulatory Bodies" p. 3.

The interaction between NCHE, ERB and UIPE is not a formalized process for consistent consultation over time but a one-off whenever accreditation of a programme or renewal of curricula is required. This lack of continued or consistent collaboration may sometimes create gaps between what is taught in universities and the skills needed in the industry. The collaboration seems more intentional at the beginning during program accreditation compared to continuous quality assurance checks to ensure that universities adhere to the standards set or the policies made.

The ERB, a statutory body, advises on curriculum design and focuses on certification and maintaining professional standards, while UIPE, a membership-based organization, ensures programs align with industry needs and advocates for continuous professional development. Both bodies collaborate with NCHE through physical visits to assess universities' staffing and infrastructure but do not have authority over curriculum design or mandate the adoption of OBE. Their role remains advisory, ensuring that engineering programs meet industry requirements in Uganda.

While the CUE was established with the mandate to accredit university programmes in Kenya, concurrently, the Engineering Act of 2011 (Government of Kenya, 2011) mandated the Engineering Board of Kenya (EBK) to approve and accredit engineering programmes. The duality in accreditation has led to uncoordinated and sometimes contradicting directives (Kenya Engineer, 2017). To address the duality, the University (Amendment) Act No. 48 of 2016 has vested an accreditation mandate on CUE superseding any other law (Kenya Engineer, 2017). In the latest version of the Act (Government of Kenya, 2024), published in April of 2024, the law states that 'If there is a conflict between the provisions of this Act and the provisions of any other Act in matters relating approval or accreditation of academic programmes offered by universities, the provisions of this Act shall prevail.' meaning that accreditation is the mandate of the CUE. However, it also states that 'The Commission may, before approving any academic programme consult with any relevant body established by written law to regulate the profession to which the academic programme relates where such law empowers the professional body to approve or accredit courses offered at any university or colleges.' The two have now tried to find a common ground, including establishing joint technical committees to work collaboratively towards accreditation of engineering programmes.

With regards to Tanzania, the involvement of the engineering professional body (ERB) in accreditation of engineering programs remains unclear looking at the information that is publicly available. For example the ERB website has a statement on that saying: “To collaborate with the Tanzania Commission for Universities and other relevant institutions on the accreditation of programs.”(http://www.erb.go.tz) There is nothing further on this on the website, therefore it is difficult to conceptualise their involvement and alignment to TCU. Further, it was previously established in Matemba (2020) that despite the engineering professional body, ERB, having legal mandate to regulate the engineering profession in Tanzania including accreditation of engineering programs which is done by a national accrediting body, TCU, with ERB involvement as an important stakeholder. Since both the TCU and the ERB have mandates to accredit engineering education, there seems to be an opportunity for universities to work with relevant professions through specific professional bodies in accreditation of engineering programs, especially in the area of learning outcomes. For instance, ERB can predefine competencies (skills) or expected learning outcomes that guide curriculum for engineering education.

While HEC is responsible for accrediting engineering programs in Rwanda, IER also plays a vital role in ensuring that the quality of engineering education meets global standards. This includes overseeing the professional training of engineers to ensure their competence aligns with internationally recognized best practices. There is currently strong collaboration between IER and HEC, especially in reviewing the demands of the job market and aligning these with appropriate legal frameworks and accredited policies. This collaboration aims to clearly define the roles and responsibilities of all stakeholders, ultimately enhancing both professional training and engineering practices in Rwanda.

1.8 Are the existing higher education policies around curriculum design advocating for OBE? What is the evidence?

Table 2 provides a list of policy documents that we collected and reviewed to support the findings below. There were the policy documents that were publicly available or accessible to the authors.

In Uganda, there has not been a unified national policy specifically advocating for Outcome-Based Education (OBE) at the higher education level. The available statutory instruments 2005 No. 85 regarding Institutional Standards does not talk about OBE but offers general guidelines regarding standards for curricula including the design and contents of curriculum and programmes. However, some universities, such as Uganda Christian University (UCU) and Makerere University, have made individual strides towards CBE and OBE adoption respectively. For instance, UCU transitioned to a learner-centred approach, focusing on skills development for workforce readiness, which aligned more closely with CBE principles, though these efforts remained institutional rather than national (UCU, 2021).

In 2011, Makerere University, Uganda's oldest public university, launched the Education Partnerships in Africa Project (EPA) with Metropolitan University (UK), focusing on employability and entrepreneurship skills. As part of this initiative, Makerere developed the "Employability and Entrepreneurship Skills Development Program" through the School of Distance and Lifelong Learning (SoDLL), aimed at enhancing practical skills and aligning the curriculum with industry needs. Makerere envisioned adopting an Outcomes-Based Education (OBE) system to emphasize learning outcomes and skills development, helping students become more employable. The program focused on integrating an OBE-based curriculum, with pilot training sessions for out-of-school leavers held in Arua, Entebbe, and Fort Portal. While the goal was to expand this initiative nationwide, it remains limited to the pilot phase and has not yet been fully implemented across all the other colleges in Makerere University or extended to other universities (Wamala, 2011).

Table 2: Existing Policies relevant to Curriculum and Accreditation

Uganda	National Council for Higher Education: Quality Assurance Framework for Universities and the Licensing Process for Higher Education (NCHE, 2014) Source: https://unche.or.ug/
Tanzania	Curriculum development framework for all levels of university education in Tanzania (University Qualifications Framework (UQF) 6–10). (TCU 2021). Procedures for Programme Accreditation (TCU n.d.) University Qualifications framework TCU 2012, Handbook for Standards and Guidelines for University Education in Tanzania. (TCU 2019) THE UNIVERSITIES ACT, 2005 All documents are sourced from the TCU website https://www.tcu.go.tz/
Kenya	An accreditation policy included as part of the Engineering Accreditation Standard (EAC/STD/01) (EAC, 2024, Chapter 2, pp. 4-16)
Rwanda	Higher Education Council: Law N° 010/2021 of 16/02/2021 determining the organisation of education (Higher Education Council, 2021) MINISTERIAL ORDER Nº 001/MINEDUC/2021 OF 20/10//2021 DETERMINING STANDARDS IN EDUCATION (Ministry of Education, 2021) MINISTERIAL ORDER N° 003/MINEDUC/2021 OF 20/10//2021 DETERMINING RWANDA QUALIFICATIONS FRAMEWORK (Ministry of Education, 2021) All documents are sourced from the HEC website https://hec.gov.rw
East Africa	Handbook for Quality Assurance in Higher Education, Volume 2: Guidelines for External Assessment at Program Level (IUCEA, 2010) Source: https://www.iucea.org

To assure quality of university programmes, the Commission for University Education (CUE), published guidelines for designing curriculum for university academic programmes (Commission for University Education, 2009) in 2009 and later in 2014, Universities Standards and Guidelines (Commission for University Education, 2014) to guide universities on the content that should be included with curriculums and how it should be arranged. The guidelines in both documents require inclusion of expected learning outcomes for the programme and for the course. Prior to the establishment of the Engineering Accreditation Council (EAC) in 2023/2024, the Engineer's Board of Kenya (EBK), working collaboratively with the CUE provided additional guidelines on the composition of content within the curriculum for engineering programmes as outlined in the Engineer's Rules of 2019 document (Kenya Law, 2019). When the EBK established the EAC, it was tasked with developing a framework for OBE in Kenyan Engineering Programmes. It now provides an Engineering Accreditation Standard (Engineer's Board of Kenya, 2025), a document developed 'to guide engineering programmes in planning, developing, implementing, reviewing the OBE system and its continual quality improvements'. It has a section that includes an accreditation policy. The Standards document provides clear descriptions of what is expected, for example, in the Programme design, there are Programme Educational Objectives (PEOs), which align to Programme Outcomes (POs) which align to Course/Expected Learning Outcomes (CLO/ELOs). It is also required that the processes used to establish/formulate/define and review PEOs and POs must be described. In addition, performance indicators, assessment instruments, Continuous

Quality Improvement (CQI) activities and Stakeholder involvement activities are also described at all levels of programme design.

While the guidelines may be clear, it is not certain that institutions are adequately prepared to develop OBE curricula and to implement them. There is a need for institutional policies on curriculum development to complement the EAC's policies.

With regards to engineering education in Tanzania, Matemba 2020 established that the engineering curriculum in Tanzania was not outcome-based despite some terms related to OBE being mentioned in some of the policy documents around higher education curriculum and accreditation. Matemba, (2020) who studied the Tanzanian context of engineering education as a case study in her PhD thesis for instance found that TCU stipulates standards and procedures for accreditation of all university programmes but leaves the task of prescribing the learning outcomes to curriculum developers in universities.

On reviewing the Tanzanian policy documents gathered (Table 3), we confirmed no explicit instruction for OBE or even CBE, although there are instructions to develop expected learning outcomes. For example, the Procedures for Programme Accreditation (TCU n.d.) document, contains a checklist for institutions to ensure that their curriculum meets the requirements in addition to its eight steps of curriculum accreditation process. One of the items in the checklist being "Well Formulate Expected Learning Outcomes". Further in another TCU document, the Curriculum Development Framework for all Levels of University Education in Tanzania (TCU 2021, p3) there is a clause that says "3.4 Programme Expected Learning Outcomes and its Associated Teaching/Learning Activities and Assessment Criteria", however there is no further description given on this to entail other aspects of OBE especially the aspect of curriculum alignment.

For Rwanda, IER sought cooperation with the Federation of Engineering Institutions of Asia and the Pacific (FEIAP) in 2018, to establish internationally recognized accreditation and certification systems for engineering programs in Rwanda. To further this effort, IER organized a workshop in Kigali in 2019, bringing together key stakeholders to discuss the development of an Accreditation Policy and Procedure Manual for Engineering Programs in Rwanda's higher education institutions. The workshop was facilitated by Ir. Professor Academician Dato' Dr. HT Chuah of FEIAP and Ir. Professor Dr. BM Goi from the University Tunku Abdul Rahman, who shared insights on engineer mobility, accreditation, and outcome-based education.

Under current law, engineering programs as well as other high learning programs in Rwanda, must be accredited by a Ministerial order based on inspection reports done by HEC through the Ministry of Education. Rwanda is transitioning from a traditional education model to a competency-based education system, with plans to eventually adopt an outcome-based education model. IER, as the professional body, has initiated the accreditation process for engineering higher education institutions, considering the outcome-based education system. However, this initiative has not yet received approval to proceed from the Higher Education Council, which has instead directed the Ministry of Education to take the lead on the matter. IER is currently awaiting further guidance on the next steps in this process.

Table 3 provides a summary and comparison, offering a general picture of how well each country is prepared for implementing OBE.

Table 3: Assessment A of OBE Features in Policy documents at Higher Education

Indicator	Uganda	Kenya	Tanzania	Rwanda
Clear Articulation of Learning Outcomes	No: OBE policy/Framework missing.	Yes: The EAC guidelines provide adequate guidelines on this process.	No: a mention of "Expected Learning Outcomes" without clear articulation in the documents	No: Rwanda learning currently is based on competences not on outcomes
Curriculum Design Alignment with OBE	No: OBE policy/ Framework missing	Yes: Alignment guidelines were not very clear previously. However, the new EAC's standards now provide more detailed direction.	No: OBE policy/ Framework missing	No: OBE policy/ Framework missing
Outcome-Based Assessment Strategies	No: OBE Policy/ Framework missing	Yes: Well-articulated. Institutions, in their curriculum documents have to describe their assessment strategies.	No: OBE Policy/ Framework missing	No: But there is competence-based assessment
National Policy Support for OBE Present	Partially Met: Support for OBE implementation present through institutional support of pilot trainings	Yes: An accreditation policy guiding on OBE is included in the EAC's Standards document.	No: National Accreditation Policy does not mention OBE	No: Existing Policy does not support. Steps towards national accreditation standards that would likely support OBE.
Stakeholder Engagement	Partially Met: Willingness to engage is present, however lack of a policy leaves a gap regarding the next steps.	Yes: requirement for evidence to show that relevant stakeholders were engaged in curriculum development and continuous improvement resulting from feedback and reviews.	Partially met: a clause in pg.3, of curriculum development framework mentions "3.2 Stakeholders Involvement"	Partially met: Collaboration step between stakeholders to discuss the importance of OBE in the engineering program, but they are not yet fully engaged to the end.
Policy Alignment	No: OBE Policy missing	Partially met: need for institutional policies to complement the EAC's policies.	No: OBE Policy missing	Partially met: The concept is available but waiting for the next step.

5 Discussion and Conclusion

Of the four countries included in our study, Kenya has transitioned and now talks about OBE. Rwanda has also started the conversation of including OBE in its curriculum at higher education. However, Uganda and Tanzania have acknowledged the importance of OBE but are yet to put in place clear structures at higher education level to support their transition.

This exploratory study has shed light on the current landscape of national and institutional policies related to curriculum development in engineering education across four African countries: Kenya, Tanzania, Uganda, and Rwanda. The analysis reveals a varying degree of alignment with the principles of Outcome-Based Education (OBE).

In some countries, there is a clear emphasis on quality assurance through national accreditation bodies like the National Council of Higher Education (NCHE) in Uganda and the Commission for University Education (CUE) in Kenya. These bodies establish national standards and ensure universities meet them through accreditation and reviews. However, specific details regarding the integration of OBE principles are often limited or not explicitly stated. This suggests that while quality assurance is a priority, the transition to OBE may not be a uniformly adopted or mandated approach across these nations.

The involvement of engineering professional bodies, such as the Uganda Institute of Professional Engineers (UIPE) and the Engineering Accreditation Council (EAC) in Kenya, indicates a recognition of the importance of aligning education with professional standards, however, the extent to which these bodies actively drive, or support OBE implementation varies. In some cases, professional bodies are involved in accreditation, but their role in shaping curriculum design towards OBE may be limited.

In the study we also encountered the efforts that have been made towards competence-based education (CBE) in relation to OBE; while acknowledging the distinct differences and similarities between OBE and CBE. Terminologies like competence-based education, criterion-referenced learning, and mastery learning are precursors to outcome-based education (Okiror, Hayward, & Winterbottom 2017). CBE is more focused on ensuring the mastery of specific competencies or skills in a self-paced manner before students' progress. OBE addresses a broad set of learning outcomes, including knowledge and skills following a systematic backwards design (Wiggins, 2005), that emphasizes the alignment of curriculum, teaching, and assessment to ensure that students achieve the defined outcomes.

The policy context surrounding OBE and Competency-Based Education (CBE) differs across the studied countries. While some institutions are exploring CBE, as noted in Rwanda, there is a general lack of explicit policy directives or activities indicating a widespread adoption of OBE or CBE from policy documents. Kenya has recently undergone the process of assessment for the Washington Accord, which necessitates changes in accreditation documents and a shift towards OBE. This will support the country's transition to CBE, which has been rolled out at primary and secondary school levels, with the first cohort into university expected in 2028/2029. This means that the competencies that are integrated into the OBE curriculum will have to factor in competencies gained in prior learning. This suggests that international agreements and accreditation requirements can be significant drivers for policy changes and the adoption of OBE.

The findings also highlight the importance of alignment between higher education councils and professional bodies for successful OBE implementation. As argued in the paper, such alignment is crucial for ensuring that curriculum development and accreditation processes support the desired learning outcomes and professional competencies. The varying levels of alignment observed across the countries may explain the different stages of OBE adoption and implementation.

It is important to acknowledge the limitations of this exploratory study. The reliance on anecdotal evidence from the authors' personal experiences and documentary analysis of publicly available information may not be substantial enough to provide a comprehensive picture of the situation. Further research involving

interviews with stakeholders, in-depth case studies, and quantitative data collection is needed to gain a deeper understanding of the challenges and opportunities for OBE implementation in these countries.

Despite these limitations, this study provides valuable insights into the policy landscape surrounding engineering education in the selected African countries. The findings serve as a baseline for further research and can inform policy decisions and strategies for transitioning to OBE. The identification of similarities and differences in policies and guidelines for curriculum development across these countries offers a useful resource for contextual benchmarking and can support regional collaborations and knowledge sharing.

In conclusion, while there is a growing recognition of the importance of quality assurance and alignment with professional standards in engineering education, the transition to OBE is still in varying stages across the selected African countries. Further efforts are needed to develop clear policy directives, enhance collaboration between higher education councils and professional bodies, and provide support for institutions in implementing OBE principles.

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Assessing mentorship of undergraduate students at the University of Johannesburg: A Case-study

Morena William Nkomo
University of Johannesburg, South Africa, mnkomo@uj.ac.za

Katlego Lokhele
University of Johannesburg, South Africa, Klokhele@uj.ac.za

Teresa Hattingh
University of Johannesburg, South Africa, teresah@uj.ac.za

Abstract

The Faculty of Engineering and the Built Environment (FEBE) at the University of Johannesburg (UJ) has used mentoring to support students at the institution. In 2024, these initiatives were centralised and expanded to an integrated mentorship programme across the Faculty. All first-year students in the Faculty are allocated mentors drawn from volunteer senior students who wish to give back to their student community. The study explores the experiences of mentees and mentors in the programme to identify expected and experienced value. Furthermore, it explores and identifies challenges encountered and opportunities for further developing and refining the programme. A survey was conducted, inviting all the mentees and mentors who participated in the mentor programme during 2024. The survey was designed to elicit experiences on the programme from the perspective of the mentees and the mentors. This study presents the findings from the survey and provides insights that could be used to design mentorship programmes in similar contexts. The study also highlights the challenges experienced when implementing a Faculty-wide programme.

Keywords: mentoring, undergraduate, engineering, student success

1 Introduction

1.1 Background

South African higher education is characterised by high attrition and low completion rates in minimum time (CHE, 2022) despite the admission of top school leavers (Smit & Wolmarans, 2010). The system also frequently marginalises those from low socioeconomic backgrounds (Vosloo & Blignaut, 2010). There is also a disparity between secondary schools; fewer than 20% of students at the University of Johannesburg originate from high-performing schools. To mitigate the challenges encountered by first-year students, Tinto advocates for institutional responsiveness (Lim et al., 2017)

Smit & Wolmarans (2010) suggest that first-year students, even those from top-performing schools, struggle as they adjust to the divide between high school and university. First-year students frequently feel overwhelmed by the curriculum, workload, academic integration, and adapting to the environment. These students seek direction and understanding regarding the expectations of higher education (Larose, 2013). Although every student requires support to adapt to university, students who perform poorly require that assistance to an even greater extent (Gibbs, 2012). Mentoring can inspire mutual growth, learning, and development and transform individuals, groups and their broader community (Ragins and Kram, 2007). Peer mentoring aims to provide intentional assistance to first-year students encountering numerous difficulties during their shift from high school to university.

The Faculty of Engineering and the Built Environment (FEBE) has used mentoring to support students at the institution. In 2024, these initiatives were centralised and expanded to a fully integrated mentorship programme across the Faculty. All first-year students in the Faculty are allocated to a mentor. The mentors are drawn from volunteer senior students who wish to give back to their student community. Mentors are trained, and various mechanisms are in place to track progress and receive feedback. There are currently 216 volunteer mentors in the programme, with a ratio of one mentor for every ten mentees.

1.2 Purpose of the study

This study aims to understand how mentoring plays out in the UJ context to identify the value that students extract from the programme and where opportunities lie for further refinement and development. The objectives of the study are to explore:

- The experiences of mentees in the programme and identify the expected and experienced value

- The experiences of mentors in the programme and identify the expected and experienced value
- Challenges experienced and opportunities for further developing and refining the programme.

2 Literature review

2.1 Structure of peer mentoring

Peer mentoring programs are designed to establish a relationship between a more experienced student (or peer mentor) and one who is less experienced (the mentee) and typically involve senior students acting as mentors to younger counterparts (Mullen & Klimaitis, 2021). The responsibilities of mentors can take on various forms, including that of a guide, friend and role model, as they provide tailored support to their mentees (Mullen & Klimaitis, 2021).

2.2 Benefits of peer mentoring

Mentoring programs can increase student engagement, learning and achievement of student outcomes (Abrahamson et al., 2019). Academic improvement is one of the most significant benefits of students who actively engage in mentoring programs (Miller, 2019). The structured support from a mentor can enable mentees to understand better complex concepts and topics, learning approaches and academic culture. Mentors can also show mentees where to access additional resources to reinforce the subjects taught. Mentoring can also support developing or reinforcing good study habits (Mullen and Klimaitis, 2021). Conversely, reflection on study habits that are not working can help the mentee learn from past errors and determine what learning strategies could be adopted instead.

The supportive environment and the relationships fostered through mentoring can also assist with developing personal and social skills (Messmann et al., 2022). Mentors can play an active role in increasing the confidence and motivation of mentees (Carvalho and Santos, 2022). Additionally, skills such as effective communication, active listening, and teamwork can be fostered when peers can discuss academic concerns and collaborate on problem-solving in academics within a social context (Abidjanova, 2024). Such benefits are critical because those who succeed academically often also possess strong social skills (Umarov, 2024). Fostering resilience is particularly important as it can promote mental health and success in other areas.

One significant component of a mentoring relationship is the mental and emotional support a mentor can provide to the mentee (Hill et al., 2022). Mentors can provide a safe space for their mentees to express their concerns and issues they are struggling with, either academically or personally (Miller, 2019; Sarabipour et al., 2022). Personal stresses can include dealing with demanding classes and fulfilling family expectations. For this to happen, the relationship must involve a level of trust where mentees feel comfortable sharing problems they are experiencing, and mentors must strive to be empathetic, compassionate, patient, and supportive. This can improve stress levels and coping strategies (Hammoudi et al., 2023).

In addition to benefits for the mentees, mentors report that mentoring enables them to develop themselves as their relationships with their mentees evolve (Carvalho & Santos, 2022). Mentors often report emotional benefits from being a mentor, such as enjoyment, pride, and personal growth (Chandrasekera et al., 2024; Seery et al., 2021).

2.3 Challenges

Peer mentoring programs are not without their challenges. (Mullen & Klimaitis, 2021). Both students and staff can be resistant to their implementation. Staff can view students as unsuitable mentors due to insufficient knowledge or personal skills or insufficient time due to their own study workloads (Mullen and

Klimaitis, 2021). Staff can also indicate that they personally have inadequate time and/or resources to support students (Miller, 2019). This suggests that, for peer mentoring to be effective and sustainable, safeguards and support structures need to be put in place to protect the welfare of the mentors (Collier, 2023) and improve the sustainability of the programme.

However, not everyone is quick to embrace their role in these mentoring programs. Participants may be held back by common concerns such as fear of judgment, reluctance to take on a mentor role, or a lack of confidence in helping others. (Hill et al., 2022) These concerns can prevent the formation or cause the early termination of mentoring relationships. Educators need to understand these concerns and take steps to alleviate them (Miller, 2019). Recruitment and the idea of becoming a peer mentor are also important. It is recommended that the starting point is introducing the mentoring concept in general and showcasing the benefits through peer testimonials, success stories or quantitative data (Collier, 2023). Furthermore, starting with receiving help by bringing up the concept of being a mentee before asking students to become mentors can alleviate fear (Collier, 2023). It is also critical to foster a culture of inclusivity, diversity and respect, as relationships should be formed in a safe space where students do not feel intimidated or judged. (Zachary and Fain, 2022)

2.4 Measuring effectiveness

Evaluating the effectiveness of peer mentoring relationships can be difficult. Relationship quality, personal growth, and similar benefits are often overlooked as they can be challenging to measure. Traditional assessment methods that target quantitative outcomes may not thoroughly evaluate or monitor the subtle and diverse benefits of a peer mentoring relationship. It is, therefore, recommended that both quantitative and qualitative data be used (McGorry et al., 2022). Eliciting the experiences of mentors and mentees can provide a more transparent view of the actual benefits and challenges (Anderson et al., 2021).

3 Method

3.1 Context

This study was conducted at the University of Johannesburg (UJ) within the Faculty of Engineering and the Built Environment (FEBE). The faculty consists of 12 departments, three engineering science programmes at the Kingsway Campus, and nine engineering technology programmes at the Doornfontein Campus. The peer mentorship programme was purely voluntary and aimed to assist undergraduate students with adjusting to their new environment and navigating university life, thus reducing student dropout and boosting student success and throughput. The faculty appointed a coordinator to manage and oversee the programme. The faculty coordinator was responsible for facilitating and monitoring the recruitment process, organising training and reflective sessions for the mentors, consolidating the feedback from mentors and providing feedback on the programme's progress to the faculty and the institutional mentorship forum.

The faculty anticipates an annual intake of over 2000 first-year students and aims to reach all students through the mentorship programme. As such, 216 students were selected as mentors, and each mentor was allocated a minimum of 6 students and a maximum of 10 mentees. The recruitment of the peer mentors was voluntarily, meaning that all students who showed interest in the programme were well aware that they would receive no compensation for being mentors. It was also communicated to them that they will receive a certificate of recognition upon completion of the programme at the end of the year. The selected mentors were therefore allocated first-year students in their respective departments. This enabled the mentors to assist with their module content if needed. Two training sessions and two reflective sessions were arranged for the mentors; the training sessions were conducted at the beginning of each semester, and the reflective sessions were held towards the end of each semester.

The mentors were also provided with a booklet comprising general and easily accessible information on mentoring. The booklet also touches on planning for effective mentoring, the various aspects of mentors' and mentees' activities, expected roles and responsibilities and the mentoring processes. It also provides valuable, practical guidelines and tips to assist them with planning and implementing their respective mentoring programmes from an informed position. Additionally, WhatsApp was used for daily communication between mentors and mentorship coordinators.

3.2 Data collection and analysis

The first phase of this study elicited the experiences of mentors and mentees in the programme during 2024. Both mentors and mentees were invited to participate in a qualitative survey. A Qualitative survey is a research method used to collect non-numeric data, often through open-ended questions that allow the participants to share their thoughts, feelings and their experiences in detail. The goal is to gain a deeper understanding of participants' perspectives and insights. qualitative research focuses on the meanings, concepts, definitions, attributes, metaphors, symbols, and descriptions of objects. Essentially, when gathering and evaluating data, qualitative research prioritizes meanings (words) over frequencies and distributions (numbers). Furthermore, qualitative research tends to be inductive rather than deductive, which generates theory from the interpretation of the data (Leedy and Ormrod, 2010). The qualitative approach is more exploratory in nature and typically entails. enumerating the voices of the participants through the identification of recurring themes). The survey included a combination of closed-ended and open-ended questions. The survey included questions in five groups: 1) general questions about the number of mentees, meeting times and mentor and mentee details such as year of study and degree studying towards, 2) expectations and understanding of the mentoring process, 3) general topics discussed during mentoring sessions, 4) perceived personal development of the mentoring process, 5) challenges experienced and suggestions for improvement. 62 (n=138) mentees and 28 (n=1360) mentors completed the survey. Participants were not asked to share personal details about themselves, their mentors, or their mentees. Questions also asked for general feedback and not specific confidential information related to any particular mentor-mentee relationship. Ethics clearance was obtained for the study.

The data for the first group of questions were analysed and presented using descriptive statistics to provide context and an overview of the study participants. The open-ended questions for groups two to five were analysed using thematic content analysis. The researcher read the participants' responses, and themes were identified to answer the research question. The emergent themes are discussed in the findings section and supported by participant quotes.

4 Discussion of Findings

4.1 Introduction to the findings

The mentors were spread across degree programmes and years of study. There was one second-year mentor, twenty third-year mentors, five fourth-year mentors and one postgraduate studies mentor. Most mentors indicated meeting with their mentees at least once a week. Some mentors met bi-weekly or monthly, while others stated that they met two or three times per week. Regarding the mode chosen for meeting with mentees, 14 mentors met exclusively in-person with their mentees, four met only online, and the balance used a mixed approach with meetings sometimes taking place on-campus and other times online. Sessions lasted, on average, for one hour, with some mentors reporting meetings that lasted 30 minutes and others that lasted up to two hours. Mentors indicated that they adopted a mixed approach to meeting arrangements, with some group sessions taking place and others taking place one-on-one. Seven mentors indicated they exclusively used group meetings, while five indicated they only met individually with their mentees.

The mentees were also asked to share their experiences of the programme. Of the 62 respondents, 20 indicated that they were never allocated a mentor, that they do not remember being assigned a mentor or that they were allocated a mentor but the mentor never met with them or was unresponsive when they tried to make contact. Of the remainder, eight respondents indicated that they interacted irregularly with their mentors, while 33 said they regularly met with them. For those who interacted with their mentors, most met in person, six met exclusively online, and one indicated a mixed approach. Most mentees stated that they met in groups with their mentors, while seven met exclusively in-person, and 10 had a mixed approach with online and in-person meetings. The following two sections will present and discuss the experiences of the participants, first the mentors, followed by the mentees.

4.2 Mentors' Experience of the Mentorship Programme

Most mentors shared that their understanding of being a peer mentor meant guiding their mentees and assisting them with navigating the transition into their new environment. When asked what motivated them to become mentors, most students expressed that they wanted to share their experience with others, assist the first-year students in adapting to university life, and assist them with challenges they may encounter with their academics. Some mentors indicated that they had a positive experience as mentees in their first year of study, and they wanted to share their knowledge and offer the same assistance they received through the programme to other students. Some indicated they wanted to acquire skills that will better equip them for their personal and professional journey. The mentors indicated that the topics covered during their mentorship sessions included tips on adjusting to university life, managing their time as first-year students, and studying tips and techniques.

> *"In my mentoring sessions with first-year students, we typically discussed adjusting to university life, managing coursework, and developing effective study habits. I also provided guidance on setting academic goals, exploring extracurricular activities, and building time management skills. Additionally, we often talked about overcoming challenges, staying motivated, and making the most of available campus resources"*

Although some mentors indicated that they experienced no challenges throughout the programme, most participants have outlined challenges they encountered as peer mentors. These challenges commonly included reluctance from mentees to participate or engage during their sessions, poor attendance from mentees and challenges with balancing their mentoring duties and other academic responsibilities. The mentors expressed that some mentees showed little or no interest in the mentoring programme. As such, they had to build trust with their mentees by creating a safe space for them to express their challenges and concerns. They shared their experiences with their mentees, engaged them on private platforms and not only on WhatsApp groups, and had regular check-ins with the mentees, especially those who were less interactive during their sessions. The mentors also focused on building meaningful relationships with their mentees, allowing first-year students to share their concerns and ask questions during their sessions while actively listening to them. Furthermore, the mentors established and maintained a sense of community and belonging by encouraging open communication and creating a welcoming environment, which contributed significantly to the success of the mentoring relationship.

> *"Yes, I encountered some challenges as a mentor. One challenge was engaging mentees who were initially hesitant to open up or actively participate in sessions. To address this, I focused on building trust by being approachable, empathetic, and sharing my own experiences.*
>
> *"Another challenge was balancing mentorship responsibilities with my own academic workload. I tackled this by staying organized, setting clear boundaries, and effectively managing my time. I viewed these challenges as opportunities to grow and adapt as a mentor."*

The mentors have reported significant improvements in their mentees. Most felt that their mentees developed increased self-confidence, improved communication skills and were better at managing their time than at the beginning of the programme.

Moreover, when the mentors were asked how the mentorship programme had contributed to their well-being, most mentors expressed that they experienced an increased sense of fulfilment and purpose and improved self-awareness. Some other skills they reported to have acquired are effective communications, strong leadership, improved time-management, and enhanced problem-solving skills. The mentors have further learnt to be kind and patient, developed a sense of empathy towards other students and people in general and learnt the importance of fostering meaningful relationships.

> *"Over the mentoring period, I noticed significant growth in my mentees. Many became more confident in navigating university life, managing their time effectively, and setting clear academic and personal goals. They also grew more comfortable seeking help when needed and utilising campus resources."*

Regarding the suggestions on improving the mentorship programme, some mentors highlighted the importance of providing more structured training for mentors and mentees at the beginning of the programme. They also expressed the significance of having regular feedback sessions with mentors to share their experiences and challenges. Some suggested that the sessions be held monthly or at least once each term. The mentors further highlighted the importance of notifying the first-year students about peer mentorship and allocating them mentors during the orientation week. Some mentors also felt that the mentorship programme should be made compulsory for first-year students.

4.3 Mentees' Experience of the Mentorship Programme

The overall feedback received from the mentees regarding the mentorship process was positive. Most mentees suggest having significantly benefited from the programme. In contrast, others proved to have not benefited at all because they were not allocated any mentors. The mentees generally have a similar understanding of what mentorship entails and the role played by the mentor. They have expressed their knowledge of a mentor in their context as a senior student who provides guidance and support and assists them in navigating through their personal and academic challenges. The data reveals that mentees mostly received educational assistance from the mentorship process. When asked to describe ways their mentors have assisted them, most mentees indicated having received a lot of support and guidance regarding their specific academic content.

> *"He assisted me with my studies especially with difficult modules, helped me with time management and getting the appropriate study material when needed"*

> *"He helped us with getting used to our campus, he showed us around campus during orientation, was very nice and approachable. He helped us with past papers and schoolwork, he also gave us online textbooks he used the year before. He advised us of what we should expect from our lecturers. I have managed to get a distinction because of her""*

Most of the mentees revealed that they learnt a lot from their mentoring experience. Some have learned that it is okay to ask for help, while some have learnt how to receive assistance from others. Moreover, based on the experiences that were shared with them, the mentees have also learned how to work smart and have gained a deeper understanding of how to navigate through academic and personal challenges effectively. Regarding their well-being, some mentees attested that mentoring has assisted them in maintaining a balanced lifestyle, gaining self-confidence and developing healthy and sustainable coping mechanisms. However, some mentees have expressed that they have not experienced any noticeable or significant change to their well-being.

> *"Having a mentor has positively impacted my personal well-being by providing a sense of direction and reassurance. Her constant support has helped me manage stress, stay motivated, and build resilience in the face of challenges. This guidance has boosted my confidence and helped me maintain a balanced approach to both personal and academic growth"*

While some of the mentees have indicated they have not experienced any difficulties or challenges, most have shared some of the challenges they encountered in their mentoring process. Some mentees expressed their dissatisfaction with their mentors. They maintain that their mentors were sometimes unreachable and could not answer their requests or questions. They have also alluded that their mentoring sessions would sometimes be scheduled during class times and that they would not be able to attend them. Furthermore, they have suggested that mentors arrange virtual sessions that do not clash with their academic responsibilities. The mentees also indicated that the faculty does constant follow-ups to ensure the mentors are organising and attending their mentoring sessions. Another suggestion is that mentees be allocated their mentors before the commencement of the academic calendar so that they can know who to contact and how to contact them.

4.4 Limitations of the mentorship programme and the research study

This study focused solely on how undergraduate mentoring plays out in a specific South African context. The response rate from participants was relatively low and may not represent the whole experience of all mentors and mentees. Furthermore, it was apparent from the findings that many students responded to the survey because they had never successfully connected with their mentor or mentee. This is an interesting finding as it shows that it is possible for the coordinators of a programme not to know the extent to which certain aspects of a programme are ineffective. This further highlights the need to engage with the students and not to take for granted that they will voice their concerns if not prompted to do so.

5 Conclusions and Recommendations

The study revealed that mentoring can result in benefits for both the mentees and the mentors, as supported by literature. These benefits included those related to the development of social skills (Messmann et al., 2022; Carvalho and Santos, 2022), the transition to university and associated coping mechanisms (Mullen and Klimaitis, 2021), managing stress and well-being (Hammoudi et al., 2023; Hill et al., 2022) and resources to support academic achievement (Mullen and Klimaitis, 2021). The study also confirmed findings from the literature that peer mentoring can be beneficial to the mentors as well as the mentees (Carvalho and Santos, 2022). The study further revealed the value that can be obtained by eliciting the experiences of mentees and mentors on the programme (Anderson et al., 2021). The experiences confirmed that the peer mentoring programme has value and can be further leveraged by addressing the identified challenges.

Although many participants expressed that the programme had made a positive difference in their lives, a significant portion were disillusioned by the programme. It is not uncommon for mentoring programmes designed to support at-risk students to result in mentors and mentees who feel personally unfulfilled with their experiences (Moeyaert et al.,2021). The mentors of underprepared students at higher education institutions often express high levels of frustration and insecurity (Schwehn,2022). In many of these cases, these experiences can be traced back to a lack of recognition, compensation and formal training and support (Carvalho & Santos, 2022; Merga & Mason, 2021).

In contrast to the existing literature on peer mentoring in higher education, which focuses on one-on-one or small group mentoring, this research suggests that peer mentoring of larger groups can also play an important role in assisting students to transition to higher education in engineering. The description of the program and benefits students derived from it offer other institutions with limited resources some ideas

about how a peer mentor program can be implemented. Peer mentoring is a powerful strategy to enhance student success and engagement in higher education. By connecting students with experienced peers, colleges and universities can foster academic achievement, boost retention rates, and create a strong sense of belonging.

For this case study, it is recommended that formal mechanisms be implemented to track all first-year students throughout the year to ensure that they have functioning access to a mentor. To address the initial anxiety first-year students experience when they first encounter the university environment, furthermore, peer mentors need to be incorporated into orientation day programs. To benefit the students even further, the peer mentor program should be implemented during the initial weeks of the academic year.

The findings revealed that many first-year students were not aware of the peer mentoring programme, and if they were, they did not know how to reach out if they did not have a mentor. Better marketing and communication need to be established so that students can easily reach out throughout the year. It is also recommended that more regular check-ins with mentors take place and that, through formal feedback and engagement, the programme is adapted throughout the year to address issues and challenges. Overall, the study has revealed that peer mentoring can make a difference in addressing the difficulties experienced by first-year engineering students at South African higher education institutions. The experiences of the participants can be used by other institutions to consider, design and implement their mentoring programmes.

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The ANCHOR Framework: A Holistic Approach to Transdisciplinary and Regenerative Built Environment Education

Calayde Davey
University of Pretoria, South Africa, calayde.davey@up.ac.za

Abstract

This paper introduces the ANCHOR Framework, a transdisciplinary pedagogical model for Built Environment (BE) education, developed over a decade of iterative reflective practice (2020-2025). It addresses how conventional BE education, constrained by rigid, discipline-specific paradigms, leaves BE graduates ill-equipped for contemporary complex and systemic regenerative challenges. Utilising Schön's reflective practices, the framework integrates ontological reframing (e.g., "waste" to "discards"), Lean practices, and systems thinking to cultivate paradigm agility. Data from practioner-led reflective cycles, student artefacts, and institutional feedback demonstrate enhanced student performance and disciplinary maturity. This pedagogy promotes cross-skilling, collaborative and transdisciplinary inquiry, and increase in student motivation for advanced, discipline-adjacent topics like circular economy or regenerative design. The ANCHOR Framework aims to prepare Built Environment graduates to move from siloed disciplinary thinking to actively navigating 'wicked problems' in interdisciplinary teams within transdisciplinary learning environments. This outcome of ANHOR aims to bridging the academic-industry gap by fostering collective adaptive reasoning and leadership for sustainable transformations. This practitioner-led reflection also highlights the need for broader applicability testing and further development.

Keywords: transdisciplinary education, built environment education, paradigm agility, reflective practice, regenerative futures

1 Introduction

1.1 Implications of conventional BE education for transdisciplinary, regenerative practice

Conventional Built Environment (BE) education, constrained by rigid and discipline-specific paradigms, leaves graduates ill-equipped for the complexities of true sustainability challenges (Fry, 2009; Wiek et al., 2011). Many professionals struggle to integrate new sustainability frameworks (such as the circular economy) with established practice protocols (Geissdoerfer et al., 2017). Tackling complex, real-world problems requires teams that can learn from each other fast (cross-disciplinary), integrate diverse skills and perspectives (interdisciplinary), and, ideally, co-create innovative solutions with societal relevance (transdisciplinary) (Brown et al., 2010; Klein, 2021; Oliveira et al., 2022) see Table 1). Yet, BE education remains largely confined to disciplinary learning (Dorst, 2018; Oliveira et al., 2022), failing to provide new competencies that go beyond conventional BE education (including shared values, social engagement, and integrated cognitive adaptability), which are needed for a just and regenerative industrial transition (du Plessis, 2024; Wiek et al., 2011) While transdisciplinary research is widely discussed (Brown et al., 2010; B. C. K. Choi & Pak, 2007; Wardani et al., 2024), there is a critical lack of practical guidance for educators on how to implement transdisciplinary learning in BE higher education, where industry projects are inherently transdisciplinary yet teaching remains siloed (Dorst, 2018; Klein, 2010; Oliveira et al., 2022).

Table 1. Distinctions between various types of disciplinary learning.

Approach	Definition & Scope	Sources
Disciplinary	Single academic field, using its unique theories and methods.	Dorst (2018); Oliveira et al. (2022)
Cross-disciplinary	One discipline applies its perspective to another's topic, borrowing tools without integration.	Brown et al. (2010); Klein (2021)
Interdisciplinary	Integrating knowledge and methods from two or more disciplines to address a shared question.	Brown et al. (2010); Klein (2021); Oliveira et al. (2022)
Transdisciplinary	Creating new knowledge, transcending individual disciplines, integrating non-academic stakeholders.	Brown et al. (2010); Choi & Pak (2007); Wardani et al. (2024); Oliveira et al. (2022); Klein (2010)

A practical transdisciplinary BE education framework is needed to move from disciplinary mastery to collective adaptive reasoning, thereby addressing the complex 'wicked problems' of contemporary BE industry. This paper proposes a new BE pedagogy with emerging, practitioner-reported evidence of impact, using Schön's (1983) reflective method to trace a decade-long evolution in my teaching in industry and higher education settings.

2 Method

This paper's method utilizes Schön's (1983) reflective practices, namely, reflection-in-action (real-time adjustments), reflection-on-action (post-activity analysis), and reflection-for-action (shaping future teaching iterations). Supported by principles of narrative inquiry (T. H. Choi, 2013; Ellic & Bochner, 1999; Wall, 2006), the analysis draws from a decade of experience as an industry and higher education educator, with a specific focus on the last five years (2020–2025) in a Global South Built Environment (BE) school. The reflections draw on classroom interactions, student performance, and external recognition to address the need for new educational models that equip students to tackle regenerative challenges in the BE collectively. The paper explores a central question:

How can a transdisciplinary Built Environment pedagogical framework cultivate the paradigm agility and competencies needed for systemic regenerative challenges?

This is investigated through three sub-questions:

1. SQ1: What pedagogical practices, shaped by industry and educational reflections, bridge the gap between conventional BE education and the needs of the contemporary BE industry?
2. SQ2: How could strategies from high-performing BE industry teams enable transdisciplinary learning environments in BE curricula?
3. SQ3: What evidence demonstrates that such a pedagogy has meaning or impact within and beyond the classroom?

3 Reflective analysis using Schön's framework

To perform the reflections, data were drawn from reflective practice cycles (journaling, peer engagement, curriculum review, direct teaching observations, and classroom dialogue), anonymised student artifacts (mapping exercises, open online exams, class projects, written motivations), and institutional feedback and public recognitions (external evaluations, teaching recognition). Materials were triangulated and reviewed qualitatively against three sub-questions to trace patterns in my pedagogical evolution, shifts in student framing ability, and the proposed pedagogical framework development over time.

3.1 SQ1 Reflection: Facilitating transdisciplinary BE classrooms on wicked-problems.

Drawing from reflective practice, particularly over the past five years, I have found a deep need for a shift in both mindset and pedagogy to address BE "wicked problems." (Brown et al., 2010; Rittel & Webber, 1973). This urgency stems from two intertwined challenges: the increasing societal pressure from emerging industrial paradigms (from 4th to 6th Industrial Revolutions) against the persistent rigidity of conventional BE educational models. The following reflections explore this through societal, educational, and industry contexts.

Societal context: challenges for integrative and regenerative BE education

BE challenges are complex "wicked problems" requiring more than technical fixes (Goel, 2019). The global construction sector illustrates this, accounting for 36% of final energy use, 39% of CO_2 emissions (Abam et al., 2023; Antunes et al., 2024) and raw material waste consuming up to 60% of extracted resources (Schützenhofer et al., 2022). With building energy consumption projected to reach 50% of global use by 2030 (Huyen Nguyen et al., 2024), regenerative and transdisciplinary solutions are critical. Addressing these challenges (from redefining waste to applying 4th–6th Industrial Revolution innovations) demands agile, systemic thinking and genuine transdisciplinary collaboration from BE professionals.

Educational context: BE learning structures reinforce paradigm rigidity

Traditional BE education emphasizes single-discipline mastery, with accreditation standards and assessment rubrics that prioritize technical proficiency and individual authorship over systems thinking and collaborative inquiry (Altomonte et al., 2014; Webster, 2008). This linear theory-to-application approach entrenches fixed paradigms and limits the integrative thinking essential for addressing complex sustainability challenges (Wiek et al., 2011), while cognitive research highlights that paradigm-switching demands up to 37% more mental effort (Kahneman, 2011). Thus, conventional BE education is generally poorly equipped to train students in the cognitive agility and integrative thinking necessary to tackle complex systemic challenges collectively.

Industry context: techniques of high-performance BE teams

Through reflective practice and industry experience, I noticed that high-performing BE teams use systems thinking, Language–Action (LAT) frameworks, Lean learning, and collective leadership to navigate "wicked problems". These approaches are critical for driving innovation, transdisciplinary collaboration, and informed decision-making. However, traditional BE education often neglects these competencies or isolates them within discipline-specific silos, leading professionals to acquire them informally, much late in their careers, and typically only through specialized organizational training.

3.2 Reflections on SQ1

The rigidity of conventional BE education and its neglect of high-performance team competencies has created a critical gap between what the industry demands to solve "wicked problems" and what BE education provides. To close this gap, I performed a critical practice reflection on shared issues from both settings.

Reflection-in-action: The importance of real-time facilitation through active language alignment

In both industry and education settings, the most important real-time adjustments in learning sessions involved translating terminology to build a shared understanding and align behaviours. I found that many high-performing teams use similar techniques but fail to recognise this due to differences in disciplinary language. A facilitator is therefore critical in redirecting the focus from competing definitions to collective action, ensuring attention remains on the common problem rather than disciplinary preferences.

Reflection-on-action: Shifting hesitation to embodied habit.

A key insight is that even experienced professionals, while readily adopting iterative practices and intuitive interdisciplinary communication, can still exhibit behavioural blind spots or hesitation without a facilitator. Conversely, students are often hesitant to respond in real-time due to fear of judgment, which inhibits learning and creativity. In both cases, regular real-time observation and feedback are essential to move from these mental hesitations to embodied practices, underscoring the critical role of active facilitation.

Reflection-for-action: Establish conceptual shifts early through LAT and Lean scaffolds

Early in my practice, I introduced full Lean innovation frameworks upfront, which often overwhelmed participants and diluted engagement. Over time, I began to build learning from the ground up instead, applying only foundational *Kaizen* principles to the learning process itself to sustain momentum that support open-ended, collaborative problem-solving. Similarly, instead of gradually introducing Language-Action Theory (LAT), I now begin with reframing shared issues from the start (for example, immediately replacing the word "waste" with "discards.") These adjustments have greatly improved clarity and engagement in both academic and professional settings.

Concluding reflection on SQ1

These reflections expose a critical gap between the BE industry's needs for addressing "wicked problems" and what conventional BE education delivers. Rigid, single-discipline BE pedagogy leaves graduates ill-prepared for the agile, collaborative solutions required in practice. Closing this gap demands a fundamental shift in educational practice, beyond simply adding new topics in curricula. Reflection-in-action showed me the value of translation between disciplinary languages to build shared understanding across diverse participants. Reflection-on-action revealed that student and professional hesitations can be overcome through real-time facilitation and demonstrations of intentional, embodied practice. Reflection-for-action led me to replace top-down practices with foundational principles. Early language reframing (e.g. shifting from "waste" to "discards") enabled quicker confidence and engagement from the outset. The reflections show that an effective transdisciplinary BE teaching framework must be deliberately scaffolded, actively facilitated, open, and iterative, converting theory into collaborative, embodied practice. This approach could shift students from passive recipients of siloed knowledge to active navigators of complex challenges, equipping them to better lead the transition toward a regenerative future.

3.3 SQ2 Reflection: Developing a transdisciplinary pedagogy in Built Environment education

Building on SQ1 reflections, I developed a transdisciplinary BE teaching framework integrating Language–Action Theory (LAT), Lean practices, and systems thinking. It aims to build paradigm agility, preparing students to work collaboratively in inter- and transdisciplinary teams on complex, real-world challenges. The following sections outline the framework's development and techniques.

Creating paradigm-agility through *LAT,* Lean learning, and systems thinking

The pedagogy unfolds over a multi-module (Table 2). Modules are formally implemented in a postgraduate architecture program with voluntary transdisciplinary participants (including engineering, urban planning, geography, real estate, quantity surveying, including engagement with professional and community stakeholders). Modules are in 6-week learning cycles, and sub-sections outline pedagogical tools used.

Table 2. Course design and teaching integration.

Module 1 (e.g. Urban Strategy Course)	Modules 2-4 (Postgraduate Research)
A collective design course focused on real-world challenges. Students use ontological reframing, fieldwork, and stakeholder engagement to develop creative, conceptual solutions.	An extension of Module 1 where students, both formal and voluntary, align their individual disciplinary research with a shared transdisciplinary challenge. This enriches individual outcomes with broader insights while maintaining disciplinary integrity.

While architecture students are formally enrolled, external students can attend without formal enrolment (Figure 1a). Students are encouraged to align their core disciplinary focus with the larger cohort's transdisciplinary problem, working with their own supervisors to achieve their pedagogical outcomes. This flexible structure removes the need to change modules, registrations, or curricula. It also allows international opportunities (Figure 1b), enabling students to work with peers abroad and participate remotely without restructuring their local modules (Davey, 2024).



Figure 1 a) Example of a transdisciplinary classroom environment, where architecture, engineering, geography, industry, and community stakeholders collaboratively explore a shared challenge and learn techniques together.



Figure 2 b) A flexible multi-module structure enables parallel international transdisciplinary collaboration, where diverse students can contribute to a common project remotely across disciplines without disrupting local modules or curricula.

Ontological reframing through Language-Action Theory *(LAT)*

Building on the principle that language shapes reality (Flores, 2012) the pedagogical process begins with ontological reframing through Language-Action Theory (LAT). To illustrate, this example presented here uses the conceptual idea of a "Zero Discard City" to address transdisciplinary challenges of circularity and waste recovery in the BE. Traditionally, urban waste is framed as a production or management issue, leading to fragmented, shallow solutions like "bigger landfills" or “faster recycling systems.” Such symptomatic and shallow solutions perpetuate the problem's wickedness. This limited perspective stems from entrenched language that treats "waste" as an external by-product and "someone else's problem" (Davey & Macomber, 2017; Liboiron & Lepawsky, 2022). In reality, waste is a holistic, systemic issue affecting all of society.

To address this, the pedagogy combines strategic language shifts with a structured goal-setting process that uses Lean practices like *Hoshin Kanri* and a simplified *Toyota Kata* (Davey & Macomber, 2017). Each learning cycle begins by introducing new language to redefine concepts and foster a shared commitment among diverse students. For instance, reframing "waste" as "discards" (Liboiron & Lepawsky, 2022) helps students

see potential value where conventional paradigms see only by-products. This intentional shift challenges fixed assumptions, fostering creative, systemic, and regenerative problem-solving. This new shared lexicon also reframes other key concepts. For example, “Failure” becomes “Iteration” (redirecting emphasis from mistakes to continuous improvement), or “Demolition” becomes “Harvesting” (underscoring untapped potential in resource recovery). Table 3 demonstrates other teacher-facilitated LAT shifts.

Table 3: Example of contextual Language-Action (LAT) shifts.

Technique	Before	After
Ontological Reframing	Disciplinary assessment: "Waste" is a useless by-product of a project/industry/practice to be disposed of, with no inherent value to anyone.	Transdisciplinary declaration: "Discards" are materials-in-transition with latent value, creating possibilities for reuse for all.
Commitment Mapping	Conventional commitment: "*My* work/project is done once my disciplinary task is complete, regardless of the by-product/consequence. This is my commitment only.”	Integrated commitment: "*Our* work/project is done when *our* 'by-product/consequence’ from the project/discipline are passed on with its known latent value for the next project/discipline, creating a chain of commitments."
Trust Cultivation	Assessment that erodes trust: "Dealing with 'waste' is a burdensome cost on everyone, someone else’s problem, and reduces our economic efficiency."	Assessment that builds trust: "Repurposing 'discards' creates economic, systemic, and environmental opportunity, making us collectively more resourceful."

This new shared language aligned diverse students to one common goal, streamlined communication, reduced definitional conflict, and fostered the collective thinking needed for responses to complex challenges. By deploying targeted LAT to real-world contextual problems (see Table 3), students are encouraged to recognize inefficiencies and potential in all aspects of human activity. This challenges the idea that a complex systemic problem (“waste”) is an inevitable, external problem and promotes holistic solutions instead.

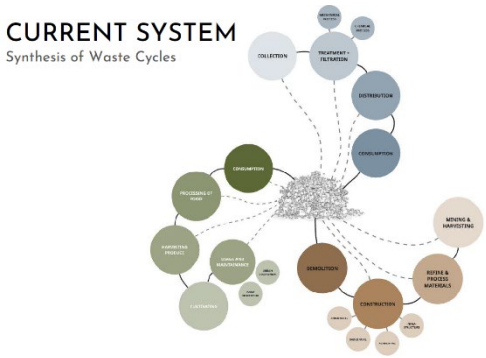

Figure 3a) student artifact showing initial grasp of disparate systems (team colours) and disciplinary contributions to the contextual problem.

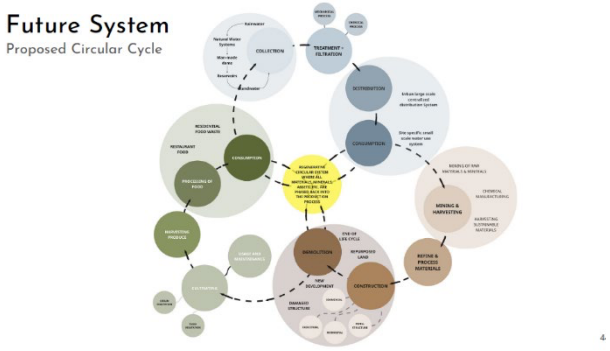

Figure 3b) 2025 student artifact showing final grasp of integrated, regenerative solutions (team colours) to the contextual problem.

This approach moves students from a paradigm of siloed 'waste-producers' to collective 'waste-finders' by reframing 'waste' as a shared challenge. This helps them transition from generating isolated, symptomatic solutions (Figure 3a) to identifying integrated, systemic root causes (Figure 3b). When reframing a shared challenge, students shift from proposing isolated, symptomatic solutions (Figure 3a) to addressing it by identifying integrated, systemic root causes (Figure 3b). Such a paradigm shift fosters transdisciplinary accountability and drives integrated, creative problem-solving (Davey & Macomber, 2017). Real-world stakeholders are invited to adopt this shared language, reinforcing collective commitment to addressing challenges and enabling a holistic environment for transdisciplinary, vicarious learning. As noted by Flores and others (Davey & Macomber, 2017; Flores, 2012; Spinosa et al., 1999), collective reframing is vital for cultivating a culture of continuous improvement and systemic innovation in organisations.

Holistic problem-framing with systems thinking and *Kaizen*

To deepen the learning process, I introduce systems thinking as foundational cognitive tool for holistic, contextual analysis. Students learn to deconstruct and frame complex problems through root-cause exploration, and recognize the interdependence of factors (such as competing stakeholder priorities, material flows, design or operational constraints) by creating systems maps together. This framing reinforces the "waste-finding" ontology and shifts student perspectives from "what is my disciplinary role" to "how can I contribute to solving the larger systemic problem" instead. Through weekly iterative development, guided by *Hoshin Kanri* and *Toyota Kata*, students cultivate a *Kaizen* mindset of continuous improvement. Regular reflection and adaptation cycles reinforce collective inquiry, adaptive learning, and systems-level engagement.

Strategic collective goal-setting with *Hoshin Kanri* and *Toyota Kata*

After initial *LAT* reframing, I use Lean-inspired goal-setting with *Hoshin Kanri* and simplified *Toyota Kata* (Davey & Macomber, 2017) to make wicked problems like urban waste actionable. *Hoshin Kanri* aligns broad transformative goals (e.g., a 'Zero Discard City') across disciplines, while *Toyota Kata* guides students' day-to-day learning and solution development. For example, students are confronted with projections of a 70% urban waste increase by 2050 (Purohit, 2021). They then use a shared concept (e.g. "Zero Discard City") as countermeasure to the real-world problem and set it as their global strategic imperative (Figure 4a). Following that, they translate this global objective into smaller, measurable target conditions that address real-world design and operational challenges in teams (Figure 4b).

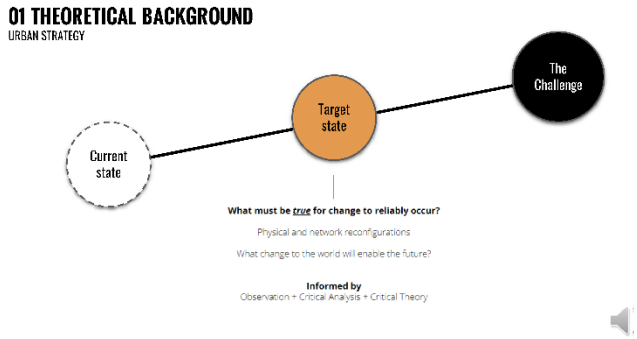

Figure 4a) 2024 Student artifact showing their theoretical understanding of *Toyota Kata* as a collective global strategic imperative.

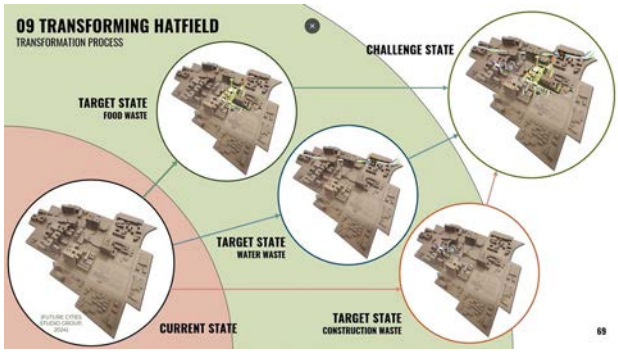

Figure 4b) 2024 Student artifact applying *Toyota Kata* to translate global objectives into measurable team targets for real-world design or operational challenges.

For example, instead of a vague goal like "society must reduce food waste," a student sub-team might target an "85% source-separated organic collection rate" for a specific urban district. This precision, emphasized in Lean leadership routines (Davey & Macomber, 2017) fosters concrete, disciplined planning while enabling flexible pathways to achieve the broader objectives central to *Hoshin Kanri*. Students continue to develop their own benchmarks based on observations and field data, balancing ambitious systems-level thinking with pragmatic, iterative improvements. Different disciplines and stakeholders contribute their unique skills and knowledge to solve the same problem, combining aspirational leadership visions with disciplined, data-informed action.

Cultivating continuous improvement with *Kaizen*

Weekly *Kaizen* coaching fosters continuous, iterative learning, showing students that ambitious targets require both individual initiative and collective wisdom. With a Socratic style, I introduce Lean improvement *Katas* such as "Go See" (direct observation), "Make One Small Change" (incremental improvements), and "Ask Why Five Times" (root-cause analysis) (Davey & Macomber, 2017). These Lean techniques help students develop technical solutions and the leadership behaviours needed for systemic change. Weekly stand-up

meetings and peer coaching sessions allow them to refine strategies as new project data emerge, reinforcing the *Hoshin Kanri* and fostering leadership, creativity, and adaptability.

3.4 Reflections on SQ2

Reflection-in-action: Embed *Kaizen* through practice rather than terminology

Early in my practice, I introduced *Kaizen* through the classic Demings' *Plan–Do–Study–Act*/*Check* cycle (Davey & Macomber, 2017; Moen, 2009), believing that explicit verbalizing and strict structure would make such techniques easier to learn. I tended to focus on the dominant discipline in the room (often, architecture). However, this approach created cognitive overload, both for architecture and especially non-architectural students. I responded by phasing out explicit terminology and instead embedded Lean techniques through guided in-class Socratic questions, allowing students to engage more intuitively from their own perspective.

Reflection-on-action: Evolve collective goal-setting strategies for transdisciplinary creativity

I reviewed student engagement and module outcomes through formal quarterly and annual reviews. Each year, I introduced a new thematic challenge to observe student responses to applied teaching techniques. Between 2018 and 2022, I used *Toyota Kata* goal-setting method only, but found it too rigid for complex systemic problems. In response, I gradually shifted to a more flexible combination of *Hoshin Kanri, Toyota Kata*, and *Kaizen*, while also formally introducing systems thinking to the course. This combined toolset better supported transdisciplinary creativity and overall problem-solving.

Reflection-for-action: Deploy deliberate speech transformation acts to build common ground

From 2020, I began slowly incorporating *LAT* by modelling deliberate speech acts. Initially too subtle, this approach gained most traction by 2023–2025 when I focused on making this practice narrow and explicit Instead of focusing on a broader vocabulary, I started focussing only on one transformative language shift (for example, from *"waste"* to *"discard.")* This, alongside the introduction of *Hoshin Kanri,* greatly improved student creativity, focus, and commitment. These shifts directly informed the development of this papers' proposed teaching framework, which centres on cultivating paradigm agility and regenerative competencies within transdisciplinary learning environments.

Concluding SQ2 Reflections

The pedagogical shifts emerged through iterative refinement. Early use of explicit Lean terminology caused cognitive overload and was too rigid for solving complex problems. A flexible combination of *Hoshin Kanri, Toyota Kata,* and *Kaizen*, alongside systems thinking, proved more effective. Focusing explicitly on a single transformative language shift (e.g., "waste" to "discard") was more impactful than subtle language reframing. Reframing a "Wasteful City" as a "Zero Discard City" and applying a strategic process for collective goals helps students move from isolated objectives to shared, actionable targets. This approach fosters interdisciplinary collaboration and cross-skilling, developing BE graduates' adaptive, systemic thinking and preparing them to drive regenerative change in industry.

3.5 SQ 3: Outcomes, student engagement and real-world relevance

The positive impact of this pedagogical approach is evidenced by enhanced student performance, higher-quality academic research, and recognition both within and outside the university. The following reflections are reflection-on-action only.

3.6 Reflections on SQ3

Academic performance and external examination feedback

From 2022 to 2025, students consistently achieved an average external exam score of 75% (academic A), reflecting sustained engagement and mastery of complex transdisciplinary concepts. Annual reviews by external industry examiners confirmed the pedagogy's academic and real-world value. The recent 2025

external examiner report confirmed the pedagogy's value, noting that students were "significantly prepared for the world" and "were able to demonstrate inquiry into some complex topics" and "really engaged with the subject and the process" (Department of Architecture, 2025).

Transdisciplinary learning environments fosters disciplinary maturity, collaboration, cross-skilling, and mutual respect

This approach guides students from a shared, transdisciplinary starting point to focused, enriched disciplinary outcomes. These pedagogical scaffolds support their first encounters with learning beyond their own fields, helping them build core competencies without being overwhelmed. This foundation enables joint fieldwork, collaborative inquiry, and network building, mirroring real-world industry projects. When returning to their home disciplines, students produce work that is richer, more relevant, and better contextualised, informed by an understanding of their own value within the larger effort in solving complex transdisciplinary problems. The approach's positive trajectory is illustrated by architecture student feedback and subsequent research choices. Following a transdisciplinary mapping activity on construction waste, many students pursued advanced research beyond conventional architectural practice, demonstrating a newfound confidence and motivation in discipline-adjacent topics. Student feedback (2025) confirms this, indicating their experience ignited interest in new topics like circular economy, material innovation, or regenerative design (Table 4).

Table 4. Student motivations for joining advance research units (Department of Architecture, 2025).

Student Interest	**A sample of excerpt from student responses**
BE Circularity	*"…As I developed my understanding of the implications of our waste patterns, my appreciation for our decision-making and intentionality around materials and systems has grown significantly…"*
Material Innovation	*"…collaboration between agriculture and the built environment is a compelling prospect, as both fields may help resolve each other's dilemmas. To utilize agricultural byproducts as construction materials is an exciting possibility that I would enjoy researching and applying in future studies and practice. Regenerative thinking is essential for the future development of both fields…"*
Technology & Systems	*"My participation in the [2025] class…ignited my interest in advancements in technology, shifts in production, and evolving ways of living that shape the built environment…"*
Waste-to-Resource	*"… focus on mapping existing material flows and exploring opportunities for integrating agricultural outputs into construction and urban development strongly aligns with my interest in transforming waste systems into a circular, net-zero model. My current research into construction waste and insights from the biomass waste group have sparked my interest in converting waste into a resource and product. I am eager to explore this framework further to advance my understanding…"*
Advanced Futures	*"…I am keen to contribute to a more sustainable, technologically advanced future — whether through research or practice. The systems thinking and research done [in class] have been incredibly informative… I feel as though I already have a springboard to embrace this new research…"*
Ecological Integration	*"…I have become fascinated by ecological integration and the potential of bio-based materials... I believe I am well-suited to engage with this research due to the skills and passions I have developed through my experience [in class], which has provided me with a strong foundation in systems thinking."*
Regenerative Design	*"…by participating in this research field, we can lead the shift toward regenerative design…redefining how cities are built and how they interact with surrounding ecosystems… incredibly interesting to research not only ways to reduce harm and waste but also how to create a built environment that actively restores. This transformative area…would be an honor to participate in."*

This teaching approach naturally fosters genuine transdisciplinary collaboration and peer-led learning. For example, in 2023, architecture and engineering students initially struggled to translate field data into digital BIM models (Figure 5a).



Figure 5 a) Architecture, engineering, and geography students collaborated with industry and heritage stakeholders to translate material reuse from the field into BIM model.



Figure 5 b) Student-led, multidisciplinary "flipped classroom" where quantity surveying students voluntarily joined the project and remained actively involved throughout the year.

Driven by curiosity, quantity surveying students voluntarily joined the module, contributing cost estimation and Life-Cycle Assessment expertise that deepened the group's rigor and built mutual respect through cross-skilling (Figure 5b). Their collaborations spontaneously evolved into a "flipped-classroom" model, where students taught each other core disciplinary concepts. Rather than using separate digital disciplinary models, students started integrated shared tools and plugins into one common model to address common questions (e.g., combining design, costing, and structural assessment). This cross-skilling reshaped disciplinary perspectives, enhancing critical thinking and problem-solving for all participants, including observing industry professionals and the teaching team.

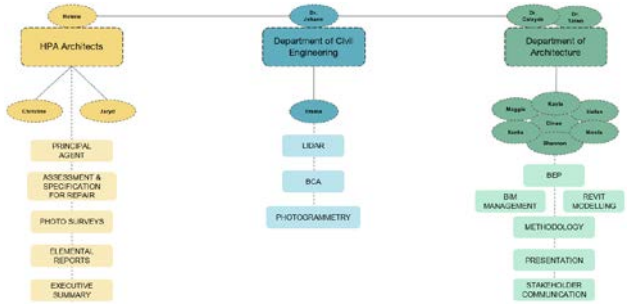

Figure 6a) 2023 Student artifact: Week 1 flowchart showing their understanding of roles within a conventional, siloed, and vertical project structure with missing stakeholders.

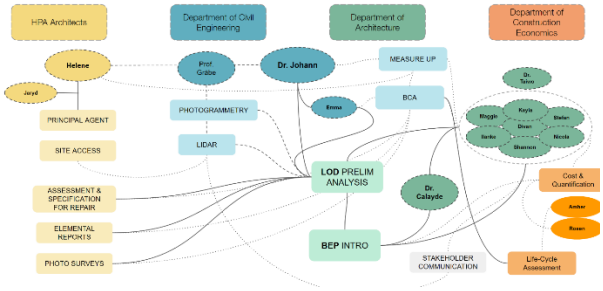

Figure 6b) Student artifact: Week 3 flowchart showing students' shift to a value-driven, skill-sharing lateral structure that dissolves traditional disciplinary silos, and includes missing stakeholders.

Initially, students viewed their contributions through disciplinary silos, as reflected in their original work structure (Figure 6a). However, this understanding evolved into an integrated, value-driven flowchart (Figure 6b), demonstrating the dissolution of disciplinary boundaries. This shift resulted directly from the transdisciplinary learning environment, which fostered genuine collaboration through learning-by-doing-together. Developing a deep respect for their peers' specialized knowledge, students actively sought and integrated multidisciplinary insights to a transdisciplinary problem, producing work that more accurately reflected the complexities of real-world practice.

Institutional impact, recognitions and real-world response.

The success of this approach is reflected in local and international teaching recognition, including Faculty and University *Institutional Teaching Awards* and the *2023 Quanser Global Sustainability Award for Engineering Education.* These recognitions affirm the framework's practical relevance and its capacity to prepare BE

professionals for real-world challenges. The teaching process also influenced the university itself, for example, prompting updates to waste policies in line with zero-waste tactics and restructuring operational BIM practices to support integrated workflows.

Concluding SQ3 Reflections

This teaching approach creates a safe-to-fail, experimental transdisciplinary environment for BE education, incubating transferable skills and generating value beyond the classroom. It enables students to move from theoretical inquiry to applied practice and research, retaining core disciplinary competencies while adding collaborative problem-solving skills. This results in more mature disciplinary outcomes and graduates equipped to drive sustainable, regenerative change in industry.

4 Synthesis of all reflection cycles

The result of these reflective cycles is the ANCHOR Framework (Table 5), a pedagogical framework that dismantles conventional BE education silos. ANCHOR prepares graduates for real-world complexity by offering structured, scaffolded learning to integrates towards regenerative practices in transdisciplinary contexts, while supporting core disciplinary competencies. Designed for 6-week cycles, the framework is adaptable to longer-term projects. ANCHOR integrates five pedagogical practices rooted in professional innovation techniques and reflective practice cycles, fostering adaptive skills development through weekly, student-centred activities.

Table 5. The ANCHOR Framework for Transdisciplinary and Regenerative Built Environment Education.

	Component	Pedagogical Method (teacher practice)	Strategic Tool (student activity)	Learning / Thematic Theory	Core Theorists
A	**Actionable Language**	Teach students to frame speech acts as commitments, not just descriptions	**(re) Frame** learning, through new language, as commitments	Language–Action Theory (LAT) - use language as performative act	Fernando Flores, Terry Winograd
N	**Narrative Reframing**	Surface and challenge hidden assumptions in established concepts (produce ontological shifts)	**(re) Frame** established assumptions; use metaphor analysis or counter-narrative exercises	Ontological/Transformative learning: shifting assumptions and worldviews	Peter Senge, Jack Mezirow, Chris Argyris,
C	**Continuous Improvement**	Promote fast, iterative improvement rather than perfection	**(re) Run** Weekly *Kaizen* loops	Experiential/ Constructivist learning: knowledge through iterative practice and reflection	Taiichi Ohno, Shigeo Shingo, W. Edwards Deming, D. A Schön
H	**Hoshin Kanri**	Facilitate collective goal alignment (whole class) towards a shared "True North"	**(re) Align** with whole class's "True North" (*Hoshin Kanri,*)	Strategic/Organizational learning: aligning goals through dialogue and shared vision	Yoji Akao, W. Edwards Deming
O	**Open** systems thinking	Encouraging holistic, interconnected views and ripple-effect awareness (even when competing views are present)	**(re) Check** systemic ripple-effects and against *Hoshin Kanri,*	Systems & Complexity: interdependence, feedback, and emergence	Donella Meadows
R	**Regenerative outcomes**	Guide student outcomes in delivering adaptive capacity for complex real-world challenges	**Deliver** incremental, improved, regenerative, systemic, and net-positive outcomes	Resilience & Regenerative learning: adaptive, net-positive outcomes for holistic living systems	Fritjof Capra, Du Plessis

5 Conclusion

This paper presents a transdisciplinary pedagogical framework that moves BE education beyond conventional constraints. By integrating intentional language reframing, Lean practices, and systems thinking, the model cultivates the paradigm agility necessary for regenerative outcomes. Enabled by a flexible Architecture postgraduate program with low student-staff ratios that allows open disciplinary participation, this approach retains existing BE modules while aligning diverse disciplinary interests around a shared 'wicked problem,' enhancing its transferability. The framework offers educators a practical, adaptable tool for existing curricula and transforms students into active, integrative problem-solvers equipped with the mindsets essential for the contemporary workplace. For industry, this pedagogy narrows the gap between academic training and professional practice, producing graduates ready to contribute to complex real-world projects. As a reflective practice of a single educator, the findings are context-specific, providing deep, situated insight while highlighting the need for further research to test its broader applicability. Key future directions for the ANCHOR framework include:

- **Situate ANCHOR within broader educational theory:** evaluate and position ANCHOR within a unifying educational theory.
- **Contextual validation:** Test ANCHOR across diverse institutions and BE disciplines to assess adaptability and identify necessary modifications.
- **Longitudinal analysis and post-intervention tracking:** Track graduates' careers to evaluate participation in transdisciplinary projects, progression, and preparedness for complex challenges.
- **Industry–Academia partnerships:** Engage BE firms to apply the same framework in professional development, creating a feedback loop between education and industry needs.

Ultimately, this work advocates a shift in BE pedagogy: from producing single-domain experts to cultivating agile, integrated navigators of complex systems. Embedding these practices within BE learning empowers a new generation to lead sustainable, regenerative transformations from the start of their careers.

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Building a Sustainable Engineering Future: The Collaborative Effort of ECSA and Academic Institutions in Reducing Attrition in the Skills Pipeline

Nonhle Tracey Sibisi*
Engineering Council of South Africa, South Africa, nonhle@ecsa.co.za

Lehlohonolo Lefalatsa
Engineering Council of South Africa, South Africa, lehlohonolo@ecsa.co.za

Sivuyile Jokazi
Engineering Council of South Africa, South Africa, *sivuyile@ecsa.co.za*

Josias Mamabolo*
Engineering Council of South Africa, South Africa, josias@ecsa.co.za

Ada Mukanya Dienga
Engineering Council of South Africa, South Africa, *mukanya@ecsa.co.za*

Brenda Nkhumise
Engineering Council of South Africa, South Africa, *brenda@ecsa.co.za*

Abstract

The engineering profession in South Africa plays a significant role in driving innovation, infrastructure development, and economic growth. However, there is high attrition rate within the engineering skills pipeline which impacts the development of a sustainable engineering workforce in the country. This study aimed to address high attrition rates using a multifaceted approach with the academic institutions and the Engineering Council of South Africa. The study explored the underlying causes of attrition and provided recommendations on how the collaboration between the Engineering Council of South Africa and academic institutions can help reduce these rates. A mixed methods research design was used and data was be collected through qualitative surveys and questionnaires. The sample included n=10 academic staff and n=263 registered engineering candidates. The qualitative data was analysed using thematic analysis, while the quantitative data was analysed using SPSS. identified foundational gaps in schooling, especially in mathematics, science, and language proficiency, as critical contributors to attrition. Financial constraints, although not statistically differentiated, were widely recognised as barriers to academic persistence due to limited bursary flexibility and food insecurity. Institutional challenges such as generic support services, insufficient advising, and overstretched staff further contributed to high dropout rates. A recurring theme in the narratives was the call for ECSA to evolve beyond its current compliance-driven role and become a proactive enabler of transformation and socio-academic support. Based on the findings, the study recommends the development of strategies for enhancing the collaboration between ECSA and higher education institutions to foster a more sustainable engineering pipeline.

Keywords: retention, skills pipeline, sustainable engineering, engineering attrition, engineering council of South Africa

1 Introduction

The engineering profession in South Africa is integral to the country's socio-economic development, catalysing technological innovation, infrastructure expansion, and industrial competitiveness. However, the long-term sustainability of the engineering workforce is at risk due to high attrition rates within the engineering skills pipeline. A substantial proportion of students enrolling in engineering programmes do not complete their qualifications, leading to a persistent shortage of qualified engineering professionals. This challenge extends beyond academia, affecting industries that depend on skilled engineers to drive innovation, economic growth, and sustainable development.

This study aims to comprehensively investigate the root causes of student attrition in engineering programmes and develop a robust framework for collaboration between ECSA and academic institutions to address this pressing issue. By integrating insights from existing research, analysing institutional data, and engaging with key stakeholders, the study seeks to identify actionable strategies that enhance student retention and graduation rates. Furthermore, the research will explore innovative approaches such as mentorship programmes, curriculum enhancements, financial support mechanisms, and industry-academic partnerships to foster a more inclusive and sustainable engineering workforce in South Africa.

The objectives of this study are as follows:

1. To assess the engineering skills pipeline, including student enrollment, progression, and dropout trends.

2. To identify factors contributing to student attrition, such as academic challenges, financial constraints, and industry misalignment.

3. To evaluate the impact of industry-academia gaps on student retention.

2 Literature review

The Engineering Council of South Africa plays a vital role in regulating the engineering profession and ensuring the competency and professionalism of its registered persons. ECSA's responsibilities include accrediting engineering programmes, registering qualified practitioners, and setting standards for professional practice (ECSA, 2024).

2.1 Pipeline from school exit examinations to professional registration

A 2022 ECSA report on the engineering skills pipeline aimed to quantify the progression of potential engineering professionals from school through to professional registration with ECSA. The report provides insights into the challenges and attrition rates at various stages of this pipeline. A total of 725 034 students wrote their final National Senior Certificate examinations in 2020. Only 20% of the 15 501 students were eligible for entrance to an engineering diploma qualification (having achieved Level 4, or 50%-59%) enrollment. 27% of eligible students enrolled in a technologist qualification, and 24% enrolled in an engineering degree qualification. While these figures suggest a reasonable transition into engineering education, they also reveal a concerning trend up to 75% of eligible students did not pursue an engineering qualification. This indicates that despite meeting the minimum entry requirements, a significant portion of potential engineering students either opt for other fields or face barriers preventing them from enrolling.

Even more concerning is the low conversion rate to professional registration. Of the students eligible to enter engineering programs, only 1.6% ultimately attained professional registration with ECSA in 2020. When considering only those who actually enrolled in engineering programmes, this figure rises to just 6%. These statistics starkly highlight the high attrition rate across the engineering pipeline, underscoring the urgent need for interventions to improve retention, support students through their academic journey, and bridge the gap between graduation and professional registration. High attrition rates among engineering students are a global concern, with South Africa experiencing particularly alarming statistics. Studies indicate that the average non-completion rate for engineering programs in the country hovers around 50%, a figure comparable to international trends (Bernold, et al., 2007). Engineering programmes often demand high levels of mathematical and technical proficiency, which, combined with socio-economic factors, contribute to student dropout rates. The consequences of these high attrition rates are significant, as they exacerbate the already critical shortage of engineering professionals needed for national development and infrastructure projects.

A case study conducted at the Faculty of Engineering at the University of KwaZulu-Natal by Pocock provides insights into these attrition trends (Pocock, 2012). The research revealed a positive trend between 2005 and 2008, with first-year engineering student attrition rates decreasing from over 22% to below 14%. However, in 2009, this trend reversed, with an uptick to over 17%, a shift that was potentially linked to changes in the national high school curriculum. This suggests that foundational education plays a crucial role in students' ability to succeed in engineering programmes. Further research supports these findings, indicating that factors such as inadequate high school preparation, financial constraints, lack of academic support, and limited industry exposure contribute to student dropouts in engineering (BusinessTech, 2015). The transition from high school to tertiary education in South Africa has been particularly challenging for students from underprivileged backgrounds, who often struggle with adapting to university-level coursework and the financial burden associated with higher education.

In addition, engineering education in South Africa has historically been criticised for its theoretical emphasis, with limited practical applications in the early years of study. This disconnect between academic learning and industry expectations often results in disengagement among students, further exacerbating dropout rates. The role of professional bodies such as the ECSA in bridging this gap by ensuring industry-relevant curricula and providing mentorship programmes has become increasingly critical in addressing these challenges. Economic hardships play a significant role in student retention within engineering programs, particularly in

South Africa, where financial exclusion remains a major barrier to higher education. Engineering degrees are typically longer and more expensive compared to other disciplines due to the need for specialised equipment, laboratory access, and practical training components. Many students, especially those from disadvantaged backgrounds, struggle to afford tuition fees, textbooks, and accommodation, which increases the likelihood of dropping out.

Pocock further found that 49% of students who left the engineering faculty cited financial difficulties as the primary reason for their departure (Pocock, 2012). The financial burden is exacerbated by additional expenses such as transportation, food, and the cost of compulsory practical training, which many students cannot afford without external financial support. While financial aid programmes such as the National Student Financial Aid Scheme provide some relief, they often fall short of covering all associated costs, leaving students vulnerable to attrition. Moreover, students from low-income households frequently take on part-time jobs to sustain themselves, which can negatively impact their academic performance. Balancing work and a demanding engineering curriculum leads to exhaustion, lower grades, and withdrawal from the programme. Research has shown that financial stress significantly reduces student engagement and increases dropout rates, particularly in Science, Technology, Engineering and Mathematics fields that require continuous focus and extensive study hours (Ahmed, et al., 2014).

Another key challenge contributing to high attrition rates among engineering students is the misalignment between academic training and industry requirements. While engineering curricula in South Africa and globally are designed to provide students with technical knowledge and problem-solving abilities, they often fall short in preparing students for the diverse skill sets demanded by the modern workforce. As a result, many students graduate with strong technical expertise but lack the practical, industry-relevant skills needed to thrive in real-world engineering environments.

3 Methodology

The pragmatic paradigm was followed in the current study, which entails the use of different methods (qualitative and quantitative research methods) to explore a phenomena (Sefotho, 2021). The study employed a sequential explanatory mixed method design which is characterised by collecting quantitative data and analysis before the collection of qualitative data. This design was used to gather complete and holistic insights from ECSA registered candidates and lecturers from academic institutions.

Non-probability sampling, specifically volunteer sampling, was employed for the qualitative and quantitative components of the study. For the quantitative component, 263 registered candidates were sampled while 10 lecturers were sampled for the qualitative component of the study. Structured and open-ended questionnaires were used to collect data from ECSA candidates and university lecturers to understand their experiences with academic, financial, and institutional challenges that contribute to attrition and their views on the recommendations on effective support mechanisms. Structured questionnaires were disseminated to ECSA registered engineering candidates while open ended questionnaires were distributed to lecturers.

The qualitative data was analysed using thematic analysis. The Kruskal-Wallis H test was employed for quantitative data. This is a non-parametric statistical method and it was used to determine whether there are statistically significant differences between the medians of the engineering candidates. It was chosen over parametric alternatives due to the nature of the data, which did not meet the assumptions of normality or homogeneity of variance required for parametric testing. Following a significant Kruskal-Wallis result, post-hoc analysis was conducted using mean rank comparisons to identify where differences existed among the groups. The mean ranks provided insight into the direction and relative magnitude of differences between groups.

A reliability test was run on SPSS to assess the reliability of the questionnaire. The KMO value of 0.765 indicated the items in the questionnaire were sufficiently correlated. The significant Bartlett's Test ($p < .001$)

confirms adequate inter-item correlation. For the qualitative component, data quality was ensured through trustworthiness including credibility, confirmability, transferability, and dependability.

The study was guided by the following ethical considerations: voluntary participation, informed consent, avoidance of harm, confidentiality, and anonymity.

4 Presentation of findings

4.1 Quantitative findings

The Kruskal-Wallis test indicated a statistically significant difference in participants' perceptions of academic workload across candidacy categories ($H = 21.006$, $p < .001$). Post-hoc analysis of mean ranks will be used to further explore the group-level differences. However, no statistically significant differences were found for items related to academic support ($p = .744$), mentorship ($p = .093$), or course content relevance ($p = .127$), and thus, mean ranks for these items will not be explored as this implies similar perceptions across all candidate groups. Candidate Technologists reported the highest perceived manageability, with a mean rank of 149.92, followed closely by Candidate Technicians (Mean Rank = 145.70) and Candidate Certificated Engineers (Mean Rank = 135.31). Candidate Engineers reported the lowest perceived manageability, with a mean rank of 110.26, indicating that this group experienced greater challenges in coping with the academic workload compared to their peers.

The Kruskal-Wallis test revealed no statistically significant differences for financial-related items, including perceptions of having sufficient financial resources to support academic progress ($p = .308$), access to scholarships or bursaries ($p = .503$), consistency of financial support from family or guardians ($p = .521$), and the belief that financial support improved academic performance ($p = .067$).

The findings indicated significant difference in perceptions of adequacy of institutional resources across candidacy categories ($H = 25.102$, $p < .001$). This suggests that perceptions regarding laboratory, software, and library resources vary considerably among Candidate Engineers, Technologists, Technicians, and Certificated Engineers. No statistically significant difference was found ($H = 2.722$, $p = .437$) on institutional support services. Similarly, perceptions about institutional staff responsiveness showed no statistically significant differences across candidate categories ($H = 2.633$, $p = .452$). This finding implies uniform experiences or concerns regarding institutional responsiveness.

Participants differed in their views on the importance of collaboration between ECSA and academic institutions ($H = 13.934$, $p = .003$), the effectiveness of joint initiatives between these entities ($H = 9.627$, $p = .022$), and the role of enhanced mentorship and academic advising programmes in reducing attrition ($H = 12.100$, $p = .007$). Significant differences were also observed for perceptions regarding the need for more practical, industry-linked learning experiences ($H = 8.536$, $p = .036$), improved institutional resources such as laboratories and software ($H = 22.479$, $p < .001$), and the potential value of regular workshops on stress management and coping mechanisms ($H = 11.767$, $p = .008$). However, no statistically significant difference was found in perceptions related to increased financial support or scholarships as a means to reduce attrition ($H = 3.296$, $p = .348$). The table below provides the mean ranks for statistically different items.

For the item on collaboration between ECSA and academic institutions as a strategy to address engineering attrition, Candidate Technologists reported the highest agreement (Mean Rank = 138.72), followed by Candidate Engineers (119.80) and Candidate Technicians (109.18), while Candidate Certificated Engineers reported the lowest agreement (68.06). A similar trend was observed for perceptions of joint initiatives by ECSA and academic institutions to address student challenges. Here too, Candidate Technologists reported the highest support (137.81), followed by Candidate Technicians (119.00), Candidate Engineers (115.79), and again, Candidate Certificated Engineers reported the lowest support (80.38).

Regarding the statement that enhanced mentorship and academic advising programmes would reduce attrition, Candidate Technologists held the strongest view (Mean Rank = 137.94), followed closely by

Candidate Technicians (117.48) and Candidate Engineers (117.27). Candidate Certificated Engineers, however, again showed the least agreement (67.44). Perceptions on the value of more practical, industry-linked learning experiences followed a similar pattern, with Candidate Technologists showing the highest level of support (136.33), while Candidate Certificated Engineers reported the lowest (81.75). Mean ranks for Candidate Engineers and Candidate Technicians were similar, at 117.56 and 117.62, respectively. In terms of improving institutional resources (e.g., labs, software), Candidate Technologists reported the highest level of perceived impact (Mean Rank = 145.98), followed by Candidate Technicians (128.51), Candidate Engineers (104.18), and Candidate Certificated Engineers (87.56), indicating a strong disparity in perceived resource adequacy and its potential to reduce attrition. Finally, regarding the perceived value of regular workshops on coping mechanisms and stress management, Candidate Technologists once again expressed the strongest agreement (138.63), followed by Candidate Technicians (126.44), Candidate Engineers (112.37), and Candidate Certificated Engineers (77.25).

4.2 Qualitative findings

The section below presents a discussion of the themes derived from qualitative findings.

Foundational gaps in schooling

A recurring theme from participant narratives was the inadequate foundational preparation that students bring from their basic education into higher education particularly in mathematics and science.

KP-10 pointed out that:

> *The quality of basic education received... fails to prepare students for the demand of the scientific fundamentals. KP-10*

KP-5 further highlighted key factors that contributes to foundational gaps:

> *Poor Maths and Science schooling; Poor conception of engineering as a field.' KP-5*

KP-4 indicated that the gap in basic education can manifest through challenges with the language, compounding students' struggle to assimilate technical content.

> *The first challenge is the high school and university gap experienced by students from previously disadvantaged schools. The quality of basic education received by a vast majority of students (who are from the low income and working class households) fails to prepare students for the demand of the scientific fundamentals. Additionally, language can be a challenge. KP-4*

The participants insights reflect a systemic issue manifested in a misalignment between secondary education and the academic demands of engineering programs. Van Broekhuizen, Van der Berg, & Hofmeyr (2016) found that the quality of school attended is a strong predictor of university success. Hlalele (2019) found that language remains a silent barrier for many students in rural and township schools. When students transition to English-dominant institutions, especially in STEM fields, they are at a double disadvantage where language delays conceptual understanding of already complex topics.

Financial constraints

Financial challenges also emerged as one of the recurring barriers to student retention and success in engineering education. While the degree of emphasis varied across participants, most agreed that financial challenges play a critical role in academic attrition. According to KP-8, financial and logistical challenges

intersects directly with attendance and academic engagement. KP-8 also noted a gap in funding structures that overlook basic living expenses such as food costs.

> *Financial constraints have a huge impact. Students who live far from campus and use public transport to reach campus may skip days of class to save on transport costs. Student loans cover accommodation, books and tuition, but do not contribute to food costs. KP-8*

KP-4 made a significant observation and highlighted that bursary and funding models often don't allow for academic setbacks which can cause attrition.

> *I think that a majority of students in all disciplines face significant financial constraints in higher education because of the socio-economic conditions of this country and their manifestation in higher education. This constraint means that students are faced with nutritional, resource and stress-related challenges that adversely impact their ability to focus on intellectual demands. Additionally, lack of funds means that there is no grace for failure, STEM students who obtained access through bursaries often lose them when they don't pass - many of these structures don't allow second chances, this adds psychological strain. KP-4*

The literature also indicates that financial exclusion and food insecurity are major drivers of student dropout, especially in STEM faculties (Mkhize, 2024; Pitsoe & Letseka, 2018; Sallee, Kohler, Haumesser, & Hine, 2023). Similarly, Del Savio, Galantini and Pachas (2022) found that financial stress leads to higher dropout rates in engineering, not only because of resource gaps but also due to emotional burnout.

In contrast, KP-7 presented a counterargument:

> *In my opinion, it is not the financial constraints that are hampering engineering student's abilities, but rather their unsuitability to be an engineering student is hampering their ability. We provide everything the engineering student needs, from free data to computer labs fully connected to the internet, to components and equipment to do all their laboratories and experiments. Just put students with an aptitude for engineering in the lecture venues and the attrition rates will become a non-issue. Lastly, put the best engineering lecturers (based on merit and not DEI) into facilitate each classroom, and attrition will become a non-issue. KP-7*

KP-7 suggested that institutions provide adequate resources such as free data, lab equipment, and internet access, implying that student failure is more about aptitude and motivation than financial hardship.

Institutional challenges

The participants indicated that institutional challenges in addressing engineering student attrition are characterised by inconsistent and a lack of program-specific interventions. KP-9 indicated a lack of confidence in the depth or impact of existing interventions to reduce attrition.

> *A few initiatives… just not sure how effective is the reach. KP-9*

KP-10 raised a critical concern regarding staff support, arguing that:

> *Academics have no support time or resources for academic development… All institutions do this superficially. KP-10*

KP-7 outlined that while support structures exist, some retention strategies may prioritise throughput over genuine academic fit or quality.

> *Several support structures exist for struggling students that deal with Psychological Self-Image issues to Time-management skills to Study Techniques, to Tutoring Mentors, etc. Unfortunately, Government Subsidies encourage Institutions to "help" students that shouldn't be studying engineering to be successful enough to graduate, but these students are the ones that contribute to the high attrition rates. KP-7*

On a more optimistic note, KP-1 indicated existing strategies at their institution used to support engineering students:

> *We have Academic Success Coaches to address study skills and educational barriers. The student counselling unit and student health centre are available for all students. We are trying to introduce more academic advising, especially for students who have failed multiple courses, to help them to make realistic and efficient subject courses when registering. KP-1*

The above comments are similar with the findings of the study conducted by Boughey & McKenna (2016) which highlighted that institutional support in South Africa is often fragmented, under-resourced, and disconnected from students' lived experiences.

Role of ECSA and institutional partnerships

Participants emphasised the need for ECSA to go beyond compliance checks and become a transformational partner in addressing socio-academic challenges within engineering education. KP-2 stated that:

> *ECSA must do real QA of academic programs, not just box-ticking exercises. KP-2*

> *Accreditation must look at pedagogy and curriculum design—not just admin compliance. KP-10*

KP-2 and KP-10 suggests that ECSA must focus on quality assurance model that does not only prioritise procedural compliance than educational effectiveness, curriculum quality or student-centred outcomes.

Moreover, KP-4 calls for a fundamental reimagining of ECSA's role:

> *As the custodian and enforcer of the Engineering Profession Act, ECSA can do more as a public body to directly address the socio-economic challenges faced by engineering students whose higher education journey does not loophole them out of the South African challenges. ECSA needs to develop ways to be more than a policy creator, and instead develop ways to be a policy enabler and supporter of the disadvantaged. ECSA needs to consider how it can start setting up policies and structures that are contextual and drive universities to address the socio-economic and socio-cultural challenges through curriculum delivery. KP-4*

KP-4 emphasised the need for contextual policy design, where ECSA works collaboratively with universities to embed social responsiveness into curriculum and support systems, particularly for historically marginalized groups.

KP-9 echoed a similar view, arguing that ECSA

> *ECSA must play a participatory role rather than just the perceived accreditation gatekeeping role. KP-9*

Winberg, McKenna, & Wilmot (2020) advocates for regulatory bodies to shift from accountability frameworks toward developmental support, where institutions are empowered through partnerships rather than penalized for non-compliance.

Strategies for retention

Participants identified a range of practical, evidence-informed strategies to improve retention in engineering programs. KP-5 recommended a shift toward learner-centred support systems that acknowledge the diverse educational and social backgrounds of students.

> *Scaffolded, mentored, extended programmes with contextualised and engaged learning KP-5*

In addition to academic strategies, KP-5 also added other retention strategies including:

> *Career advice, mentorship, visibility of ECSA on campuses. KP-5*

KP-3 proposed a systemic approach:

> *We need to foster deeper connections between industry and universities, as well as developing a greater identity of engineers, technologists, and technicians as part of an ecosystem. These are marketing opportunities which could be incentivised by the structures already in place for registration. KP-3*

KP-8 stressed the value of proactive support, noting:

> *Early detection and sufficient resource to support where applicable. KP-8*

Winberg, Adendorff, Bozalek, Conana, Pallitt, Wolff, Olsson and Roxå (2019) emphasised interverntions centrered around the importance of building professional identity in engineering education, noting that students who understand the value and scope of the profession are more likely to persist. Ahmed, Muldoon and Elsaadany (2021) found that structured mentorship programs improved students' sense of belonging and resilience.

5 Discussion of findings

Attrition in engineering education is influenced by a complex mix of academic, socio-economic, and institutional factors. Across the data, academic staff reflected a shared concern that students are not adequately prepared for the rigors of engineering programs. The academic pressures, particularly the overwhelming workload experienced during the first year of study, emerged as a critical factor contributing to early student attrition in engineering programmes. The transition from secondary to tertiary education has been identified in the literature as challenging for students who lack the foundational competencies in mathematics, science, and academic literacy (Hlalele, 2019; Van Broekhuizen, et al., 2016). According to Hlalele (2019), the initial academic shock can lead to a rapid decline in confidence and performance, especially in highly technical fields such as engineering.

The findings of this study highlight that academic factors, particularly workload and self-regulation skills, play a critical role in engineering student attrition. Qualitative responses from academic staff revealed that beyond academic preparedness in mathematics and science, competencies such as time management, self-discipline, and independent learning are essential for success in engineering programmes. Several participants noted that many students, particularly those from under-resourced schooling backgrounds, enter higher education without these foundational skills, making it difficult to cope with the intensive demands of the curriculum.

Quantitative results support this perspective. The Kruskal-Wallis test identified a statistically significant difference in perceptions of academic workload across candidacy categories, with Candidate Engineers reporting the highest levels of difficulty, suggesting they experience the most pressure. In contrast, Candidate Technologists and Candidate Technicians reported higher levels of perceived manageability. These findings point to a mismatch between institutional expectations and student readiness, especially in the early stages of engineering education. These insights are consistent with previous studies which have found that academic workload and inadequate time management are common predictors of student dropout in STEM fields (Aina, Aktaş, & Casalone, 2024; Ejiwale, 2013; González-Pérez, Martínez-Martínez, Rey-Paredes & Cifre, 2022; Ortiz-Lozano, Rua-Vieites, Bilbao-Calabuig, & Casadesús-Fa, 2020). Ortiz-Lozano et al. (2020) argued that persistence in higher education is closely linked to academic and social integration, and that students who are overwhelmed early in their studies are less likely to remain enrolled. Similarly, Aina et al. (2024) emphasised that engineering students must be supported not only through academic content but also through structured interventions that develop soft skills, such as planning and self-directed learning.

While no statistically significant differences were found across candidacy groups in terms of perceptions of financial support, qualitative data confirmed that financial challenges remains a systemic barrier. The lecturers frequently mentioned that students from low-income households struggle with food insecurity, transport costs, and rigid bursary structures that offer little room for academic recovery. These insights are consistent with prior research showing that financial stress impacts both academic performance and mental health (Pitsoe & Letseka, 2018; Sallee et al., 2023).

Moreover, Candidate Engineers reported the highest satisfaction with institutional resources while Candidate Certificated Engineers reported the lowest. This reflected discrepancies in access to labs, software, and learning tools across different streams or institutions. However, no significant differences were found regarding institutional support services or staff responsiveness. Yet, the qualitative responses painted a more complex picture, with some lecturers describing institutional support as fragmented, under-resourced, and insufficiently targeted. This supports Boughey and McKenna's (2016) findings that academic development efforts in South Africa often lack depth and coherence.

Another key insight that emerged from both groups of participants is the need for ECSA to shift from a regulatory to a more developmental and participatory role. Statistically significant differences were found in how different candidate categories perceived the value of ECSA-academic collaboration and joint initiatives. However, other lecturers expressed concerns that ECSA's current role is overly focused on procedural compliance, with little emphasis on pedagogical quality or social responsiveness. As suggested by Winberg, McKenna, and Wilmot (2020), professional bodies must evolve into partners that enable transformation rather than enforcing rigid accreditation processes. ECSA is thus encouraged to develop contextual and enabling policies, in collaboration with universities, that address the socio-academic realities of students.

Multiple retention strategies were identified across the data, many of which received statistically significant support in the survey. These included enhanced mentorship and academic advising, improved institutional resources, scaffolded and learner-centred programmes, stronger mentorship structures, and greater career exposure and industry engagement. Literature reinforces the value of professional identity development and resilience-building through structured mentorship (Pitsoe & Letseka, 2018; Sallee et al., 2023; Winberg et al., 2020).

6 Conclusion

The findings emphasise that student attrition in engineering is not the result of a single factor, but rather a convergence of academic, socio-economic, institutional, and systemic issues. Addressing this complex challenge requires a coordinated approach involving universities, ECSA, and broader educational reforms. Ultimately, reducing attrition and improving retention in engineering education is not only a matter of

academic performance but a national imperative tied to transformation, skills development, and social justice.

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Enhancing engineering professional skill development through industry-led guest lectures: A transformative learning approach in African engineering education.

Vicent Rutagangibwa
University of Cape Town, South Africa, *rtgvic001@myuct.ac.za*

Irene Magara
University of Nebraska-Lincoln, USA, *imagara2@huskers.unl.edu*

Comfort Musiimenta
University of Cape Town, South Africa, *msmcom001@myuct.ac.za*

Abstract

This study examined the impact of integrating industry-led guest lectures with reflective learning on the professional skill development of final-year electrical engineering students at Mbarara University of Science and Technology (MUST), Uganda. Grounded in Kolb's Experiential Learning Theory and using Maxwell's interactive research design, the study explored how this combined approach enhances students' professional competencies and industry readiness. A mixed-methods design was employed, involving 73 students who participated in pre- and post-intervention surveys, reflective journals, and sessions led by three expert guest lecturers in maintenance engineering. Quantitative analysis showed statistically significant gains in students' confidence and readiness to tackle industry-related challenges. Reflections further revealed improved problem-solving, deeper understanding of real-world practices, and growth in professional identity. Students reported high motivation and perceived relevance of the sessions. These findings underscore the effectiveness of structured industry engagement in developing both technical and soft skills among engineering students. The study offers practical strategies for bridging the academia–industry divide, particularly in resource-constrained settings, and contributes to emerging scholarship on experiential and practice-oriented engineering education.

Keywords: Industry-led guest lectures, professional skills development, industry readiness, reflective learning, African engineering education.

1. Introduction

Engineering education in Africa faces persistent challenges in effectively equipping graduates with industry-relevant skills due to resource constraints, infrastructural limitations, and insufficient university-industry collaborations (Kehdinga et al., 2020). While traditional interventions such as internships and industrial visits have been implemented to bridge this gap, they often face sustainability issues and limited accessibility in resource-constrained institutions of higher learning (Nawaz et al., 2023). Addressing these challenges is crucial for enhancing the employability of graduates and ensuring that engineering education meets the evolving needs of industry.

Recent studies highlight that university-industry partnerships enhance students' employability and technical competency through direct engagement with industry professionals (Shah & Gillen, 2024). One increasingly recognized approach is the integration of industry-led guest lectures, where experienced professionals deliver targeted industrial knowledge aligned with academic curricula (Gambheer & Acharya, 2024). This approach has been effectively used in controlling engineering education, demonstrating its potential to improve technical comprehension and professional readiness among students (Hoernicke et al., 2017). Moreover, experiential learning frameworks, such as Kolb's Experiential Learning Theory, emphasize the importance of active engagement and reflective practices in reinforcing industry-based learning (Tembrevilla et al., 2024). Given these promising findings, this study explores how integrating such approaches can address the gaps in engineering education in resource-constrained settings, particularly in enhancing industry readiness.

This study explored how industry-led guest lectures, integrated with reflective learning, impacted the development of professional engineering skills and industry readiness among final-year electrical engineering students at Mbarara University of Science and Technology (MUST), a resource-constrained African institution. Guided by Kolb's Experiential Learning Theory, the intervention involved experienced industry practitioners aligned with course content. Using a mixed methods approach, data were collected from students through pre- and post-intervention surveys and bi-weekly reflective journals. Quantitative data were analysed using paired t-tests and effect size, while qualitative data underwent thematic analysis to assess changes in technical skill application and professional growth. This research aimed to create an evidence-based model for incorporating transformative industry experiences into engineering education and provided practical recommendations for African universities seeking to enhance industry readiness within resource limitations. The findings demonstrated how well-structured Industry- led guest lectures could bridge the academia-industry gap in such contexts.

1.1 Research gap

Despite the benefits of industry engagement in engineering education, there is a lack of empirical studies evaluating the effectiveness of industry-led guest lectures, particularly in resource-constrained African universities. While internships and industrial visits have been extensively analyzed, the role of structured industrial-led guest lectures as an alternative means of fostering industry engagement remains underexplored. Furthermore, the integration of reflective learning practices within such models has not been sufficiently

investigated in relation to professional skill development and industry readiness in African higher education institutions.

1.2 Objectives and research question

This study investigates how industry-led lectures, integrated with reflective learning practices guest lectures, contribute to the professional skill development and industry readiness of final-year electrical engineering students in a resource-constrained African university setting. Employing a mixed methods approach, the study examines both quantitative and qualitative data to assess students' skill acquisition, engagement, and perceptions of this learning model. This study explores the following research question:

> *How do industry-led guest lectures, when integrated with reflective learning practices, influence the development of professional engineering skills and industry readiness among final-year* electrical engineering *students at Mbarara University of Science and Technology?*

The study objectives include:

- Evaluating the impact of industry-led guest lectures on students' professional competencies, technical application skills, and industry readiness.
- Analyzing students' experiences on the benefits and limitations of industry-led guest lectures in engineering education.
- Developing strategic recommendations for integrating industry-led guest lectures in resource-limited educational settings.

2. Literature Review

2.1 University–Industry Collaboration in engineering education

University–industry collaboration (UIC) plays a crucial role in bridging the gap between theoretical knowledge and practical application, enhancing graduate employability, and fostering innovation. UIC provides students with hands-on learning, professional networking, and ensures curricula meet industry needs (Mohamedbhai, 2015; Vuoriainen et al., 2025). The success of these partnerships depends on factors such as strong institutional support, effective communication, and alignment between academic and industrial goals (Mohamedbhai, 2015). Vuoriainen et al. (2025) highlight the "Six Cs of collaboration": communication, commitment, clarity, coordination, culture, and capacity, as essential elements for effective UICs. Universities that integrate these principles produce graduates with both advanced technical skills and essential soft skills, such as leadership and interdisciplinary collaboration, which are vital in today's complex professional environments (Morin & Willox, 2022; Pepple et al., 2025; Shah & Gillen, 2024). In resource-constrained settings, where traditional forms of experiential learning may be limited, fostering such collaborations can provide a scalable solution to bridge the gap between academia and industry, enhancing both the quality of education and the employability of graduates.

Despite these advantages, significant disparities persist in the implementation and outcomes of UICs, particularly in Africa. While global studies emphasize the benefits of such collaborations, barriers like weak institutional support and financial constraints remain prevalent in many African nations (Bolu et al., 2024). These challenges

highlight the need for further research on how successful UIC models, developed in more resourced settings, can be adapted to meet the unique socio-economic and institutional needs of African engineering education.

2.2 Industry-led guest lectures as a pedagogical tool

Industry-led guest lectures are increasingly recognized as a valuable pedagogical tool for integrating real-world industry insights into academic curricula. This approach provides students with direct exposure to current industry practices, expectations, and emerging trends, which are often difficult to replicate within traditional classroom settings. Research consistently shows that when guest lectures are aligned with course content, they significantly enhance students' understanding of industry demands and increase engagement (Hoernicke et al., 2017; Pepple et al., 2025). Latorre and Meier (2022) demonstrate that guest lectures focused on leadership help students gain a clearer vision of their future roles and better understand the professional relevance of their academic coursework. This direct exposure creates a stronger connection between theoretical learning and practical application, fostering a deeper and more contextualized understanding of the subject matter.

Moreover, industry-led guest lectures cater to diverse learning styles and foster intrinsic motivation. According to Self-Determination Theory (SDT), guest lectures address students' psychological needs for autonomy, competence, and relatedness (Trenshaw et al., 2016). Exposure to varied perspectives and real-world problem-solving enhances students' autonomy, while understanding the practical applications of theoretical knowledge builds competence. Interaction with professionals in their intended field helps establish relatedness, encouraging students to reflect critically on the content. Trede and Jackson (2021) emphasize that this reflective engagement is key to developing student agency and shaping a robust professional identity, enabling students to visualize their roles within the broader professional landscape.

However, despite the clear benefits, further research is needed to assess the long-term impact of industry-led guest lectures. While existing literature highlights their positive effects on student engagement and relevance, there is a gap in studies that track the sustained influence of these lectures on graduates' career trajectories, problem-solving abilities, and leadership development. A more thorough understanding of these outcomes could provide a stronger case for transitioning from exposure to transformative learning experiences, particularly in educational contexts where resources and access to industry professionals may be limited.

2.3 Engineering education challenges in Africa

Engineering education in Africa faces significant challenges that hinder its ability to produce graduates ready for the workforce. Despite global advancements in pedagogical approaches, systemic issues like outdated curricula, inadequate funding, and a shortage of experiential learning opportunities persist. These factors create a growing gap between academic training and the evolving demands of the industrial sector (Kehdinga et al., 2020). Mohamedbhai (2015) argues that without comprehensive reforms, many African nations will struggle to develop the engineering talent needed for sustainable economic and social growth. Moreover, this disconnect disproportionately affects under-represented and low-income students, exacerbating inequalities within the engineering profession across the continent (Halabieh et al., 2022). Addressing these issues is crucial to ensuring that engineering education in Africa becomes more aligned with industry needs and provides equitable opportunities for all students, particularly in resource-constrained environments.

These challenges highlight the urgent need for innovative and resource-conscious solutions. One promising approach is the integration of industry-led guest lectures with reflective learning practices, which offer a cost-effective alternative to traditional experiential learning methods, such as internships or extensive industry visits. This model has been shown to bridge the academia-industry divide by simulating critical workplace experiences within the classroom, without requiring substantial financial investment (Badenhorst et al., 2020). By strategically leveraging industry partnerships, universities can provide students with valuable exposure to real-world engineering scenarios, fostering critical thinking and professional skills that are essential for employability (Turns et al., 2014). In institutions with limited resources, such as Mbarara University of Science and Technology, this approach offers a practical solution to overcoming financial constraints while improving graduates' readiness for the workforce (Chadha & Heng, 2024). When embedded into institutional policies and curricula, industry-driven initiatives like guest lectures can not only enhance employability outcomes but also contribute to the professional mobility of engineering graduates across the African continent, promoting a more responsive and relevant engineering education system.

2.4 Experiential and reflective learning in engineering education

Experiential learning (EL) and reflective practices are fundamental to effective maintenance engineering education. Based on Kolb's theory, EL remains central to modern engineering pedagogy, fostering deep learning through hands-on experience (Kolb & Kolb, 2018). Research indicates that when engineering students engage in reflective activities, such as journaling, discussions, or writing assignments, they develop a deeper understanding of professional practices (Badenhorst et al., 2020; Turns et al., 2014). These practices enhance metacognitive awareness and help students connect theoretical knowledge to real-world scenarios.

In the context of project-based learning, such as the Shell Eco-Marathon case study, reflection allows students to refine their professional identities and learn from their experiences (Von Solms & Nel, 2017). Similarly, research by Chadha and Heng (2024) emphasizes that reflective learning contributes to the development of critical soft skills, including communication, leadership, and teamwork, which are vital in today's multidisciplinary engineering teams. Badenhorst et al. (2020) further highlight the role of narrative reflection in shaping engineering students' professional identities. While traditional engineering education has focused on technical skills, recent literature underscores the necessity of reflective literacies for 21st-century engineers, who must adapt to an increasingly globalized and interconnected workforce

3. Methodology

3.1 Research design

This study employed a mixed methods research approach to gain a comprehensive understanding of the impact of industry-led guest lectures on engineering students' professional development. The design was framed using Maxwell's interactive research model (Maxwell, 2013) which emphasizes the interconnectedness of research goals, conceptual framework, methods, and validity strategies. This framework provided the flexibility and coherence necessary to explore not only measurable shifts in student confidence and readiness but also the nuanced, reflective experiences that shape professional growth thereby aligning closely with the study's emphasis on experiential and reflective learning within engineering education.

3.2 Participants and sampling

The study was conducted at Mbarara University of Science and Technology (MUST) in Uganda, targeting final-year Bachelor of Science in Electrical Engineering students enrolled in the Maintenance Engineering course (EEE 4102) during the first semester of the academic year 2023/2024. This fourth-year undergraduate course was selected due to its strong emphasis on bridging theoretical knowledge with industry practices, making it an ideal setting for integrating industry-led guest lectures as part of the learning experience.

Of the 92 students registered for the course, 73 voluntarily consented to participate in the study. These students formed the primary sample for the quantitative and qualitative survey, which included both pre- and post-intervention measures. In addition to the student participants, 3 industry practitioners (alumni) working in relevant maintenance engineering sectors were purposively recruited to serve as guest lecturers. Their professional backgrounds were strategically aligned with the course objectives, and the intended learning outcomes extracted from the curriculum were shared with them as a guide for preparing lecture materials. The guest lectures covered topics directly aligned with the course objectives, including preventive and corrective maintenance strategies, troubleshooting of electrical power distribution systems, and the use of industry-standard software tools for maintenance reporting. Each session was designed to connect theoretical concepts taught in class with practical applications in real-world engineering contexts.

To complement the survey data, reflective journal entries submitted by students as part of the course requirements were also reviewed. This document analysis provided deeper insights into students' learning processes and their evolving professional identities. The involvement of industry experts and engineering educators as guest lecturers and facilitators contributed to creating a rich learning environment, which in turn supported the collection of diverse data from the student surveys and reflective journals.

3.3 Data collection methods

This study employed a mixed methods approach to comprehensively investigate the impact of industry-led guest lectures on students' professional skill development and industry readiness. Data was collected through two primary methods: pre- and post-intervention surveys, and reflective journals. Firstly, structured questionnaires were administered to students at two distinct time points: before the commencement of the industry-led guest lectures and upon their completion.

The surveys were designed to assess changes in students' self-reported professional skills, confidence, and industry readiness. Likert-scale questions focused on problem-solving, technical application, communication, and teamwork skills. For example, students rated items such as *"I feel confident in troubleshooting real-world electrical faults"* and *"I can effectively communicate technical information to industry professionals."* Open-ended questions invited reflections on how guest lectures influenced their problem-solving approaches and professional identity. By comparing pre- and post-intervention responses, the study aimed to measure the quantitative impact of the intervention on these outcomes, addressing research objective 1, which evaluates the impact of industry-led guest lectures on students' professional competencies and industry readiness.

In addition, students maintained bi-weekly reflective journals to document their learning experiences, critically analyse skill development, and identify areas for improvement. Prompts guided their reflections, encouraging them to connect lecture content with existing knowledge, identify learning gaps, and outline action points for addressing those gaps. This process also allowed students to track their evolving perceptions of professional growth and readiness for industry.

3.4 Data analysis

Quantitative data from pre- and post-intervention surveys were analysed using paired t-tests to assess changes in students' self-reported professional skills, confidence levels, and industry readiness. This method was chosen to compare related data points from the same individuals, effectively measuring changes over time.

Qualitative data from reflective journals and open-ended survey responses underwent thematic analysis. This process involved coding and categorizing data to identify key themes related to professional skill development, problem-solving approaches, and professional growth. The integration of quantitative and qualitative findings provided both breadth and depth, with the surveys capturing the extent of change and the reflective narratives explaining how and why those changes occurred, offering deeper insights into the impact of the guest lecture intervention.

3.5 Ethical considerations

Informed consent was obtained from all participants, who were informed about the study's purpose, their involvement (surveys, reflective journals), and assured of confidentiality. Participation was voluntary, and students were told they could withdraw at any time without academic consequences. To minimize potential bias, special care was taken given that one researcher was also the course instructor. Data were anonymized, with unique participant codes assigned, and securely stored. Methodological rigor, including mixed methods, data triangulation, and reflexivity, ensured the validity and trustworthiness of the data. Peer debriefing and maintaining an audit trail helped minimize bias during analysis.

4. Results and discussion

4.1 Results

This section presents the results from both the quantitative and qualitative data analyses. First, the quantitative findings are discussed, focusing on key measures such as student confidence, readiness for industry, motivation, and perceived benefit of the industry-led guest lectures. These are followed by the qualitative findings, which explore the students' reflections on skill development, problem-solving approaches, and professional growth. The results from both data sources are integrated to highlight the impact of the guest lectures on students' learning outcomes.

4.1.1 Quantitative findings

Quantitative data were analysed to process pre- and post-survey responses. Table 1 and Figure 1 summarize the key findings:

- Confidence increased from a mean of 3.5 to 4.3, with a Cohen's d of 0.39, indicating a small-to-moderate effect size.
- Readiness for industry challenges rose from 3.77 to 4.19, yielding a Cohen’s d of 0.51, which reflects a moderate effect.

- Motivation and Perceived Benefit received post-intervention scores of 4.25 and 4.40, respectively, indicating strong student engagement and appreciation of the relevance of the guest lectures.

These findings suggest that the guest lecture intervention had a positive impact on both cognitive and motivational outcomes.

Table 1 Pre- and Post-Intervention Student Ratings and Effect Sizes Across Key Learning Outcomes

Measure	Mean (Pre)	Mean (Post)	Cohen's d	Notes
Confidence	3.5	4.3	0.39	Small-to-moderate effect
Readiness	3.77	4.19	0.51	Moderate effect
Motivation	N/A	4.25	N/A	Only post-intervention rating
Perceived Benefit	N/A	4.40	N/A	Only post-intervention rating

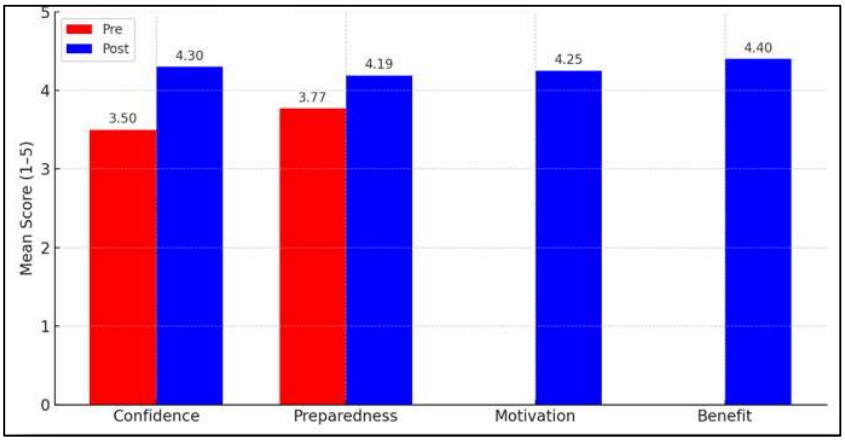

Figure 1 Student Ratings Pre- and Post-Intervention for Confidence, Readiness, Motivation, and Benefit

4.1.2 Qualitative findings

The thematic analysis of the reflective journals and open-ended survey responses from 73 students revealed three major themes that underscore the positive impact of industry-led guest lectures on skill development and professional readiness. The analysis was guided by Braun and Clarke (2006) principles, ensuring a comprehensive and systematic interpretation of the qualitative data. The following themes emerged:

(1) Professional Skill Development: Students frequently reported gaining hands-on knowledge and practical insights that bridged the gap between academic theory and industry practice. One student remarked, *"The guest lecture gave me the skills to handle real maintenance challenges,"* particularly in *"troubleshooting electrical faults in power distribution."* Another noted, *"The session on using PowerPoint for maintenance reports was something I hadn't considered, but it's an invaluable tool for professional communication."* These responses show that the guest lectures provided not only technical skills but also industry-specific practices directly applicable to students' future roles. Additionally, many

students highlighted the acquisition of transferable skills, such as "interpersonal communication," "project management," and "task scheduling," which are essential in real-world engineering environments.

(2) **Problem-Solving and Innovation:** A prominent theme was the shift in students' approaches to problem-solving. Several students noted that the guest lectures provided tools to think more systematically and analytically about engineering challenges. One student shared, *"I now gather all the necessary information and plan before starting any task,"* reflecting a more structured problem-solving approach. Another remarked, *"The real-world examples helped me see the practical side of problem-solving and think through constraints in ways I hadn't before."* This suggests that the guest lectures enhanced students' critical thinking skills, enabling them to apply theoretical knowledge to real-world scenarios and develop innovative solutions.

(3) **Strengthening of Professional Growth:** A key finding from the qualitative data was the strengthening of students' professional identities and career direction. Many students reported that the guest lectures deepened their understanding of the engineering profession. One student remarked, *"I now understand why maintenance is critical in ensuring the reliability of engineering systems,"* while another shared, *"I feel more competent and prepared to enter the workforce after these sessions."* These responses suggest that, in addition to developing technical skills, the lectures had a significant impact on students' professional confidence and their evolving sense of identity as engineers.

(4) **Breadth and Variation in Responses:** While most students reported positive outcomes from the guest lectures, there were variations in responses, particularly regarding the relevance of industry-specific knowledge. Some students felt certain topics, like advanced technical tools, were beyond their current level of study. One student noted, *"While the session on advanced fault diagnosis was interesting, I feel it was a bit ahead of where I am right now."* This highlights the need to tailor guest lectures to students' educational stages and technical proficiency levels. Overall, the findings underscore the multifaceted impact of industry-led guest lectures and the depth of student engagement, with a nuanced appreciation for how the content relates to both their career goals and current learning needs.

4.2 Discussion

The results of this study provide strong evidence that industry-led guest lectures significantly impact students' professional development. The positive quantitative changes in confidence and readiness (with moderate effect sizes) suggest that guest lectures help bridge the gap between academic learning and real-world application. This finding aligns with previous research that highlights the value of industry exposure in enhancing students' self-efficacy and preparing them for future careers in engineering (Pepple et al., 2025; Vuoriainen et al., 2025).

The high post-intervention scores for motivation and perceived benefit (4.25 and 4.40) further confirm the value students place on guest lectures. Although no pre-intervention baseline was available for these variables, the strong post-only ratings support the idea that students found the lectures highly engaging and relevant to their career aspirations. These results echo similar studies showing that guest lectures can stimulate students' interest in their fields and increase their commitment to professional growth (Morin & Willox, 2022; Shah & Gillen, 2024).

The qualitative data complement the quantitative findings by providing insights into how students internalized the information shared during the guest lectures, highlighting the development of practical skills and a deeper understanding of problem-solving, consistent with prior research on experiential learning in engineering

education (Braun & Clarke, 2006). The theme of professional growth underscores the broader value of guest lectures, fostering not only technical knowledge but also the confidence and mindset necessary for success in the professional world. While the results are promising, further research is needed to evaluate the long-term impact of guest lectures on career outcomes, such as job placement and leadership development, and to explore how to integrate them into resource-constrained institutions like many African universities to maximize their effectiveness.

5. Implications and future work

The findings highlight the potential of industry-led guest lectures as an alternative to traditional internships in resource-constrained settings, providing authentic industry exposure when placement opportunities are limited. To maximize their impact, these lectures should be strategically integrated into curricula with strong institutional and policy support. Additionally, the study emphasizes the value of structured reflective practice, which deepens understanding and fosters professional growth, helping students transition confidently into the engineering workforce. Future work will include follow-up studies to examine long-term impact on career outcomes, as well as extending the study across departments and institutions. Comparative studies with traditional experiential methods (e.g., internships, industrial visits) would further strengthen the evidence base for this intervention.

6. Limitations

This study relied on self-reported data, which may introduce bias and affect the accuracy of the findings. Additionally, the lack of a control group limits the ability to directly attribute improvements solely to the guest lectures, as we cannot rule out other external factors that may have influenced the results. The instrument used to measure these outcomes was not validated, which further impacts the generalizability and robustness of the findings. Furthermore, this study was conducted as a single-institution case study, meaning the results may not be generalizable to diverse educational settings or institutions with different resource contexts. Despite these limitations, the study offers valuable insights into scalable, low-cost interventions for improving the relevance of engineering education, particularly in resource-constrained environments in Africa and similar contexts worldwide.

7. Conclusion

This study shows that industry-led guest lectures, when integrated into engineering education, can enhance student confidence, preparedness, and motivation. These findings contribute to the discourse on context-sensitive pedagogies, particularly in Africa, where traditional experiential learning may be limited. The combination of guest lectures and reflective practice offers a promising approach to developing professional competencies and bridging the gap between academia and industry. Expanding this model can help cultivate holistic, employable, and globally competent engineers, especially in resource-constrained settings.

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A Comparative Analysis of Embedding Responsible Innovation in Integrated Engineering Curricula: A case study of Established vs Emerging Universities

Vivek Ramachandran
University College London, UK, v.ramachandran@ucl.ac.uk

Rhythima Shinde
TEDI-London and KLH Sustainability, UK, rhythima.shinde@klhsustainability.com

Emanuela Tilley
University College London, UK, e.tilley@ucl.ac.uk

Abstract

As engineering education evolves to meet the demands of an increasingly complex world, especially in times of a climate crisis, universities must prepare students to develop technologies that are ethical, sustainable, and socially responsible. Responsible Innovation provides a framework for achieving this by integrating ethics, sustainability, risk mitigation, and equity, diversity, and inclusion into engineering curricula. Engineers have long influenced society through innovation, acting as agents of change. Given the lasting impact of engineering decisions, future engineers must be equipped to anticipate risks, uphold ethical standards, and design inclusive solutions that serve diverse communities. Many institutions are shifting toward integrated education models that emphasise real-world applications through project-based learning (PjBL). This paper compares how RI is embedded within two academic frameworks: (a) the established Integrated Engineering Programme at University College London (UCL), an interdisciplinary approach that works within that a discipline-based departmental structure (e.g., mechanical, electrical, chemical engineering) by combining project- and lecture-based learning, and (b) the Interdisciplinary Global Design Engineering Programme at emerging institutions like The Engineering & Design Institute London (TEDI-London), which employs a fully project-based learning approach. By examining these programmes, through an auto-ethnographic study, by interviewing two early-career academics from these institutions, capturing their reflections on the challenges and opportunities of embedding RI in engineering curricula. Ultimately, this paper offers recommendations for strengthening the integration of RI within engineering curricula, tailored to each programme's unique characteristics. It contributes to ongoing discourse on preparing engineers to navigate global challenges, emphasising inter- and trans-disciplinary competencies as essential for future demands.

Keywords: Responsible Innovation, Project-based Learning, Interdisciplinarity, Auto-ethnography

1 Introduction

Engineering innovation has long prioritised technological advancement without fully accounting for its ethical, social, and environmental impacts. The climate crisis, a stark consequence of unchecked innovation, is one of the most urgent and existential threats to our planet (Sveiby, Gripenberg, Beata, Eriksson, & Aminoff., 2009; Biggi & Giuliani, 2022). Engineers, as the architects of industrial progress, hold a profound responsibility in this crisis (Stilgoe, 2013). They have shaped the world through technological advancements, but too often at the expense of people and the planet. At the same time, engineering also has the means to resist - by working across disciplines and challenging extractive systems, engineers can help shift priorities toward sustainability and collective well-being and contribute to positive transformative change (Alwi, Manan, Klemeš, & Huisingh, 2014). Given this capacity for change, there is a growing recognition that universities must play a central role in equipping engineering students with the skills and competencies necessary to address the climate crisis (Filho, 2011). To support this shift, the United Nations' Education for Sustainable Development (ESD) framework has been widely adopted, shaping curriculum revisions to embed sustainability within higher education (Rieckmann, 2017).

In this context, the latest edition of the UK Engineering Council's Accreditation of Higher Education Programmes (AHEP4) underscores the growing recognition of the eco-social dimensions of engineering (Engineering Council, 2020). AHEP4 highlights key aspects of Responsible Innovation (RI) - encompassing Ethics, Sustainability, Risk mitigation and Safety, and Equity, Diversity, and Inclusion (Owen, Bessant, & Heintz, 2013). This shift acknowledges that engineers must be equipped not only with technical expertise but also with the values and critical awareness necessary to make ethical, sustainable, and inclusive decisions. In response, engineering programmes are deliberately adopting an integrated approach that fosters interdisciplinary education, recognizing that today's global challenges cannot be addressed by any one discipline alone (Van den Beemt, et al., 2020).

This interdisciplinarity is reinforced through active inquiry-based learning methods, such as Project-Based Learning (PjBL), which immerse students in real-world challenges and encourage collaboration across disciplines to develop socially responsible and innovative solutions (Kokotsaki, Menzies, & Wiggins, 2016). Adapting to its unique context and institutional goals, some programmes have focused on blending multiple engineering disciplines within a single curriculum while other programmes have brought students from different disciplines to develop solutions to interdisciplinary challenges (Richter & Paretti, 2009).

Despite the diversity of approaches, many programmes still face significant challenges in effectively integrating RI in their respective interdisciplinary contexts (Foley & Gibbs, 2019). In many cases, curriculum changes are not sufficient; faculty members lack the experience or training required to manage interdisciplinary team projects or to guide students in addressing the social and ethical implications alongside technical expertise (Summers, Childs, & Corney, 2005).

While much of the existing literature focuses on student experiences, there has been insufficient exploration of the challenges faced by faculty in adapting to these new roles. Without adequate institutional support, many educators struggle to integrate these critical topics on RI into their courses. There is little guidance on how to navigate this transition effectively, particularly for early-career academics who must balance disciplinary traditions, institutional expectations, and novel pedagogical approaches.

This paper seeks to address the question: *What are the challenges and opportunities faced by early-career academics in embedding responsible innovation within interdisciplinary engineering curricula, and what institutional support mechanisms are needed to facilitate this transition in their unique contexts?*

By answering this question, the authors aim to highlight the key skills required for successful implementation for enhancing institutional support structures for (early-career) educators undertaking this transition.

2 Methodology

To explore the research question, the first two authors employed an auto-ethnographic approach. The paper took direct inspiration from a similar auto-ethnographic study carried out for reflections on leading Large-Scale Interdisciplinary Team Project Modules (Truscott & Smith, 2024). Auto-ethnography, especially in education paradigm, enables a reflexive analysis of personal and professional experiences, offering rich, contextual insights (Denshire, 2014; Dyson, 2007). These two authors drew on their personal experiences and reflections as early-career academics, each working in distinct interdisciplinary engineering programmes with a focus on teaching social responsibility in engineering education. By positioning themselves as both researchers and participants, they critically examined their own challenges, strategies, and institutional contexts in integrating RI within engineering curricula. In this context, auto-ethnography served as a valuable method, enabling them to systematically translate their experiences into a broader understanding of the opportunities and challenges faculty face. The third author, serving as Programme Director of the IEP (IEP), provided critical oversight and analytical perspective to the study. They provided the institutional context and programmatic insights that was necessary for this autoethnography.

The two institutions - University College London (UCL) and TEDI-London - both emphasise interdisciplinary, project-based learning as a core component of their engineering curricula, adopting different pedagogical methods to match their unique contexts while sharing similar values that drive them. Similarly, the first two authors also share the same commitments to fostering socially responsible engineering education as part of their individual practice. Therefore, this study is created to elicit the ways in which the different institutional contexts and pedagogical approaches shaping their experiences and the challenges they face as being representative of other early career academics in similar positions.

At UCL, the Integrated Engineering Programme encompasses most of the flagship engineering undergraduate degrees offered by the departments within the Faculty of Engineering Sciences. The IEP emphasises interdisciplinary learning in which students collaborate with peers from other departments/disciplines. The programme complements project-based learning with skills-training in topics such as technical communication, academic research, teamwork, project management, and responsible innovation. Students engage with engineering challenges in single- and multi-disciplinary problems while considering the social impact of their solutions. Combining lectures and hands-on projects, the IEP cultivates both technical proficiency and societal awareness within its diverse annual cohort of approximately 1,000 students. At TEDI-London, the Global Design Engineering programme is an innovative programme that adopts an interdisciplinary and project-focused approach, with flipped classroom model, and emphasis on emerging topics like smart cities, sustainability, and user-centred design. With an annual cohort size of about 50 students, the programme offers immersive, hands-on projects supported by online learning and strong industry collaborations. This encourages students to apply their learning directly to contemporary global issues in each module.

The first author, based at UCL, is an early-career academic specialising in social responsibility within engineering education. Their role involves supporting students in interdisciplinary teamwork, helping them navigate ethical dilemmas and develop a broader awareness of engineering's societal implications. In addition to teaching, they contribute to curriculum development, ensuring that social responsibility is meaningfully embedded across the IEP's interdisciplinary projects. The second author is also an early-career academic at TEDI-London, where they play a key role in embedding social responsibility and sustainability within the curriculum. Their teaching centres on interdisciplinary, project-based learning that blends technical and socio-environmental considerations. Through industry and community collaborations, students engage with authentic engineering challenges that mirror real-world complexities.

Over six months, the authors met regularly in semi-structured reflections, examining their motivation and roles, teaching methodologies, challenges, and institutional contexts. By systematically comparing the reflections, the authors identified key themes on personal motivations (why), institutional context and support (where), instructional strategies (how), and challenges & opportunities (what). This approach not only provided insight into their own pedagogical practices but also contributed to a growing conversation about the evolving role of engineering educators in shaping ethically and socially conscious engineers

3 Results and Discussion

In this section, we delve into the identified key themes that emerged during our exploration of the two engineering education frameworks.

3.1. Motivation and Institutional Context

How do your personal motivations align with your institution's pedagogical approach in embedding RI, including sustainability, ethics, and inclusivity into the engineering curriculum?

For the first author, the appeal of the IEP at UCL Engineering was compelling for multiple reasons. What stood out was its bold trailblazing approach - pioneering a shift in engineering education despite resistance. Unlike traditional programmes that are isolated by discipline, the IEP prioritised interdisciplinarity from the outset, embedding responsible innovation at its core. Having studied at large universities, the first author had faced similar challenges of departmental isolation and a lack of exposure to social responsibility topics in engineering curricula - issues they had been passionate about since their undergraduate days. Joining the IEP felt like an opportunity to bridge that gap and teach the socially engaged engineering education they had longed for. The programme's reputation for producing graduates who challenge norms and drive change reinforced their belief that this was the right place to be.

For the second author, their personal multidisciplinary background aligned very well with TEDI's interdisciplinary global design engineering programme. In contrast to the large, academic institutions where they previously studied - characterised by slow-moving, bureaucratic processes that often stifled innovation and student agency - they found TEDI's project-based learning approach refreshingly direct. The absence of artificial disciplinary boundaries meant that real-world problems were tackled in collaboration with industry partners from the outset, an approach that strongly aligned with their personal interest in applied engineering skills. With a small, tight-knit community, they had the opportunity to shape the programme in meaningful ways, ensuring that sustainability, ethics, and inclusivity weren't just abstract ideas but embedded in tangible projects. As someone with experience running both an NGO and a company, she found that her personal entrepreneurial spirit aligned well with TEDI's agility, entrepreneurial nature, and applied focus, viewing it as a place where she could make a real impact.

3.2 Institutional Support

How have the availability of resources, administrative support, and institutional training influenced the success of integrating sustainability and ethics into your curriculum, and what gaps have you identified?

At UCL, the vastness of the institution provides both opportunities and challenges in integrating RI into the engineering curriculum. While there is a wealth of expertise and resources available, such as the Higher Education Development and Support Institute (Arena), the sheer size of the university can make it overwhelming to navigate, with unclear signposting for whom to approach for specific needs. The IEP team works collaboratively with faculty from all engineering departments to co-teach modules throughout Years 1-3, ensuring students are exposed to diverse disciplinary perspectives. In recent years, UCL has driven the

development of teaching and research toolkits at the university level through its Grand Challenges initiative, reflecting a growing momentum to engage more deeply with RI themes. Nonetheless, gaps remain in providing clear, centralised guidance and ensuring broader, more consistent institutional support for embedding sustainability and ethics education across departments in each faculty.

At TEDI London, the small and new academic team (the institute is only 5 years old), with only 2-3 educators per discipline, has ensured coherence and consistency in the delivery of these topics. However, this structure also means that perspectives can be limited or biased, as there is little room for diverse viewpoints within each discipline. As the team grows, sustainability and ethics are increasingly embedded in a bottom-up approach, where each educator, administrative member, and institutional policy plays a role in fostering these values. This growing inclusivity makes it easier to introduce new teaching topics, methods, tools, and industry practices. On the administrative side, the small team, though limited in terms of resources, personnel, and facilities compared to larger institutions, has allowed for more direct interaction with staff and fewer bureaucratic hurdles. While this means there is limited access to extensive institutional resources, the direct and flexible support system allows for quick access to necessary resources, whether it's access to VR tools or makerspaces, when needed. This allows an easier way to introduce new interdisciplinary methods and quicker access to industry real-world applied projects and support.

3.3. Instructional Strategies

Based on our teaching experience, which specific teaching methods, tools, and strategies have proven most successful in helping students grasp and apply sustainability and ethics in their engineering education?

According to the first author, they implement direct classroom instruction through the "Engineering Challenges" and "Design and Professional Skills" (DPS) modules in Year 1. In Engineering Challenges, multidisciplinary teams tackle real-world problems such as setting up a tuberculosis vaccine plant in Uganda, with students encouraged to consider the premise and social impact of the project. In DPS modules, content is tailored to different disciplines, connecting engineering practice with social justice issues like the climate crisis and industry responsibility, effectively making these topics relevant to students' fields of study. The author also supports scenario-based learning - an immersive, week-long experience where students from the same discipline apply their DPS knowledge to real-world projects. Additionally, the author provides support to scenario teaching leads in integrating RI through tailored pedagogical and curriculum development, including lectures and assessment design. These complementary approaches have proven effective in helping students recognise their responsibilities in engineering projects.

In the experience of the second author, at TEDI-London, all modules have integrated industry-linked projects, group assessments, stakeholder workshops, presentations, and site visits, engaging students with real-world challenges and develop understanding of the social and environmental implications of their work. In the “Ecological Design” module that they run, students gained hands-on experience with sustainability tools such as Life Cycle Assessment and engaged in mechanical engineering simulations using digital tools like MATLAB. Additionally, systems thinking was incorporated through interactive modules, encouraging students to consider the interconnectedness of engineering systems and the broader impact of their decisions. Key skills such as communication, portfolio design, and project management were also emphasized, fostering the ability to lead projects with an ethical and sustainable focus. Furthermore, in modules like “Smart Cities” and “Global Design Engineering”, students were encouraged to design inclusive and accessible solutions, with varying assignments that fostered both individual and collaborative work, ensuring they were well-equipped to navigate the complexities of ethical and sustainable engineering in diverse contexts.

3.4. Challenges

What significant challenges have you faced as educators in embedding sustainability and ethical considerations into your teaching model, and how have you worked to overcome them in practice?

The isolated nature of first-year RI lectures limits long term engagement, with only a small cohort (30 students) continuing to the second-year Engineering Design for Society module. At a faculty level, embedding RI into engineering education programmes like the IEP presents specific challenges, that include institutional resistance, curriculum constraints, student engagement, and faculty preparedness. Disciplinary silos can create inconsistencies in how RI is addressed - some departments see RI related accreditation requirements as a box-ticking exercise, while others embrace RI as central to their subject. Time constraints exacerbate this issue, with faculty members either lacking the time to prepare content on social responsibility or struggling to fit it into an already packed curriculum. Additionally, many first- and second-year students enter with rigid expectations about their disciplinary identities, often anticipating a traditional, technical focus.

At TEDI-London, the limited size of the academic team and the constraints of time are the key challenges. Additionally, there has been limited training of educators in interdisciplinary methods, which further complicated the integration of these critical topics into the curriculum. Balancing structured, meaningful sustainability education within the project-based model of the curriculum posed another challenge, particularly when it came to assessing individual contributions in team projects while also integrating ethics alongside technical learning. Furthermore, maintaining student engagement across diverse cohorts, each with varying levels of prior knowledge and interest in sustainability, added another layer of complexity.

3.5. Opportunities

What further institutional changes or support do you feel are necessary to improve sustainability education and better equip engineering graduates with the skills they need to address pressing global challenges?

At UCL Engineering, a growing transdisciplinary interest could be enhanced through cross-faculty collaborations with RI-focused units and local community partnerships for service-learning. The priority should be to weave RI themes into existing courses by critically evaluating existing content e.g. by developing meaningful assessment methods that measure sustainability competencies effectively. Many educators struggle to integrate RI due to limited training and institutional backing, thus, the university must provide resources and professional development opportunities that empower faculty to navigate these complex topics and embed RI across the curriculum.

TEDI-London should continue expanding its industry and global academic partnerships to diversify the types of projects available to students. Additionally, strengthening and pushing the boundaries of disciplinary contexts to evolve new fields, such as responsible robotics and ecological design, will help broaden students' understanding of how sustainability and ethics intersect across various domains. It is also crucial to increase support for specialized training and qualifications for interdisciplinary educators. Furthermore, leveraging digital technologies responsibly - such as through projects involving robots used for educational purposes - would help students see the potential for innovation to address global challenges.

4 Conclusion

This study addresses the key challenges early-career academics face in embedding responsible innovation, such as institutional resistance, curriculum constraints, and insufficient faculty training—while also highlighting opportunities for improvement through interdisciplinary collaboration, institutional support, and industry partnerships. At UCL Engineering, the challenges include navigating disciplinary silos and

inconsistent faculty engagement, whereas TEDI-London's smaller, agile structure allows for quicker adaptation but faces limitations in resource depth and faculty diversity. Despite the differences in experiences, authors believe that at both institutions, RI need to be viewed and embedded as a set of values, not merely a set of skills. The study highlights actionable pathways for improvement, including faculty development programmes, and centralised guidance. For early-career academics, institutional backing is critical to overcoming resistance and ensuring that sustainability, ethics, and inclusivity are not treated as add-ons but as foundational pillars of engineering education. By prioritizing these changes, universities can empower educators to cultivate a new generation of engineers who are not only technically proficient but also ethically and socially responsible- equipped to address the urgent challenges of our time.

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Caring Pedagogies in Action: Utilising Student Engagement Data to Develop Sustainable Learning Environments

Kristo Kotsi

Department of Chemical Engineering, UCL, London, WC1E 7JE, United Kingdom, kristo.kotsi.20@ucl.ac.uk

Mian Xie

Department of Civil, Env. & Geomatic Engineering, UCL, London, WC1E 6BT, United Kingdom, mian.xie.18@ucl.ac.uk

Matheus O. de Andrade

UCL Centre for Engineering Education, UCL, London, WC1E 7JE, United Kingdom, m.deandrade@ucl.ac.uk

Abstract

In the context of growing class sizes and limited institutional resources, student-centred and responsive education is increasingly important although challenging to implement effectively. A central part of responsiveness involves interpreting and acting on student-generated data -a task that can be particularly challenging for novice engineering educators, as their background and training often guide both how they understand the data and how they respond to it. This paper reflects on our experiences, as teaching assistants and course lead, in developing and running a data analysis process for a large-scale problem-based learning engineering mathematics course. Using autoethnographic data from written reflections and transcripts, we applied an adapted version of Sochacka et al.'s (2009) three-tier reflexivity model to analyse how our understandings evolved regarding (i) what counts as data, (ii) how it can be interpreted, and (iii) what matters in its analysis. Through dialogic exchange, we identified significant shifts in our conceptualisations of the task of educational data analytics, as well as the value we placed on the different types of data.

Keywords: Learning analytics, virtual learning environments, adaptive learning, reflexivity in educational research, critical quantification

1. Introduction

The integration of virtual learning environments (VLEs) in higher education offers valuable opportunities to collect and analyse educational data for monitoring and improving teaching and learning strategies (Siemens & Long, 2011). However, ethical concerns around privacy, consent, and bias still remain prominent (Floridi & Taddeo, 2016) with the British Educational Research Association calling for transparency, accountability, and respect of student rights. Meanwhile, educators must reflect on how their own values can influence the data interpretation and pedagogical decisions (Denscombe, 2003).

For engineering educators, reflecting on personal values and biases can be particularly challenging, given a professional background that tends to prioritise positivist, pragmatic, and numerical data analysis over interpretive, contextual, and qualitative understandings. This tension between technical rigour and interpretive approaches has already been noted by engineering education researchers, who suggest that engineering faculty are often trained to prioritise quantitative precision over interpretive rigour (Borrego, 2007; Koro-Ljungberg and Douglas, 2008).

Responding to these challenges, this paper reflects on our collective experience over three years designing, and implementing data analytics processes to support a large-scale engineering mathematics

problem-based learning (PBL) module delivered through a flipped classroom format. Our main practise question is:

What have we learned from this collaborative process, and how has this shaped our current identities as engineering educators?

Through writing and collaboration, we aim to make visible how our perspectives on educational data interpretation have evolved and to encourage other educators engaged in student data analytics to adopt reflexive practices. Finally, we draw practical implications for data-informed PBL approaches and for training and onboarding teaching assistants involved in interpreting student data collected via virtual learning environments (VLEs).

2. Institutional Context

The study is situated in a faculty-wide, first-year mathematics course with approximately 900 students across eight engineering departments at University College London. The module covers calculus, linear algebra, complex numbers, differential equations, mathematical modelling, and data analysis, using a flipped-classroom format: students complete self-paced online activities before participating in face-to-face departmental workshops, where they collaboratively solve real-life engineering mathematics problems. The online module material, hosted on Moodle®, generates both quantitative data (grades, completion rates) and qualitative inputs (short-answer responses, uploaded diagrams, perception surveys). In 2022, a small data analysis team, formed by two teaching assistants (TAs), was created to process and analyse this data weekly, producing reports for teachers leading the module's problem-solving workshops and for the course lead who oversees the teaching delivery, faculty-wide.

3. Methodology and Reflexivity Framework

To answer our practice question, we produced autoethnographic data through written reflections and "think-aloud" dialogic meetings with automatic transcription. Our reflections were prompted by three activating questions, initially answered individually in writing and then discussed collectively over the course of two meetings:

- What did you expect this data analytics role to involve when it started?
- How has your understanding of the role and of data analysis changed over time?
- What is the engineering educator identity that you developed through this role?

The autoethnographic data was then analysed deductively through an adaptation of the three-tier model of reflexivity designed by Sochacka et al. (2009) in an attempt to help engineering education

researchers examine how their disciplinary background, personal values and experiences shape their research in interpretive contexts. We made minor *a priori* adaptations to the framework which originally consisted of ontology and epistemology as the first dimension, values (axiology) as the second, and lived experiences as the third. In designing this study, we decided to split the first dimension and merge the second and third, where our reflexive framework consisted of:

- Ontology: the things that exist, what they look like, and how these things interact with each other.
- Epistemology: how can we gain knowledge about something, and what are the criteria for this knowledge to be valid.
- Axiology: how our values, orientations and lived experiences shape our actions in the educational environment.

This split follows Bhaskar's (1975) critical realist position that ontology (what exists) and epistemology (how we know) are distinct domains of inquiry.

4. Discussion and Findings

Throughout our discussions, we identified clear shifts across all three tiers of reflection. A central theme was our relationship with quantifiable data such as grades in formative activities, completion rates at departmental and faculty level, and how these indicators changed over time. At first, we treated them as direct measures of learning and engagement. Over time, we came to see them as partial signals that hide important aspects of student experience. A low completion rate, for instance, might reflect conceptual difficulty, time pressures, digital literacy issues, or alternative learning strategies. None of these factors, however, are visible in the numbers alone. We interpreted this as our ontological shift from assuming “the data tells the whole story” to recognising that “data have blind spots” and must be interpreted in context.

This recognition prompted an epistemological shift in how we interpreted and acted on data. Early on, our approach was to focus on what the data showed. If completion rates dropped or grades decreased in a certain topic, we responded directly by encouraging students to complete preparatory work or spending more class time on problems with low average grades. Later, we began asking why these changes occurred and how the data might meaningfully inform teaching. That is, the initial focus on metrics on their own changed to a focus on what the metrics could be an indicator of, which requires interpretation.

Our most important epistemological shift was that patterns in performance were sometimes more reflective of the structure or validity of the assessment items than of student understanding, and that engagement rates were not necessarily related to motivation, interest, or conscientiousness as initially assumed, but more so of the clarity and accessibility of the digital activities. For example, coding activities by theme revealed that questions with numerical answers had consistently higher average scores than questions with symbolic answers, prompting us to reconsider how we interpreted grades, now including the "type of answer" as an important explanatory variable.

Going back to the theme of "invisibility in data" identified in our reflections, we also considered whether VLE-generated statistics were representative of the student population at all. One of the team members mentioned "a constant left-skew" in the data, meaning that most completions were concentrated at high grades with few at the lower end of the distribution, which could indicate a type of "self-selection" bias where there is a possibility that proficient students completed the activities possibly to confirm their ability, whilst students struggling decided not to complete them to avoid receiving low formative grades. Although this inference was made as a possible explanation to the behaviour observed, it suggests that the common frequentist statistics performed on the data might be inappropriate to yield valid and actionable educational insights.

Recognising that important aspects of student experience lie beyond the scope of our datasets (ontology) forced us to rethink how we interpret and act upon those datasets (epistemology). Taken together, these shifts reshaped the values we brought to our data-informed practice (axiology) and to our identities as educators. As we became more critical of what our analytics could and could not reveal, we placed increasing emphasis on fairness, transparency, and relational aspects of data-informed education, which formed the basis of our reflections on axiology and lived experiences.

We became more deliberate in ensuring that analytics were used to support learning rather than to police or punish. Respecting student agency meant recognising that non-engagement could be a valid strategic choice rather than simply a deficit. For example, in the weeks prior to multiple deadlines we started to expect a drop in completion rates. We also prioritised transparency about what data was collected and why, which was ultimately to uphold our values of student-centred learning experiences. For example, instead of uniformly redesigning workshops based on aggregate data, we considered the diversity of student circumstances and used targeted, non-punitive interventions.

Relational and pastoral considerations became central to our practice. Building rapport and approachability in classes, responding to individual circumstances with empathy, and creating psychologically safe spaces for feedback and discussion all became priorities. A clear shift in values occurred from

attempting to “fix” what the numerical data indicated as problems to facilitating conditions for students to succeed, combining analytics with dialogue to understand the stories behind worrying numbers. As one of the team members put it, we learned to “believe people, not numbers”. This included targeted one-to-one support for persistently low-engagement students, and practising triangulation by weighing quantitative indicators against qualitative accounts. These changes marked our evolution from technically oriented data analysts to reflective educators, comfortable with the ambiguity of data, and committed to co-constructing interpretations and actions with students.

5. Conclusions

In this paper we have explored challenges of using data analytics in a large-scale, hybrid mathematics course through the lens of Sochacka et al.'s (2009) three-tiered model of reflexivity, focusing on how ontological and epistemological assumptions, underlying values, and lived experiences shape the collection and interpretation of student data. Our findings suggest that while data analytics can offer insights into student engagement and learning, their effectiveness depends not only on technical accuracy but also on a deep awareness of the assumptions and values embedded in the process.

The paper argues that the value of educational data lies not in its capacity to classify or measure students, but in its potential to inform thoughtful, dialogical, and values-driven educational practices within problem-based learning environments. For educators working with large and diverse cohorts, especially in engineering education -and for teaching assistants- this approach offers a valuable model for including reflexivity and care into data-informed teaching.

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Mathematics for Sustainable Development (MATH4SDG): A Capacity Building Project in Uganda and Tanzania

Bettina Dahl
University of Bergen/Aalborg University, Norway/Denmark, *bdahls@plan.aau.dk*

Guttorm Alendal
University of Bergen, Norway, *guttorm.alendal@uib.no*

Eunice Mureithi
University of Dar es Salaam, Tanzania, *mureithi.eunice@udsm.ac.tz*

John Mango
Makerere University, Uganda, *mango.john@mak.ac.ug*

Abstract

Mathematics for Sustainable Development, MATH4SDG, is a capacity building project funded by the NORHED II programme under the Norwegian Agency for Development Cooperation (NORAD) involving the mathematics departments at the University of Dar es Salaam (Tanzania), Makerere University (Uganda), and the University of Bergen (Norway). The project aims to enhance mathematics education and research in Tanzania and Uganda. Central to MATH4SDG is 11 PhD-students, with four in secondary mathematics education and seven in applied mathematics and statistics. All PhD-students are supervised by both Norwegian and local supervisors. Another component involves outreach to schools and research collaboration workshops with local industry and governmental organizations. By aligning university mathematics programmes with the needs of these stakeholders, graduates become more attractive to employers and the workforce benefits from a strong foundation in mathematics and its applications thus aiding in the digital transformation for sustainable development. MATH4SDG contribute to educating much needed schoolteachers and enhance the proficiency in mathematics.

Keywords: Mathematics; Capacity building; Applied mathematics; Secondary mathematics education; Outreach

1 Introduction: The Significance of Mathematics

As part of achieving the overall aim of MATH4SDG to increase general mathematical lit

The Italian philosopher, physicist, and astronomer Galileo Galilei is in the 17th century referred to as stating that mathematics is the language in which God has written the universe (Maddy, 2011). In the subsequent centuries, we saw tremendous scientific development leading to the industrial revolution, and more recently the digital revolution. During this development, mathematics evolved and confirmed its role as the language of the sciences. However, in 2015 UN estimated that more than half a billion children in schools were not achieving the needed proficiency in reading and mathematics. The problem of illiteracy is most profound in developing countries. Globally there has been little progress in the percentage of trained primary school teachers, around 64% in sub-Saharan Africa. In the 2019 progress report on the UN's 2030 Agenda for Sustainable Development (United Nations, 2019), the UN states that there is a need to harness science, technology and innovation with a greater focus on digital transformation for sustainable development. To achieve this, the need for mathematics becomes even more important as numeracy is also mentioned explicitly in Target 4.6 in the Sustainable Development Goal 4 (SDG4), Quality Education (United Nations, 2015).

Mathematics lies at the foundation of most subjects in the natural sciences, technology, economics, health, and the social sciences, hence it is taught at all levels of education and universities worldwide. With the ongoing digitalisation of our societies, the inflation in data availability and the acknowledgement that many previously qualitative fields are getting more quantitative, basic knowledge in data science, including artificial intelligence and machine learning, has become important generic knowledge expected from university graduates in many fields. In Norway, most of the technical and natural science studies at the largest universities are now being reformed to reflect this.

Globally the world recently faced a huge health crisis with the COVID-19 pandemic causing deep social, economic, and political crises. Mathematicians were contacted globally to use mathematical models to do projections and explain the dynamics of COVID-19. Africa is in addition plagued by several health problems such as vector-borne diseases, HIV, and Ebola. Malaria has continued causing morbidity and mortality in the East African region. The role of mathematics in health matters cannot be over-emphasized. Climate change

is another concern globally. It has caused and continues to cause many negative impacts such as floods, droughts, bushfires, cyclones, etc., thus affecting agriculture, water availability, the ecosystem, etc. The role of mathematics in the development of science and technology is acknowledged globally.

In response to this, Mathematics for Sustainable Development (MATH4SDG) is a capacity building project running 2021-2026 funded with 20 million NOK (approx. 2+ million USD) by NORHED II, the Norwegian Programme for Capacity Development in Higher Education and Research for Development under the Norwegian Agency for Development Cooperation (NORAD). It is a collaborative initiative involving the mathematics departments of the University of Dar es Salaam (USDM, Tanzania), Makerere University (Uganda), and the University of Bergen (UiB, Norway) (https://math4sdg.w.uib.no/). The overall aim of MATH4SDG is to increase the general mathematical literacy in Tanzania and Uganda and develop and strengthen the capacity in postgraduate training and research in mathematics in these countries. This includes the education of 11 PhD candidates. MATH4SDG has therefore executed a research programme in collaboration with colleagues within health and medical institutions in the three cities, focusing, e.g., on the epidemiological modelling as well as initiated activities to strengthen secondary mathematics education in Tanzania and Uganda. Three outcomes are defined as follows:

- Better mathematical research at the two African universities,
- Updated and relevant educational programmes in mathematics and mathematics education, and
- Higher visibility of the departments.

Below we will describe the various activities in MATH4SDG, particularly the projects done by the 11 PhD students, which form a core of MATH4SDG. Next, we describe outreach activities and finally some evaluation of these activities.

2 The 11 PhD Students

2.1 Four students in Mathematics Education

Good mathematics schoolteachers are essential to trigger interest and learning of mathematics for the next generations thereby contributing to the development of proficiency in mathematics. At the two African universities, education of primary and secondary school teachers takes place at their respective Schools of Education. For this reason, four PhD projects were allocated to secondary mathematics education in the following areas:

Makerere University: Two male students. One (Ssali et al., 2025) is focused on the application of Problem-Based Learning (PBL). The Uganda Ministry of Education and Sports (UMoES) promoted the inclusion of PBL compentencies such as critical thinking and problem-solving, creativity and innovation in the new competence base school curriculum starting 2020 (UMoES, 2019). Therefore, this project implements PBL in some schools and evaluates upon this. The other PhD student (Gaanya et al., 2025) is implementing Mathematics for Sustainable Development (Math4SD) projects as an attempt to adhere to the inclusion of the cross-cutting issues in Uganda's new curriculum (UMoES, 2019) at the lower secondary level. The cross-cutting issues are attached to the three categories of the Math4SD perspectives such as environmental awareness, diversity and inclusion, and socio-economic challenges.

University of Dar es Salaam: Two female students. One (Boki, 2025) works within the area of technology application in schools, particularly how technology can be used in classes that frequently suffer from lack of teachers. In Tanzania, the shortage of teachers is severe and persistent. In the year 2022/2023, Tanzania faced almost 66% shortage of mathematics and science teachers as 70,327 teachers were needed, but only 23,647 were available (Mosenda, 2024). Another PhD (Kihaga et al., 2025) is focused on the challenges of teaching and learning in large classes, which is a common phenomenon in Tanzania due to, e.g., higher demand for formal education, shortage of human and physical resources, pupils repeating years, and national

economy (Shukia, 2020). In fact, Tanzania's secondary schools have up to 70+ students in a single classroom, contrary to the national benchmark of 40 students per teacher (Mazana et al., 2020).

2.2 Seven students in Applied Mathematics

As stated above, there is a greater need for more knowledge and training in the field of data science, which is an emerging multi-disciplinary field. This will create professionals with knowledge and skills on how to collect data from various sources, organize data into information, and interpret the data. In East Africa, like other Sub-Sahara countries, data science is a young field. Thus, there are challenges in recruitment, training and retention of data scientists. Consequently, there is a demand in building human capacity in this field, which is a research field of the mathematicians in Bergen.

Makerere University: Two male and one female student, two of whom are working in mathematical statistics. One student is working with random matrix theory: Dimensionality reduction in the presence of missing values and outliers. Another with Computational Mathematics, Data Science, Partial Differential Equations, Reconstruction, and the third with Dynamic Ensemble modelling of Reserve Risk in General Insurance.

University of Dar es Salaam: Three male and one female student, all in applied mathematics. One works with Mathematical Modelling of the Effects of Vaccination, Water sanitation, Education programme and Treatment interventions on the Transmission Dynamics of Typhoid. The second one is working on the evolutionary dynamics of Antimicrobial resistance using a data-driven modelling approach; the third one on transmission dynamics of brucellosis with interventions; while the fourth one works on the transmission dynamics of two-strain TB model, with drug-sensitive and drug-resistance to treatment.

3 Outreach

As part of achieving the overall aim of MATH4SDG to increase general mathematical literacy in Tanzania and Uganda, the project also participated in several outreach activities aiming to improve the teaching of mathematics in colleges and schools. These were to complement the work done by the 11 PhD students. These activities have been carried out in various regions in Tanzania and Uganda in collaboration with the Mathematical Association of Tanzania (MAT) and the Uganda Mathematical Society (UMS). The project did workshops on, for instance, the use of GeoGebra, an interactive geometry software, for high school mathematics teachers in Tanzania and Uganda. These activities focused on motivating teachers and introducing them to new teaching methods and technologies. In Tanzania, MATH4SDG has managed to train more than 600 mathematics secondary school teachers and has visited 30 secondary schools to motivate and inspire students about mathematics. Also, two workshops have been organised on alignment of university mathematics research and education with industrial needs.

Collaborative research has been achieved between industry and academia (mathematics research) i.e. within various research institutes and government authorities involved in medical research, weather forecasting and climate modelling, among others. Through these workshops, it has been possible for the PhD students and some staff members to present their research and to show the relevance of mathematical modelling in solving real-life societal and industrial problems.

4 Lessons Learnt and Recommendations

MATH4SDG had a midterm evaluation where three project coordinators were interviewed and a questionnaire was sent to all the participants with 49 respondents: 4 project coordinators (the co-authors), 29 other academic staff, 4 admin/finance management staff, and 12 students. 33 from USDM, 8 from Makerere, 8 from UiB. Some of the findings are referred to below.

4.1 Progress and impact

Traditionally, mathematics is a male-dominated sector in Tanzania and Uganda. Women are under-represented among the academic staff of the mathematics departments at the higher learning institutions in Tanzania and Uganda and in the areas of applications of mathematics. Therefore, the project aimed at recruiting at least 30% female PhD students. The project is therefore proud to have one female southern partner coordinator and one other woman in the steering committee working with the didactics part of the project. The recruitment of 3 female PhD candidates (of 6) in Tanzania and 1 female PhD candidate (of 5) in Uganda is therefore an important achievement. One of the female PhD students has been supported with a babysitter for longer travels. Besides, the project collaborates with Uganda Women in Mathematics Association, Tanzania Women in Mathematics, and the Eastern African Network for Women in Basic Sciences. The project has been providing annual support to the Science Camps for high school girls organised by the partner institution in Tanzania. Makerere has implemented affirmative action to boost female admission in general, and this is expected to also play a positive future role for the interest in mathematics.

The collaborative partnership impacts the quality of new or revised study programmes in several ways. The partners have organised common workshops to revise academic courses. They organise exchanges of students and study visits, so the students get exposure in areas they are not conversant with.

Scholarship and Research Visits to Bergen: The 11 PhD students were granted full scholarships: fees, stipend, book allowance and laptops. Female PhD candidates receive special allowances. Most students have been to Bergen twice, for periods of at least two months. They receive joint north-south supervision that has an emphasis on the quality of the publications. Furthermore, students have acquired new computational skills.

Some of these students had never been outside their countries and gained very valuable personal experiences on top of the academic achievements. An additional benefit for them is access to the university library in Bergen, which continues and is renewed after they return home. In particular, the four PhD students in mathematics education visited Norwegian secondary schools and observed mathematics teaching as part of their stay in Bergen; and subsequently wrote a paper comparing Norwegian school teaching with Uganda and Tanzania. They also presented their work to Norwegian secondary mathematics teachers at a seminar as part of a master's programme for in-service mathematics teachers.

Conferences: Several staff and students have received support to attend conferences, workshops, and extended visits abroad. MATH4SDG organized its first conference "The African-Nordic Conference in Mathematics", at Makerere University in August 2023, where the eleven PhD students were among those who presented papers. The students have also attended other conferences/workshops, and some students have won awards for their presentations.

4.2 Sustainability beyond the life of the project

Most results from the project are sustainable and will last. For instance the curricula reviews will have impact on future generations of students, and the publications produced are adding to the body of knowledge internationally. This includes the implication of the teaching interventions done both as part of PhD studies and outreach activities. Also the established networks, with both industry and among the partner institutions, are something that can be build upon in the future. Finally, the University of Bergen is one of the original partners in the CoRE-MATH, an Africa-Europe Cluster of Research Excellence under the collaboration of African Research Universities Alliance (ARUA) and The Guild of European Research-Intensive Universities, established in 2024 (https://www.the-guild.eu/africa-europe-core/index.html). MATH4SDG is now connected with this network, which may also likely yield other future projects.

4.3 Some challenges in the project

The 11 PhD students are followed closely by their local supervisors and co-supervisors at the University of Bergen. There were challenges in developing a suitable supervision culture partly due to geographical distances. These challenges were overcome through communicating expectations. In addition, Mega-Supervision was developed among the PhD students in education, where all four joined with their Norwegian co-supervisor and several of the local supervisors for joint sessions in which the students took turn in giving feedback to each other's drafted papers. The students are supposed to have publications in reputable journals, but many experience very long review processes, which is very frustrating.

Although MATH4SDG so far appears to be successful, the project is also limited to two African institutions in two different countries. Although the project will likely have impact, much is yet needed. Implementing changes in school systems lacking resources, particularly teachers, and with other teaching traditions is not something that is fixed through one project, but we hope that at least it is a move in the right direction.

5 Conclusions

The project is ongoing and on track. One respondent to the survey expressed that it is a main strength of MATH4SDG that is has a strategic focus on strengthening higher education and research capacities in developing countries. In addition, by supporting local institutions to produce higher-quality graduates and more inclusive, impactful research, the project aids in building a competent workforce, hence lays a foundation for sustainable development. Other respondents said the strengths of the project are highly experienced project leaders who constantly follow up on the progress and the commitment of the supervision team with north-south supervision. Also, the high competence of the PhD students recruited, and the capacity built at the PhD level that can take lead in their home countries and improve quality of staff, are found to be important strengths. Students themselves highlighted the collection and analysis of data as strengths, and academic staff emphasised that the project is improving the research environment within their institutions. Furthermore, the outreach to the schools and schoolteachers, and the opportunity to travel to different countries and get to inquire about their education system for learning purposes are mentioned as strengths of the project. In addition, the visits to Bergen had an impact on Norwegian students as well as academic staff learning about mathematics teaching outside of Europe. International collaboration and networks, such as those fostered by the Core-Math (https://www.the-guild.eu/africa-europe-core/innovation-technology/innovation-technology-old/Mathematics.html) network under African Research Universities Alliance (ARUA, https://arua.org/) and The Guild (https://www.the-guild.eu), are crucial for amplifying the impact of and synergies between individual projects like MATH4SDG beyond their initial scope.

Acknowledgements

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Exploring Shared Understanding and Practices of Experiential Learning Among African Engineering Educators

Cedrick A. K. Kwuimy,
University of Cincinnati, USA, *Cedrick.kwuimy@uc.edu*
Yashin Brijmohan,
Utah State University, USA , *yashin.brijimohan@usu.edu*
Precious Biyela,
The University of the Witwatersrand, South Africa, *Precious.Biyela@wits.ac.za*
Michelle Maphosa,
University of Cape Town, South Africa, *mphmic006@myuct.ac.za*
Vicent Rutagangibwa,
Mbarara University of Science and Technology, Uganda, *rutagangis@must.ac.ug*

Abstract

The definition, practice, and assessment of experiential learning (EL) globally and within Africa vary significantly across institutions, even within the same country. This inconsistency is largely due to a lack of research focused on educational landmarks shaped by Africa's unique socio-cultural challenges, technological divides, and financial struggles. Additionally, there is a lack of knowledge on how to structure Afrocentric practices for EL. This research seeks to address the challenges and disparities in the implementation of EL initiatives across African educational contexts. It aims to identify commonly employed methods of EL and explore the shared understanding of EL practices among African engineering educators. Thirty-two participants from seven African countries completed a survey on their understanding and experiences with EL. Responses from nineteen of those participants were discarded due to incompleteness. The remaining thirteen participants, from seven African countries, were divided into two groups: those familiar with and actively using EL, and those familiar with EL but who have not yet used it. The analysis highlights shared practices, perceived impacts, and participants' understanding of EL. The results emphasize the need for future research to harmonize EL practices across Africa.

Keywords: Experiential Learning, Shared Understanding, Africa Engineering Education, Afrocentric Education, Harmonizing Experiential Learning Practices

1 Introduction

1.1 Experiential Learning

As pervasive and "natural" as learning is for humans, it can be challenging to define in simple and succinct terms. Learning could be "*any process that in a living organism leads to permanent capacity change and which is not solely due to biological maturation or ageing*" (Illeris, 2007, p.3 in Illeris, 2009). There are several learning theories (explaining how knowledge acquisition and learning happen in humans) that are recognized, but most scholars agree that learning theories can be grouped into three frameworks; behaviourism, cognitivism and constructivism. Constructivist learning theories centre learners, rather than teachers and/or teaching, as ultimate drivers of learning. According to these theories, learners construct their own understanding, while teaching provides some of the building blocks, in the form of content, that can be used in knowledge construction (Illeris, 2009; Ferreira and Lemmer, 2021). The context in which teaching happens becomes one part of the context in which learning is constructed. The process of knowledge construction is active and involves biological, psychological and social conditions (Illeris, 2009). Experiential learning (EL), some of whose definitions are outlined below, is more constructivist in nature (Kong, 2021), with students being both the main agent in terms of driving the learning (Kong, 2021) and the agent who experiences "*change […] that*

results from reflection on a direct experience" (Itin, 1999, p. 92 in Tembrevilla et al., 2023). Several authors have expressed varying understandings of experiential learning.

For example, Kolb's Experiential Learning Theory (Kolb, 1984; Kolb and Kolb, 2018; Wijnen-Meijer et al., 2022), which outlines an experience-based learning process, is foundational to experiential learning. In this framing learning happens via going through a four-step cycle. This cycle consists of a concrete experience, which triggers the learning process as the learner interacts with some form of reality; reflective observation, during which the learner looks back to their experience (so this is only possible after the learner has been through the concrete experience); abstract conceptualization (thinking), whereby the learner mulls over everything in order to theorize or make testable principles or some deductions; and active experimentation, during which the learner tests his/her theory and/or uses what was learned from steps one through three of the cycle to get feedback. Because this is a cycle, in step four, i.e., active experimentation, the learner also creates their subsequent experience and then goes through the cycle again. Because experiential learning is cyclic, with multiple iterations of the cycle, experiential learning fosters lifelong learning and personal development and improvement (Kolb and Kolb, 2018; Ferreira and Lemmer, 2021; Wijnen-Meijer et al., 2022).

While Kolb's conception of experiential learning mainly credits individual cognitive process for learning and zooms in on the construction of knowledge by one individual learner, there are more broader interpretations of experiential learning which emphasize the context and social interactions involved in learning. Consequently, they consider the influence of areas like teamwork, mentorship, and the real-world environment on learning. For example, while Wenger (2009) recognizes and accepts learning theories that view learning as an individual feat, he postulates a social theory of learning. For Wenger (2009), participating in society is not something that enhances learning, but is necessary for learning to happen. He argues that human beings best learn through active participation in communities of practice (CoPs). Wenger stresses that it is not just belonging to CoPs that matters, but actual active participation and identity making, all of which he says are continuous rather than "events" with clearly marked beginnings and endings (Wenger, 2009).

Another variation of understanding EL is where it can be expressed based on some kind of experience as the main trigger for the learning cycle. Both authentic, i.e., real world experiences, and simulated experiences (Clark et al., 2016; Wijnen-Meijer et al., 2022; Nhan, 2024) can be used to anchor experiential learning. Regardless of whether the anchoring experience is real or simulated, it is vital for it to closely mimic professional engineering practice in terms of both the context and types of problems (Nhan, 2024). For engineering students, the context is often internships, either located at certain intervals between years of study or after students have completed all coursework but before they can graduate; community-based projects, often done in the second to last or last year of study, industry collaborations, which can take different forms; and co-ops, amongst other situations. There are many reasons why a simulated experience might be preferred, either to supplement and or in place of a real-world experience. An example of simulated experiences could include case studies, and capstone projects undertaken within the academic environment. In their study, Clark et al (2016) highlights that simulated experiences provide students with the benefits of an experience "at a low cost" and with a lower risk than what students might be exposed to in real world professional environments. This is not unlike what motivates the creation of experiential learning in clinical programs, whereby students might work with models and or contribute towards "old" case analysis, rather than work with real patients (Wijnen-Meijer et al., 2022). Here the concern is patient safety more than it is the safety of the students undergoing experiential learning, but both configurations are about providing a context that closely mimics a real professional setting, so students can learn through experience, while lowering the risk that comes with such learning.

Experiential learning is popular, and very widely used, because of its many benefits. These include but are not limited to deep learning, skill development (Nhan, 2024), increased students' engagement and motivation (Nhan, 2024; Kong, 2021) opportunities to practically apply knowledge (Clark et al., 2016; Wijnen-Meijer et al., 2022; Nhan, 2024), employability, and personal and professional growth (Wijnen-Meijer et al., 2022; Nhan, 2024). In addition, experiential learning can improve student academic outcomes and enhance performance

in the classroom (Kolb, 2013; Tembrevilla et al., 2024) In modern engineering, experiential learning is indispensable due to its focus on “learning by doing" and “reflecting on the experience” (Clark et al., 2016). The focus on the development of skills that are personalized, accessible, inclusive, problem-based, collaborative, lifelong, and student-driven (Nhan, 2024) further strengthens the position of experiential education as a serious contender for a category of teaching methodologies capable of educating the engineer of the future.

1.2 Motivation: Codifying Experiential Learning in Africa

Africa is a continent rich with opportunities for experiential learning, leveraging diverse approaches like internships, project-based learning, and field visits. It is important to note that African indigenous education traditions have long embodied experiential principles through apprenticeships, storytelling, and community involvement. Learning by doing and oral knowledge transfer are deeply rooted in African cultures (Odendall, 2013; Frimpong et al., 2024). Across Africa, experiential learning is conceptualised as a transformative pedagogy that makes education more relevant to social needs and student development. Although such experiences may not be systematically documented in mainstream literature, they represent a culturally relevant mode of experiential education, one that warrants deeper exploration in the context of African engineering pedagogy. For example, in Engaging Communities in Sustainable Development: Universities as Active Partners, university students in Lesotho collaborated with local communities through culturally grounded environmental education, drawing on the Botho philosophy and indigenous knowledge to co-develop ecotourism and conservation initiatives (United Nations University, 2018).

While EL in African engineering education faces several challenges, its integration is crucial for developing a workforce capable of meeting the local and international demands of the engineering sector. Efforts to expand and improve experiential learning should continue, with an emphasis on aligning educational outcomes with industry needs and enhancing the overall quality of engineering education. Africa's diverse educational needs and resource limitations highlight the necessity for innovative approaches tailored to local contexts. As such, Africa could serve as a valuable research context to explore how experiential learning can be adapted and optimized to enhance its impact.

Future initiatives should aim at enhancing university-industry collaborations and developing robust accreditation systems to ensure the quality and international recognition of engineering programs. This will not only improve the quality of education but also enhance the employability of graduates within the global market. Across the African continent, there is a lack of a shared understanding among educators and regulatory bodies regarding the definition, application, and assessment of experiential learning.

Given the multiple variations in the understanding of experiential learning from literature, and the incorporation of EL into engineering curricula in Africa, a shared understanding of EL's practice and definition could enhance graduates' mobility and employability, particularly when seeking employment outside their home country. To aid this understanding, this paper explored how engineering educators in Africa define, apply, and perceive the usefulness of experiential learning practices. The research question is defined as*:*

How do engineering educators in Africa perceive and implement experiential learning in engineering undergraduate studies?

2 Research Method

2.1 Methods/Design

A mixed method design has been employed to answer the research questions. This approach integrates both quantitative and qualitative research designs and have informed the data collection. The qualitative design was primarily used to understand how experiential learning was understood, and the quantitative design provided more insights on the understanding of EL but was more focussed on understanding the perceived usefulness of EL practices and how it was implemented.

Most authors agree that there are two research approaches that mix qualitative and quantitative data collection and handling, namely, the mixed method and multi method approaches (Anguera et al., 2018; Creswell and Tashakkori, 2007; Weller and Barnes, 2017). Recognising that some studies use mixed method and multi method approaches interchangeably Kasirye, 2021), it is vital for one to explain that this study is considered mixed method due to its alignment with the criterion put forward by Creswell and Tashakkori (2007) who asserted that in mixed methods, researchers use both qualitative and quantitative approaches to collect and analyse data, integrating discoveries and drawing a unified set of conclusions (Creswell and Tashakkori, 2007). This approach was chosen to allow more robust analysis than what is possible with simple methodologies.

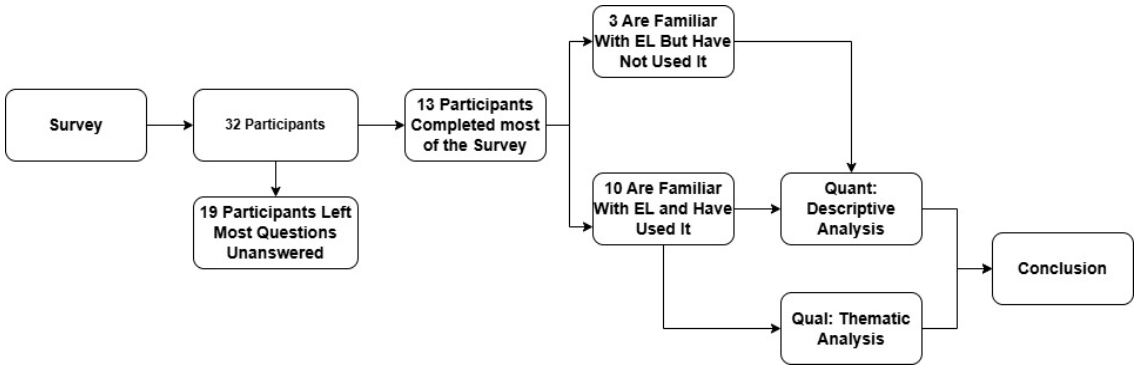

Figure 1: Research Design

2.2 Participants and Data collection

Participants were recruited for this study using surveys. The participants include African engineering educators, and persons from professional and educational engineering institutions across three African regions. They were recruited through communities of practice using snowballing. These communities will include the Engineering Education Research Network-Africa, the Africa Engineering education Forum, and Africa Engineering Education Council. Data was collected using a Qualtrics Survey distributed via email and WhatsApp groups. 32 people completed the survey. However, only 13 (9 male, 4 female) respondents completed the questions. They were from Cameroon, Gambia, Ghana, Kenya, South Africa, Uganda, Zimbabwe.

2.3 Quantitative and Qualitative Data analysis

Thematic analysis was used for qualitative analysis. We first familiarized ourselves with the data to gain a deeper understanding by reading and re-reading it. Secondly, initial codes were generated by identifying important features of the data that are relevant to the research question based on the diverse perspectives of the participants. Two AI tools (ChatGPT and NotebookLM) were used to analyze the data to produce the initial codes. After the researchers familiarized themselves with the data, they used specific prompting to interrogate the data further. To prevent hallucination effects, two tools were used, and the data analysis was compared between them. Furthermore, the functionality of NotebookLM allowed the researchers to review the analysis. Thirdly, the codes were organized into broader patterns or themes, and then refined, revised, and named for coherence. Given the limited number of quantitative data, quantitative analysis was limited to general descriptive analysis, and graphical representation for visualization using Excel.

3 Results

3.1 Shared Perceived Impact of Experiential Learning on Learning Outcomes

The survey includes a question on a 6-point Likert scale to invite participants to express the extent to which they believe experiential learning supports key associated outcomes published in the literature (Brijmohan, 2025; Wurdinger & Allison, 2017) (1) *Creativity, (2) Communication, (3) Collaboration, (4) Time management, (5) Social/Contextual, (6) Social responsibility, (7) Skills for lifelong learning, (8) Ethical Reasoning, (9) Critical Thinking, (10) Inquiring and analysis, (11) Global Competence, (12) Technical skills.* The average score and the corresponding variability for the 13 responses received is plotted in Figure 2.

Group 1 was categorized as those participants who were both familiar with and used experiential learning, while Group 2 included participants who were familiar with experiential learning but did not use it. Each group was asked to rate the extent to which they agreed that each learning outcome is enhanced in developing engineers through experiential learning. It was found that Group 2, who did not use experiential learning, had a higher belief that experiential learning could enhance various learning outcomes compared to Group 1, who did implement it. The finding that Group 2 held a higher belief in its potential to enhance learning outcomes compared to Group 1 presents a seemingly paradoxical situation. While conventional wisdom and much of the literature suggest that direct experience often leads to a stronger understanding and appreciation of a method's effectiveness, several factors could contribute to this counterintuitive result.

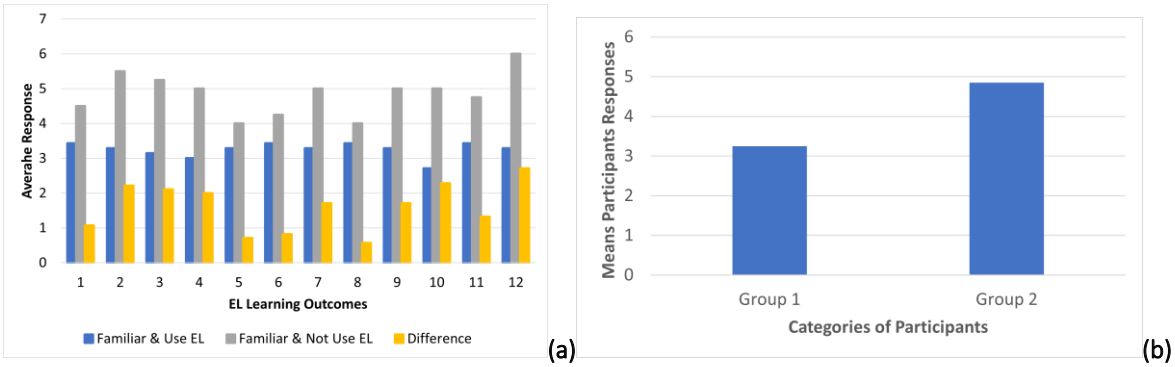

Figure 2: Perceived Impacts of Experiential Learning.
(a) Mean Response for (1) Creativity, (2) Communication, (3) Collaboration, (4) Time management, (5) Social/Contextual, (6) Social responsibility, (7) Skills for lifelong learning, (8) Ethical Reasoning, (9) Critical Thinking, (10) Inquiring and analysis, (11) Global Competence, (12) Technical skills. (b): Aggregate Response – Group1: Familiar with Experiential Learning and Have Use It. Group2: Familiar with Experiential Learning but Have Note Used It.

One potential explanation lies in the realm of idealized perceptions. Individuals who have not directly engaged in a particular practice might hold an overly optimistic view of its benefits, unburdened by the realities of its implementation. Research on enthusiasm for new organizational practices suggests that individuals might perceive greater benefits in novel or unfamiliar approaches (Van Eerde & Van der Velde, 2005). In this context, Group 2 may focus on the theoretical advantages of experiential learning, overlooking the potential challenges and complexities that Group 1 encountered.

Furthermore, the Dunning-Kruger effect could offer another lens through which to understand this phenomenon. This effect posits that individuals with low competence in a particular area tend to overestimate their ability or understanding (Kruger & Dunning, 1999). Group 2, lacking direct experience with experiential learning, might have a superficial understanding of its nuances and therefore hold an inflated belief in its universal efficacy compared to Group 1, who have a more grounded perspective informed by their practical engagement.

Conversely, the challenges inherent in implementing EL effectively could have influenced Group 1's beliefs. Literature on scaffolding and complex learning often highlights the difficulties in orchestrating meaningful experiential activities that lead to desired outcomes (Hmelo-Silver et al., 2007). If Group 1 faced significant hurdles or did not perceive the implementation as entirely successful, their belief in experiential learning's potential might be tempered by their actual experience.

In contrast to these explanations, much of the foundational literature on experiential learning suggests that direct experience should lead to a greater appreciation of its value. Kolb's (2015) theory emphasizes that learning is derived from experience, implying that those who have engaged in experiential learning should have a deeper understanding of its impact. Similarly, the emphasis on reflection in experiential learning (Moon, 2004) suggests that if Group 1 engaged in meaningful reflection on their experiences, they should have a clearer grasp of the learning outcomes and thus a potentially stronger belief in its effectiveness. Moreover, principles of self-efficacy (Bandura, 1977) suggest that positive experiences generally foster stronger beliefs. If Group 1 had positive learning experiences through EL, their belief in its potential should logically be higher than that of Group 2.

3.2 Shared Perceived Understanding of Experiential Learning

Participants in Group 1 were asked to select from a list of experiential learning practices (Yates et al., 2015) the practices they had employed. Aggregated results are plotted in percentage in Figure 3.

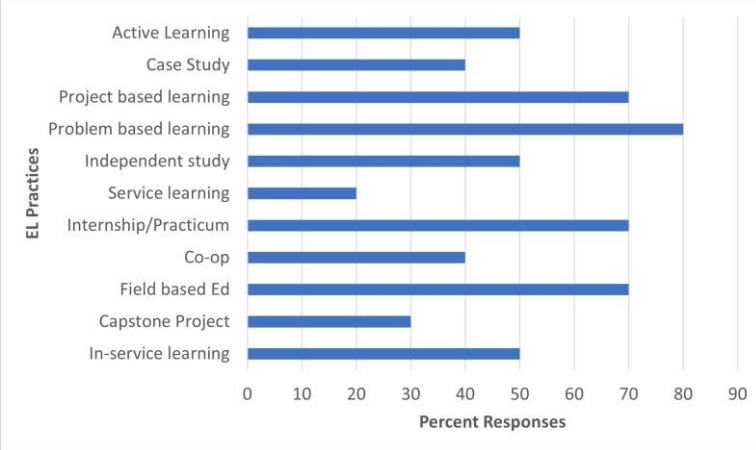

Figure 3: Percentage Used of Experiential Learning Practice

A variety of experiential practices were found to be implemented across the African continent, albeit to varying extents. A greater number of these practices were reported in academic institutions compared to those implemented outside. Within academic settings, problem-based learning, project-based learning, and active learning were the most frequently cited, whereas case studies and capstone projects received the least mention. Outside the classroom, internships and field-based education were the most referenced, with internships being significantly more prevalent than co-ops. While we observe a diverse range of implementation types for experiential learning, it remains unclear whether the responses were based on a consistent or varied understanding of each type. Despite these potential discrepancies, further investigation was conducted into how these EL types are perceived across the African continent.

Question 1: Shared Understanding of Experiential Learning Practices

Participants in Group 1 defined these experiential learning practices. Their responses are synthesized below. The aggregate Cohen's Kappa coefficient $\kappa = 0.67$ indicates substantial agreement.

Experiential Education: While one participant declared, "I don't know what this is", other participants attempted defining the expression. Themes include the following. **Learning through Experience:** Experiential education is defined by learning through real-life experiences, emphasizing direct engagement rather than theoretical or abstract learning. This theme points to the process of learning through doing, through experiments or engaging with experiences that foster deeper understanding. ***Key Phrases***: "Learning through experiments," "learning through experience." **Reflection and Guidance:** Experiential education involves not only engaging in experiences but also reflecting on them. Reflection plays a crucial role in this process, allowing students to derive meaning from the experience. Additionally, guidance helps students navigate and learn from their reflections to gain insights. ***Key Phrases***: "Have an experience to reflect on," "be guided through." **Practical Application: EL** provides students with opportunities to apply theoretical knowledge in real-world settings. This theme highlights the importance of practical activities that connect theory to practice, making learning more meaningful and relevant. ***Key Phrases***: "Students being offered an opportunity to be exposed to practical activities," "bring meaning to what they have learned."

Active learning: The responses were divided in three themes. **Active Participation:** Students are engaged directly in their learning, which goes beyond just listening to a lecture. ***Key Phrases***: "*Learning through engagement," "students are actively involved with learning," "actively participate*." **Student Accountability:** Learners take responsibility for their educational progress with guided support. ***Key Phrases***: "*Students take responsibility for their learning," "guided instructions," "actively engaged process*." **Full Participation:** Students are encouraged to participate fully, with no reluctance or passive involvement. ***Key Phrases***: "*Actively participate without reservation*."

Case study: The responses were divided in four themes*:* **Contextual Learning:** Case studies are defined by specific examples and their contextual backgrounds. ***Key Phrases***: "*Specifying a specific example and contexts*." **Focused Inquiry:** Students focus their analysis on a particular topic or problem. ***Key Phrases***: "*Students are asked to concentrate on a particular topic*." **Real-Life Scenarios:** Case studies provide scenarios that challenge students to study and analyze real-world situations. ***Key Phrases***: "*Learners are given a scenario to study and analyze*." **Real-World Relevance:** The cases are drawn from real environments and often involve real-world challenges. **Key Phrases:** "A piece of work from a real environment," "real world tensions." **Student Engagement and Understanding:** Case studies actively engage students and help them demonstrate their understanding of the material. ***Key Phrases***: "*Animate the students' engagement," "Using objects to demonstrate understanding*."

Cooperative Education: The responses were divided in four themes: **Work-Based Learning:** Cooperative education is like an internship, where students gain practical work experience during their undergraduate studies. ***Key Phrases:*** *"Like an internship, but typically during an undergraduate program."* **Collaborative Learning:** The learning environment involves collaboration, where learners work together and share knowledge. ***Key Phrases:*** *"This involves collaboration," "Learners collaborate and share knowledge."* **Peer Teaching and Collective Knowledge:** Students not only learn individually but also teach their peers, ensuring collective understanding. ***Key Phrases:*** *"Students learning themselves and teaching others," "All of them know everything at the end without studying everything themselves specifically."* **Industry-Academia Collaboration:** Cooperative education connects academic learning with real-world industry experiences, giving students the chance to apply theoretical knowledge in practice. ***Key Phrases:*** *"A place to coordinate the process of allowing students to go to industry for practical purposes."*

Internship/Practicum: The responses were divided in five themes: **Work-Based Learning During Breaks:** Internships or practicums often take place during academic breaks, allowing students to engage in industry-related work outside of their regular academic schedule. ***Key Phrases:*** *"Learning during breaks in industry."* **Skill Development:** Internships and practicums are primarily focused on providing students with practical, hands-on skills that are essential for their future careers. ***Key Phrases:*** *"Learner being sent to institutions to acquire practical skills."* **Mentorship and Professional Guidance:** Students receive guidance from professionals, which helps them understand the realities of the profession and the tasks they will perform in the future. ***Key Phrases:*** *"Completing some work at an engineering practice with guidance," "What the profession looks like*." **Practical Application of Learning:** Internships and practicums involve direct, hands-on experience where students work on relevant tasks and gain insights into the day-to-day responsibilities of their profession. ***Key Phrases:*** *"Students attached to industry for hands-on experience during their course."* **Job-Specific Learning:** Internships and practicums provide students with opportunities to apply discipline-specific knowledge in real job settings, enhancing their preparedness for their chosen careers. ***Key Phrases:*** *"Opportunity to learn about a job based on their discipline."*

Field-Based Education: The responses were divided in five themes: **Long-Term Practical Experience:** Field-based education often provides students with years of hands-on exposure and learning, accumulating practical knowledge over time. ***Key Phrases:*** *"Years of experiencing."* **Experiential Learning Beyond the Classroom:** It emphasizes learning outside of the classroom, where students are immersed in real-world contexts and gain experiential knowledge. ***Key Phrases:*** *"Learning outside the classroom."* **Mentorship and Goal-Oriented Learning:** Students work alongside mentors in the field, focusing on specific outcomes and developing

professional competencies relevant to their discipline. ***Key Phrases:*** *"Work on site with a mentor towards a specific outcome," "Develop competencies."* **Real-World Job Application:** It bridges the gap between academic learning and professional practice by providing students with hands-on experience in job settings, allowing them to connect their theoretical knowledge with industry expectations. ***Key Phrases:*** *"Hands-on experience in the job market."* **Practice in Real-World Settings:** Field-based education allows students to actively engage in practice, providing them with the opportunity to apply classroom knowledge to real-life challenges. ***Key Phrases:*** *"Going to the field for practice purposes."*

Problem-Based Learning (PBL): The responses were divided in five themes. **Active Problem Engagement:** PBL is driven by the active engagement of students with real, relevant problems. The learning process starts with the problem, making it central to educational experience. ***Key Phrases:*** *"Learning by engaging with a problem."* **Problem-Solving as the Core Learning Activity:** Students learn through the process of problem-solving. This hands-on approach challenges students to use their knowledge and skills to find solutions to complex, real-world issues. ***Key Phrases:*** *"Learning by problem solving*." **Guided Inquiry and Self-Directed Learning:** While PBL involves some guidance from instructors, it largely promotes self-directed learning. Students are encouraged to inquire and explore independently, fostering deeper understanding through discovery. ***Key Phrases:*** *"Guided active learning," "The problem is the centre," "Learning is unscripted."* **Problems as Learning Context:** Problems are not just topics for study in PBL; they are the mechanisms by which learning happens. By addressing these problems, students develop critical thinking, collaboration, and analytical skills. ***Key Phrases:*** *"Using problems to learn."*

Project-Based Learning (PBL): The responses were divided in five themes. **Active, Hands-On Learning:** PBL is centred around students actively engaging in projects. Learning takes place through direct involvement in tasks that have real-world applications, promoting experiential learning. ***Key Phrases:*** *"Learning while undertaking a project."* **Investigation and Problem-Solving:** Students are given a problem or challenge to investigate. The process of working through this issue, gathering data, and reporting findings is crucial to the learning experience, fostering problem-solving and analytical skills. ***Key Phrases:*** *"Learners being given a problem to investigate and report."* **Structured, Guided Learning:** While the project is the central focus, students are not left entirely on their own. There is guidance provided to help them engage effectively with the project and to develop the competencies required to complete it successfully. ***Key Phrases:*** *"Project is the centre of the learning," "Guided engagement," "Support the students' ability to engage with the project."* **Projects as Learning Tools:** Projects in PBL are not just tasks to complete but are the main instruments through which learning occurs. They are designed to promote critical thinking, collaboration, and the application of knowledge. ***Key Phrases:*** *"Using projects to learn."*

Independent Study: The responses were divided in five themes. **Self-Directed Learning:** Independent study is rooted in the learner's ability to take control of their own learning. The individual decides on the content, pace, and methods, making the process more personal and tailored to their needs. ***Key Phrases:*** *"Learning on my own."* **Autonomy and Independence:** Learners in independent study are not reliant on teachers or peers for regular guidance. They are expected to navigate their own learning, which fosters self-reliance and independence. ***Key Phrases:*** *"Learners learning on their own."* **Minimal Guidance with Initial Structure:** Although independent study is primarily self-guided, there is sometimes initial structure or guidance, such as starting questions or frameworks provided by a mentor or knowledgeable other. This structure helps learners get started but leaves the rest of the learning process up to the individual. ***Key Phrases:*** *"Work on your own," "Starting guiding questions from a knowledgeable other."* **Self-Paced Learning:** Independent study allows learners to set their own pace, deciding when and how to engage with their studies. This flexibility is central to the concept, as it places the responsibility for progress on the learner. ***Key Phrases:*** *"Study on your own."*

Service Learning: The responses were divided in five themes. **Community-Based Learning:** Service learning is anchored in the concept of learning through community engagement. Students actively participate in community service, bringing real-world contexts into their learning process. ***Key Phrases:*** *"Learning in a community."* **Service as a Learning Process:** Students learn not just through lectures but also through the act

of rendering services, which connects their academic knowledge with practical, community-oriented outcomes. ***Key Phrases:*** *"Learning through rendering services."* **Experiential Learning with Real-World Challenges:** Service learning combines problem-based and project-based learning approaches, where students engage in real challenges in the community. This combination encourages active learning in real-world contexts. ***Key Phrases:*** *"Problem and project-based learning combined," "Partner in community with a real challenge," "Students can engage with."* **Real-World Exposure and Social Responsibility:** Service learning takes students out of their academic comfort zones and exposes them to diverse societal issues. This exposure helps develop professional skills while encouraging social responsibility. ***Key Phrases:*** *"Taken out of their comfort of university confines," "Engage with society," "Take responsibility as a developing professional."* **Professional Development and Societal Impact:** Service learning fosters a deeper understanding of how students' academic disciplines can directly affect society. It encourages students to see themselves as responsible professionals contributing to society. ***Key Phrases:*** *"Seeing how the discipline can influence and impact society."* **Service as a Learning Tool:** Service is not just an altruistic activity; it is a tool for learning. Through service, students gain practical skills and insights that enhance their academic and professional development. ***Key Phrases:*** *"Provide service for the sake of learning."*

In-Service Training: There were four these identified in the responses: **Practical Learning in Industry Settings:** In-service training offers an opportunity for learning within the industry, where employees or students gain practical experience that complements their academic knowledge. ***Key Phrases:*** *"Learning in industry."* **Professional Development and Skill Enhancement:** The primary aim of in-service training is to improve and upgrade the skills of employees, ensuring they stay competitive and aligned with industry needs. ***Key Phrases:*** *"Training employees to upgrade them."* **Structured, Focused Learning Experience:** In-service training is designed to be more structured and guided compared to internships, providing a more curated and goal-oriented learning process. ***Key Phrases:*** *"Similar to internship but perhaps more curated and guided."* **Bridging Theory and Practice:** In-service training helps bridge the gap between theoretical education and real-world practice by allowing students or employees to apply their academic knowledge in an industry setting. ***Key Phrases:*** *"Students going to industry after they are done with their theoretical work."*

Capstone Project: There were four of these identified in the responses: **Integration of Learning and Application:** The Capstone project allows students to integrate and apply knowledge from different areas learned throughout their academic program. It serves as a comprehensive learning experience that synthesizes multiple disciplines. ***Key Phrases:*** *"Project-based learning after key learnings," "Execute projects to gather knowledge."* **Practical Application of Knowledge:** The project is a hands-on opportunity for students to implement their theoretical learning into practice, providing real-world relevance and testing the application of knowledge. ***Key Phrases:*** *"Executing projects to gather knowledge."* **Independent and Self-Directed Learning:** The Capstone project encourages students to take ownership of their learning process, fostering autonomy and responsibility. Students can work independently or in teams to demonstrate their abilities. ***Key Phrases:*** *"Final year project," "Independent learning."* **Holistic Skill Development and Competency Integration:** The project requires students to apply and showcase a variety of competencies, including technical, problem-solving, and communication skills, often involving cross-disciplinary work. ***Key Phrases:*** *"Integrates multiple competencies."* **Real-World Relevance and Industry Collaboration:** Many Capstone projects involve industry-based problems, which enhances the students' understanding of real-world challenges and prepares them for their professional careers by linking academia with industry. ***Key Phrases:*** *"Using industry-based projects to learn."*

Question 2: Could you briefly describe your understanding of experiential learning?

Two themes were identified for participants who self-declared to be familiar with experiential learning but have not use it (3 responses): **Practical and Hands-on Learning:** Emphasizing that experience is gained through practice and the real-world application of learned concepts. Illustrations include: "*Experience by practising," "Hands-on learning," and "Practical application of concepts*." **Active Engagement and Reflective Learning:** Highlighting that engagement and reflection are integral components that enhance the learning process and

deepen understanding. Illustrations include: *"Teaching approach that encourages active engagement," "Reflection," and "Real-world application."*

Four themes were identified for participants who declared to be familiar with experiential learning and have used it (6 responses): **Practical and Hands-On Learning:** Experiential learning emphasizes learning by doing and applying knowledge through hands-on experiences, often in real-world settings. Illustration Includes: *"Learning by doing," "Hands-on experience," "Practical application of theory," "Working with the community."* The second theme was found to be **Real-World Application and Challenges:** Experiential learning prepares students for the real world by presenting them with challenges they are likely to face in their careers, such as internships and work-related learning journeys. Illustrations Includes: *"Internships/work-related learning journeys," "Real-world challenges," "Embodied experience of engineering practice*." The third theme includes **Collaborative Learning and Global Interaction:** Through engagement with peers from different countries and cultures, experiential learning encourages collaboration, global interaction, and the exchange of diverse ideas. Illustration Includes: *"Students from different countries interact and learn together," "Active learning pedagogies," "Engagement with real-world challenges. "The fourth theme was found the be* **Bridging the Gap Between Theory and Practice:** Experiential learning helps students connect theoretical knowledge with real-world applications, making learning more meaningful and reinforcing the fundamentals of their field of study. Illustration Includes: *"Putting theory into practice," "Understanding through involvement," "Gaining more understanding."*

4 Conclusions and Limitations

4.1 Shared Perceived Impact of Experiential Learning

The observed finding that Group 2 holds a higher belief in experiential learning's potential could be attributed to a combination of idealized perceptions stemming from a lack of direct experience, a potential manifestation of the Dunning-Kruger effect, and the possibility that challenges encountered during implementation might have tempered Group 1's enthusiasm. While conventional wisdom and established theories often suggest that direct experience should bolster belief in a method's efficacy, the specific context and quality of implementation play crucial roles in shaping these perceptions. Further investigation into the specific experiences of Group 1 and the understanding of experiential learning within Group 2 would be necessary to fully elucidate this intriguing finding.

4.2 Shared Perceived Practices and Understanding of Experiential Learning

Among the proposed EL practices, problem-based learning, project-based learning, field-based education and internship form the top four most used EL practices, while service learning, capstone project, case study, co-op, and independent study form the top four of unpopular EL practices. The research reveals a variation in the definition application of EL. It underscores the need for harmonizing EL practices to foster greater coherence and effectiveness in engineering education across Africa.

4.3 Limitations & Future Investigations

This study was based on a small set of participants. Yet, the findings make the case for future investigation into the factors driving the choice and perceived impacts of EL, as well as a depth analysis of the shared understanding of EL practices. This research warrants further investigations in the integration of EL practices within the African engineering education context, to include indigenous education. For instance, the following questions should be considered: How can African indigenous knowledge systems be meaningfully structured into formal EL? In what ways can traditional experiential approaches, such as those rooted in observation, imitation, and community storytelling inform the design/adaptation of EL? Could similar culturally embedded EL practices enrich engineering education in Africa? What models exist for leveraging community knowledge and indigenous practices to develop contextually relevant EL practices? From a qualitative point of view, using AI for qualitative analysis is relatively new in the field, with the risk of AI generating hallucinations about the

data. Although the methods outlined in this paper offer a way to reduce hallucinations, researchers might have overlooked other perspectives on the data. A future study comparing AI qualitative analysis results with human-only qualitative analysis results could help identify differences and insights. This future study can highlight perspectives missed by AI and include aspects overlooked by human analysis.

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CREATE-ing New Perspectives: A Transformative Learning Approach to Sustainability in First-Year Engineering Education

Bronwyn Swartz
Cape Peninsula University of Technology, South Africa, swartzb@cput.ac.za

Abstract

This paper examines how integrating challenge-based/problem-based learning (CBL/PBL) with creative expression triggers perspective transformation in first-year engineering students' understanding of sustainability. The Crafting Resourceful Engineering and Artistic Transformations for Education (CREATE) project, framed by Mezirow's Transformative Learning Theory, used artistic creation as a disorienting dilemma to challenge preexisting assumptions about engineering's role in sustainability while developing ECSA Graduate Attributes.

Funded by South African Society for Engineering Education (SASEE), the project engaged students with SDGs through four interconnected assessments: individual essays and presentations, group artistic artifacts and TikTok videos. First-year engineering students consulted with a Fine Arts student on project designs, creating interdisciplinary collaborations that challenged traditional engineering paradigms.

Longitudinal survey data revealed evidence of perspective transformation aligned with Mezirow's theory. Students progressed from viewing sustainability as isolated technical problems to understanding it as interconnections between society, technology, and environment. This shift was evident in their enhanced ability to communicate technical concepts while considering broader societal implications—a key indicator of transformative learning in engineering education.

Keywords: Transformative Learning, Sustainability, Challenge-Based Learning, Creative Expression

1 Introduction

Engineering education faces growing pressure to prepare graduates capable of addressing complex sustainability challenges. However, Graham (2021) and Bryne and Mullally (2016) remind us that traditional engineering curricula often emphasise technical problem-solving skills while giving less attention to the broader societal, environmental, and ethical dimensions of engineering practice. This disconnect creates a gap between technical education and the interdisciplinary thinking required to address pressing issues such as waste management, resource depletion, and environmental degradation. The challenge is particularly relevant in the South African context, where engineering solutions must navigate complex socio-economic realities while addressing urgent sustainability needs. Engineering Council of South Africa (ECSA) recognises this through Graduate Attributes that extend beyond technical competence to include communication capabilities, interdisciplinary collaboration, and professional ethics (Gwynne-Evans, Chetty & Junaid 2021). However, effective pedagogical approaches for developing these broader attributes while fostering deep understanding of sustainability remain underexplored.

Funded by the South African Society for Engineering Education (SASEE), the Crafting Resourceful Engineering and Artistic Transformations for Education (CREATE) project embedded creative expression within a year-long communications course, aligning with five ECSA Graduate Attributes: Investigations, experiments and data analysis (GA4), professional and technical communication (GA6), individual, team and multidisciplinary working (GA8), independent learning capability (GA9), and engineering professionalism (GA10). Students engaged with Sustainable Development Goals (SDGs) through four interconnected assessments: two individual (an oral presentation and an essay) and two group-based (an artistic artifact and a TikTok video).

The novelty of this approach lies in its intentional use of creative expression not merely as an engagement tool but as a catalyst for perspective transformation. By requiring students to translate technical knowledge about waste management into artistic artifacts and digital media, the project challenged traditional engineering communication norms and created opportunities for students to reconsider fundamental assumptions about engineering practice, sustainability, and their professional identities.

2 Background

The CREATE project was implemented in a first-year communications class (Professional Communication – course code PCM150X) for the extended curriculum Industrial Engineering Diploma (ECP) at Cape Peninsula University of Technology. This year-long course, which typically covers foundational communication skills including the origins of communication, presentation techniques, writing support, and conflict management, became the setting for an innovative approach to engineering education. Of the 39 registered students, 35 actively participated throughout the course, with four withdrawing early from the course.

At the beginning of the academic year, students were introduced to the broad concept of waste beneficiation as an organising theme for the year course. The project took a significant turn during the second term when an opportunity arose to collaborate with Engineers Without Borders South Africa (EWB-SA) and the Integrated Engineering Curricula (IEC) team. This partnership enabled the communication students to participate in a pilot local design challenge focused on sustainability issues in Cape Town townships, specifically the Dunoon township.

EWB-SA and the IEC team developed a comprehensive design challenge supported by extensive resources: a high-quality informative video about Cape Town townships that contextualised the socio-economic and environmental challenges; municipal data including road and traffic information, maps, and details about local facilities; and comprehensive information about the United Nations Sustainable Development Goals (SDGs). To build on these resources, students received a dedicated lesson on the SDGs to establish a sustainability framework for the project, participated in four facilitated design thinking sessions to help

student groups conceptualize their designs, and accessed support from the institutional writing centre to strengthen their writing processes.

Through consultation with students, four interconnected assessments were developed to comprise the final evaluation (contributing 40% of the course grade). These included two individual components—an oral presentation where students presented their understanding of the design challenge and proposed solutions in relation to the SDGs, and a 2,500-word essay that elaborated on the concepts presented in the oral presentation. The remaining two assessments were group-based: an artistic artifact made from waste materials supplemented with art supplies, and a TikTok video that presented the design solution in a digital format. This structure balanced individual accountability with collaborative creation, with students receiving formative feedback on draft versions of their individual submissions to support their learning and development.

The integration of artistic expression through both physical artifacts and digital media was deliberately designed to challenge traditional engineering communication norms and potentially trigger perspective transformation regarding engineering's role in addressing sustainability challenges. This approach aligned with the development of ECSA GAs, while the principles of Mezirow's Transformative Learning Theory, creating opportunities for students to reconsider fundamental assumptions about engineering practice and sustainability.

3 Transformative learning theory in Engineering Education

The foregoing scenario serves as a case study to illustrate how Jack Mezirow's transformative learning theory (Mezirow, 1997, 2010) can provide a framework for understanding the notable shifts in professional practice comprehension experienced by engineering students through CBL/PBL. This approach is particularly pertinent in the context of contemporary engineering education in South Africa, where the cultivation of generic competencies such as leadership, teamwork, and cross-cultural competence is imperative due to the requirements of ECSA (GA 6 to GA11).

Mezirow's influential framework has been widely adopted, adapted, and examined by scholars over time. From early interpretations (Christie, 2003) to more recent applications researchers (Shandilya, Yoon, Raju, & Kwuimy 2023; Beckett, 2018; Sahin Izmirli & Kabakci Yurdakul, 2014), have engaged with the framework's ten stages: (1) disorienting dilemma, (2) self-examination, (3) critical assessment, (4) recognition, (5) exploration, (6) planning a course of action, (7) acquisition of knowledge, (8) provisional trying of new roles, (9) building of competence and self-confidence, and (10) reintegration. Moreover, Nohl (2015) offers a valuable synthesis of these stages, condensing them into five phases: (1) a nondetermining start, (2) a phase of experimental and undirected inquiry, (3) a phase of social testing and mirroring, (4) a shifting of relevance, and (5) social consolidation and the reinterpretation of biography. This restructuring presents a more streamlined yet comprehensive model for assessing transformational learning processes.

Furthermore, this framework resonates with Paulo Freire's assertion in his seminal work on problem-posing education, where he states: "*In problem-posing education, people develop their power to perceive critically the way they exist in the world with which and in which they find themselves; they come to see the world not as a static reality, but as a reality in process, in transformation*" (Freire, 1970: 83). Freire's perspective highlights the dynamic and transformative nature of education—a concept that is consistent with Mezirow's theory, reinforcing the transformative potential of PBL in engineering education.

4 Praxis

This study employed a longitudinal approach, conducted from July 2024 to March 2025. Mixed data was collected at three intervals through surveys administered in July 2024, October 2024, and February 2025, capturing student perspectives at the beginning, conclusion, and several months after the project. The project commenced when first-year Industrial Engineering students in the Professional Communication

course (PCM150X) were introduced to the Dunoon township case study developed by EWB-SA in July 2024. Students were organised into project teams and guided through a structured 12-week process that integrated engineering design thinking with artistic expression.

The pedagogical approach followed a carefully sequenced progression over eleven weeks, beginning with contextual immersion and empathy-building exercises in which students examined video documentation of Cape Town townships. They then conducted simulated stakeholder interviews to develop engineering communication competencies. This foundation was followed by theoretical framing through SDGs alongside practical problem identification exercises, reinforced by team-building activities centred on conflict management and negotiation. By week five, students collaboratively established assessment criteria, resulting in four interconnected tasks (individual essays and oral presentations, group artistic artifacts, and TikTok videos) while receiving supplementary municipal data from the EWB-SA website. The middle phase focused on problem definition refinement using root cause analysis techniques, followed by academic writing development with institutional writing centre support and formative feedback on drafts. The sequence culminated in an artistic workshop facilitated by a second-year Fine Arts student—funded through a SASEE grant—before students submitted their final assessments in a staggered schedule spanning the first week of October.

4.1 Data Collection and Analysis

Data were collected through three online surveys (n=12 in July 2024, n=21 in October 2024, and n=4 in February 2025). The survey instrument incorporated Likert-scale questions and open-ended responses to obtain comprehensive insights and track students' perceptions of their learning experience. Internal validity of the Likert-scale items was verified using Cronbach's alpha coefficient. Quantitative data were analysed using SPSS to explore five constructs aligned with transformative learning theory: (1) a non-determining start, (2) a phase of experimental and undirected inquiry, (3) a phase of social testing and mirroring, (4) a shifting of relevance, and (5) social consolidation and reinterpretation of biography. Qualitative data from open-ended survey questions underwent thematic analysis to identify recurring patterns. To mitigate potential bias, the analysed data was reviewed by a colleague not involved in the research project. The research was conducted with appropriate ethical oversight, with institutional ethics clearance granted (certificate 2024FEBEFREC-ST-13).

5 Results and Discussion

The participants' feedback on the use of creative and unconventional methods (the art projects and TikTok) suggests these approaches enhance engagement and made learning more interesting and relevant. Students reported greatly valuing the integration of creative projects for conceptualising complex engineering challenges in new ways. One participant noted, *'The TikTok project made me think differently about how to communicate technical concepts to a broader audience.*' Another highlighted, *'Working on the art project helped me realise the real-world impact of waste management technologies.*'

An additional insight derived from data analysis was that participants frequently mentioned the development of graduate attributes and reflected on their future professional roles and responsibilities. This suggests that the project was effective in helping students envision themselves as future engineers who are ethically responsible and sustainability-oriented. These responses underscore a significant shift in relevance, from viewing engineering as purely technical to appreciating its societal implications. Participants also reflected on the social aspects of learning, emphasising the importance of collaboration and communication skills they developed through group-based activities.

From the analysis of initial (benchmark) survey in July 2024, it was observed that at the outset, students had varied levels of confidence across key competencies such as presenting technical information, writing technical reports, and working in teams. This initial variance, as well as the anxiety participants reported highlights the diverse background and skills set the students brought to the course. Essentially, it set a

baseline for the transformative journey. This aligns with Mezirow's 'disorienting dilemma', 'self-examination' and 'critical assessment' stages, or Nohl's (2015) 'nondetermining start'.

Subsequent analysis of the second survey data in October 2024, highlighted that the integration of creative components such as art projects and TikTok videos served as catalysts for experimental learning. Participants expressed that these activities made learning more interesting and enjoyable, suggesting an initial engagement that prompted deeper inquiry into both technical content and collaborative processes. The general view expressed by participants was that this pivotal in allowing students to explore concepts and ideas beyond traditional engineering education paradigms. This is consistent with Mezirow's 'recognition' and 'exploration' stages or Nohl's (2015) phase of 'experimental and undirected inquiry'.

The second survey data also suggests that as the course progressed, students reported increasingly engaging in teamwork and leadership roles, evidenced by improved confidence in leading group discussions and working collaboratively on complex projects. The feedback from peers and instructors during these activities provided critical social testing, where students could mirror professional behaviours and refine their interpersonal and technical skills. Thus, it may be deduced that this constituted 'planning a course of action', 'acquisition of knowledge' and 'provisional trying of new roles' in Mezirow's framework or 'social testing and mirroring' phase in Nohl's (2015) framework.

Finally, survey 2 data also implies that as the course progressed, there was a noticeable shift in how students valued their role in addressing sustainability through engineering. This was reflected in their growing confidence in proposing sustainability elements to complement engineering solutions and their enhanced understanding of the socio-environmental impacts of engineering decisions. The relevance of interdisciplinary skills became more apparent, aligning students' learning with the broader goals of sustainable development. It is believed that this represents 'building of competence and self-confidence' of Mezirow's framework or 'shifting of relevance' of Nohl's (2015) framework.

Finally, the analysis of the third survey indicated that by the end of the project, many students reinterpreted their professional identities (as an engineering student) and also recognised their future potential impact as engineers committed to sustainable practices. This is consistent with Mezirow's final stage 'reintegration' or Nohl's (2015) 'social consolidation and the reinterpretation of biography' phase.

6 Main challenges, lessons learned and future perspectives

The inception of this project was characterised by a lack of a predefined plan, which subsequently evolved through collaborative efforts with a subgroup of the IEC team and EWB-SA. The project's structure and objectives crystallized progressively as it unfolded. This iterative development process, while marked by considerable uncertainty, proved effective as indicated by the research data, which suggests that the project achieved meaningful results. During the project execution however, several areas were identified that could benefit from improvement. Notably, the project rubrics, initially developed collaboratively with students during the course, were refined following the initial formative assessments. This experience highlighted the importance of providing students with well-defined rubrics at the commencement of the course to better guide their learning and expectations. For future iterations, it is recommended to establish and share rubrics upfront to enhance the clarity and effectiveness of assessments

7 Limitations

Several limitations must be acknowledged. The small and declining sample sizes across data collection points (n=12, n=21, n=4) severely limit generalisability, particularly the final survey with only four participants. The study's implementation within a Professional Communication course, while providing flexibility for creative expression, raises questions about transferability to core technical engineering subjects where curriculum constraints and pedagogical norms differ significantly. Additionally, the focus on Industrial Engineering students within an extended curriculum program may limit broader applicability to traditional first-year

engineering cohorts across diverse disciplines. The resource-intensive nature of the intervention, requiring specialized partnerships, art supplies, and facilitation support, presents scalability challenges for implementation in different institutional contexts. Future research should examine larger samples, explore adaptations for technical courses, and investigate resource-efficient implementations across diverse engineering disciplines.

8 Acknowledgments and funding

Special acknowledgment is extended to the SASEE, whose financial support was instrumental in procuring art supplies and resourcing the art workshop integral to this project. The availability of these resources was key to the success of the research.

9 Conclusion

The CREATE project demonstrates how transformative pedagogies can be integrated into existing engineering curricula through embedding transformative learning opportunities within a required communications course and connecting them to real-world sustainability challenges. By leveraging artistic expression as a disorienting dilemma, the project successfully triggered perspective transformation in first-year engineering students' understanding of sustainability concepts, as evidenced by the longitudinal survey data collected over nine months.

This study confirms that the integration of CBL and PBL with creative expression provides a powerful mechanism for facilitating the phases of transformative learning. Students progressed from a non-determining start through experimental inquiry and social testing, ultimately experiencing a shifting of relevance and social consolidation that transformed their understanding of engineering's role in addressing sustainability challenges. The four interconnected assessments—particularly the artistic artifacts and TikTok videos—served as catalysts for this transformation, challenging traditional engineering communication norms while simultaneously developing key ECSA Graduate Attributes.

Ultimately, the findings of this study aligns with Mezirow's assertion that "*it is not so much what happens to people but how they interpret and explain what happens to them that determines their actions, their hopes, their contentment and emotional well-being, and their performance*" (1997, p. xiii). Through the CREATE project, students became active agents in their own transformation, supported by a carefully structured pedagogical approach that provided opportunities for critical reflection on assumptions about engineering practice and sustainability. Students' progression from viewing sustainability as isolated technical problems to understanding it as a complex web of interconnections between society, technology, and environment represents exactly the kind of perspective transformation needed in contemporary engineering education.

This research contributes to engineering education practice by demonstrating a concrete, implementable approach to developing both technical competencies and broader professional attributes through transformative learning experiences. The CREATE project thus offers a promising model for engineering educators seeking to prepare graduates capable of addressing complex sustainability challenges through integrated socio-technical understanding.

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The concept of Global Transformation Labs

Anders Rosén (aro@kth.se), Lena Gumaelius, Susanne Nilsson
KTH, Sweden

Bernard Shibwabo
Strathmore University, Kenya

Eva Shayo, Moses Ismail
University of Dar es Salaam (UDSM), Tanzania

John Batani
Botho University, Leshoto

Abstract
Global Transformation Labs (GTLs) are intended to be arenas, where students, teachers, researchers and various societal partners come together to explore and experiment with new collaborative ways of addressing global challenges and contribute to green and just transitions. The GTLs are thought to be spaces for mutual learning and reflection and places where participants can engage as change-makers, taking initiative, testing ideas and developing innovative approaches to complex societal challenges. The aim is to enhance the global perspectives of all participants, strengthen their understanding of human, societal, and

planetary predicaments and opportunities, build their capabilities to navigate, act and contribute both creatively and responsibly in a changing world, and to drive transformation.

This white paper presents a generative vision and an initial conceptual framework as a basis for further exploration through critical and creative conversations and co-development by interested partners.

Keywords: Global Transformation Lab, Transformation, Education for Sustainable development, Challenge driven education

1 Introduction

For almost a decade, a close collaboration has been going on between Botho University (BU) in Botswana/Lesotho, the Royal Institute of Technology (KTH) in Sweden, Strathmore University (SU) in Kenya, and University of Dar Es Salaam (UDSM) in Tanzania (see: www.kth.se/gdh). Together, a vibrant community focusing on testing innovative pedagogical approaches and new models of collaboration has been built up, aiming to explore how the role of the university can be transformed into one where students and staff are better equipped and empowered to actively contribute to societal transitions towards sustainable futures. Through joint development of approaches to challenge-driven education, faculty trainings, student mobility programmes, and annual or biannual conferences where ideas and experiences have been shared, and a vast number of challenge-driven student projects, this community has developed into a strong and trust-based network (Rosén et.al. 2022, Högfeldt et.al. 2019, Ibwe et.al. 2017). What began as a KTH-initiated network coordinated by the KTH Global Development Hub (GDH) has evolved into a truly mutual community, where learning is reciprocal and co-created. As a result of this long-standing collaboration, the concept that we call *Global Transformation Labs* is emerging as a means to further enhance these activities and aims. The GTL concept is inspired by and grounded in the collective experiences built over the years, and hubs and centres that have been established at the respective institutions such as the Y4C Innovation Hub at UDSM and Openlab at KTH. The GTLs are envisioned as platforms for transformation, designed to be tested, evaluated, and further developed. This paper aims to share thoughts and ideas that help frame this concept, much like a white paper intending to invite discussion, critique, and co-creation. Section 2 elaborates on the problem landscape that motivates the need for such an initiative. Section 3 sketches the GTL concept. Section 4 theorises the transformative and self-evolutionary potential. Finally in Section 5, we describe our current stage of development, share some brief insights, and outline the next steps we will take to further evolve the concept — ensuring that the GTL lives up to its full intended potential.

2 Societal Needs and the Role of Universities

“Civilization is at a unique moment, a juncture. Pandemics, wildfires, and wars swirl around us as we write, sure signs that societies remain extremely vulnerable to shocks despite unprecedented progress. Beyond the immediate turbulence, we are in the midst of a planetary emergency of our own making. … Can ‘we’ - meaning all people and peoples - come together to navigate this century? Can we take a collective leap in human development with courage and conviction? Can we overcome divisions, neocolonial and financial exploitation, historic inequalities, and deep, deep distrust among nations to deal with the long-term emergency? Can we achieve systemic transformation in decades, not centuries?”

This quote from the ‘Earth for All’ report (Dixson-Declève et al 2022, pp. 1-2) effectively captures the critical situation of our planet and society and poses a set of fundamental questions to humanity. Universities have for long positioned themselves as positive forces in society, contributing knowledge, innovation, and talent to address societal challenges. Yet, it is important to acknowledge that universities in general are also deeply embedded in and, at times, complicit with the development trajectories that have led us to the ”planetary emergency of our own making” where climate change, biodiversity loss, pandemics, economic and social inequalities and instability, and war, degrade humanity’s prospects and may lead to systemic breakdowns (Lawrence et al., 2024). If universities are to play meaningful roles in the future, they must both respond to

external challenges as well as look inward and examine their own values, structures, and modes of operation. As UNESCO (2018) puts it:

"*The learning environment itself must adapt and apply a whole-institution approach to embed the philosophy of sustainable development. It involves rethinking the curriculum, campus operations, organizational culture, student participation, leadership and management, community relationships and research*."

Transformation, both of society and of the university, does however not come easy. It requires courage, humility, willingness, and new alliances. It also requires universities to rethink how education, research, and innovation are approached: in what contexts, under what assumptions, toward what ends, who is involved in shaping ideas and technologies, and whose needs are prioritized?

3 The GTL Concept

Building on pragmatism as a philosophy of evolutionary learning through continuous inquiry, reflection, deliberation and experimentation (Ferraro et al 2015) the Global Transformation Labs are intended to be arenas for collaborative experimentation on transformations within as well as through education, research, and innovation. The idea is to bring together students, teachers, researchers, and representatives from industry, public sector, and the civil society, to jointly identify and formulate deep questions and perspectives on global challenges, and co-create new knowledge, ideas, interventions, and solutions. A key ambition is to accelerate systemic transformation guided by the principles of sustainability, frugality and regeneration, which are increasingly recognized as essential innovation drivers (e.g. Weyrauch & Herstatt, 2017; Hossain, 2018). These principles promote circular, resource-efficient, and socially regenerative design, supporting transitions that are not only sustainable, but also equitable and resilient.

The GTL concept is intended to be **Global** in the meaning acknowledging planet Earth as our common home and the ongoing "planetary emergency of our own making". It is intended to serve as arenas for meaningfully addressing dysfunctions, tensions and risks, as well as opportunities, of our globally interconnected society and the entangled complex challenges humanity is facing. This will require capacity to zoom out to understand complex systems at a global level, identifying structural patterns and long-term dynamics, and zoom in to local contexts where the impacts of these global issues are experienced and where meaningful transformation can begin. Such multi-scalar perspective shifting is essential for developing understanding and interventions that are both context-sensitive and systemically relevant and significant. The global dimension is further reflected in the diversity of participants, representing various regions across national, cultural, and other, borders and barriers. The GTL concept is intended to be **Transformative** by promoting transformative learning among all involved actors, developing key sustainability competencies (Bianchi et al., 2022). It is further promoting inter- and trans-disciplinary approaches and innovations that go beyond 1st order changes that are '*doing things better*' through optimization and technology shifts, towards 2nd and 3rd order changes that are examining and changing norms, assumptions, and values and enabling '*doing better things*' and '*seeing things differently*' by also challenging prevailing worldviews and paradigms (Sterling 2011). As **Labs** the GTLs will be physical spaces for knowledge sharing, reflection, and learning, where actors collaboratively explore and experiment with innovations and ideas. One GTL can preferably have several closely interconnected nodes physically located at different partner universities.

As illustrated in Fig 1. the activities within a GTL are thought to be structured in three major interrelated activities. At the core are 'Transformation-driving projects'; it could be challenge-driven project courses for undergraduate students, final year BSc or MSc thesis projects, or doctoral student or senior research projects which run in parallel or interconnected in various ways. Critical questions and challenges to be addressed by such projects are identified and framed in the 'Think tank' which is constituted by students, academics and representatives from industry, public sector, and the civil society that populates a GTL with a joint interest in the focus area of that particular GTL. The focus area and identity of a GTL should involve complex global-local tensions and opportunities and could for example be a certain nexus area such as 'food-water-energy' or

certain “leverage points” or “regenerative interfaces” i.e. critical points where multiple forces interact, and interventions are more likely to have the most significant impact. The ‘transformation-driving projects’ generates learning outcomes and project outcomes, some which can be taken further through various ‘Post-project actions’. As illustrated in Fig. 1 there will also be various other activities such as seminars, workshops, and trainings, that are more or less closely related to certain major activities. To promote openness and inclusion it should also be possible for students and others who are not directly involved in the activities to ‘hang around’ to get acquainted with the activities and the GTL members.

The organizational structure is meant to be shaped by personal agency, as participants actively design and evolve their roles over time. Students, young professionals, and early-career faculty are encouraged to lead the way, supported by the guidance and encouragement of more experienced peers. In addition, it is important to set up a business model grounded in shared risk and collective benefit. By maintaining transparent financial practices—often referred to as "open books"—we continuously assess and discuss the value and contributions of each participating organization. Recognizing that resources vary among participants, we encourage contributions—financial or otherwise—that align with each organization's capacity and strategy.

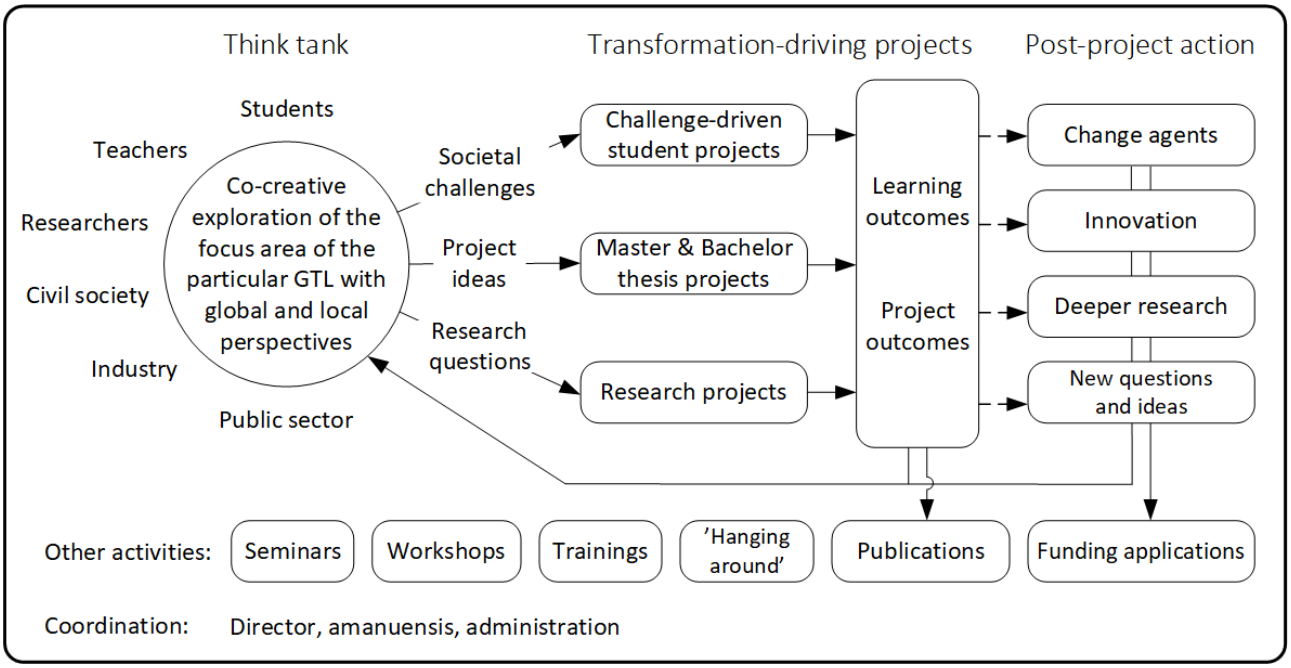

Figure 1: Sketching the organisation and activities of a GTL.

4 Built for Change: How GTLs Drive Transformation by Design

The GTL concept and its transformative and self-evolutionary potential can be explained in relation to the sociological concept of *robust action*. As Ferraro et al. (2015) suggests, disruptive transformative systemic change can emerge through incremental development, where small steps open the way for further advancements. As Ferraro et al. (2015) highlights, this will however require fruitful dynamics between the three interlinked strategies illustrated in Fig. 2 and outlined in the following:

A participatory architecture, i.e. a structural dimension for bringing the stakeholders together, both at a point in time and over time. As described above, such architecture is already in place since the GTL concept has emerged from the deep long-term partnership between the four involved universities. The aim is to further strengthen the transformative collaboration within the existing network, while gradually expanding the community by inviting additional academic institutions and societal partners, and creating new platforms and formats for collaboration.

A multivocal inscription, i.e. principles, policies, methods, etc, that frame the principal direction of the activities and facilitate experience sharing and articulation, discussion, and negotiation of meaning across the different actors, times, and places. Taking a starting point in the conceptualisation outlined in this paper and the experiences from collaborating on challenge-driven education and research, the multivocal inscription is thought to be subsequently co-developed by the GTL actors based on mutual learning and complementary frameworks and agendas, for example the EU GreenComp sustainability competency framework for framing learning needs and opportunities (Bianchi et al., 2022) and the *Earth for All* report for framing transformative needs and opportunities (Dixson-Declève et al. 2022 which in turn builds on fundamental work such as Meadows et al. 1972, UN 2015, and Richardson et al. 2023).

Distributed experimentation in specific projects whereby the actors collaboratively address certain global challenges and also improve their capacity for subsequent problem formulation and problem solving. The approach is intended to be life-centred (rather than merely human-centred), action-oriented, and grounded in—while also promoting—systems thinking, critical thinking, sustainability transitions, global competence, frugal innovation, and the navigation of wicked problems. By reflecting on both successful and less successful outcomes, we not only build collective knowledge about how to foster sustainability and transformations but also gain valuable insights into how the GTL concept itself can be better designed and made more relevant.

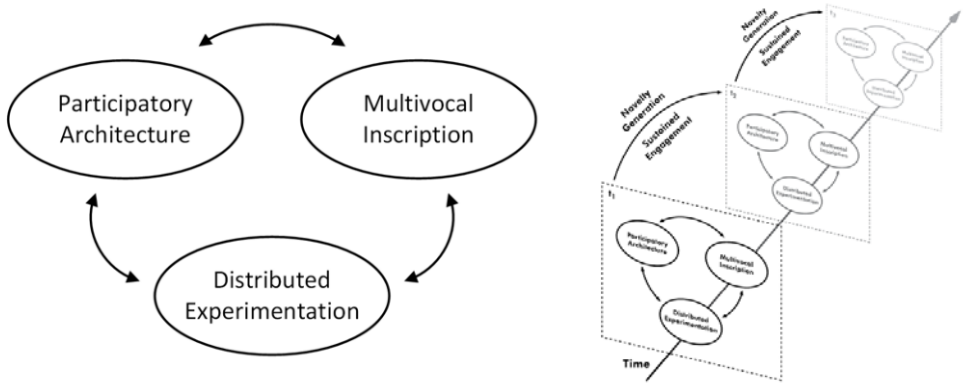

Figure 2: The three interacting strategies of robust action (Ferraro et al 2015).

5 Moving forward – Implementation and Follow-up

The first GTL prototype was initiated by the KTH Global Development Hub and tested in 2024 together with KTH teachers, three Stockholm-based industries and institutes, and students from KTH, Strathmore, Botho, as well as other international students on exchange at KTH. Another round of prototyping is going on during 2025, and dialogue is going on between the partners on how to develop joint GTLs. In many ways, the concept can be considered a success, as all involved stakeholders, including the organizing institution (KTH), expressed a clear desire to continue and further develop the model for a second year. Industry partners for example expressed that they saw a great value for their employees engaging in GTL activities to develop broader understanding of society and futures thinking. They also saw in connecting their involvement in GTL activities to their internal career development and life-long learning programs. Students for example expressed that this was the first time during their studies that they experienced educational activities where they took part as full humans, as opposed to attend as ´brains´, and becoming graduates, where the whole range of earlier life experiences was valued and useful in the projects. Teachers were for example positive in seeing students utilising the physical space in new and creative ways but on the other hand also saw clear limitations in students' as well as external stakeholders' knowledge and methods related to governance in complex contexts.

Key in the further development and implementation of the GTL concept will be to studying, evaluating, and researching whether and how it delivers on its ambitions. The key research questions we aim to explore

include several dimensions. In terms of governance of the participatory network, we are interested in understanding what conditions enable successful initiation of GTLs across diverse contexts, and how co-leadership models can balance power and promote equity between different partners, between academic and societal actors, and empower students to not only be beneficiaries of education but also take leading roles in transforming education and society (Niessner & Rosén 2025). In the area of distributed experiments, we seek to understand how GTLs support transformative learning among students as well as among involved educators and professionals. We also aim to identify which competencies are most critical in driving systemic change across various thematic nexus areas. From an innovation and impact perspective, we investigate how GTLs function as innovation ecosystems—what types of innovations they generate and through which mechanisms these innovations can be scaled or deepened for greater impact. Finally, we consider it essential to find out how GTLs can be durably accepted and embedded within existing structures while at the same time critically and creatively contributing to transforming those structures, and which organizational models are suited to support their long-term evolution.

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Emotions, Well-being, Collaboration, and Social Responsibility

Emotion norms in engineering education – more diverse than expected

Johanna Lönngren
Umeå University, Sweden, johanna.lonngren@umu.se

Katerina Pia Günter
Umeå University, Sweden, katerina.gunter@umu.se

Somayeh Ebrahimi Nejad Rafsanjani
Umeå University, Sweden somayeh.ebrahimi@umu.se

Maria Berge
Umeå University, Sweden, maria.berge@umu.se

Abstract

Engineering education has long been described as characterized by cultural norms that value rationality over emotions. Norms that devalue emotions are problematic because they can hinder engagement with value-laden issues, such as ethics and sustainability, and they may disproportionately impact students from minoritized populations. While previous research has shown that these norms exist in specific contexts, we lack knowledge on how widespread and dominant they are across contexts. We address this gap by describing a systematic and critical review of the literature on emotion norms in engineering education, asking: (1) What is the extent of the existing literature about emotion norms in engineering education? (2) What is known about emotion norms in engineering education?

Based on a Scopus search and systematic screening process, we identified 18 publications describing empirical studies on emotion norms in engineering education. Here, we describe preliminary results from our abductive analysis of seven papers. **The reviewed publications do not describe one coherent emotion norm across all engineering education**. Rather, emotion norms appear to be highly context- and community-specific. This finding supports previous research stating that some social groups are more adversely impacted by emotion norms than others. However, identifying variations in emotion norms can also open possibilities for change.

Keywords: emotion norms, rationality, systematic review, engineering education

1 Introduction

> *"Historically, the social institution which we call the profession of engineering has … largely functioned as a haven and a refuge for intellectually gifted emotional misfits. The system of engineering education, in turn, has actually functioned mainly as a filter and a pipeline which selects individuals who are emotionally disturbed in a certain standard way, and funnels them into the so-called engineering profession" (Mortensen, 1975).*

> *"Engineers should use their emotions in order to develop morally responsible technologies. This requires a new understanding of the competencies of engineers: they should not be unemotional calculators; quite the opposite, they should work to cultivate their moral emotions and sensitivity, in order to be optimally engaged in morally responsible engineering"(Roeser, 2012).*

As the above quotes illustrate, the stereotypical engineer has long been depicted as unable to feel emotions and interact with others. Examples from Western popular culture include Mr. Spock in Star Trek and engineering humor (Riley, 2008) about engineers who lacks social skills and can't think of anything but calculations, let alone having emotions. Engineering education research also tends to describe engineering education cultures as valuing technical rationality, while emotions – along with other "soft" or "social" issues – are frowned upon at best (see also, e.g., Boler, 1999; Faulkner, 2007; Lönngren et al., 2021; Ottemo et al., 2021). Research has also shown that stereotypes that devalue emotions can hinder engineering students' engagement with value-laden issues, such as ethics and sustainability (Holmén & Lönngren, 2025; Lönngren et al., 2020), due to the intimate connection between emotions and values. Moreover, in educational cultures where displaying emotions is perceived as a weakness, minoritized students are likely to be disproportionally punished for displaying what they feel and may be forced to exert higher levels of emotional labor than others (Boler, 1999; DeCuir-Gunby et al., 2009; Huff et al., 2021; Pradell, Parmenter, Galliher, & Berke, 2024).

But is this stereotypical image really true? Is there solid empirical evidence to back this claim or are we as engineering education researchers simply reproducing existing stereotypes? In a mixed-methods study with 200 engineering students from a higher education institution in Canada, Guntzburger et al. (2019) did *not* find convincing evidence for this claim. While students in their study stated that one should not let

emotions affect one's judgment, they also said that emotions could potentially be important for ethical risk management. Similarly, Lönngren et al. (2021) found evidence of students struggling to reconcile conflicting norms according to which emotions were both problematic and important for engineering problem solving.

To better understand the reasons for such ambivalent findings about the role of emotions in engineering education, we conduct a systematic and critical review of the literature on emotion norms in engineering education. We address two research questions:

RQ1. What is the extent of the existing literature about emotion norms in engineering education?
RQ2. What is empirically known about emotion norms in engineering education?

For this study define *emotions* as short-lived, but intense and immediate responses to specific situations. Emotions are complex, multi-componential phenomena involving physiological changes, subjective experience of physiological changes, cognition about the experience, motivation to act in a certain way, and embodied expression (Scherer, 2005; Shuman & Scherer, 2014). As such, emotions are interactional (i.e., people respond with and to others), contextual (i.e., people respond within and to specific physical and social contexts), continuously evolving (i.e., changing gradually rather than abrupt), and diverse (i.e., widely varying). Emotions serve as rich information for people as they engage and make meaning in the worlds (e.g., personal, cultural, professional) around them.

Our definition of *emotion norms* is based on Hochschild's (1979, 1983) seminal work in the sociology of emotions, where *emotion norms* refer to social rules about who should feel and display what emotions in which situations. Hochschild (*ibid.*) described two types of emotion norms: First, *feeling rules* are norms about what emotions someone from a given social group should (not) feel (and how) in a given socio-cultural-material context. For example, Secules et al. (2021) identified the following feeling rule in their analysis: "allowing deeply felt experiences of stress is not acceptable in the male engineering student's social world. It is an example of engineering students' defined social rules that they share a set of 'right' ways to deal with stress" (p. 873). Second, *display rules* are norms about what emotions someone from a given social group should (not) express (and how) in a given socio-cultural-material context (Hochschild, 1979, 1983). For example, Secules at al. (ibid.) suggested that "men likely experience more extreme emotions than they revealed" (p. 875). Our definition of emotions norms does not include beliefs or assumptions people may have about what emotions engineering students are likely to experience, not does it include information regarding the prominence (frequency or strength) of certain emotions among engineering students.

2 Methods

Most of the previously conducted empirical research on emotion norms in engineering education consists of in-depth qualitative studies. Therefore, we employ an approach to systematic reviews that is particularly useful for reviews of qualitative research: Meta-synthesis systematic reviews aim to "synthesize qualitative studies on a topic in order to locate key themes, concepts, or theories that provide novel or more powerful explanations for the phenomenon under review" (Siddaway et al., 2019, p. 756). Our review proceeds through three stages: (1) scoping and database searching; (2) abstract screening and full text screening; (3) in-depth review. An overview of our search and screening process is shown in Figure 1.

2.1 Scoping and database searching

The overall focus of our review is on publications describing empirical research that combines three thematic foci: emotions, norms, and engineering education (Figure 2). To develop our search query, we used the SPIDER tool for qualitative evidence synthesis (Cooke et al., 2012), which outlines important dimensions to consider in designing a database search for systematic reviews. Our application of the tool is outlined in Table 1. To identify suitable search terms related to emotions and engineering education, we took inspiration from a recent systematic review on emotions in engineering education (Lönngren et al.,

2024). To identify search terms related to norms, we read publications on identity in engineering education (Hatmaker, 2012; Matusovich et al., 2011; Morelock, 2017; Patrick & Borrego, 2016; Rodriguez et al., 2018; Tonso, 2014), social identity (Jenkins, 2014), and the sociology of emotions (Schrock & Knop, 2014; Stets & Trettevik, 2014; Turner, 2009) and extracted a total of 99 search terms. The full search query is provided in Appendix 1. We performed our search Scopus on 7 January 2025, searching in title, abstract, and author key words. After removing duplicates and conference publications, we obtained 249 unique publications.

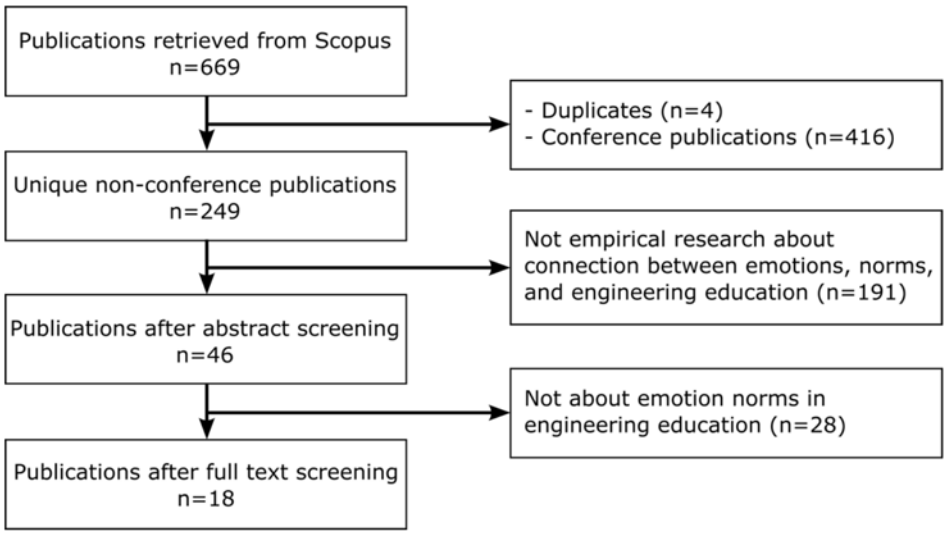

Figure 1. Overview of the search and screening process

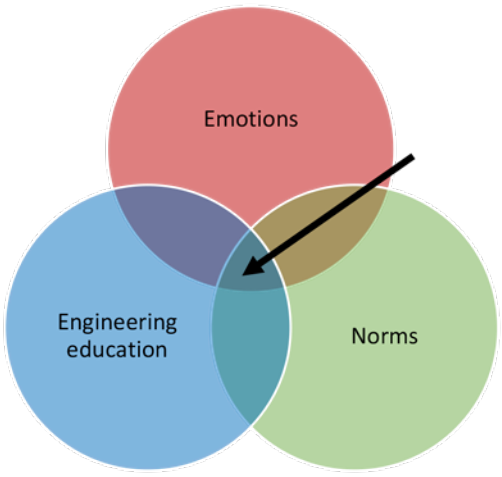

Figure 2. The overall thematic focus for the review lies at the intersection of emotion, norms, and engineering education

2.2 Abstract screening and full text screening

The purpose of abstract screening was to remove publications that do not describe empirical studies and/or do not deal with the intersection of our three thematic foci: emotions, norms, and engineering education. The purpose of full text screening was to ensure that retained publications focus specifically on *emotions norms*, excluding publications that combined the concepts emotions and norms in other ways. For example, several of the publications deal with emotions that are caused by norms in engineering education, such as masculinity norms, but they do not deal with norms about what emotions are considered appropriate in an engineering education context. For both abstract and full text screening, we used detailed codebooks that are available upon request. Each publication was screened independently by two authors and inconsistencies were resolved by discussions among all authors.

Table 1. SPIDER tool applied for our study

SPIDER dimension	Focus of our study	Terms and parameters for database search
Sample and context	people involved in engineering education	"engineering educat*" **OR** "technology educat*" **OR** "engineer* student*" **OR** "engineer* facult*" **OR** "engineer* instruct*"
Phenomenon of Interest	emotion norms (feeling rules, display rules)	(emoti* **OR** affective **OR** feeling*) **AND** ([see Appendix 1])
Design of research	all theoretical frameworks and research approaches	N/A
Evaluation	all types of outcomes	N/A
Research types	all empirical	[selected through screening]
Publication type*	peer reviewed, not conference papers, English language	[automatically filtered in Scopus, selected through screening selected through screening]

*not originally part of the SPIDER tool, but it is standard procedure to define this before searching.

2.3 In-depth review

For this paper, we conducted in-depth review for seven (Cech & Waidzunas, 2011; DeCuir-Gunby et al., 2009; Martin et al., 2020; Miller et al., 2023; Ottemo et al., 2023; Pradell, Parmenter, Galliher, Berke, et al., 2024; Wolfe & Powell, 2022) of the 18 included publications. The analysis for the in-depth review proceeded in four steps:

The aim of the first step was to identify excerpts describing findings from original empirical analysis providing insights about emotion norms in engineering education. Two authors independently coded each of the seven papers line-by-line, deductively applying Hochschild's (1979, 1983) original distinction between *feeling rules* and *display rules.* However, we encountered excerpts that we clearly identified as emotion norms, but that were neither feeling nor display rules. Rather, they were norms about what emotions someone from a given social group should (not) talk about (and how) in a given socio-cultural-material context. To account for these norms, we developed a third code: *talk-about rules*. Due to our focus on empirical findings, most of the coded excerpts were found in the results, discussion, and conclusion sections of the reviewed publications.

In the second step, we compared the coding results for each publication across the two independent coders, resolving inconsistencies through discussion and continuously nuancing our understanding of the different types of emotion norms. These discussions also sensitized us to the rich contextual information that some of the studies provided and that could provide insights for a more nuanced understanding of emotion norms in engineering education.

In the third step, we systematically mapped the contextual information for each coded excerpts, including the context in which an emotion norm was identified, the person(s) for whom the norm applied, the (types of) emotions for which it applied, what those emotions could be about (the objects of emotion), and which other person(s) in whose presence the norm applied. To ensure consistency, we rephrased all identified emotion norms in a standardized sentence format. For example, we identified the following display rule in empirical findings presented in DeCuir-Gunby et al. (2009):

> In engineering education in a United States context [context], women professors of color [person(s) for whom the norm applies] should not display assertiveness [(type of) emotion] about their rights [object of emotion] in front of their colleagues [other person(s)].

Finally, we analyzed across all emotion norms we identified, highlighting similarities and differences in emotion norms and the conditions under which they applied.

3 Results

3.1 The extent of the existing literature about emotion norms in engineering education

Our results show that the extent of the literature describing empirical studies about emotions norms in engineering education is very limited. We only found 18 publications matching our inclusion criteria and, of those, only five substantially focused on emotion norms. This is surprising, considering the strong discourse in the field stating that engineering education is characterized by strict emotion norms. Further, in our initial search, we retrieved almost twice as many conference publications compared to journal articles. Again, this is surprising (in a broader review of the literature on emotions in engineering education, we retrieved approximately as many conference publications as journal articles; Lönngren et al., 2024), and it speaks to a general lack of empirical research on emotion norms in engineering education.

Moreover, as we developed our coding scheme for the line-by-line analysis, we noticed that much of what we initially were tempted to code as emotion norms was *not* based on empirical findings. Rather, we found descriptions of emotion norms in the introduction and background sections of the reviewed publications, reproducing taken-for-granted assumptions about engineering education without adequate support from empirical research. References were often used, but they were primarily references to theoretical or philosophical publications (e.g., Roeser, 2012). For example, Hess et al.'s work (2021) was based on the (implicit) assumption that engineering students need to become more empathetic and attuned to their emotions. The authors investigated if a course concerning ethical issues in biomedical engineering practice would change the students' emotion regulation for the better, assuming it was not good from the start.

In other publications, we found implicit evidence of emotion norms, primarily in quotes from research participants that were not explicitly analyzed by the authors. In other words, the empirical data underlying several of the reviewed publications clearly contained valuable information about emotions norms in engineering education, but the authors did not focus on those norms in their analyses. For example, in Cech's and Waidzuna's study (2011) on lesbian, gay, and bisexual (LGB) students' experiences of engineering education, one student said: "You don't talk about your feelings, you don't talk about the world and what's happening in it, you don't talk about [...]. Really, we're just doing the technical stuff" (p. 11). Another student explicitly reiterated the image of the stereotypical engineer as unemotional: "But, I don't think I am a stereotypical engineer, either. The stereotypical engineer is good at math, not that emotional, really logical, they're just personally inept at times" (*ibid*., p. 18).

In summary, we found very little intentional, empirical research on emotion norms in engineering education. Hence, there may not be enough research to support the widely reproduced, general claims about emotions being taboo in (all) engineering and engineering education.

3.2 RQ2: What is empirically known about emotion norms in engineering education?

We found some statements of emotion norms in engineering education which were presented as general claims. In these cases, information about contextual factors was largely missing, which may lead readers to assume that the emotion norms are applicable across broad populations (e.g., all engineering students), for all types of emotion(s) and emotion objects, and irrespective of who else is present. For example, in Cech's and Waidzunas's (2011) study, one of the respondents formulates the norm that engineering students at their institution should not feel or display strong emotions: "The stereotypical engineer[ing student] is good at math, not that emotional, really logical, they're just personally inept at times" (p. 18). Figure 3 illustrates this emotion norm (the colors in this and the following figures are chosen to match the color-coding of contextual factors in the example sentence above).

The above excerpt provides an example of a claim to a general emotion norm, but many of our other coded excerpts paint a much more complex picture; contextual factors could vary independently from each other,

with wide-reaching implications for social dynamics in engineering education contexts. In the following sub-sections, we present examples that illustrate different ways in which emotion norms could vary across contexts, social groups, emotions, and emotion objects.



Figure 3. Illustration of emotion norms for engineering students at a major research university in the Western United States, based on data presented in Cech and Waidzuna (2011).

1.1.1. Emotion norms can differ for persons from different social groups

The findings presented in Cech's and Waidzunas's (2011) study do not only illustrate a monolithic understanding of emotion norms in engineering education (Figure 3), they also illustrate how talk-about rules could differ for persons belonging to different social groups and different objects of emotion, even within the same educational institution (Figure 4).

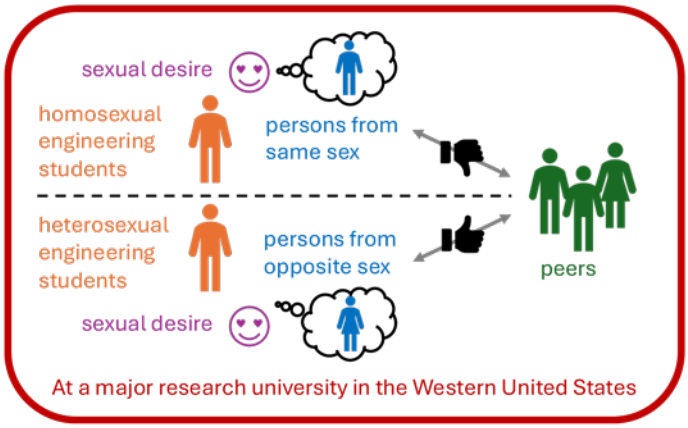

Figure 4. Illustration of differences in emotion norms for homosexual and heterosexual engineering students at the same institution, based on data presented in Cech and Waidzuna (2011).

For heterosexual students in the study, it appeared to be unproblematic to talk about sexual desire towards persons from the opposite sex. Homosexual students, on the other hand, expressed that they could not talk about their desire towards persons from the same sex:

> "People are accepting [of me as a gay man] up to a point. They're fine with you being gay, but they don't want you to talk about having a boyfriend. They're fine in the abstract, but let's just not go there. And the fact that they talk about their girlfriends in the lab I find kind of hypocritical."

1.1.2. Emotion norms can differ depending on who else is present

Findings from Miller, Castaneda, and Alemán (2023) illustrate how the persons one interacts with matter for emotion norms: female faculty recount how tenured male professors would not allow engineering students to display sadness (crying) in their presence. Instead, they would call on a non-tenured female professor to deal with the crying student (Figure 5). In other words, it was okey for students to cry in front of a non-tenured female professor, but not a tenured male professor:

> "This week, yet another engineering student in crisis. I gesture for Arielle to sit down across from me. She plops herself down on the chair and drops her backpack on the floor beside her. Tears start

streaming down her face. I pass her a box of tissues from my desk. Is this why Johnny passed her off? Because she's crying?"

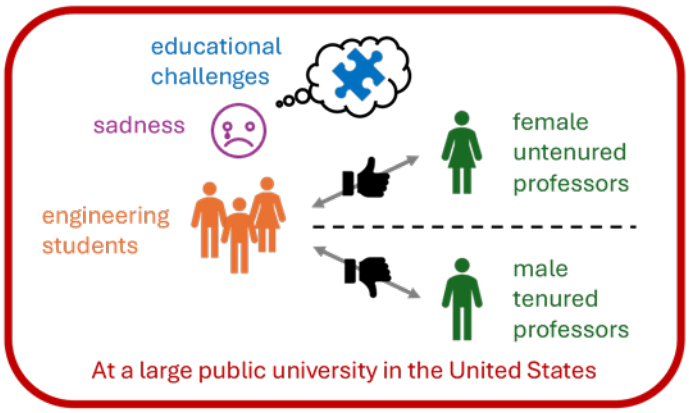

Figure 5. Illustration of differences in emotion norms for engineering students depending on who else is present in the situation, based on autoethnographic findings presented in Miller, Castaneda, and Alemán (2023).

1.1.3. Emotion norms can differ for different emotions and emotion objects

In addition to variation in emotion norms depending on who is involved in an interaction, Ottemo et al.'s (2023) study shows how different emotion norms can apply to different emotions and emotion objects (Figure 6): passion for technology and making things is to be expected in the context of a makerspace in Sweden; on the other hand, truly passionate makers do not and should not care too much about other people and their opinions:

> "That there was a relation at MakerClub between being passionate about technology and not being so attentive to or concerned with what other people think was also something hinted at by Anders, who suggested that: 'If you are interested in something and interested enough, you do not care much about the others, what they think'".

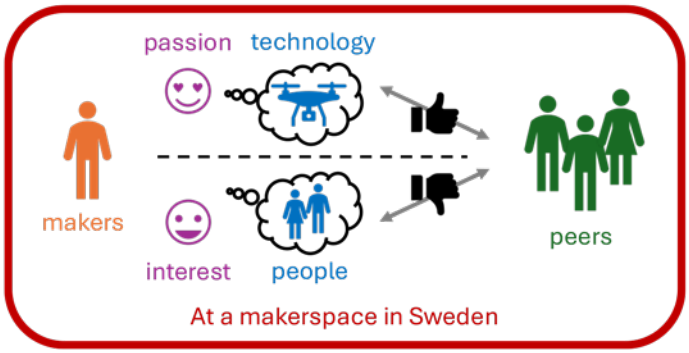

Figure 6. Illustration of different emotion norms at a makerspace in Sweden that apply for different emotions and emotion objects, based on data presented in Ottemo et al. (2023).

1.1.4. Emotion norms can differ between contexts

Finally, Miller, Castaneda, and Alemán (2023) also provide evidence that emotion norms can differ between contexts. In the context of their autoethnographic collaboration involving three engineering educators, they experienced that they could display vulnerability in the face of their gendered teaching experiences:

> "One of the things that was so striking to me in our early conversations was how vulnerable and open you both were."

The quote above illustrates surprise about the possibility for such vulnerability, showing that they did not feel that they could not display such vulnerability outside of their close circle, in other contexts within the same educational institution (Figure 7).

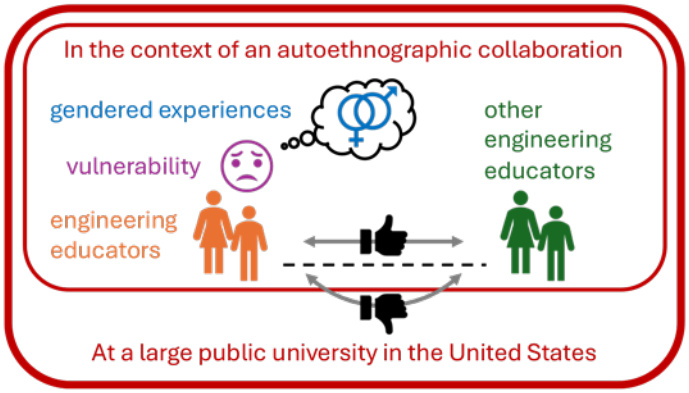

Figure 7. Illustration of differences in emotion norms for engineering educators at a large public university in the United States, inside and outside of an autoethnographic collaboration, based on findings presented in Miller, Castaneda, and Alemán (2023).

4 Discussion

The findings from our preliminary analysis clearly show that much more research is needed to develop a nuanced and well-grounded understanding of emotion norms in engineering education. We observed that, how emotions can be displayed and talked about, depends on *who* is displaying and talking, as well as *who* is receiving that information, and *in what contexts* the respective interaction takes place. In other words, emotion norms are *situated*, they can neither be disconnected from the people involved nor from the context in which they are enacted (Zembylas, 2005). Using an identity lens, it further becomes clear that emotions are deeply entwined with processes of social recognition and misrecognition along intersecting identity axes of oppression (e.g., gender, race, class; Avraamidou, 2020). Several of the reviewed studies (e.g., Cech & Waidzunas, 2011; Miller et al., 2023) provide first insights into the complexities of identity negotiations vis-à-vis emotion norms and a better understanding of what emotions are considered "normal" and for whom. Future research should continue on this track, leveraging social constructivist and sociological theories of emotions (for an overview of such theories, see, e.g., Lively, 2024; Mesquita & Parkinson, 2024) and intersectional identity frameworks (e.g., Avraamidou, 2020) to move beyond purely personal narratives of emotion norms and emotion-based identity formation in engineering education and to instead recognize the broader social and political implications of these narratives. This shift will allow for a deeper understanding of how social recognition and emotions influence systemic inequalities and how they can contribute to social change. To support such research, we offer an analytic framework for studying emotion norms as situated, intersectional phenomena (Figure 8). The framework outlines three aspects of emotion norms – *social identities*, *emotions*, and *emotion objects* –that interact within an *immediate social context* in which people interact in various ways. The immediate context is, in turn, situated within *wider social contexts*, each of which comes with its own social norms, structures, and practices. Recent work (published after our database search), complements our framework with a hierarchical model of emotion norms and empirical evidence of "various combinations of nested, context-dependent, and partly conflicting norms that guide [computing] educators' emotion display" (Grande et al., 2025, p. 1).

Future research should also take measures to avoid the unintentional reproduction of harmful narratives of engineering education as an emotion-free zone, populated by "unemotional calculators" (Roeser, 2012). Some researchers have begun to problematize monolithic descriptions of emotion norms in engineering education, demonstrating a more nuanced and reflexive approach. For example, Huff et al. (2021) suggested that we should not fall into the trap of reproducing an emotion norm according to which shame

is an undesirable emotion in engineering education: While shame is unlikely to lead to productive outcomes for students' learning and well-being, reiterating that shame is bad will not prevent minoritized students from feeling it, it will only lead to them feeling ashamed even of their shame.

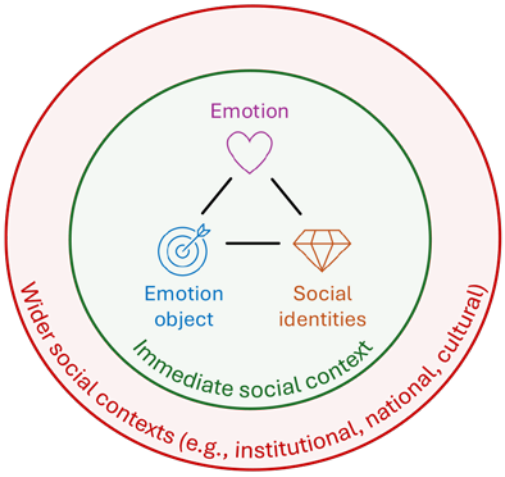

Figure 8. Analytic framework for studying emotion norms in engineering education as situated, intersectional phenomena.

Another insight from our analysis is that several publications dealt with emotion norms that neither fit the category of *feeling rules* nor that of *display rules*. Rather, they were norms about what emotions someone from a given social group should (not) talk about in a given socio-cultural-material context and how (e.g., norms related talking about desire, Cech & Waidzunas, 2011). To account for these norms, we need to expand Hochschild's (1979, 1983) conceptualization of emotion norms by introducing a third category, *talk-about-rules*. This conclusion is in line with previous research on emotional positioning, showing how engineering students negotiate who is allowed or expected to express and/or talk about what emotions in a specific interactional context (Lönngren et al., 2021; Lönngren & Berge, 2024).

5 Conclusion

In research as well as popular culture, engineering education has long been described as characterized by cultural norms that value rationality over emotions (e.g., Boler, 1999; Faulkner, 2007; Lönngren et al., 2021; Ottemo et al., 2021; Riley, 2008; Roeser, 2012). However, preliminary findings from this systematic literature review suggest that there is very little empirical evidence supporting such descriptions. In fact, the reviewed publications clearly illustrated how emotion norms can differ across social identities, contexts, and types of emotions. Much more empirical research will be needed to better understand the complex situated and intersectional nature of emotion norms in engineering education. Social constructivist and sociological theories of emotion, and intersectional frameworks of identity will be particularly valuable for future research, preventing unintentional reproduction of harmful and exclusive narratives about emotions in engineering education.

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7 Appendix: Search string used for database searching

(TITLE-ABS (emoti* OR affective OR feeling*) OR AUTHKEY (emoti* OR affective OR feeling*)) AND

(TITLE-ABS ("engineering educat*" OR "technology educat*" OR "engineer* student*" OR "engineer* facult*" OR "engineer* instruct*") OR AUTHKEY ("engineering educat*" OR "technology educat*" OR "engineer* student*" OR "engineer* facult*" OR "engineer* instruct*")) AND

(TITLE-ABS (“affective econom*” OR “emotional econom*” OR “micro-economic*” OR microeconomic* OR micropolitic* OR “micro-politic*” OR {capital} OR {exchange} OR circulat* OR discourse* OR discursive OR cultur* OR storyline* OR negotiat* OR “figured world*” OR “cultural world*” OR identit* OR positioning* OR identification* OR {norm} OR {norms} OR {normative} OR {normality} OR ideolog* OR “moral field*” OR {power} OR {prestige} OR authority OR privilege* OR “social status” OR “status symbol” OR “social structur*” OR hierarch* OR segragati* OR stratification OR structuration OR “in-group*” OR “out-group*” OR “rites of passage” OR “social field*” OR habitus OR habituation OR socialis* OR socializ* OR reproduc* OR “social class*” OR {race} OR racial* OR gender* OR sexualit* OR ethnic* OR intersectional* OR minorit* OR disabilit* OR queer OR masculin* OR feminin* OR discriminat* OR inequal* OR marginali* OR stereotyp* OR prejudic* OR conformity OR “ideal type*” OR “labelling process*” OR “labeling process*” OR “role model*” OR “type of person” OR “role configuration” OR “framing rule*” OR dramaturg* OR script* OR {display} OR “role tak*” OR “role-tak*” OR “symbolic interaction*” OR ritual* OR symbolization OR symbolisation OR symbolism OR attribution OR “expectation state*” OR “verificat*” OR selfhood OR personhood OR alienat* OR reflexiv* OR “self-categori*” OR “self-identi*” OR “self-image” OR “sense of self” OR “self-perception” OR “feeling rule*” OR “display rule*” OR “emotion rule*” OR “emotion work” OR “emotional lab*” OR “emotion management” OR “emotional management”) OR AUTHKEY (“affective econom*” OR “emotional econom*” OR “micro-economic*” OR microeconomic* OR micropolitic* OR “micro-politic*” OR {capital} OR {exchange} OR circulat* OR discourse* OR discursive OR cultur* OR storyline* OR negotiat* OR “figured world*” OR “cultural world*” OR identit* OR positioning* OR identification* OR {norm} OR {norms} OR {normative} OR {normality} OR ideolog* OR “moral field*” OR {power} OR {prestige} OR authority OR privilege* OR “social status” OR “status symbol” OR “social structur*” OR hierarch* OR segragati* OR stratification OR structuration OR “in-group*” OR “out-group*” OR “rites of passage” OR “social field*” OR habitus OR habituation OR socialis* OR socializ* OR reproduc* OR “social class*” OR {race} OR racial* OR gender* OR sexualit* OR ethnic* OR intersectional* OR minorit* OR disabilit* OR queer OR masculin* OR feminin* OR discriminat* OR inequal* OR marginali* OR stereotyp* OR prejudic* OR conformity OR “ideal type*” OR “labelling process*” OR “labeling process*” OR “role model*” OR “type of person” OR “role configuration” OR “framing rule*” OR dramaturg* OR script* OR {display} OR “role tak*” OR “role-tak*” OR “symbolic interaction*” OR ritual* OR symbolization OR symbolisation OR symbolism OR attribution OR “expectation state*” OR “verificat*” OR selfhood OR personhood OR alienat* OR reflexiv* OR “self-categori*” OR “self-identi*” OR “self-image” OR “sense of self” OR “self-perception” OR “feeling rule*” OR “display rule*” OR “emotion rule*” OR “emotion work” OR “emotional lab*” OR “emotion management” OR “emotional management”)

Rewiring from Within: Exploring how participation in curriculum development impacts engineering academics professional and personal well-being

Lelanie Smith, Janine Hechter, Liesel Ebersöhn
University of Pretoria, South Africa

Bronwyn Swartz
Cape Peninsula University of Technology, South Africa

Inês Direito
Universidade de Aveiro, Portugal

Abstract

Addressing complex global challenges requires more than technical solutions; it demands an integrated approach involving economic, environmental, and social dimensions. Engineering education is a driver for Sustainable Development Goals (SDGs), but transformative engineering education requires a 'shift of consciousness' and focus on socio-emotional development. Our project developed a process called 'Clear,' rooted in Theory U for systemic transformation in engineering education and applying meta-patterns to support shifts in personal perspectives. The process enables engineering educators to slow down and explore fundamental questions about identity, purpose, and response-ability, which are essential precursors to effective engagement with complexities of developing an engineering curriculum. This approach is particularly relevant for developing innovative engineering curricula in South Africa and in comparable low- and middle income settings transforming away from inequality to justice. The study aims to explore how focusing on intrapersonal transformation, through the 'Clear' process, can facilitate systemic change in engineering higher education. Specifically, it explores personal awareness and development as foundational intrapersonal capacities to enable broader curriculum shifts. Research assistants conducted online interviews with 34 engineering educators engaged in the 'Clear' process. Audio-recorded interviews were transcribed verbatim and analysed using inductive thematic analysis to understand the participants' experience during and after the 'Clear' process. The analysis revealed themes such as the importance of community, the need for balanced reflective practice, and the interplay between intrinsic and extrinsic motivations for change. Participants highlighted the role of networking and the complexities of building learning communities, with their narratives showing evidence of both professional and personal well-being as a result of participating in the curriculum intervention. These insights suggest that individual transformation is crucial before addressing larger institutional goals, aligning with the principles of the Inner Development Goals (IDGs) framework. This work-in-progress suggests that integrating IDGs, such as "Being" into academic development can create a foundation for innovative, student-centred curricula. Future research will explore how individual attributes—such as career phase, personality, and socio-cultural values —shape engagement with systemic transformation efforts.

Keywords: engineering educators, innovative engineering curricula, transformation, well-being

1 Introduction

The challenge of transforming collective social systems, particularly within fields like engineering education, reflects broader global issues of violence, social injustice, and environmental degradation (Nordin & Sundberg, 2018; Case et al., 2016; Mitchell et al., 2021). These challenges often stem from a disconnection in how individuals relate to themselves, others, and the environment. To address these complex systemic problems, a shift is required from an ego-centric worldview to one that is ecosystem-aware—emphasizing mindfulness, inner leadership, and connection (Ankrah et al. 2023; Woiwode, 2020). This shift involves adopting new ways of observing, reflecting, and acting, fostering holistic solutions that address the root causes of systemic issues, leading to more meaningful and sustainable change (Ives et al., 2020).

However, the process of facilitating deep change in both individuals and systems requires an acknowledgment of the inherent complexity involved. Change theories often present simplified, linear models, overlooking the unique and subjective experiences of individuals as they navigate transitions. The reality is that every individual's capacity to respond to change is unique, influenced by personal context and pace of movement. This complexity is compounded within collective systems, where it becomes nearly impossible to pinpoint which decisions trigger specific outcomes (Mason, 2008; Morrison, 2008).

Recognizing these challenges, the Innovative Engineering Curricula (IEC) team—established through the Transforming Systems through Partnerships (TSP) project, co-funded by the Royal Academy of Engineering (RAE) and the South African Department of Higher Education and Training (DHET)—engaged with transformation coaches and academic leaders who had previously navigated institutional change. Their reflections revealed a key insight: before meaningful curriculum change can occur, educators themselves must feel resourced, connected, and clear. In their reflections, deep personal development emerged as the often-missing foundation for sustainable systemic change.

In response, we developed the *Change Makers in Engineering Education* program, using a structured reflective process we call *Clear*. This process integrates Theory U's approach to systemic transformation (Scharmer, 2009) with the Meta-States model of personal and cognitive development (Hall, 2000). We then tailored it by mapping key Meta-States to the specific tensions that engineering educators are likely to encounter, enabling participants to explore fundamental questions around identity, agency, and professional purpose. Over 18 months, we refined this process to support educators in navigating change while recognizing their own needs and boundaries.

By guiding participants through reflective inquiry and structured engagement, the *Clear* process provides strategic tools to help them move beyond resistance and uncertainty. It supports a mindset shift, equipping educators with the confidence and insight to make informed decisions about their own growth and, in turn, contribute resourcefully to curriculum transformation.

This paper explores the experiences of engineering educators who participated in the Change Makers program, analyzing how their individual transformations have influenced their engagement with systemic change. Through qualitative thematic analysis, we examine how themes such as belonging, reflection, mindset, and capacity-building emerged.

2 Literature

As is the case in other postcolonial and low-and middle income countries, engineering education in South Africa operates within a complex landscape shaped by multiple intersecting challenges and imperatives. The higher education sector has undergone significant transformation since the end of apartheid, with institutions working to address historical inequalities while simultaneously responding to global technological advances, industry demands, and student needs. Engineering faculties, in particular, face unique pressures at this nexus of transformation, technical education, and professional accreditation requirements. Globally, frameworks such as the Washington Accord and the Bologna Process have sought to standardize engineering qualifications across borders (Kasuba & Ziliukas, 2004; Anwar & Richards, 2015), but these initiatives rarely account for deeply local challenges.

Within South African institutions, as in other countries, engineering educators often enter academia with deep technical expertise but little pedagogical training (Felder, Brent, & Prince, 2013). They juggle demanding teaching loads, research expectations, administrative duties, and professional accreditation requirements (Ogude et al., 2005), often without access to sustained academic development. Their classrooms reflect vast socioeconomic disparities in students' educational backgrounds, language proficiencies, and access to resources (Leibowitz et al., 2015). These pressures are compounded by shifts toward competency-based and employability-driven curricula, which require new pedagogies and a rethinking of teaching identities (Kolmos et al., 2016; Nodine, 2016).

Academic development programs often focus on surface-level teaching techniques or curriculum design, failing to support the deeper capacities needed to navigate these complexities (Graham, 2025). The Change Makers program was developed precisely to fill this gap: not as a set of tools, but as a developmental process rooted in reflective practice, personal clarity, and relational learning. It aligns with the Inner Development Goals (IDGs) framework, which argues that the Sustainable Development Goals (SDGs) will not be met without cultivating human capacities for self-awareness, collaboration, and intentional action.

Drawing on Scharmer's (2016) Theory U and Meta-States (Hall et al., 2001; Linder-Pelz & Hall, 2008), the program creates a structured yet open space for educators to recognize and act on their own developmental needs. This approach reflects Barnett's (2000) call for higher education to embrace epistemologies of uncertainty: helping academics not just deliver knowledge, but interrogate their roles, adapt to complexity, and act with clarity and purpose.

In this sense, Change Makers is less about training and more about transformation. It helps educators move beyond surface compliance with reform agendas toward a deeper ownership of change. Rather than prescribing what educators should do, it asks who they need to be. This human-centered approach to faculty development reframes curriculum reform as a relational, emotional, and ethical endeavor.

The approach is also rooted in Wenger's (1999) social theory of learning, which emphasizes identity formation through practice, meaning-making, and participation in communities. Change Makers acts as a community of practice, where educators can share experiences, build trust, and make sense of their roles in the transformation of engineering education.

By positioning faculty development as a key driver of curriculum transformation, Change Makers aligns with broader global conversations on engineering education reform that stress the importance of empowering educators to be agents of change within their institutions (Besterfield-Sacre et al., 2014; Walkington, 2002). This highlights the need for professional development strategies that extend beyond technical curriculum reform, supporting engineering educators in navigating the complex realities of higher education in an evolving global and local context (Case et al., 2016; Coso Strong et al., 2023).

3 Context

It is within this landscape that the *Innovative Engineering Curricula* (IEC) project (2021–2026) was launched. Funded through the TSP initiative by RAE and DHET, the project brought together seven South African engineering schools and the South African Society for Engineering Education (SASEE), with strategic input from University College London (UCL). While inspired by UCL's Integrated Engineering Programme, the IEC team recognized the need for local adaptation—to design a model responsive to the South African context and its institutional diversity.

From early 2021, the IEC team met regularly online, creating a collaborative space where partners from research-intensive universities, universities of technology, and comprehensive institutions could co-develop approaches. This inclusive structure enabled cross-pollination of ideas and helped surface shared challenges and possibilities for curriculum innovation.

A central realization was that curriculum reform cannot succeed unless both staff and student ability to engage with change are addressed. Facilitating integrated curricula and professional competencies requires more than new content or delivery models—it requires emotionally resourced, relationally connected educators. This insight catalyzed the development of the Change Makers program as a core component of the IEC project.

Change Makers was designed to offer safe, developmental spaces where engineering educators could reflect on their own identities, connect with peers, and develop the resilience needed to lead change. Unlike typical faculty development initiatives, it is not a 'training' but a process of self-alignment and collective inquiry. Participants explore the tensions they face in academic life and identify sustainable practices to support both personal well-being and professional engagement.

By encouraging a culture of trust and dialogue, the program enables participants to build shared language, articulate challenges, and engage more confidently in curriculum transformation. It addresses the human conditions under which reform can actually succeed.

4 Method

This study aimed to explore the value participants derived from attending the Change Makers program. The research design was qualitative and interpretive, employing semi-structured interviews and thematic analysis to address the research question: *What is the value that participants derived from attending the Change Makers program?*

4.1 Participant Recruitment and Context

The Change Makers in Engineering Education program consists of a two-day workshop designed to support engineering academics and administrative teams in navigating change. While each iteration follows a structured process, the format is adapted to the composition and developmental needs of the participating group. All workshops are grounded in the *Clear* process—a reflective, experiential model that integrates Theory U and Meta-States—and support individuals in identifying personal and professional tensions, articulating change strategies, and engaging with others around shared challenges across institutions, departments or administrative teams.

The national open group format invites participants from all 16 engineering schools in South Africa to attend as individuals. These sessions are highly diverse and cross-institutional, with participants bringing a wide range of professional identities, institutional contexts, and disciplinary backgrounds. The first day focuses on self-reflection, exploring personal well-being, identity, and agency in relation to participants'

roles as academics. On the second day, the emphasis shifts toward developing personal change strategies. While individual journeys are foregrounded, participants often find resonance in one another's experiences, discovering common systemic tensions across institutions and gaining insight from their peers.

In contrast, departmental groups attend the workshop as part of a broader curriculum transformation effort at their home institution. Here, the first day similarly emphasizes individual reflection and baseline setting, but the second day transitions into team-based work. Participants co-develop departmental change strategies aligned with their shared curriculum goals. These sessions are often timed to coincide with either the start of a curriculum renewal process or a point where momentum has stalled. The language and focus are more explicitly tied to curriculum design, teaching practices, and team alignment.

Finally, administrative department sessions are tailored to professional and support staff who hold critical but often overlooked roles in enabling academic transformation. The first day mirrors the other formats, offering space for individual insight and personal leadership development. The second day is highly contextual, focusing on team functioning, interdependencies, role clarity, and navigating institutional tensions. These sessions create opportunities for greater cohesion and enable staff to contribute more resourcefully to institutional change processes.

Across all formats, participants are grouped intentionally based on their roles and affiliations—national participants apply or are nominated independently, while departmental and administrative teams attend as intact units. The format of each session is responsive to this structure, ensuring relevance and resonance.

Invitations were distributed randomly, ensuring that participants across different institutional roles and workshop types were represented. From this pool, eight participants were selected for in-depth analysis in this paper—six from national open groups and two from engineering departments. While the selection was random, the resulting sample captured a rich diversity of institutional contexts, disciplines, career stages, and personal experiences. This diversity enabled us to explore how the *Clear* process resonated across different roles, shedding light on how participants engage with systemic change through the lens of personal clarity and belonging.

4.2 Data Collection

Two research assistants conducted semi-structured interviews with each participant. The interviews explored personal and professional experiences related to the program using a set of 7 predefined open-ended questions:

1. What were your experiences of attending the Change Makers workshop?
2. What were your expectations before attending the workshop?
3. How did you feel after attending the Change Makers workshop?
4. Elaborate on the value, if any, your attendance had to you personally or professionally.
5. Do you mind sharing some of the changes, if any, you made after attending the workshop?
6. When you reflect on yourself, your life, your job personally or professionally, are there any changes you still plan to implement?
7. If there was a learning community where you could actually engage in and get resources for your classroom. What would that look like for you?

The interviews provided rich narratives that illustrate participants' experiences, expectations, and outcomes from the program.

4.3 Data Analysis

The data analysis followed a collaborative, iterative process:

1. Initial Observations:
   The 34 interview transcripts were divided among eight researchers. Each researcher reviewed a subset of four transcripts and wrote initial observations and impressions based on participants' narratives.
2. Team Review:
   The research team consisted of:
   - Two main facilitators and designers of the Change Makers program.
   - Two researchers who participated in the Change Makers program but were not part of the national Innovative Engineering Curricula (IEC) team.
   - Three engineering education researchers from the IEC core team.
   - One researcher with an educational psychology background who had no prior involvement with the Change Makers program.
3. The team convened to share their observations and impressions, collectively discussing and refining initial insights.
4. Thematic Analysis:
   The collective observations informed the development of a list of emergent themes. The themes were iteratively refined through group discussions, with researchers building on each other's reflections. This collaborative process ensured that diverse perspectives were integrated and that themes were grounded in participants' narratives.

5 Findings

Participants approached the Change Makers program with varying expectations, often anticipating structured sessions on engineering curriculum or conventional team-building activities. Instead, they encountered a program that prioritised personal growth, reflective practices, and resilience building. This shift in focus surprised many participants, with some expressing deep gratitude for the unexpected emphasis on self-reflection and personal well-being. They found value in stepping back to consider aspects of their lives and professional identities that they often neglect.

A particularly memorable feature of the program was the "laptop framing" activity (explained further), which many participants highlighted as impactful, underscoring the program's thoughtful design. Across the various groups—departmental teams, national Change Makers participants, and administrative staff—experiences diverged. Voluntary attendees, especially those in the national program, were more open to the reflective nature of the sessions, while mandated participants often viewed the program as an imposition. Despite this, common outcomes emerged, including a stronger sense of community and belonging, shifts in mindset toward professional integration, and reflections on the importance of balancing work and personal well-being. The program also allowed insights into team dynamics and conflict resolution, equipping participants with strategies applicable to both academic and administrative environments.

Sense of Belonging and Human Connection
Participants consistently expressed how the program cultivated a deep sense of belonging and community. As one attendee shared,

"I think I felt, for the first time at a workshop, that I felt seen. I felt seen as a human, and not just seen as a lecturer." P13

Another participant stated "that it is important to take it easy sometimes and *be a human being as opposed to being a tool. P33*

This sentiment of being valued extended beyond professional roles, facilitating genuine connections among participants. Another participant reflected,

"It can be lonely sometimes. So, it's nice to be in a community of like-minded individuals." P4 Another person experienced it as "kind of inspirational, because you're surrounded by people with similar sort of intentions. P23

The value of shared experiences was another recurring theme. Participants found solace in sitting down with peers from different institutions to discuss shared challenges. One noted, *"It was a great thing to sit down… You sit down and talk with people who are facing the same challenges, the same pressure of offering the best education. I realised that people are feeling the same thing that I'm feeling. The first thing that I gained is confidence." P13 .* Another attendee confirmed, *"it's been nice to share experiences, share ideas, get other people's perspectives and so on." P1*

Personal reflection, baseline and setting boundaries

The workshop participants were *"pleasantly surprised that it's the first time ever I've been to something where they said: Don't focus on the student, focus on yourself. And so those two days were actually probably the first two days I've ever spent in my career in academia thinking about myself and reflecting on me and making me think about things that I've probably never even had the inclination to think about." P1*

Participants realized that they *"need to set a correct baseline, and we need to recognize the non-negotiables so that we can be able to function properly in our daily basis, so that, I think that was a highlight for me, when they referred to sleep and eat." P3.* Another participant stated *"it also pushes me to love myself more because for me to honor my non- negotiables, says I'm taking myself seriously. So I need to take myself seriously, so that my surroundings or the people around me can take me seriously, right, and that I can then be the best version of myself." P13*

A participant at the burnout stage voiced that boundaries are necessary for finding work-life-balance: *" I tried to work on my personal self with getting more sleep and prioritizing my work a bit. So I worked on my sleep patterns. … Balancing my life, my workload, my personal life, my studies, my family life. I need to prioritize that and work it out, get it balanced. Because one is dominating the other. So I do not have enough time for all the other things. … So obviously, I don't have time for myself, like exercises, I'm not sleeping enough, being married. So I'm at the burnout stage." P32*

"I don't think I implemented that, but it's in my mind. I have that thinking the whole time that at some point I must take it easy. Yeah." Like taking it easy, taking your work at work. And when you're at home, be at home. Which is something that sometimes I don't find time for. I'm always on on a busy mode and that is not good because it takes a toll. So just being easy and being at home. And that is something that we also learned out of that session." p33

Support and Capacity Building

The program's emphasis on personal development and resilience was deeply appreciated, providing participants with tools to navigate both professional and personal challenges. One participant noted,

"You know, we don't have all the answers. We're learning with the students as well. Sometimes you can stand up and say, 'I don't have the answers. It's not me, and I need to learn more.' This session gave us that support." p7

The safe, supportive environment also encouraged participants to express themselves openly.

"It allowed you to express. It was a safe place where you could say what you wanted and be free, and I think we didn't have that before," P7

Beyond the immediate outcomes, participants left feeling renewed and empowered. As one participant described,

"I felt energised. You feel like you've got some extra tools to deal with everything that's coming your way. You feel inspired and ready to carry on." P23

This renewed energy often came with a reminder of the importance of self-care.

"If you want to do the best work that you need to do, then you can't… You have to ground yourself first. You've got to take care of yourself." Another attendee agreed that "we also need to take care of ourselves. Because when we take care of ourselves, that's how we are able to also take care of others. P23

6 Discussion

The findings from the Change Makers program offer powerful evidence that meaningful curriculum transformation in engineering education must begin with the personal and professional well-being of educators. Participants entered the program expecting technical discussions on curriculum or traditional team-building exercises. Instead, they encountered a reflective process centered on personal growth, resilience, and relational engagement. This unexpected emphasis—rooted in Theory U's premise that internal transformation precedes external change (Scharmer, 2016)—elicited a deep, and at times disorienting, re-evaluation of self, work, and purpose.

A key theme to emerge was participants' experience of being genuinely "seen"—not just as professionals, but as full human beings. This was particularly powerful in an environment where faculty often feel reduced to performance metrics, student throughput, and institutional compliance. The experience of being recognized for who they are, rather than solely for what they produce, created a sense of psychological safety and connection. "I felt seen as a human, not just a lecturer," one participant reflected. This speaks directly to the Inner Development Goals (IDGs), which highlight *being*, *relating*, and *acting* as core developmental capacities essential for transformative systems change. By nurturing self-awareness, empathy, and purpose, the Change Makers program helped participants access and develop these inner resources.

The sense of belonging and community was especially important. Wenger's (1999) concept of communities of practice is helpful in understanding how this sense of connection enabled deeper learning and professional identity development. Participants described the value of sharing their struggles, learning from one another, and realizing they were not alone in facing systemic constraints. This mutual recognition supported a growing confidence to act differently—not just within the classroom, but within their broader institutional roles. It also reflects the *relating* dimension of the IDGs, where interpersonal connectedness and collaboration become foundational for wider professional change.

In addition to relational shifts, the program also encouraged participants to critically examine their own boundaries, well-being, and work-life balance. Several reported recognizing the need for healthier personal baselines—what one participant described as honouring "non-negotiables like sleep and eating." These practices, though seemingly basic, represent an important form of self-leadership and resilience. They align

with the *being* dimension of the IDGs, which stresses the importance of inner grounding, presence, and care in contexts of complexity and stress.

The program also shifted how participants thought about curriculum—not simply as content to be delivered, but as a space for reflection, adaptability, and shared inquiry. One participant noted: "It's definitely shifted the way I think about things… There's a lot that it did to me in terms of mind-changing and the way I see things now." These emerging perspectives mirror Barnett's (2000) argument that higher education must prepare educators and students alike for supercomplexity—through the development of critical action, epistemological openness, and the capacity to operate amidst uncertainty.

Despite differences in institutional context and participant motivation—some attended voluntarily, others as part of mandated departmental efforts—the findings revealed a consistent appreciation for the program's approach. Even participants who initially resisted the reflective format acknowledged its long-term value. This broad resonance across contexts suggests that programs like Change Makers meet a widely felt but often unarticulated need among educators for spaces of pause, meaning-making, and peer connection.

However, the findings also highlight a challenge: integrating these reflective and relational approaches into institutional culture. While the program created a powerful developmental experience, the broader university context often lacks the structures, incentives, and time to support such work. For these practices to scale, institutions must begin to view faculty well-being, identity development, and community-building not as peripheral "extras," but as integral to academic excellence and systemic transformation.

Taken together, the findings point toward three key implications for engineering education reform:

- Faculty development must attend to inner capacity building, emphasizing well-being, clarity of purpose, and self-leadership as foundations for curriculum change.
- Intentional communities of practice should be cultivated, not only to share expertise but to foster belonging and reduce isolation.
- Institutional transformation requires rethinking academic support structures, prioritizing developmental time, reflective space, and relational learning as critical to both educator and student success.

By engaging educators as whole people, the Change Makers program demonstrates that faculty can become more grounded, connected, and capable agents of transformation. This supports not only curriculum reform, but the deeper cultural and systemic shifts needed for South African engineering education to flourish in a complex and uncertain world.

7 Limitations and future research

While this study provides valuable insights into the impact of the Change Makers program, several limitations should be acknowledged. First, the study relies on self-reported experiences, which, while rich in narrative detail, may be subject to response bias. Second, the analysis is based on a sub-set of 8 interviews out of a total of 34. Although the selected interviews reflect a diversity of roles and experiences, this limited sample may not fully capture the breadth of perspectives present in the full dataset, potentially affecting the generalizability of findings. Future research will include analysis of the full dataset to provide a more comprehensive understanding of the impact of the Change Makers program.

Third, the study focuses primarily on engineering educators within the South African context. While the findings may have broader applicability, further research is needed to explore how similar faculty development models function in different national and institutional settings. Given the growing emphasis on holistic faculty development in higher education, comparative studies across diverse educational systems would be beneficial.

Additionally, the study raises important questions about the role of personal attributes—such as career phase, personality, and socio-cultural values—in shaping engagement with systemic transformation efforts. Future research should explore these dimensions in greater depth to better understand how different individuals experience and apply the insights gained from faculty development programs.

8 Conclusion

This study affirms that meaningful transformation in engineering education cannot be achieved through curriculum reform alone—it must begin with those who enact change: the educators themselves. The Change Makers program, embedded within the broader IEC initiative, offers a compelling model for how personal development, self-awareness, and community-building can become strategic levers for systemic educational reform.

By intentionally shifting the focus from technical knowledge and curriculum delivery to the inner development of educators, the program enabled participants to reflect on their identities, set personal boundaries, and reconnect with their purpose. These individual shifts created the conditions for deeper engagement with curriculum transformation, not as a top-down directive, but as a personally meaningful and contextually grounded process. The resulting mindset shifts, increased sense of belonging, and strengthened professional agency point to the value of approaching faculty development as both a relational and reflective practice.

At the same time, the findings highlight the systemic tensions within higher education—particularly the lack of institutional space, time, and recognition for faculty well-being and reflective engagement. For faculty development to have a lasting impact, institutions must go beyond supporting curriculum design and begin to prioritize the inner capacities and lived experiences of academic staff. The Inner Development Goals (IDGs) offer a helpful lens for framing these capacities—such as self-awareness, connection, and purposeful action—as central to the future of higher education.

Ultimately, the Change Makers program demonstrates that educators who are supported as whole people—grounded, connected, and clear—are far more likely to become effective agents of curriculum innovation and institutional transformation. As South African engineering education continues to evolve in response to global and local challenges, the integration of personal and systemic development will be critical for sustaining change. Faculty development initiatives that honour this complexity, and that begin

with individual transformation, will be essential for cultivating the kind of resilient, adaptable, and human-centered educational systems our future demands.

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Bridging Gaps in Engineering Teamwork: A Literature Review through the Lens of Cultural-Historical Activity Theory (CHAT)

Ranthekeng Jones Moloisane
Tshwane University of Technology, South Africa, moloisanerj@tut.ac.za

Nicky Wolmarans
University of Cape Town, South Africa, nicky.wolmarans@uct.ac.za

Abstract

Teamwork is a core competency in engineering education, yet persistent challenges remain in cultivating collaboration that prepares graduates for professional practice. This study reports a systematic literature review (SLR) of 22 peer-reviewed studies (2010–2024) examining how Cultural-Historical Activity Theory (CHAT) can be applied to understand and strengthen teamwork development in engineering programmes. Guided by PRISMA 2020 procedures, the review identifies recurrent contradictions between intended learning outcomes and prevailing educational practices, particularly regarding assessment design, role distribution, and inclusivity. Five thematic clusters emerged: assessment misalignment, role clarity and flexibility, technology as mediator, diversity and inclusion, and instructor facilitation, each mapped to CHAT components to illustrate systemic influences on teamwork learning. The synthesis highlights that while project-based and blended learning environments show promise, contradictions persist when institutional rules and assessment reward individual performance over collective achievement. The findings contribute to a clearer picture of how CHAT can structure evidence-based interventions to align curriculum, pedagogy, and assessment with teamwork objectives. The paper concludes by outlining practical implications for curriculum redesign, faculty development, and equitable assessment reform, positioning CHAT as a valuable framework for building teamwork competence in engineering education.

Keywords: Teamwork Competencies, Engineering Education, Cultural-Historical Activity Theory, Collaborative Learning, Curriculum Design

1 Introduction

Teamwork has become an indispensable competency in engineering education, reflecting the increasing demand for graduates who can operate effectively in interdisciplinary and multicultural professional environments (Sekhar et al., 2023; Kropp, 2024; Hutson et al., 2025). While industry stakeholders consistently highlight collaboration as essential for solving complex problems (Case School of Engineering, 2023), higher education institutions continue to struggle with designing and assessing learning experiences that intentionally cultivate teamwork skills (Goldsmith et al., 2024; Burgess et al., 2023).

Research indicates that engineering students often face challenges in team settings, including communication barriers, unequal participation, and cultural or gendered differences that undermine group effectiveness (Belanger et al., 2022; Zhang et al., 2024). Post-pandemic transitions to hybrid and online learning environments have further complicated these dynamics, requiring new strategies to integrate technology, equity, and flexibility into collaborative learning (Okoye Ifeanyi, 2023; Burr, 2025; Darby, 2025). Addressing these challenges requires more than ad-hoc adjustments; it calls for a systemic lens that connects individual behaviours, community norms, institutional rules, and cultural contexts.

Cultural-Historical Activity Theory (CHAT), as advanced by Engeström (1987), provides such a lens by conceptualising learning as a mediated activity shaped by tools, rules, division of labour, and community engagement. CHAT foregrounds systemic contradictions, such as when assessment practices reward individual achievement while curricula promote teamwork, which are particularly relevant to engineering education (Mentz & de Beer, 2021; Núñez, 2021).

This study applies CHAT to a systematic literature review (SLR) of 22 empirical studies on teamwork in engineering education. The objectives are threefold: (a) to synthesise how teamwork has been

conceptualised and studied in engineering education, (b) to map emergent findings onto CHAT components to reveal systemic enablers and tensions, and (c) to identify pedagogical strategies for more inclusive and effective teamwork instruction. By distinguishing between theoretical framing and empirical synthesis, the paper contributes a clearer account of teamwork challenges and provides evidence-based recommendations for curriculum and assessment design.

2 Literature Review

Teamwork has long been recognised as a central outcome of engineering education, with accreditation bodies such as ABET and the Washington Accord emphasising collaborative competence as a key graduate attribute (International Engineering Alliance, 2021; ABET, 2023). Despite this recognition, systematic evidence indicates that teamwork is often treated as an implicit by-product of project-based learning (PBL) rather than as an intentionally designed and assessed outcome (Burgess et al., 2023; Goldsmith et al., 2024).

2.1 Teamwork in Engineering Education

Studies consistently highlight the gap between the importance of teamwork in professional practice and the limited strategies available to foster it in curricula (Sekhar et al., 2023; Kropp, 2024). Engineering students frequently report challenges related to role ambiguity, uneven workload distribution, and interpersonal conflict (Belanger et al., 2022). While collaborative projects provide opportunities to engage in authentic teamwork, without explicit scaffolding, students often reproduce inequitable participation patterns (Oberprieler, 2019; Garcia & Treude, 2025).

2.2 Assessment and Institutional Practices

A recurring barrier lies in assessment practices. Traditional grading schemes frequently privilege individual performance, creating contradictions between what is taught (teamwork as a goal) and what is rewarded (individual output). Such misalignments reduce motivation for collaboration and can exacerbate tensions among students (Karlovsek & Ruiz, 2020; Ryan & Deci, 2020). Alternative approaches, such as peer assessment or group contracts, have been explored, yet their implementation remains inconsistent across institutions (Okoye Ifeanyi, 2023).

2.3 Technology and Teamwork in Contemporary Contexts

The increasing use of digital platforms has reshaped collaborative practices, particularly in hybrid and online learning contexts. Tools such as learning management systems, shared documents, and communication platforms have the potential to strengthen teamwork, but studies show that unequal access and variable digital literacy often create new challenges (Lo & Hew, 2019; Divis et al., 2022). These findings underscore the importance of examining how technology mediates collaboration rather than assuming it will inherently improve outcomes.

2.4 Equity, Diversity and Inclusion

Issues of equity and inclusion also shape teamwork in engineering education. Research demonstrates that gender, cultural background, and language proficiency significantly influence participation and leadership within teams (Zhang et al., 2024; Garcia & Treude, 2025). Without deliberate facilitation, these dynamics risk

reproducing systemic inequities rather than promoting inclusive collaboration (Koh et al., 2016; Marra et al., 2016).

2.5 Gaps in the Literature

Although the literature provides valuable insights into barriers and opportunities for teamwork instruction, most studies approach the issue in a fragmented way, focusing on isolated interventions or single institutional contexts. Few reviews have systematically synthesised this body of work, and even fewer have analysed teamwork development through a systemic theoretical framework capable of explaining underlying contradictions across contexts. This gap highlights the need for an integrative approach that can both synthesise existing evidence and guide practical strategies for curriculum and assessment reform.

3 Theoretical and Conceptual Framework

3.1 Cultural-Historical Activity Theory (CHAT)

Cultural-Historical Activity Theory (CHAT) provides a systemic perspective for examining human activity, highlighting how individual actions are shaped by tools, rules, community expectations, and the division of labour (Engeström, 1987; Vygotsky, 1978). Building on socio-cultural traditions, CHAT conceptualises learning as the outcome of dynamic interactions within activity systems rather than as an isolated cognitive process (Cole & Engeström, 1993).

3.2 Key Constructs

An activity system in CHAT consists of six interacting components: subject, object, mediating tools, rules, community, and division of labour, all of which collectively shape the activity outcome. Contradictions within or between these components are viewed not as failures but as opportunities for transformation and learning (Engeström, 2001). For example, tensions between assessment rules that privilege individual performance and teamwork-focused curricular goals can reveal structural misalignments that undermine collaboration.

3.3 CHAT and Teamwork in Engineering Education

In the context of engineering education, CHAT has been increasingly recognised as a useful framework for unpacking the systemic nature of teamwork development (Mentz & de Beer, 2021; Núñez, 2021). By situating teamwork as an activity system, CHAT allows researchers and educators to identify where contradictions emerge, whether in role distribution, assessment practices, or access to collaborative technologies and how these tensions shape students' learning experiences.

3.4 Conceptual Framework for this Study

This paper adopts CHAT as the guiding framework for analysing and synthesising findings from 22 studies of teamwork in engineering education. Figure 1 illustrates the conceptual model, mapping teamwork competencies against CHAT components to highlight how systemic elements interact in shaping teamwork preparedness. The framework was used to guide data coding and synthesis in the systematic review.

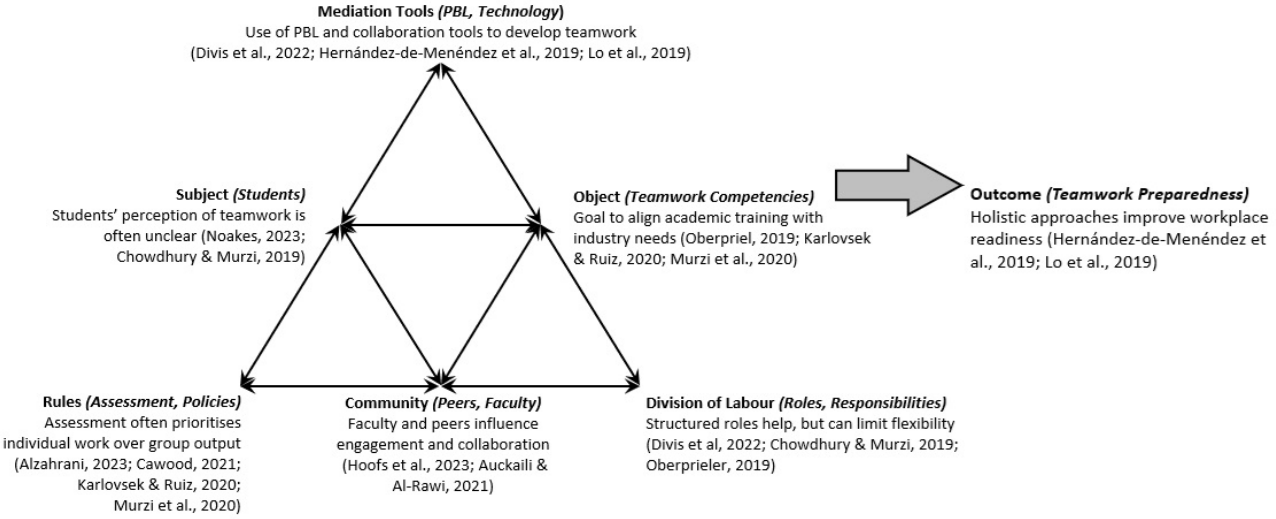

Figure 1: CHAT model applied to teamwork competencies (Adapted from Engeström, 1987 and Cole & Engeström, 1993, with application to teamwork in engineering education)

It is essential to note that Figure 1 illustrates the conceptual framework of this study. The empirical findings derived from the systematic review are presented separately in Section 5. This distinction ensures that theoretical grounding and evidence synthesis remain clearly delineated, thereby addressing common challenges in literature reviews where conceptual and empirical elements overlap.

4 Methodology

4.1 Research Design

This study employed a systematic literature review (SLR) to synthesise evidence on how teamwork is intentionally taught and assessed in engineering education. The review was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework, ensuring transparency in search, screening, and synthesis procedures (Page et al., 2021). CHAT served as the analytical lens for coding and interpretation, but was applied only after eligible studies were identified.

4.2 Search Strategy

Electronic databases, including Scopus, Web of Science, ERIC, and IEEE Xplore, were searched for peer-reviewed publications between 2010 and 2024. Search strings combined keywords such as teamwork, engineering education, project-based learning, and Cultural-Historical Activity Theory. The reference lists of selected articles were also screened to identify additional relevant studies.

4.3 Inclusion and Exclusion Criteria

Studies were included if they:

- Focused on teamwork or collaborative learning in higher engineering education,
- Reported empirical findings, and
- Addressed learning design, pedagogy, or assessment.

Studies were excluded if they:

- Did not focus on engineering education,
- Lacked a connection to teamwork or collaborative competence, or
- Provided only a conceptual discussion without empirical evidence.

4.4 Screening Process

The initial search identified 88 records. After removing eight duplicates, 80 records remained for abstract and title screening. Forty-two were excluded for not meeting the inclusion criteria. Full texts of 38 studies were then assessed for eligibility, resulting in the exclusion of 16 papers: five that were not related to engineering education, five that lacked any CHAT relevance, and six that had insufficient empirical data. This process yielded a final corpus of 22 studies. The screening process is summarised in Figure 2.

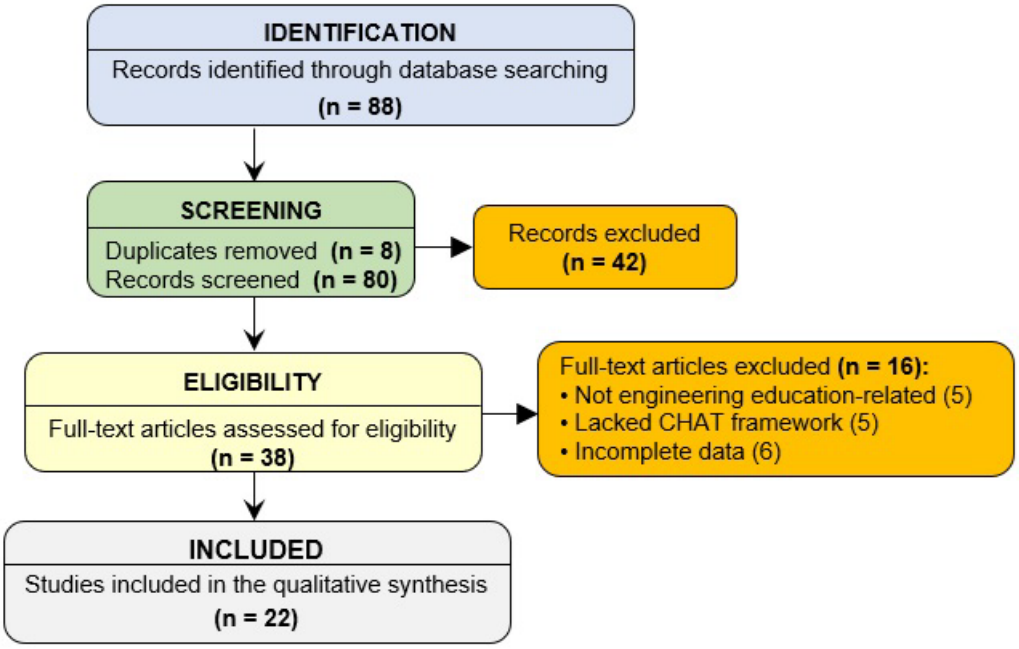

Figure 2: PRISMA 2020 flow diagram of study selection (Adapted from Page et al., 2021)

4.5 Data Extraction and Analysis

Data were extracted systematically using a coding matrix that captured publication details, research design, context, teamwork interventions, and outcomes. CHAT components, subject, object, mediating tools, rules, community, and division of labour were used to guide thematic coding. Two researchers independently reviewed each study, and discrepancies in coding were resolved through discussion until consensus was reached.

4.6 Synthesis Approach

The analysis proceeded in two stages. First, descriptive mapping provided an overview of study characteristics. Second, thematic synthesis clustered findings across studies into recurring patterns aligned with CHAT components. This approach enabled both an empirical account of teamwork practices and a theoretically informed interpretation of systemic tensions. The results of this synthesis are presented in Section 5.

5 Results and Discussion

This section presents the findings of the systematic review of 22 studies on teamwork in engineering education, organised into five thematic clusters. The analysis was guided by CHAT, which provided a lens for identifying how systemic elements, rules, tools, division of labour, community, and subject-object relations shaped teamwork practices. The aim is to demonstrate not only what the studies reported but also how their findings collectively reveal systemic contradictions and opportunities for improving teamwork instruction.

5.1 Overview of the Corpus

The 22 studies spanned a range of geographical contexts, including North America, Europe, Asia, and Africa, and covered both undergraduate and postgraduate levels. Research designs included case studies, surveys, quasi-experiments, and mixed-method approaches. Most studies were situated in project-based or problem-based learning environments, reflecting the dominant pedagogical strategy for embedding teamwork in engineering curricula.

5.2 Thematic Synthesis

Across the corpus, five major themes emerged: assessment misalignment, role clarity and flexibility, technology as mediator, diversity and inclusion, and instructor facilitation. These themes are summarised in Table 1, which maps them to CHAT components and illustrates their systemic significance.

Table 1: Synthesis of 22 studies mapping teamwork to themes to CHAT components (Developed by the authors, based on thematic synthesis of the 22 included studies)

Theme (from 22 studies)	CHAT Component(s)	Key Findings	Example Studies
Assessment misalignment	Rules, Object	Individual-focused grading discouraged collaboration and created tensions.	Ryan & Deci (2020); Karlovsek & Ruiz (2020)
Role clarity and flexibility	Division of Labour, Community	Structured roles supported teamwork but often limited adaptability and innovation.	Chowdhury & Murzi (2019); Oberprieler (2019)
Technology as mediator	Tools	Collaboration platforms enhanced communication, though unequal access remained a barrier.	Lo & Hew, 2019; Divis et al. (2022)

Theme (from 22 studies)	CHAT Component(s)	Key Findings	Example Studies
Diversity & inclusion	Subject, Community	Gender and cultural differences significantly shaped patterns of engagement.	Zhang et al. (2024); Garcia & Treude (2025)
Instructor facilitation	Rules, Community	Faculty scaffolding was critical for sustained teamwork skill development.	Koh et al. (2016); Marra et al. (2016)

5.3 Theme 1: Assessment Misalignment

A recurring contradiction concerned assessment practices that emphasised individual achievement, while teamwork was presented as a core outcome. Studies have reported that when grades are primarily allocated based on individual contributions, students are less motivated to engage meaningfully in teamwork (Karlovsek & Ruiz, 2020; Ryan & Deci, 2020). Within CHAT, this tension reflects misalignment between the rules (grading criteria) and the objective (teamwork development). Addressing this contradiction requires assessment systems that reward both individual accountability and collective performance.

5.4 Theme 2: Role Clarity and Flexibility

Several studies emphasised the importance of clearly defined roles in supporting effective teamwork (Chowdhury & Murzi, 2019; Oberprieler, 2019). Structured role allocation helped distribute workload and supported accountability. However, rigid roles sometimes constrain adaptability and creativity, leading to frustration among students. In CHAT terms, this tension lies within the division of labour and its interaction with the community. Effective teamwork pedagogy must therefore balance structured role clarity with opportunities for role negotiation and rotation.

5.5 Theme 3: Technology as Mediator

The increasing integration of digital tools was found to mediate teamwork in both positive and problematic ways. On one hand, platforms such as shared documents, virtual workspaces, and messaging systems enhanced communication and coordination (Lo & Hew, 2019; Divis et al., 2022). On the other hand, unequal access to technology and varying levels of digital competence created new forms of exclusion. From a CHAT perspective, this highlights the mediating role of tools, which both enable and constrain teamwork depending on their accessibility and integration into learning design.

5.6 Theme 4: Diversity and Inclusion

Team composition significantly shaped teamwork experiences, particularly regarding gender and cultural diversity. Studies reported that while diverse teams brought richer perspectives, they also faced challenges such as unequal participation and implicit bias (Zhang et al., 2024; Garcia & Treude, 2025). These dynamics are situated within the subject and community components of CHAT, illustrating how social identities influence interaction within activity systems. Inclusive teamwork instruction requires proactive facilitation to ensure equitable participation and recognition of contributions.

5.7 Theme 5: Instruction Facilitator

Finally, instructor involvement emerged as a critical factor in sustaining teamwork development. Faculty who actively scaffolded teamwork processes through feedback, coaching, or structured reflection helped students develop collaboration skills more effectively (Koh et al., 2016; Marra et al., 2016). In CHAT terms, instructors act as part of the community while also shaping the rules that govern interaction. Effective facilitation transforms contradictions into learning opportunities, reinforcing the value of teamwork as a central educational outcome.

5.8 Discussion of Findings

Taken together, these themes underscore the systemic nature of teamwork instruction. CHAT proved useful in highlighting contradictions, such as the gap between teamwork goals and assessment rules, which recur across diverse contexts. Unlike prior narrative reviews, this synthesis contributes a structured mapping of teamwork practices to CHAT components, offering a clearer account of where interventions are most needed.

The findings suggest that engineering programmes must adopt integrated strategies: aligning assessment with teamwork objectives, balancing role clarity with flexibility, ensuring equitable access to digital tools, addressing diversity proactively, and strengthening faculty capacity for facilitation. By making these systemic contradictions explicit, the review provides a foundation for evidence-based curriculum redesign that foregrounds teamwork as both a learning process and an assessable outcome.

6 Implications

The synthesis of 22 studies through the lens of CHAT provides a structured understanding of teamwork in engineering education that extends beyond fragmented findings in individual studies. By highlighting recurring contradictions between curricular intentions and institutional practices, the review identifies targeted opportunities for both educators and researchers.

6.1 Implications for Practice

For practitioners, the findings emphasise the importance of aligning curricular design, pedagogy, and assessment to create coherent support for teamwork development. Specifically:

- Assessment reform is essential. Group assessments should strike a balance between individual accountability and recognition of collective achievement to avoid undermining collaboration (Karlovsek & Ruiz, 2020; Ryan & Deci, 2020).
- Role scaffolding should be intentionally designed. Structured role allocation can help distribute responsibilities, but it should also allow for flexibility in negotiation and adaptation (Chowdhury & Murzi, 2019).
- Inclusive facilitation is critical. Instructors must proactively address equity issues to ensure that diverse student populations are supported, particularly in multicultural and multilingual contexts (Zhang et al., 2024).
- Technology integration must be strategic. Digital platforms should be accompanied by guidance and equitable access measures to prevent new forms of exclusion (Divis et al., 2022).

6.2 Implications for Research

For researchers, the review highlights the potential of CHAT as both an analytical and design tool. Future studies should:

- Move beyond descriptive accounts by systematically examining contradictions in teamwork pedagogy across contexts.
- Investigate assessment innovations that operationalise teamwork learning outcomes without defaulting to individualised grading.
- Explore equity and inclusion more explicitly, examining how systemic factors shape diverse students' teamwork experiences.
- Develop longitudinal studies to track how teamwork competencies evolve across curricula and into professional practice.
- Together, these implications underscore the value of CHAT not only as a theoretical lens but also as a practical framework for guiding evidence-informed interventions.

7 Conclusion

This study synthesised 22 empirical investigations of teamwork in engineering education through the lens of Cultural-Historical Activity Theory (CHAT). The analysis identified five recurrent themes: assessment misalignment, role clarity and flexibility, technology as mediator, diversity and inclusion, and instructor facilitation, each mapped to CHAT components to reveal systemic enablers and tensions.

Unlike prior narrative accounts of teamwork pedagogy, this review offers a structured, theory-informed synthesis that makes visible the contradictions undermining teamwork development. By distinguishing clearly between conceptual framing and empirical findings, the paper contributes both methodological clarity and substantive insights.

The key contribution of this study lies in demonstrating how CHAT can structure evidence across contexts to highlight leverage points for change in engineering curricula. In particular, it shows that contradictions far from being obstacles can serve as opportunities for designing more intentional teamwork instruction. The findings have direct implications for aligning assessment, supporting inclusive practices, and strengthening faculty facilitation, while also pointing to new directions for systematic research.

By reframing teamwork as a systemic activity rather than an isolated skill, this study advances understanding of how engineering education can more effectively prepare graduates for collaborative professional practice.

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The First Year Experience: Engineering for Social Change

Naasirah Mohamed, Luvuyo Kakaza, Bronwyn Swartz, Ayesha Reiners, Suresh Ramsuroop
MohamedN@cput.ac.za; KakazaL@cput.ac.za; SwartzB@cput.ac.za; ReinersA@cput.ac.za; RamsuroopS@cput.ac.za

Cape Peninsula University of Technology, South Africa

Abstract

The first-year transition period is a crucial phase in a student's university experience as it can significantly impact their academic performance and future career prospects. However, research indicates that approximately 30% of first-year students drop out due to academic expectations and newfound independence. In response to this concern, a Faculty of Engineering at a South African University of Technology has implemented a tailored First-Year Experience (FYE) programme to support students. This reflective paper examines a tailored First-Year Experience (FYE) programme implemented to support students' transition into university. The FYE programme is informed by Kolb's Experiential Learning Cycle (ELC).

Based on reflections from the four core team members and their unique perspectives from the various roles they bring with them to the FYE programme, the paper seeks to offer an in-depth practice based account and insights into the learning environment of the first-year student by reflecting on the programme's development and impact using the four phases of the ELC framework. The 'Concrete Experience' phase discusses the experimentation with technological platforms and software tools to facilitate the programme, highlighting insights, challenges, and student engagement. In the 'Reflective Observation' phase, student involvement is analysed, emphasising the importance of fostering student ownership of the programme. The 'Abstract Conceptualisation' phase identifies areas for programme improvement, including addressing social concerns specific to the university and it proposes developing a credit-bearing compulsory subject called "Engineering for Social Change." The 'Active Experimentation' phase provides insights into best practices for supporting first-year students' successful transition and engagement in engineering education.

Keywords: First Year Experience; Kolb's ELC; Student support

1 Introduction

The first year of university poses several challenges for students, especially those in technical fields like engineering. Universities worldwide, including the Cape Peninsula University of Technology (CPUT) in South Africa, are concerned about the high number of first-year students dropping out. To address this issue, the university's Faculty of Engineering has launched a customised First-Year Experience (FYE) programme to help students transition to university life.

In this paper, a group of lecturers who developed the FYE programme share their reflections. They drew inspiration from Kolb's (1984) Experiential Learning Cycle and described how they used its four phases to assess the programme's development and impact. The authors experimented with various technological platforms and software tools to facilitate the programme and measure student engagement to gauge the overall effectiveness of the programme. They also reflect on critical areas of improvement, such as addressing context-specific social concerns and food insecurity among first-year students.

Although this study is based on reflections from only four core team members, their roles as coordinators and designers of the Faculty's FYE programme afford them unique, embedded perspectives. The aim is not to generalise but to offer an in-depth, practice-based understanding of how the FYE programme evolved to meet the complex challenges of first-year transition. Drawing on collaborative autoethnography and Kolb's Experiential Learning Cycle, these reflections surface insights that are both context-specific and broadly relevant for informing more supportive learning environments in engineering education. Although we do not

claim to measure impact definitively, the study highlights critical adaptations and lessons that can guide similar interventions elsewhere.

This study highlights the importance of targeted FYE programmes and provides insights into best practices for supporting students' successful transition and engagement in engineering education. The authors' reflections will inform the future development of the FYE programme, which they propose calling "Engineering for Social Change." They suggest making it a credit-bearing compulsory subject for all first-year students. This paper provides useful insights for educational institutions looking to create effective FYE programmes that support students' academic success and well-being.

2 Conceptual framework

This study applies Kolb's (1984) Experiential Learning Cycle as a framework to analyse the researchers' reflections on the programme's development and impact. The framework consists of four phases: concrete experience, reflective observation, abstract conceptualization, and active experimentation. These phases will be discussed in the literature review and findings and discussion sections of the paper. The framework highlights specific practices for both lecturers and students within each phase. It is important to note that the steps can be entered at any point in the cycle but must follow the sequential order.

Furthermore, there are four learning styles: divergers, assimilators, convergers, and accommodators. It is essential to consider both the phases of the cycle and the learning styles together, as the learning styles can describe how students learn within the phases. This information is significant because the authors' reflections can provide reflective data on the learning processes in Kolb's cycle. The authors have considered the students when constructing the content, and they themselves have acted as learners or students while learning to create content in a specific way using technology.

3 Literature Review

The approach to learning designed by Kolb consists of three components which include the theory of experiential learning, the learning cycle model, and learning styles (Bergsteiner, Avery and Neumann, 2010:29). The experiential theory is described by Healy and Jenkins (2000:185; Fenwick, 2001) to structure a course or session by using a learning cycle, and where they further emphasise that Kolb's theory shows ways in which to do so through a learning process through knowledge and experience.

As an alternative to traditional classroom approaches, several authors (Healey and Jenkins 2000; Holman, Pavlica and Thorpe 1997; Bergsteiner et al., 2010: 29) relate that Kolb’s experiential learning theory is a good approach as a learning cycle, as it allows students to develop themselves and change their personal method of learning. The approach allows for learning, as a holistic process, to be a cognitive process which includes engagement and adaption, and where students can create knowledge through experience (Bergsteiner et al., 2010: 30). In this way individuals can make their own decisions around engagement and learning (Kolb and Kolb, 2009).

The learning cycle model, seen in Figure 1 below, shows four phases of the cycle: concrete experience, reflective observation, abstract conceptualisation, and active experimentation. The individual can enter the cycle at any time, but they will have to follow into the next phase in the cycle (Healy and Jenkins, 2000:186).

Concrete experience refers to the place where learning is taking place, for example, the lecturers discussed content topics and brainstormed in a meeting as to how content will be delivered. Reflective observation is the second phase where the individuals reflect, analyse, and observe their experience from the first phase. In abstract conceptualization phase the participant attempt to make sense of their experience by developing concepts, theories, or generalizations, and then look for any patterns and connections between their experiences and their knowledge. In the last phase, active experimentation, the participant uses the concepts and theories developed in the third phase to form innovative ideas and actively experiment with different approaches.

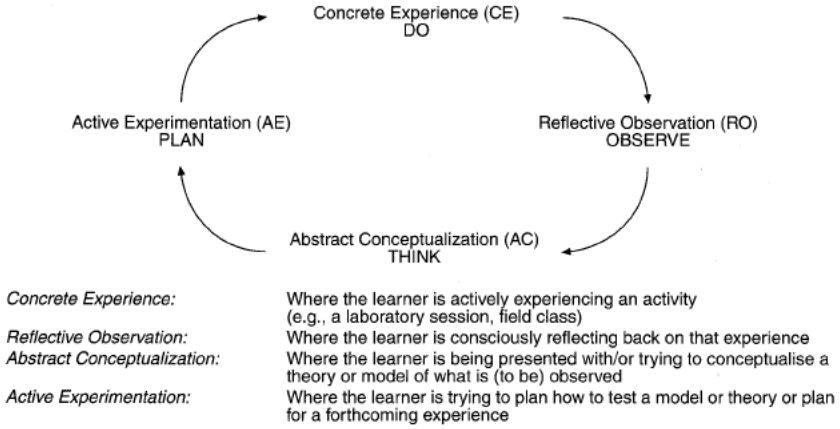

Figure 1: Kolb's Experiential Learning Cycle (based on [Jenkins, 1998:43])

Each of the phases in his framework has activities associated with them (Bergsteiner et al., 2010: 33). For example, concrete experience looks at a person's direct experience (including in-class experience), simulations and lecture examples. Reflective observation includes discussion and brainstorming. Abstract conceptualisation has activities such as project proposals, text reading and lecture descriptions, and lastly active experimentation includes fieldwork, homework, case studies, and simulations (Bergsteiner et al., 2010:36).

Kolb's work in management education was the basis for his work on learning styles and his learning model (Bergsteiner et al., 2010: 30). He suggested that students learn in particular ways and develop a preference over time (Kolb, 1984). The four learning styles he outlined are divergers, assimilators, convergers, and accommodators (Healy and Jenkins, 2000:187). Divergers perceivet a situation by considering numerous perspectives and rely mostly on brainstorming ideas. Assimilators use reasoning and can develop theoretical models of the information they are working with. Hypothetical thinking is used by those that are convergers, and lastly, accommodators are that can plan, carry out, and adapt to their situations (Healy and Jenkins, 2000:187). Each person uses their preferred learning style among these, including teachers, as they reflect and shape their teaching according to their learning style (Healy and Jenkins, 2000:189-190). This could lead to a mismatch with the students' learning style, which could affect the students learning (Fielding, 1994). Therefore, Kolb emphasizes that the teacher should use a mixture of various teaching methods to accommodate the styles of learning in the classroom (Healy and Jenkins, 2000:186). To accomplish this, FYE used the digital platforms to provide students with a range of learning material to support the learning styles of students and broaden that of the teachers who created the content.

4 Research Design

This study adopted a constructivist and interpretivist methodological approach. Cresswell and Clark (2018) argue that these philosophical frameworks emphasize the subjective and socially constructed nature of knowledge. Constructivism posits that individuals actively build their own understanding of the world through interactions and personal experience of their environment. Concomitantly, interpretivism underscores the significance of interpretation in comprehending human behaviour and social phenomena. Interpretivism contends that there is no objective reality outside the social and cultural contexts in which it is constructed. Thus, individuals create meaning through their experiences and interpretations of the world. The combination of these two perspectives forms the philosophical foundation of this study, emphasizing the importance of understanding individuals' perceptions and interpretations of their experiences to gain deeper insights into social phenomena.

Based on the views of Roy and Uekusa (2020), the strategy adopted to perform data collection and analysis is a collaborative autoethnography (CAE). Roy and Uekusa (2020) explain that CAE integrates the principles of autoethnography, where the researcher reflects on their individual experiences, with collaborative research, involving joint data collection and analysis with others. In this study, multiple collaborators engaged in reflection on our individual experiences, contributing to a collective narrative that delved into a shared topic or issue.

4.1 Participant Autoethnographers

The reflective data presented in this study was generated by four core members of the Faculty of Engineering's FYE programme team. These include three faculty-level coordinators responsible for Language, Learning and Teaching, and Student Engagement, as well as one departmental coordinator for Learning and Teaching based in the Department of Electrical, Electronic and Computer Engineering. All four team members contributed to the collaborative development and implementation of the FYE programme, and data was collected from each of them to inform the collaborative autoethnographic reflections discussed in this paper.

4.2 Data Collection Instrument

Kolb's (1984) Experiential Learning Theory served as the underpinning theoretical framework for the development of reflective questions in the data collection instrument of this study. These questions were crafted to prompt individual academics' reflections. Drawing on the work of Kolb (1984), three prompting questions were developed for each aspect of the framework, namely (1) Concrete Experience, (2) Reflective Observation, (3) Abstract Conceptualization and (4) Active Experimentation. The prompting questions can be seen in Table 1.

Table 1: Three prompting questions for each aspect

Concrete Experience	What were the specific tasks and activities involved in developing the FYE programme? How did you collaborate with your colleagues during the programme development process? What were the challenges and obstacles you encountered while working on the programme?

Reflective Observation	How did the use of different technologies (MS Teams, MS Excel, Blackboard Collaborate, H5P interactive software, LinkedIn Learn) impact programme development? What feedback or responses did you receive from colleagues or students during the development phase? How did your experiences during the development process influence your thoughts and perceptions?
Abstract Conceptualization	What were the key themes and patterns that emerged from your experiences and observations? How did the FYE programme align with the specific needs of first-year students in your faculty? In what ways did you envision the programme contributing to broader social impact and student success?
Active Experimentation	What lessons did you learn from developing the FYE programme, and how do you plan to apply them in the future? How will your experiences inform future programme enhancements or other educational initiatives? Describe your vision for the future development of the FYE programme, including its potential impact on student success and well-being.

4.3 Data Analysis

By engaging with the prompting questions in Table 1, we drew on our direct experiences and undertook a process of critical self-examination. We performed the initial thematic analyses of the dataset as individuals. The initial individual analysis enhanced the study's veracity by mitigating potential bias. Following this, we had group discussions to converge our findings collaboratively. Simultaneously, determinations were made regarding the inclusion or omission of specific themes and codes. A consensus-driven approach underscored the collaborative nature of code clustering and theme development in our study.

5 Findings and Discussion

This section presents the findings and discussion from the themes that emerged from the analysis in the four phases of Kolb's framework of the lecturer reflections.

5.1 Concrete Experience

There were various tasks and activities involved in the development of the FYE programme and during the development, the reflectors indicated that there was huge emphasis placed on conceptualising what the programme would look like. This became evident when respondent 1 indicated that "I was quite involved in drawing up possible timelines, following order of topics." This was later corroborated by respondent 3 who stated that "tasks involved in developing the FYE programme ranged from identifying the correct placement of the programme". R4 was supported by R1 and R3 when indicating that the planning of topics was a key component in developing the programme. R4 also stated that "To deploy the lessons, we needed to plan topics and then decide how to present each topic"

As the tasks grew, the programme called for collaboration with colleagues during the development process. Based on the responses received, it is evident that no roles were allocated. Collaborators on the project

performed any role they were confident in and contributed towards the success of the programme. R1 stated that “I was one of the core developers and also assisted those that were developing content material for the programme.” The collaboration between the developers was cited as supportive, inspirational, and constructive. R4 indicated that “I found the whole experience interacting with the core team was supportive and constructive.” R4 also reflected on her joining the project by stating that “I did not yet feel like I was part of the project. I Could not see my value.” After that, R4 also went on to say “However, seeing what they were doing - when it came to my turn to do something - I was inspired”

However, the programme was not without challenges and obstacles. Based on the responses provided, it became evident that departmental buy-in was a challenge in some cases. Not all departments had bought into the project at the planning and implementation stage. R2 stated that “I had to spend lots of time motivating people to support the project”. This was also evident from the response from R4 who stated that “We had to include people from all departments, but it was clear that not everyone “bought into” the programme.” This was supported by R3 who indicated that “Some departments continued to engage students in academic activities during the time set for developmental programmes outside of the classroom.”

Based on Kolb’s (1984) Experiential Learning Cycle, the reflectors underwent a first-time experience through the implementation of this programme. It is evident in the reflection that at this stage of the cycle, neither of the reflectors was certain of the outcome nor the learning to be taken from this programme. However, as the stages progress, a certain level of cognitive understanding was to be expected as revealed by Kolb (1984).

5.2 Reflective Observation

To implement the programme, we experimented with and used various technologies including MS Teams, MS Excel, Blackboard Collaborate, H5P interactive software, and LinkedIn Learning. Using these positively impacted the programme development. This became evident in the reflection by R1 who indicated that “As the team had had some online sessions that were not pre-recorded, it became easier to use MS Teams to hold the session as it allowed for more control with access for the students and the relevant presenters”. This control became crucial after the first session was derailed by students as stated by R1.

Pre-recorded sessions were also made possible with the use of technology. R1 stated that “I would use Zoom Meetings to do a video and audio recording as I found it was a simpler option to use to create a recording for free and at a fraction of the file size.” As can be seen from the response from R1, technology allowed the programme to be developed at a cost-effective rate due to the compressed size of pre-recorded. R3 supported this indicating that “The use of virtual platforms to deliver content meant that students could attend the programme from wherever they are,” meaning that they would not incur any travel costs solely to come and attend the sessions. R4 indicated that “We could not have presented the programme without technology (the Learner Management System (LMS) - Blackboard and then MS Teams) because of the size of the class (the number of first years in the faculty). It would have been impossible to put them all in one physical venue.

Some of the feedback that was received from colleagues and students during the development phase which was indicated, and reiterated in the reflection, centred around the volume of work. R1 indicated that “there were some issues in terms of the volume of work students or items students were expected to go through in one afternoon”.

The experiences during the development process also influenced the thoughts and perceptions of the team. The responses provided indicated the realisation that a programme of this nature could not be successfully implemented as individuals due to the wideness of their reach. This was evident in R4's response where they indicated how intimidating the project came across at first because of its magnitude. R4 stated that "During the development, I realised the importance of the work – developing this programme as in – it was for all the first years. Not just my small class in one department. It was for all the first years across that faculty." R3 also reflects on the intimidating nature of the programme due to its size by stating that "During this phase, it became very clear that a project of this magnitude, no matter how important it is for the development of students; it would not be possible without the buy-in of every stakeholder."

R4 reflects on the project after implementation and teamwork by stating that "On the whole though, after the delivery of the programme, my work and everyone else's combined I feel pretty darn proud of us." Based on R4 responses, it is evident that the teamwork and partnership from the core team of the programme led to the successful implementation of the initiative. R1 supports R4 on the positive experience gained from the collaboration by stating that "It was overall a great experience as I was able to learn from my colleagues about their technological use, their thought processes and provide input from my thoughts as well." R1 also goes on to say, "It became an innovative space that broadened my thinking and allowed me to consider situations in advance."

As can be seen from the findings, the core team reflected on each session that passes to improve on the next session. R1 stated earlier in the findings that a session was derailed by students due to the students having equal rights on the online delivery platform as the presenters. This allowed them to unmute themselves at any point, not allowing the presenter to continue without disrupting them. This became more of a joke for the class as others would then unmute themselves to laugh at the joke.

Upon reflecting on this, we realised that this was the students' first online session of this nature, where all engineering students were in the same virtual class. With many of them attending an online session for the first time.

Kolb (1984) alludes to the notion that these reflections taking place in the reflective observation phase are the ones that form the basis for learning and improvement in the reflectors' understanding of a situation. For this project, the various changes that took place to improve the development and delivery of the programme were all determined during this phase after each session was held.

5.3 Abstract Conceptualisation

Several key themes and patterns emerged in the programme, R4 reflected on the uncertainty fuelled by a determination to succeed. This brought about the remerging of a concept presented at a conference referring to the experience as "building a plane while flying it". R4 also indicated a sense of "pride and closeness" that developed among the core team of coordinators. This is supported by R3 who states that "having been tasked with student development in the faculty, certain projects were not successful because of the lack of deliberate collaboration and partnerships with colleagues who had the necessary passion and reach to garner support for similar student development projects."

The programme aligned with some specific needs of the first-year students as R1 stated that “The themes focused on more humanistic elements that were quite noticeably missing in the student's development or socialization into the tertiary education space.” This was supported by R3 who stated that “first-year students in the engineering faculty are expected to be experts in mathematics and science; if they can master the scientific part of their studies, they will be regarded as good students” R3 and R1 both advocate for the wholistic development of the students for them to understand the diversity of the environment they are in.

As stated in the literature reviews, Kolb (1984) states that abstract Conceptualization is the phase where the participant attempts to make sense of their experience by developing concepts, theories, or generalizations. During this phase, the reflector started developing theories and generalisations not initially realised as pertinent within the faculty. These theories and generalisations emerged due to the unpredicted environmental changes that took place on campus; realising that students are less equipped to deal with various elements such as peer pressure, stress, on-campus protests, and decision-making skills among others; leading to actions of violence that have become one of the biggest concerns of the institution.

The programme, therefore, envisioned contributing to this broader social concern among others and student success. All respondents reflecting on the programme indicated the need to develop a module to address the socialisation of first-year students in the higher education space. This was seen from statements including that of R1, who stated that “I envisioned that the programme would assist the students in the process of socialization into the university space and introduce them to issues they might not have taken into account at the school level”. R3 indicated that “the programme may not have immediate results or impact the students to a great extent at the beginning. However, with the discussion and presentations, the students are expected to display more awareness of societal differences.” R4 indicated that this programme needs to be evaluated as a longitudinal study over 3 years to determine its true impact.

5.4 Active Experimentation

This phase allowed for learning in the programme as it showed ways in which the programme can be improved in the future. It highlighted the value of teamwork as a clear lesson learnt by the core team. This was seen from a statement by R1 who stated that “I learnt that team members that take on equal weighting in their respective duties makes for a smooth and great team.” This was supported by R4 who stated that “I think for starters get the right people on board if you want it to be successful. It is ok to ‘build a plane while flying it’ if you have the right team.” R4 alluded to the value of all stakeholders forming part of the team by indicating that “we should make the students our partners in this.” This means that students should be involved in the development of the modules. Involving students as stakeholders were supported by R3 when he alluded to ‘full participation’ by students to ensure engagement with these sessions for them to not become information dissemination sessions only, but fully engaging sessions that spark thoughts, ideas and change in the students.

The active experimentation phase by Kolb (1984) requires the participants to use the concepts and theories developed because of the previous phase. R2 indicated that the feedback received cited that “the programme was moving too quickly for students”. R3 also indicated the need to incorporate more activities during the delivery and leave all content that can be studied outside of the session. This is to increase the interaction of students with the content via exercises. In the second semester, the core team reduced contact time and involved more outsourced experts for facilitating workshops around the development of the students as ‘social’ beings. The use of external parties was cited by R1 who stated that “the careful scaffolding of the

programme and bringing in speakers could be a point of consideration for the development of the programme".

Upon looking at the need to monitor this project, R4 indicated the need for developing a similar programme for the Final Year Experience. The success of this programme warrants the core team to explore further than just the first-year experience. With the experience gained, developing future programmes of this nature will become much easier. To support this, R1 states that "This entire experience has been much better than there was bad and will make any future projects easier to handle and develop."

The core team has envisioned the future development of the programme and its potential impact on student success and well-being. R4 indicated the need to convert this into a formal module linking to the Dean's vision for a module called "Engineering for Social Change". This module aligns with the institution's Vision 2030 and the Graduate Attributes. R4 and R3 agree that content from this envisaged module would provide students with the "critical and soft skills" that they need to be "good citizens" and to be "successful and socially aware" in the world.

6 Conclusion

Kolb's (1984) framework allowed the authors to reflect on their practices using the four phases. It provided a holistic questioning of the content, technological use, collaboration, and future improvements. In this way it considered the lecturers as both learners and teachers of the content as each individual played crucial roles, as well as multiple roles in the programme's development and deployment. It was also agreed that using the digital space in various innovative ways allowed for creativity from the lecturers and engaged the first-year students in the delivery and engagement of the content in the online space.

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Investigating Factors that Influence Faculty Learning in Service Learning

Surendra Bandi
Hyderabad Institute of Technology and Management (HITAM), India, surendra.mca@hitam.org

Rohit Kandakatla
KG Reddy College Engineering and Technology (KGRCET), India, rohit.kandakatla@kgr.ac.in

Samyuktha Penta
KG Reddy College Engineering and Technology (KGRCET), India, samyukthapenta@kgr.ac.in

Abstract

Service-learning integrates community service with academic instruction, focusing on critical, reflective thinking and personal and civic responsibility. Faculty members engaged in service-learning often report significant professional and personal growth. However, understanding what specifically influences faculty learning in these settings is less explored. This research investigates the factors impacting faculty learning through service-learning, aiming to enhance educational strategies within engineering education. The study is taken up in a private university in India. The research question addressed in this study is - What are the factors that influence faculty learning in service-learning? This study aims to identify key elements that enable faculty learning. The target participants are the faculty who teach service-learning courses with community immersion experience. Qualitative study is used to collect the data. Data were collected through semi-structured interviews focusing on faculty experiences and perceptions. Thematic analysis of interviews with 20 faculty members who have participated in service-learning programs is carried out. The study identified several key factors influencing faculty learning in service-learning contexts. Service-learning contributes to faculty research opportunities, career advancement and enhanced teaching methodologies. Faculty reported that the scope of validating their experience in service-learning . This was by submitting articles in the conferences and journals of engineering education. Direct interactions with the community enhance faculty empathy towards societal issues. It was motivating them to integrate social responsibility into their teaching methods. Service-learning encourages faculty adopt various roles. They become innovators and problem solvers. They apply design thinking to real-world problems. Support from educational institutions helps faculty engagement and effectiveness in service-learning. The results indicate that service-learning influences faculty learning. The learning aspects are inculcating professional growth, enhancing empathetic understanding and encouraging innovative teaching approaches.

Keywords: Service Learning, Faculty Learning, Adult Learning, Engineering Education

1 Introduction

Service-learning(SL) is an educational strategy that connects community service with academic teaching. The focus of the service-learning is nurturing critical and reflective thinking. Inculcating personal and civic responsibilities among the learners is achieved through SL. Benefits of service-learning for students are acknowledged and well-documented. Its impact on faculty development in the discipline of engineering education needs further exploration(S. R. Bandi et al., 2023). Faculty members who engage in service-learning report benefits in both professional growth and personal satisfaction . However, the specific factors that facilitate such benefits are less studied. A comprehensive understanding of these factors is not clear. Recent studies highlight the nature of service-learning and its potential to influence faculty towards innovation in their teaching (S. R. Bandi et al., 2023). One of the most important aspects that faculty experience while facilitating service-learning is empathy (S. R. Bandi et al., 2023). For example, service-learning encourages faculty to adopt design thinking to real-world problems. It will be enhancing their teaching methodologies and advancing their own careers (Garvin & Acosta Lewis, 2022). This is relevant in engineering education as well. The integration of practical, real-world challenges can improve the academic curriculum and faculty teaching strategies (S. Bandi, 2020).

Motivations for faculty participation in service-learning are based on several factors (Surendra et al., 2024). Institutional support, personal values and the opportunity for professional advancement are few examples. The requirement for specific training to undertake service-learning courses suggests a need for continuous professional development to improve teaching effectiveness (Derreth et al., 2022). This need for training shows an institutional role in facilitating faculty engagement in service-learning. It is by providing the necessary resources, support and recognition. In the context of a private university in India, where this study is situated, these factors play a crucial role. The unique challenges and opportunities presented by the Indian higher education landscape affect how service-learning is implemented and perceived by faculty. By looking into the experiences and motivations of faculty members who facilitate service-learning courses, this research aims to identify and analyze the key factors that enhance faculty learning and development in engineering education.

This study will answer the research question: What factors influence faculty learning in service-learning? Qualitative method is used to explore the experiences of 20 faculty members involved in service-learning. The aim is to provide insights that can help educational institutions maximize the benefits of service-learning for faculty development. Through this, the study contributes to an understanding of how service-learning can be leveraged to support faculty development. We emphasized the need for a supportive institutional framework. Adequate training and recognition of faculty efforts in integrating service-learning into their teaching practices are the other needs.

2 Literature Review

2.1 History of Service-Learning

Service-learning(SL) combines academic learning with community service. SL provides benefits to both students and the community (Delaine et al., 2023). The roots of service-learning can be traced back to the early 20th century. It was aslo used in the education during the late 20th century. The evolution of service-learning is marked by several key developments. Initially conceptualized as a method to improve student learning and civic engagement, service-learning was shaped by the experiential education movement (Bringle & Hatcher, 1996). This movement emphasized the importance of learning through direct engagement with real-world problems. The seminal work "Service Learning: A Movement's Pioneers Reflect on Its Origins, Practice, and Future" by Stanton, Giles, and Cruz (1999) gives a review of the origins and theory of service-learning. The authors discuss how early adopters of service-learning

understood to address social issues through integrated academics. They were aiming to educate students who were academically proficient and civically responsible (Kandakatla et al., 2023). Academic research into service-learning expanded during this period. The scholars like Barbara Jacoby (2014) and her associates contributed extensive literature on the practice. Their book, "Service-Learning Essentials: Questions, Answers, and Lessons Learned", is notable for details about effective practices in service-learning. The review by Furco and Norvell (2019) synthesizes research, highlighting the sustained impact of service-learning on student learning. This work highlights the ability of service-learning for students, faculty and educational institutions.

The history of service-learning gives its evolution from an educational idea to an established teaching practice. It has proven to be an effective method for enhancing educational experiences with a commitment to civic and social responsibilities(Oakes et al., 2025)

2.2 Faculty Roles in Service-Learning

Service-learning needs faculty involvement to link academic content with community engagement. The roles of faculty in service-learning include course design, facilitating partnership with community and assessment of learning outcomes. Faculty are responsible for designing and implementing service-learning courses. These courses integrate academic learning objectives with community needs. Jacoby (2014) emphasize that service-learning requires faculty to develop curriculum that meet educational standards and engage students in meaningful community service activities. This involves creating projects that are beneficial for both students and the community. We need to ensure a reciprocal relationship that helps student learning while addressing community issues. Building and maintaining partnerships with community organizations are crucial for the sustaining of service-learning programs. O'Meara & Niehaus (2009) discuss the importance of faculty acting as liaisons between their institutions and the community.

Assessment of student learning and the impact of service-learning projects on the community are important to faculty responsibilities in service-learning. Bringle and Hatcher(2009) outline that faculty must develop appropriate assessment tools to measure the educational outcomes and community impact of service-learning initiatives. This includes creating reflective assignments that help students connect their service experiences with academic content and personal growth (Dustker et al., 2021). Faculty involved in service-learning find advocate for the value of integrating community engagement into the academic curriculum. Zlotkowski (1998) highlights the role of faculty as advocates within their institutions for the expansion and support of service-learning programs.

2.3 Existing Research on Faculty Learning through Service-Learning

Research indicates that faculty who engage in service-learning understand connections with both their academic subject matter and the communities. Eyler and Giles (2001)note that this engagement enhances faculty's teaching skills and improves their understanding of the practical applications of their academic expertise. This focus improves faculty teaching methods. It also helps providing real-world contexts for research and publication. Faculty participation in service-learning has been linked to professional development opportunities. Antoniou and Kyriakides (2013) highlight that through service-learning, faculty members encounter diverse teaching scenarios. That challenges them to innovate and adapt their pedagogical strategies. This leads to the development of new teaching materials and methods. Those can be shared across the academic community, enhancing the overall quality of educational offerings.

Service-learning also impacts faculty attitudes. This happens towards students and the educational process. Bennett (2012) discusses how people involved in service-learning tend to adopt more people-centered approaches. Those prioritize the learning needs and experiences of students over traditional lecture-based methods. This shift affects how faculty teach. It also changes how they perceive their

role in the educational system. This will be leading to a empathetic and responsive educational practice. Abes, Jackson and Jones (2002) identify some barriers too. Examples are time constraints, lack of institutional support and difficulty in aligning service projects with academic content. This can deter faculty from fully embracing service-learning methodologies. Addressing these challenges is important for adoption and deeper impact of service-learning in higher education.

2.4 Gaps in the Literature and Justification for the Current Study

The past research studies explored the impacts of service-learning on students and communities. Very less studies focused on the faculty experience. Furco (2019) points out that the faculty perspective is required when designing service-learning programs. Vogelgesang and Astin(2000) suggest that more research is needed to explore the factors behind faculty participation in service-learning. Understanding what drives faculty to engage in these programs can help institutions support and encourage faculty involvement. Strait and Lima (2023) propose that future research should also explore how service-learning affects faculty in different disciplines and career stages. This could lead to approaches that maximize the benefits of service-learning across diverse academic contexts.

The gaps identified in the current literature justify the need for further research into the factors influencing faculty engagement in service-learning.

3 Methodology

3.1 Study Context and Participants

This study is on faculty learning experiences in service-learning. The context is through the facilitation of a Design Thinking and Social Innovation (DTSI) course at a private engineering institution in southern India. DTSI is an experiential learning course offered to first-year undergraduate engineering students. They work on real-world social challenges using a design thinking framework. Faculty members guide students through community-based problem-solving. This enabled co-learning between students, faculty and community. DTSI follows a service-learning model where academic coursework integrates with meaningful community engagement and faculty members play the role of facilitators rather than just being traditional instructors. A purposive sampling approach was used to select 20 faculty members from various disciplines. Participants had diverse teaching backgrounds, ranging from three to 21 years of experience and they have varied perspectives on service-learning facilitation.

3.2 Research Design and Data Collection

The case study approach was selected for its strength in offering contextualized, in-depth understanding of the details of faculty learning processes. The research was conducted at a private technological university in South India that has integrated service-learning into its undergraduate curriculum over the past six years. This setting was chosen due to its institutional commitment to experiential education. Accessibility of faculty participants with varying levels of involvement in SL was also another plus point. Data were collected through semi-structured interviews with 20 faculty members across various engineering disciplines. Participants were selected using purposive sampling, targeting those who had facilitated service-learning courses for at least two consecutive semesters. This criterion ensured that participants had exposure to SL practice and could reflect meaningfully on their learning experiences.

An interview protocol was developed. The protocol was pilot-tested with three faculty members outside the final sample to refine question clarity and flow. Each interview lasted between 45–60 minutes. Few interviews were conducted in-person or few others were via video conferencing, The data were analyzed using thematic analysis following guidelines in a standard book of research methods (John W. Creswell & J. David Creswell, 2018). Two researchers independently coded a representative subset of transcripts to ensure reliability. Codes were then compared and discussed

and a final coding framework was developed collaboratively. The themes were derived inductively, capturing recurring patterns across faculty narratives.

3.3 Validity and Researcher Reflexivity

Triangulation of perspectives was ensured by interviewing faculty from diverse departments. The participants were with varied teaching experience (ranging from 3 to 25 years) and different levels of engagement with SL. Member checking was conducted with a few participants. It is to validate the authenticity of interpreted themes and some selected quotes supporting the claims.

The coding process was cross verified by two researchers. This is to ensure consistency in theme generation. Disagreements were resolved through discussions. The lead researcher has experience in service-learning facilitation and faculty development in engineering education. A reflexive journal was maintained throughout the research process to capture observations. This helped minimize researcher bias and ensured self-awareness in the analysis. The co-authors have expertise in engineering education. Their contributions were there in refining the analysis, interpreting results and aligning the findings faculty development and social impact education.

4 Results

Themes and analysis of faculty interviews is presented in this chapter. We will be exploring the factors that influence faculty learning during the facilitation of service-learning (SL) courses in Indian engineering education.

The results are organized into three themes crisply.

1. Institutional Ecosystem for Faculty Engagement and Growth
2. Teaching Practices Through Service-Learning
3. Empathetic Awareness as a Catalyst for Faculty Learning

Each theme is discussed with sub-themes with some participant quotes.

Theme 1: Institutional Ecosystem for Faculty Engagement and Growth

This theme highlights the role of institutional aspects. It includes policies, structures and culture in shaping faculty engagement and learning in SL. Some faculty joined initially through formal deputation or departmental assignment. Through their sustained participation and growth they were influenced by institutional encouragement, resources and recognition systems.

Sub-theme 1.1: Institutional Mandate and Departmental Encouragement

Many faculty members began their SL journey through institutional deputation, reflecting an early-stage compliance. However, support from colleagues and institutional culture helped transition them from reluctant participants to active facilitators.

“Initially it was not a choice, but as part of the teaching-learning process. I gained interest as I engaged more deeply with the course.” (Participant H1)

“I was deputed by the department, but as I got trained and understood its societal angle, I started enjoying it.” (Participant B9)

Sub-theme 1.2: Recognition in Appraisal and Career Advancement

Service-learning became a professional opportunity, It is through its inclusion in appraisal systems and institutional visibility. Faculty appreciated the tangible rewards that followed their involvement.

"Our appraisal system includes questions on developing new courses or methodologies. Service-learning definitely helps here." (Participant H1)

"It has helped me in my career also—community engagement, soft skills, reflection, and complexity—all these added value." (Participant B12)

Sub-theme 1.3: Resource and Logistical Support

Faculty emphasized the role of logistical assistance—transportation, schedules, team support—which allowed them to focus on facilitation and reflection.

"All sorts of support were given. Community visits were arranged with institutional vehicles. That made it easier for us." (Participant B10)

These insights emphasize that institutional structures—such as departmental mandates, appraisal systems and logistical support—serve as powerful enablers of faculty learning in service-learning contexts.

Theme 2: Teaching Practices Through Service-Learning

Faculty described pedagogical learning as they navigated the demands of SL. The shift from traditional lecture-based instruction to facilitation in dynamic, real-world settings. It required adaptability, student-centered methods and interdisciplinary approaches.

Sub-theme 2.1: Shifting from Expert to Facilitator

Faculty learned to let go of control and co-create learning environments with students, becoming flexible and adaptive in their teaching roles.

"Before, we taught fixed content. Now we tailor based on students' capacity and community needs." (Participant B4)

"I had to manage the students, interact with stakeholders, and find new ways to explain complex concepts. It helped me a lot." (Participant B8)

Sub-theme 2.2: Reflection, Feedback and Iterative Learning

Faculty gained insights by iterating their course delivery, refining their facilitation style and reflecting on what worked.

"With each batch, I improved. Accumulated learning helped me better support students later." (Participant H2)

"It made me a better person personally and professionally. I teach service-learning now much better than before." (Participant B10)

Sub-theme 2.3: Integration of Interdisciplinary Perspectives

Teaching in SL required crossing disciplinary boundaries, prompting faculty to explore concepts outside their expertise and support peer learning.

"I'm from CS, but we had to deal with mechanical and electronics content. We learned, then we were able to teach better." (Participant HP2)

"It pushed us to think in multidisciplinary ways. It helped in our professional growth too." (Participant B9)

This theme reveals that service-learning catalyzes pedagogical innovation. This compels faculty to move beyond conventional teaching methods and embrace dynamic, reflective and student-centered approaches.

Theme 3: Empathetic Awareness as a Catalyst for Faculty Learning

Interacting with communities exposed faculty to social realities. These are absent in traditional academic settings. This led to the development of empathy and faculty identity.

Sub-theme 3.1: Learning Through Community Immersion

Faculty reported significant learning by listening to community voices and witnessing local challenges firsthand.

“When we go to the community, we understand things, observe better, and learn how to define problems from multiple perspectives.” (Participant HP2)

“We visit schools, NGOs, and localities. Every visit is a warm welcome and a learning experience.” (Participant B4)

Sub-theme 3.2: Building Empathy and Social Responsibility

Exposure to societal issues led to increased sensitivity, compassion, and ethical awareness.

“We learn empathy in SL. I try to understand people’s problems deeply now.” (Participant HP2)

“Even highly qualified people don’t know the pain of others. SL helped me see that.” (Participant B12)

“I started using empathy in my department too, especially in automation and robotics design thinking.” (Participant HP1)

Sub-theme 3.3: Reimagining the Role of the Educator

Faculty reflected on their evolving roles—from subject experts to socially responsible facilitators and mentors.

“It helped me see how engineering connects to society. We’re creators—we must help.” (Participant H2)

“This course changed how I teach and how I think about my responsibility as an educator.” (Participant B7)

Faculty engagement with real communities imporves their understanding of societal challenges. It also helps with emotional intelligence, empathy and ethical responsibility.

The three themes reflect the multiple aspects through which faculty learn in SL contexts through institutional frameworks. It evolves pedagogical practices and meaningful community engagement. These findings show that faculty learning in SL is not incidental. It is influenced by support of institutions, reflective practice and experiences in real-world settings.

5 Discussion

The factors influence faculty learning in service-learning (SL) are studied in this study. The focus is on how engineering faculty in India experience changes in their engagement in SL courses. Herbert Kelman’s (1958) Social Influence Theory is used as a conceptual lens. The results show how faculty learning happens through the stages of compliance, identification and internalization. These are the

three processes through which individuals adopt new behaviors and attitudes in response to social influence. The discussion analyses and synthesizes insights across three major themes.

5.1 Navigating Institutional Structures and Expectations

Institutional mandates and regulations influence initial faculty engagement in SL. It is through deputation or top-down directives. This coincides with Kelman's concept of compliance. Faculty adopt service-learning due to formal expectations, appraisal benefits or workload allocation. Faculty described how their institutions assigned them to SL courses as part of their teaching responsibilities, prompting initial engagement without prior interest. This form of compliance may appear passive. It was a critical starting point for deeper learning to occur.

Institutional ecosystems that provided curricular flexibility, training and supportive leadership became crucial enablers of learning. This reinforces existing scholarship. This emphasizes the role of organizational support in educational innovation (Lewing & York, 2024). Faculty who received administrative backing and participated in orientation or Faculty Development Programs (FDPs) found it easier to adapt community-based projects. These institutional factors functioned to support SL as a valid and recognized academic integrated activity.

5.2 Developing Pedagogical and Professional Identities

Faculty engaged more actively with SL. Their professional identities shifted. They were demonstrating Kelman's process of identification. Individuals adopt behaviors because they align with meaningful social roles. Through iterative course facilitation, collaboration with students and real-time decision-making, faculty redefined their pedagogical roles. They moved from being content deliverers to facilitators. They started using experiential, interdisciplinary and problem-based learning.

Faculty reported acquiring new mentoring capabilities, adaptability and assessment techniques. These reflect findings from Dewey (1986) and Kolb (2013). This confirms experiential learning helps deeper teaching competence. They recognized that SL demanded integrating real-world complexity, local knowledge systems and collaborative learning with students. These changes show how SL acts as a professional learning context. It influences both teaching strategies and career trajectories (Kawai, 2021) (Camus et al., 2022).

SL created avenues for research innovation and recognition. It was also providing opportunities to publish, present and network within interdisciplinary domains. Faculty began to see themselves as engaged scholars, professionals whose work bridged education and societal relevance. This identification with SL as a unique and meaningful was critical in sustaining long-term faculty learning.

5.3 Internalizing Empathy and Community-Centered Values

Learning occurred when faculty internalized the values and principles of service-learning. This marks transition from professional engagement to personal transformation. This phase relates to Kelman's internalization. Individuals adopt behaviors that align with their belief systems. Through immersion in community contexts, faculty gained emotional insight into social issues. It began reflecting on their own positionality and ethical responsibilities.

Faculty narratives demonstrated heightened empathy. It shows growing sensitivity to inequality and a shift toward socially conscious teaching. These findings links with transformative learning theory (Mezirow, 2000) and the role of critical reflection in faculty growth. SL offered a reflective mirror. Through this faculty could assess what they teach. It also covers why and how they teach. The integration of empathy into classroom practices suggests a shift towards human-centered education. It bridges the gap between technical knowledge and societal need (Resch & Schrittesser, 2023).

Faculty described a sense of purpose and satisfaction. They were highlighting that their involvement in SL aligned with intrinsic values of giving back to society. Educational equity and ethical engagement was also equally mentioned. This form of internalization confirms authentic learning in SL. This reinforces Paulo Freire's (1970) view of education as a space for critical consciousness.

Implications for Faculty Development and Institutional Strategy

Findings of the study indicate that faculty learning in SL evolves through multiple stages. It is influenced by institutional structures. Pedagogical engagement and value-driven reflection are also other factors. These stages can be supported by institutions as explained below:

Introducing SL through policy. Following up with mentorship, peer communities and reflection spaces to support engagement.

Offering training that combines technical guidance (stakeholder interviews, project design) with emotional and ethical dimensions of SL pedagogy.

Including SL contributions in promotion and appraisal systems. Reinforcing the academic value of engaged teaching and scholarship.

Establishing cross-functional support structures (service-learning centers, interdisciplinary forums) to foster institutional learning cultures.

By recognizing and supporting these influence mechanisms, higher education institutions can improve faculty learning outcomes. It will scale service-learning as a transformative force within engineering education.

6 Conclusion

Factors that influence faculty learning in service-learning (SL) were explored in this study. It is within Indian engineering institutions. The findings show that faculty learning is not a one-time event, but a layered one. It is an evolving process shaped by institutional settings, teaching experiences and community immersion.

Faculty begin their journey through compliance. The tasks were assigned or encouraged to participate in SL. They gradually identify with the educator role in socially engaged learning. With time, many internalize the values of empathy, reflection and social responsibility. These are integrated into their professional identity. These stages are as per Herbert Kelman's Social Influence Theory. This followed te sequence of framing faculty learning as a transition from compliance to identification and eventually to internalization.

Three major themes explain the process:

- A Supportive Institutional Ecosystem. This enables faculty initial participation in SL. Followed by long-term engagement through curriculum flexibility and trainings.
- Pedagogical Adaptation and Growth. This occurs as faculty work on real-world challenges.
- Ethical Commitment through Community Immersion. This supprts reflective practice and change faculty perspectives.

Faculty learning in SL is socially influenced. Institutions that recognize this complexity by supporting reflection, valuing community work and aligning incentives. This can help better educators and socially responsive engineers.

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Enhancing Engineering Education Through Reflective Practice in a Public University in Nigeria

Daniel Salau
University of Lagos, Nigeria, danielpelumi03@gmail.com
Esther Osho
University of Lagos, Nigeria, oshoesther70@gmail.com
Olayinka Omowunmi Adewumi
University of Lagos, Nigeria, oadewunmi@unilag.edu.ng
Moses Olayemi
Oklahoma University, United States, molayemi@ou.edu

Abstract

This work-in-progress paper presents emerging empirical findings of an ongoing comparative research effort that hypothesizes that Reflective Practice (RP) enables engineering educators to better serve students in the Nigerian higher education context. It considers RP as a pedagogical intervention and presents the results of an evaluation of its impact on student learning at a public university in Nigeria. Seventy-six (76) undergraduate engineering students participated in the study. The research questions (RQ) guiding this study were: What is the impact of RP on students' learning experiences (RQ1), and how do these experiences compare with the control courses that did not employ RP (RQ2)? Utilizing Kolb's reflective cycle as the theoretical framework, a causal-longitudinal approach was adopted to design two pre- and post-intervention surveys on Qualtrics, each comprising items that explored student engagement, perceptions of instructional design, and impacts on learning outcomes. The instructors' reflections and pedagogical interventions were tracked using Penzu, an online diary. Preliminary findings, comparing RQ1 and RQ2 with the control and treatment courses, suggest that students had better learning experiences. This study argues that RP enhances educators' teaching styles and positively influences students' learning experiences and the result using the Wilcoxon Signed-Rank Test showed a statistically significant difference in student experience ($p < 0.05$) but no significant difference in student engagement ($p > 0.05$), suggesting that the intervention had a positive impact on student experience but not on engagement.

Keywords: Reflective Practice, Applied Thermodynamics, Students Learning Experiences

1 Introduction

A strong educational foundation in engineering, one that produces superior graduates, directly impacts any nation's economic growth, prosperity, and development (Igbokwe et al., 2019). The achievement of these goals requires a shift towards student-centered learning, where students play a critical role in identifying which teaching and learning methods best suit their context (Wong, 2021). Traditional teacher-centered learning, characterized by passive information delivery, can lead to student disengagement and lower academic performance in STEM fields (Freeman et al., 2010). To foster a deeper understanding and align teaching practices with learning objectives, a strategic approach is needed to facilitate this shift (Weimer, 2013). One such approach is Reflective Practice, a widely recognized tool for professional and educational development that involves critically examining one's thoughts and actions to improve knowledge, skills, and practices (Schön, 2017).

While Reflective Practice is a valuable tool for educators to enhance teaching styles and foster critical thinking, its empirical application in engineering education within the Nigerian context remains underexplored. This gap limits the understanding of how such interventions can be effectively implemented in underrepresented educational settings. This study addresses this gap by adopting Reflective Practice as a pedagogical intervention to enhance engineering education in a public university in Nigeria. Guided by Kolb's reflective cycle (Ivala, 2013; Kolb et al., 2014).

1.2 Research Questions (RQ) and Hypotheses (H_o)

This work-in-progress paper aims to assess the impact of reflective teaching on student learning, with a focus on two key areas. The research questions guiding this study are:

RQ1: What is the impact of Reflective Practice on students' learning experiences?
RQ2: How do students' learning experiences in a course employing Reflective Practice compare with a

control course?

H_o: Our null hypothesis states that Reflective Practice has no significant impact on students' learning experiences, specifically regarding student engagement and overall experience.

1.3 Kolb's reflective cycle as the theoretical framework

Kolb's Reflective Practice has been adopted and discussed in the literature to highlight three distinctive styles of reflection: reflection-in-action, reflection-on-action, and reflection-for-action (Ivala, 2013; Journal, 2018). Reflection-in-action refers to instances where instructors or practitioners reflect on their practices while they are ongoing. Reflection-on-action typically occurs afterward, allowing for a better understanding of what transpired, which practices were effective, which were counterproductive, and which had no impact on the intended goals. Reflection-for-action is a proactive approach that looks forward, anticipating the steps necessary to achieve a desired objective. This study aims to employ Kolb's reflective cycle (Ivala, 2013; Kolb et al., 2014) alongside two of the three distinctive styles of Reflective Practice (as shown in Figure 1) to assess the impact of reflective teaching on student learning at a Nigerian public university, using students enrolled in an applied thermodynamics course as a case study. A description of Kolb's reflective cycle in the context of education follows below.

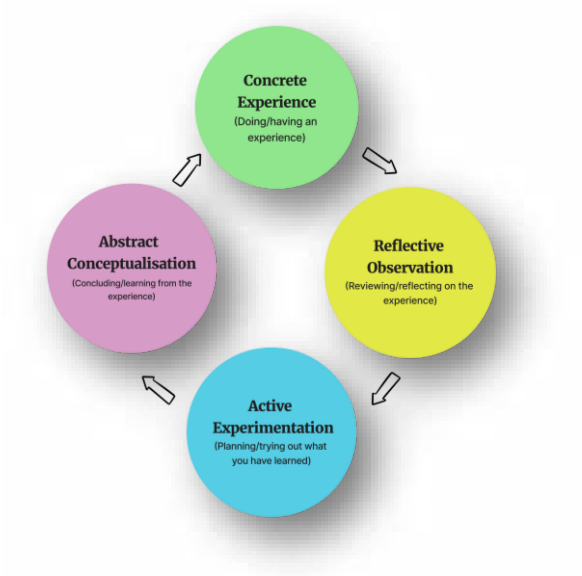

Figure 1:Kolb's Reflective Model

Concrete experience is an area of interaction between educators and students, whether in-person or virtual. At this initial stage, both students and educators share observations, thoughts, and perceptions about their interactions (Loughran, 2002; Osterman, 1990). *Reflective observation* helps educators assess what worked and what did not in their interactions with students and in the students' learning experiences. *Active experimentation* requires educators to apply all reflections and ideas for improvement back into practice by testing new strategies. *Abstract conceptualization* concludes with a follow-up action plan derived from the active experimentation stage. Here, educators reflect on the strategies implemented for improvement and seek input from experts and/or colleagues to build on successful ideas from similar situations.

2 Literature Review

Reflective Practice can serve as a valuable tool in both undergraduate and postgraduate training. However, in Nigeria and throughout Africa, research studies on the application of Reflective Practice within the engineering education ecosystem are limited. For example, Omosule et al. (2021) aimed to evaluate Reflective Practice and its benefits for resident doctors and their professional development. They suggested

integrating Reflective Practice into postgraduate training programs. Furthermore, Hyacinth and Mann (2014) examined the use of Reflective Practice among 19 teachers, with each participant documenting their reflections to better understand Reflective Practice.

These examples illustrate the scarcity of studies on the application of Reflective Practice in Nigeria. There is a pressing need for more research on the effective use of Reflective Practice in Nigeria to enhance student-centered learning and improve teaching practices.

2.1 Impact of RP on student learning

Research from South Africa (Von Solms & Nel, 2017), linking RP to project-based learning, and from Vietnam (Hoa & Tuấn, 2020), addressing the theory-practice gap in graduates, show that RP aids students in transferring academic knowledge to workplace problem-solving. The text proposes using student engagement metrics - particularly feedback on course structure and delivery - as key indicators of RP's effectiveness.

The impact of Reflective Practice on student learning can be measured in several ways. One of the most common methods is through student engagement (Davis et al., 2009; Mathew, 2012). In this paper, we define student engagement as the feedback received from students regarding the design and execution of the Thermodynamics course. By examining the students' perceptions of the instructional design, we aim to explore their attitudes toward changes in course structure, attendance, tutorials, and learning outcomes.

3 Methodology

The data for this study is derived from the classroom experiences of a single instructor (Third Author) while teaching two Applied Thermodynamics courses over two semesters at a public university in Nigeria. This section aims to explain the methodology used in the research, starting with the first course, Applied Thermodynamics (I), taught by the instructor to participants in their 300-level second semester. Subsequently, the second Applied Thermodynamics course (II) was delivered by the same instructor to the same group of students in their 400-level first semester. Approval for this study was granted by the institution's administrative board. Also, this section explains the research design, sampling, and data collection process, with a focus on how the theoretical framework guided the study.

3.1 Sampling and Participant Recruitment

Students were recruited for the study using a consent form to eliminate hierarchical bias and ensure voluntary participation (Thorne, 1980). Additionally, they were assured that their grades would not be influenced by their involvement in the study. Participants were selected through purposive sampling, a non-probability technique where researchers intentionally choose participants based on specific characteristics or criteria (Creswell, 2009). For this research, enrollment in Applied Thermodynamics (I) and (II) served as the selection criterion to ensure that the sample was most relevant to the research question. This method was preferred over random selection from a larger population within the department, as it focused on students directly engaged with the subject of study.

3.1.1 Data Collection

Data collection occurred in two phases: Phase 1 spanned from November 2022 to February 2023, with 67 students participating in the Applied Thermodynamics (I) course. The initial survey included ten questions, six of which were analyzed for this paper. Phase 2 ran from May to August 2023, and included 76 students in the Applied Thermodynamics (II) course. At the end of this semester, a second survey with 14 questions was

administered, with seven questions selected for analysis in this paper to assess the impact of the new strategies

3.2 Research Design

Using Kolb's reflective cycle as the theoretical framework, a causal longitudinal approach was employed to design two pre- and post-intervention surveys on Qualtrics. A causal longitudinal approach in research refers to a study design used to examine cause-and-effect relationships over an extended period (Biazoli Jr. et al., 2024). This approach combines two elements: causality, which seeks to understand whether one variable influence or causes changes in another, and longitudinal study design, which involves collecting data from the same subjects or groups at multiple time points.

A quasi-experimental design was adopted to evaluate whether changes in students' learning outcomes resulted from the Reflective Practice conducted. This design is a research approach that tests the causal consequences of long-lasting treatments. But unlike "true" experiments where treatment assignment is at random, assignment in quasi-experiments is by self-selection or administrator judgment (Maciejewski, 2020). In this research, students were not randomly assigned to the control and treatment courses; instead, their grouping was naturally determined based on the courses they were studying.

3.2.1 Research Design Limitations

It is important to acknowledge that the control courses (other subjects the students were taking) were not a true control group due to inherent differences in subject matter and instructor. This makes a direct, causal comparison problematic. Our analysis, therefore, focuses on the effects of the intervention over time within the treatment courses, rather than a direct comparison with a true control group. This approach allows us to observe changes in student learning and experience that may be attributed to the RP intervention, while recognizing the limitations of a perfect causal inference.

3.3 Operationalization of Kolb's Reflective Cycle

Kolb's reflective cycle served as the guide for the entire research process, from intervention design to data collection. We operationalized each stage of the cycle to create a continuous loop of teaching, reflection, and refinement, as follows:

- **Concrete Experience:** This stage was operationalized as the zone of interaction between the instructor and students. These interactions took place both physically in-class and virtually via Zoom throughout the course.
- **Reflective Observation:** Following these interactions, a weekly Google feedback form was designed to gather students' feedback. The instructor then used a free online digital diary, Penzu, to document reflections on this feedback. These reflections provided insights into effective teaching practices and identified areas for improvement, such as hard-to-comprehend topics and student requests for learning interventions.
- **Active Experimentation:** To implement this stage, a comprehensive end-of-semester survey was designed using Qualtrics. This survey evaluated the overall impact of the weekly interactions and reflections on students' learning experiences. The results from this survey guided the refinement of teaching strategies for the next course.
- **Abstract Conceptualization:** This final stage involved using the follow-up action plan from the first phase of the research to refine strategies and enhance student learning experiences in the next

semester's Applied Thermodynamics course (Thermo II). The instructor used the data from the initial survey to build on successful ideas and develop new strategies for the new course.



Figure 2: Application of Kolb's Reflective Model in Data Collection



Figure 3: Snapshot of a journal entry on Penzu

The second research process was also based on Kolb's reflective model. The abstract conceptualizations documented for a follow-up plan from the active experimentation stage of the first phase of the research, aided by the comprehensive data obtained from using Qualtrics, were utilized by the educator in the following semester's applied thermodynamics course to refine strategies and enhance student learning experiences in this new course.

Finally, member checking involved weekly mentorship meetings held throughout the research study. During these meetings, the primary instructor answered clarifying questions to ensure the research's accuracy.

3.4 Data cleaning

A proper data cleaning process was carried out by anonymizing the participants and by deleting missing data (see Table 5 in Appendix).

3.5 Analysis of Qualitative Data

The weekly Penzu journal entries and Google feedback forms served as a continuous source of qualitative data. The instructor analyzed this data to identify recurring themes related to student comprehension, engagement, and suggested improvements. This analysis directly informed the "active experimentation" stage of the study, guiding the adjustments to teaching methods and curriculum for the following course. The open-ended comments from students provided rich insights that supplemented the quantitative survey data, helping to diagnose learning challenges and track the evolution of student perspectives over the two semesters. The instructor's journal entries also showed a clear shift in pedagogical approach, moving from a focus on content delivery to a more responsive, student-centered style. This is evidenced by entries that detail changes made in real-time, such as creating a more collaborative problem-solving session in response to student feedback. These themes from the qualitative data provide a deeper, more nuanced understanding of how the Reflective Practice intervention led to a statistically significant improvement in the student experience

4 Statistical Analysis

Before selecting a statistical test, we first examined the structure of our dataset. The data consisted of two sets of engagement scores: one collected before the intervention and one after. Since each student had a corresponding score in both conditions, this confirmed that we were working with paired data, where each observation in the "pre-intervention" group has a directly related counterpart in the "post-intervention" group. A paired t-test is typically used to compare two related datasets and determine whether their means significantly differ (Gravetter & Wallnau, 2017). This test assumes that: a) the differences between paired observations follow a normal distribution; b) the data is continuous and measured on an interval scale.

Given that our study measured engagement scores on a numerical scale, the paired t-test initially seemed appropriate. To validate the use of a paired t-test, we conducted a normality test using the Shapiro-Wilk test, the Anderson-Darling test, and the Kolmogorov-Smirnov (KS) tests on the differences between the pre- and post-intervention scores. From the results of the Python code (see Appendix A), we observed that the Shapiro-Wilk and Anderson-Darling tests suggested normality, indicating that our data did not significantly deviate from a normal distribution. However, our data failed the Kolmogorov-Smirnov normality test. Since two out of three tests confirmed normality, we performed a final check using a Q-Q (Quantile-Quantile) plot to visually assess whether the data follows a normal distribution (see Appendix B).

In conclusion, our dataset meets the normal assumption of the difference between the “pre-” and “post-intervention” scores, allowing us to proceed with the paired t-test as the suitable statistical test.

A paired t-test was conducted to compare the two conditions under study. To ensure accuracy, we utilized both Microsoft Excel and Python (SciPy) for statistical analysis. The purpose of this test was to determine whether there was a significant difference between the two paired datasets. The paired t-test was applied under the assumption of normality, which was verified through a Q-Q plot analysis. The test was executed using both Excel and Python (SciPy) codes. The results from the two tools were cross-validated to ensure consistency and accuracy.

5 Results & Discussions

The results obtained from both methods are summarized in Table 1. The p-values from both Excel and Python confirm a statistically significant difference ($p < 0.05$) between the two groups. This leads to the rejection of the null hypothesis (H_o), supporting the assertion that the observed differences are unlikely to be due to randomness, which suggests that Reflective Practice played a role in the students’ learning experiences.

Table 1: Paired T-test Results (Excel vs Python)

Method	t-Statistic	p-Value	Decision ($\alpha = 0.05$)
Excel	-12.7512	4.48×10^{-19}	Reject H_o ✅
Python (SciPy)	-12.6527	< 0.0001	Reject H_o ✅

5.1 Analyzing Student Experience & Engagement Differences

We decided to investigate further the effect of Reflective Practice on students in two areas: their experiences and the engagement/activities carried out to ensure understanding of the course. This additional assessment would determine whether the students have experienced an increase in their interactions with the educator and in their engagement with activities. We grouped specific items on the survey into two categories: student

experience and student engagement. The students' mean scores on each of these variables is presented in Tables 2a and b.

Table 2a and 2b: Simple Descriptive Statistics of Before and After Data

Q	Thermo 1 "Before"	Mean(μ1)
1	Opinion_expressed	4.190
2	learning_materials_organized	3.825
3	IU_GroupAssessment	4.270
4	IU_Tutorials	4.603
5	IU_ClassActivities	4.492
6	Feedback_clarity	4.762
n =65		

Q	Thermo 2 "After"	Mean(μ2)
1	Opinion_expressed	4.406
2	learning_materials_organized	4.344
3	IU_Lectures	4.469
4	IU_Tutorials	4.578
5	IU_ClassActivities	4.328
6	IU_Assessments	4.500
7	Feedback Clarity	4.797
n = 76		

Before conducting a t-test on the student experience and engagement categories, we needed to check for normality in each subgroup. This check was essential to determine if both subgroups adhered to a normal distribution. The normality tests for student experience and engagement yielded p-values below 0.05 after performing the Shapiro-Wilk and Kolmogorov-Smirnov Tests. These results demonstrated that the data did not conform to a normal distribution.

Table 3: Normal Distribution tests result on the subcategories

Test	Experience (p-value)	Engagement (p-value)	Interpretation
Shapiro-Wilk Test	0.0419	0.0304	❌ Not normal
Kolmogorov-Smirnov Test	0.0000	0.0121	❌ Not normal

Since the Shapiro-Wilk and Kolmogorov Smirnov tests rejected normality ($p < 0.05$), we selected a nonparametric test that does not assume normality to ensure accurate analysis.

5.2 Wilcoxon Signed-Rank Test on Subcategories

Based on the Wilcoxon Signed-Rank Test, the two subgroups—Student Experience and Student Engagement were analyzed to determine if a significant difference existed between their "Before" and "After" scores. The results are summarized in Table 4.

Table 4. Results of the Wilcoxon signed-rank test

Metric	Wilcoxon Statistic (W)	p-value	Statistical Significance	Mean Difference (|μ1 - μ2|)	Conclusion
Student Experience	0.0	4.2924e-12	Significant ($p < 0.05$)	5.246	Significant difference
Student Engagement	481.0	0.6741	Significant ($p > 0.05$)	0.092	No significant difference

The Wilcoxon statistic for student experience was 0.0, while for student engagement, it was 481.0 with an extremely small p-value (≈ 4.29e-12), indicating that the "After" responses are significantly higher from the "Before" responses. This shows the educator reflective practice had a significant impact on student experience but not on student engagement. Since the Wilcoxon test assesses whether the median differences are significantly different from zero, these results confirm that the changes in student responses were not due to random chance (see figure 6 in Appendix).

Based on the results of the statistical test, we can infer the following about student experience:
a) the extremely small p-value (4.29e-12) indicates a highly significant difference between the "Before" and "After" scores; b) the mean difference of 5.246 suggests a substantial improvement in student experience following the intervention; and c) this result confirms that the intervention had a **positive impact** on student experience.
Similarly, based on the results of the statistical test, we can infer the following regarding student engagement: a) the p-value (0.6741) is greater than 0.05, meaning the difference is not statistically significant; b) the mean difference of 0.092 is very small, suggesting little to no change in student engagement/activities after the intervention; and c) this implies that the intervention did **not** have a statistically significant effect on engagement levels.

5.3 Impact on Student Experience and Engagement

Our statistical analysis, using the Wilcoxon Signed-Rank Test, revealed a significant positive impact on student experience ($p < 0.05$), with a Wilcoxon Statistic of 0.0. This suggests a substantial improvement in how students perceived the course, from the organization of learning materials to the clarity of feedback. This improvement can be directly linked to the instructor's process of reflection-on-action. Each week, the instructor reflected on the feedback from students and the Penzu journal entries to identify which teaching practices were most effective and where improvements were needed. This process of reviewing past interactions and data helped to diagnose challenges and refine instructional strategies.

However, the same test showed no statistically significant difference in student engagement ($p > 0.05$), with a Wilcoxon Statistic of 481.0. This is an important finding, as it suggests that while the reflective intervention enhanced the overall student experience, it did not have a measurable impact on the level of student engagement and participation

5.4 Analysis of Open-ended Questions and their Connection to Kolb's Cycle

The analysis of open-ended questions provides a deeper understanding of these results, particularly in relation to the "active experimentation" and "abstract conceptualization" stages of Kolb's cycle. After the first phase, the instructor performed reflection-on-action by analyzing student feedback from the weekly Google forms and Penzu journal entries. This led to the identification of five key areas for improvement, including the need for more breaks, balanced study groups, and active learning activities.

These findings were then used in the next semester's course as a basis for active experimentation and abstract conceptualization. The instructor used the data from the first semester to develop a follow-up action plan and implement refined strategies in the second semester, effectively closing the reflective cycle. The results from the second survey, which showed a significant improvement in student experience, indicate that these data-driven, reflective adjustments were successful in positively impacting the student experience

6. Limitations, and Implications

Several limitations affected our study, with the primary one being the *inability to track individual survey responses without identifying participants.* One of the key challenges was the inability to track individual

participants across both surveys while maintaining their anonymity. This limitation became evident during data cleaning, as we discovered that some participants had completed the second survey without having participated in the first. Specifically, 11 additional responses were recorded in the second survey, but we lacked any means of determining whether these responses came from new participants or from those who had previously completed the first survey. This discrepancy complicated the decision of whether to retain or exclude these overlapping responses, as we could not verify if they were exclusively from carryover students. To address this issue, we decided to analyze the average responses per question instead of the total number of responses. By concentrating on the average, we ensured that the extra 11 responses did not unduly impact our statistical analysis.

The second limitation of this study was the *unequal number of questions in the first and second surveys.* Another limitation arose from the inconsistency in the number of questions across both surveys. The first survey contained six questions (Q1 - Q6), while the second survey included a seventh question (Q1 - Q7). This discrepancy affected our ability to perform the Wilcoxon Signed-Rank Test, as it introduced an imbalance in the two main analytical categories: Student Experience and Student Engagement. The additional question in the Student Experience category may have significantly influenced the results, potentially skewing the comparative analysis. Upon reviewing the survey questions, we observed that two questions addressed similar aspects of the student experience. To ensure analytical consistency and maintain data integrity, we removed one of the redundant questions. This adjustment facilitated a more balanced comparison between the two surveys, ensuring that the statistical analysis remained valid and meaningful. By systematically addressing these limitations, we improved the reliability of our findings and ensured that our conclusions were grounded in a rigorous and well-structured analytical approach. To address the issue of tracking individual responses in a survey, Qualtrics can assign an identifier to each respondent by providing a unique link that can be reused by the respondent.

7 Conclusion

This study, a work-in-progress, presents preliminary findings on the use of Reflective Practice as a pedagogical tool in a Nigerian public university. The results suggest that the intervention had a statistically significant positive impact on students' learning experiences, although it did not show a similar significant effect on student engagement. These findings indicate that Reflective Practice, particularly when integrated using Kolb's cycle, can serve as a valuable tool for instructors to enhance student experience in engineering courses.

The insights gained from this study contribute to the limited body of knowledge on Reflective Practice in African engineering contexts. This work highlights the potential for reflective teaching to improve student-centered learning in underrepresented educational settings.

Future work will involve a more controlled experimental design to validate these findings and further investigate the nuanced relationship between Reflective Practice, student experience, and engagement. Our hope is that this study serves as a foundation for subsequent research on adapting and implementing effective pedagogical strategies that enhance engineering education in Africa and beyond.

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Appendix A: Summary of Normality Test Results

```
✅ File loaded successfully! First 5 rows:
   before  after  Unnamed: 2  Difference
0      28     33         NaN           5
1      29     34         NaN           5
2      27     30         NaN           3
3      29     30         NaN           1
4      27     27         NaN           0
🔍 Available columns: Index(['before', 'after', 'Unnamed: 2', 'Difference'], dtype='object')
📊 First 5 values for normality testing:
 0    5
1    5
2    3
3    1
4    0
Name: Difference, dtype: int64

📌 Shapiro-Wilk Test:
   - Test Statistic: 0.9846
   - p-value: 0.5950
   - ✅ Normally distributed

📌 Anderson-Darling Test:
   - Test Statistic: 0.4255
   - Critical Value at 15.0%: 0.5460
   - Critical Value at 10.0%: 0.6210
   - Critical Value at 5.0%: 0.7460
   - Critical Value at 2.5%: 0.8700
   - Critical Value at 1.0%: 1.0340
   - ✅ Data appears to be normally distributed (Anderson-Darling Test)

📌 Kolmogorov-Smirnov Test:
   - Test Statistic: 0.8388
   - p-value: 0.0000
   - ❌ Not normally distributed
PS C:\Users\TTC COMPUTERS\Vscode Practice.py>
```

Figure 4: Normal Distribution Tests Result on Python

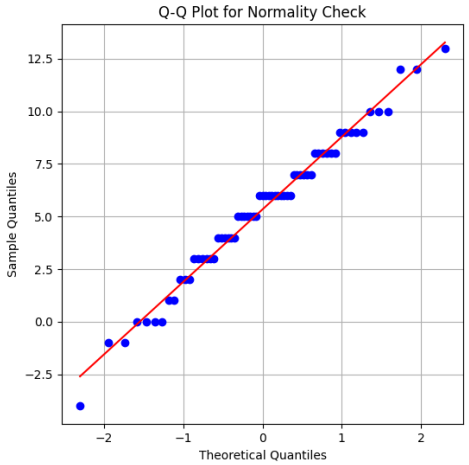

Figure 5: Q-Q Plot for Normality Check from Python

1. Shapiro-Wilk Test
    a. p-value = 0.5950 (> 0.05) → Fails to reject normality
    b. Indicates the data is normally distributed.
2. Anderson-Darling Test
    a. Test statistics are lower than all critical values at conventional significance levels.
    b. This suggests that the data does not significantly deviate from normality.
3. Kolmogorov-Smirnov Test
    a. p-value = 0.0000 (< 0.05) → Rejects normality
    b. However, this test is highly sensitive to sample size, and given that the other two tests confirm normality, this result may not be as reliable.
4. Q-Q Plot Analysis
    a. The data points mostly align with the diagonal line, indicating normality.
    b. Minor deviations at the tails suggest some potential outliers, but these do not significantly affect the overall normality.

Appendix B: T-Test Results

Python Code

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import seaborn as sns
from scipy.stats import ttest_rel

# Load dataset (use pd.read_csv for CSV files)
file_path = "C:/Users/TTC COMPUTERS/Documents/RESEARCH WITH DR MO AND DR OO/IRSPBL 2025/RPresult.csv"
df = pd.read_csv(file_path)  # Corrected: Use read_csv instead of read_excel

# Extract the paired samples
before = df['before']
after = df['after']

# Calculate the paired t-test
t_stat, p_value = ttest_rel(before, after)

# Print results
print(f"  Paired t-Test Results")
print(f"   - t-statistic: {t_stat:.4f}")
print(f"   - p-value: {p_value:.4f}")

# Interpretation
alpha = 0.05  # Significance level
if p_value < alpha:
    print("Reject the null hypothesis: There is a significant difference.")
else:
    print("Fail to reject the null hypothesis: No significant difference.")

#  ◇  Visualization 1: Before vs After Scatter Plot with Lines
plt.figure(figsize=(8, 5))
plt.plot(before, after, 'o', color='blue', alpha=0.6, label="Before vs. After")
plt.plot([min(before), max(before)], [min(before), max(before)], 'r--', label="No Change Line")
plt.xlabel("Before Scores")
plt.ylabel("After Scores")
plt.title("Before vs. After Paired t-Test Visualization")
plt.legend()
```

```
plt.grid(True)
plt.show()
```

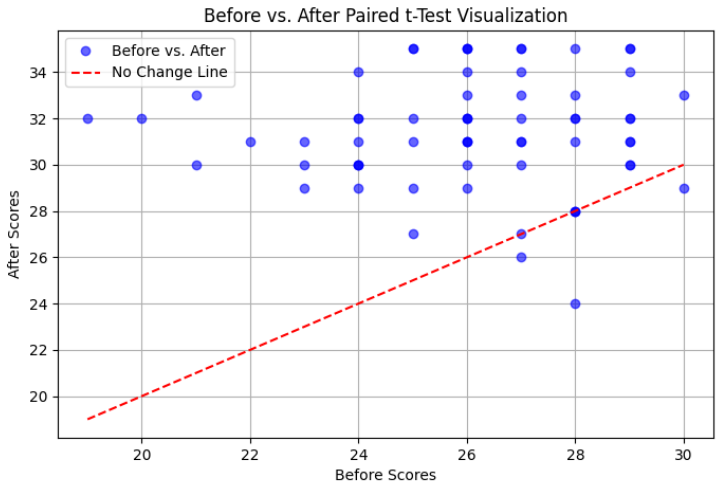

Figure 6: Visualization of the paired t-test result from Python

Before vs After Scatter Plot (with Line of No Change)

- Each **dot** represents a participant's **before and after score**.
- The **red dashed line** shows where scores would be **if there were no change**.

First Principle (Microsoft Excel)

Microsoft Excel does not directly return the t-statistic value in the T.TEST function. It was computed manually using the formula: =AVERAGE (A2:A66) / (STDEV.P(B2:B66) / SQRT (COUNT (B2:B66))) Where A2:A66 and B2:B66 represent the paired sample columns.

Data Cleaning

Table 5: Treatment and Control Courses

Year	Course	Categorization	Description
2022	Applied Thermo I	Treatment	Taught by Author 3 Reflection-in-action implemented
2023	Applied Thermo II	Treatment	Taught by Author 3 Reflection-in-action, reflection-on-action, reflection-for-action implemented
	Mechanical Engineering II Machine Design II Heat and Mass Transfer Advanced Mechanics of Materials Engineering Materials Selection & Economics Technology Policy and Development Laboratory Practical Numerical Methods Technical Communication Economics for Engineers	Control	Taught by peer instructors, RP not implemented

Table 6: Survey Items

Item	Item Description	New Variable Name	Code
Common to Surveys I and II			
Comfort expressing opinions	How comfortable did you feel expressing your opinions or asking questions in this course?	Opinion_Expressed	1 = "Not at all" 2 = "Slightly" 3 = "Moderately" 4 = "Very" 5 = "Extremely"
Organization of learning materials	How organized were the learning materials?	Learning_Materials_ Organized	
Improving understanding (IU)			
…Tutorials	…tutorials in improving…. course material?	IU_Tutorials	1 = "Not applicable" 2 = "No impact whatsoever" 3 = "Useful" 4 = "Extremely useful"
…Class Activities	…class activities in improving …course material?	IU_ClassActivites	
Feedback Clarity	How well did this instructor provide clear, constructive feedback?	FeedbackClarity	1 = "Not applicable" 2 = "Not well" 3 = "Slightly well"

			4 = “Extremely well”
Ranking of pedagogical activities	Rank these teaching practices in order of how useful they were to your learning experience (Rearrange starting from the most useful to the least useful) …Lectures, Tutorials, Class Activities		
Improvements	What are some teaching practices that this instructor could improve on?		
	What are some teaching practices that this instructor should retain?		
Unique to Survey I			
Group assignments	How useful were the …group assignments in improving your understanding of the course material?	IU_GA	
Unique to Survey II			
Lectures	How useful were the lectures in improving your understanding of the course materials?	IU_L	1 = “Not applicable” 2 = “No impact whatsoever” 3 = “Useful” 4 = “Extremely useful”
Online Assessments	How useful were the online tests in assessing your understanding of the course materials?		1 = “Not applicable” 2 = “No impact whatsoever” 3 = “Useful” 4 = “Extremely useful”
Best Course Learning Experience	This semester, in which course did you have your best learning experience?		
	Please provide two or three reasons why you chose this course as the one in which you had the best learning experience this semester.		
	Did this instructor teach you *Applied Thermodynamics* last semester?		
	Based on the feedback you gave last semester; how would you rate the teaching practice this semester?		1 = “Better” 2 = “No impact whatsoever” 3 = “Worse”

Notes:

Table 7a and 7b. Parent Categories for Student Learning Experience

Survey 1

Variable name	Parent category
1. Opinion Expressed (Q1) 2. Leaning Materials Organized (Q2) 3. Feedback Clarity (Q6)	Student Experience
1. IU_GroupAssessment (Q3) 2. IU_Tutorials (Q4) 3. IU_ClassActivities (Q5)	Student Engagement

Survey 2

Variable name	Parent category
1. Opinion Expressed (Q1) 2. Leaning Materials Organized (Q2) 3. Feedback Clarity (Q6)	Student Experience
1. Lectures Improve Understanding **2.** IU_Lectures **3.** IU_Tutorials **4.** IU_ClassActivities	Student Engagement

Density Plot

A visual representation of the density distribution plot of the pre-intervention (Before) vs post-intervention (After) Data is presented in Figure 7.

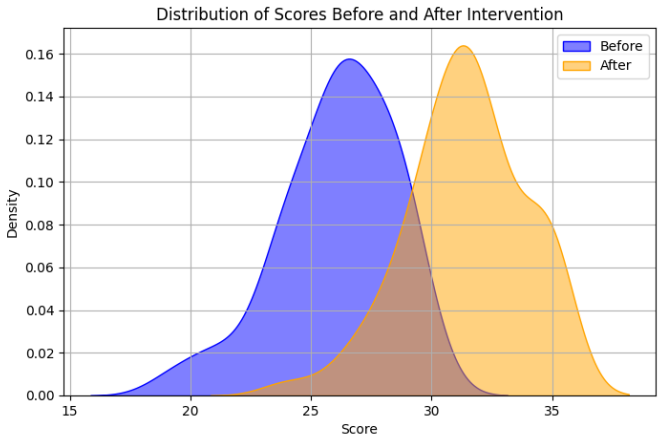

Figure 7: Visualization of Density Distribution Plot of Pre-intervention (Before) vs Post-intervention (After) Data

The density distribution plot illustrates the spread of the "before" and "after" scores, helping us to observe any overlap or shift in scores following the intervention. Next, we present a box plot of the students' pre- and post-intervention scores (figure 5), which displays the mean scores for both pre- and post-intervention and includes error bars to represent the standard deviation from the mean.

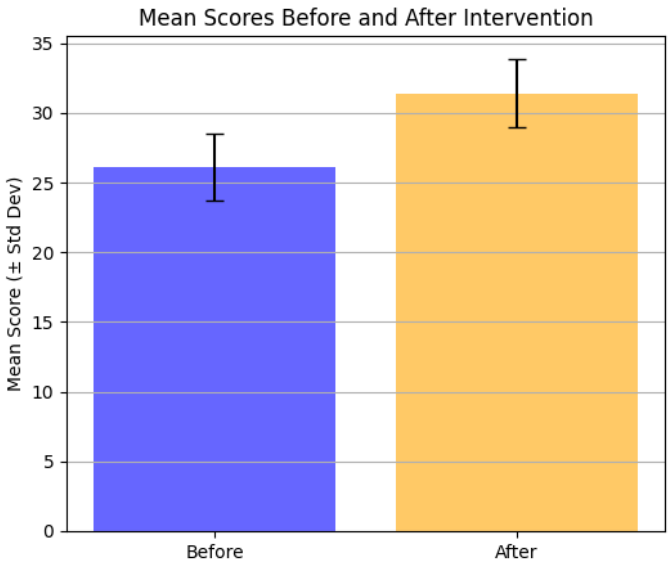

Figure 8: Box plot of Mean Scores Before and After Intervention

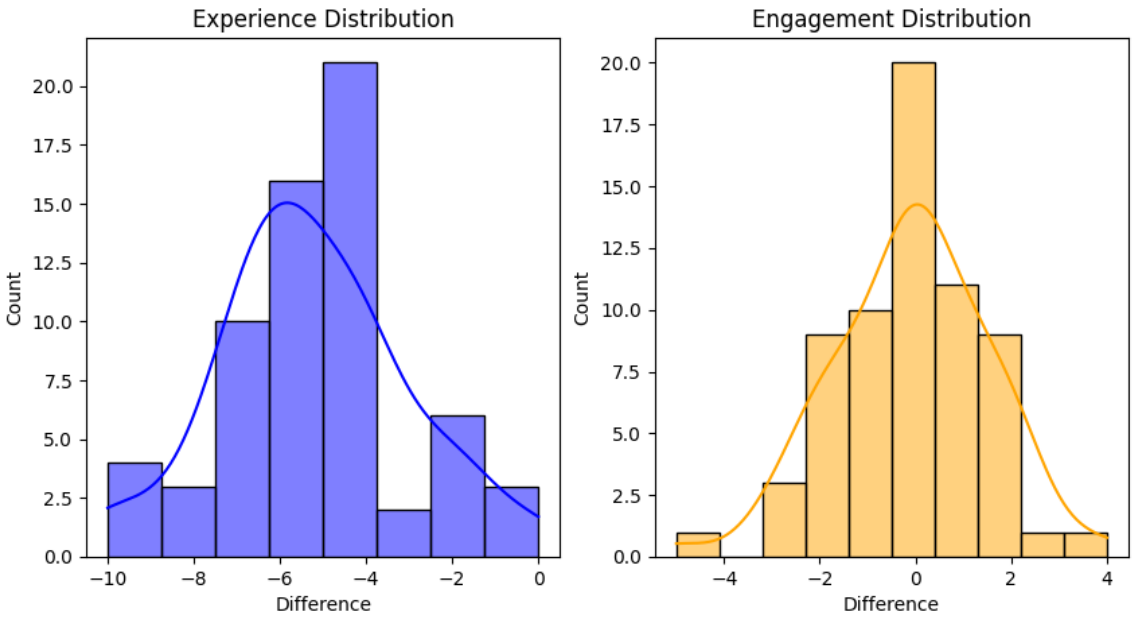

Figure 9: Normality Checks for the student engagement and student Experience groups.

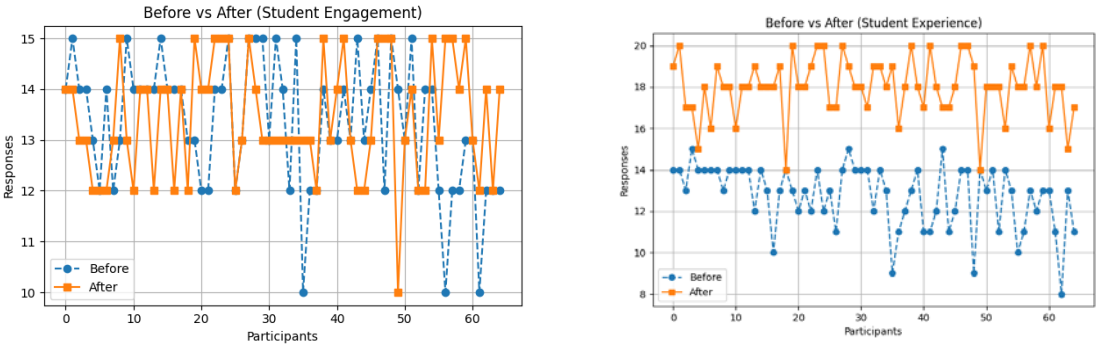

Figure 10: The Visualization of the Wilcoxon signed ranked test on the Student Experience and Engagement

Building bonds: the transition from teamwork to friendship in engineering education and its influence on the well-being of female students

Sandra I. Cruz Moreno
Technological University Dublin, Ireland, *Sandra.I.Cruz@mytudublin.ie*

Shannon Chance
Technological University Dublin, Ireland, *Shannon.Chance@tudublin.ie*

Abstract

This paper explores the lived experiences of female students implementing collaborative project/problem-based learning (PBL) within undergraduate engineering programmes at TU Dublin, in Ireland. The paper emphasises the significance of teamwork in promoting meaningful connections among students that can result in gender inclusivity.

Drawing on a longitudinal dataset of 32 interviews with 13 female engineering students, the research adopts a phenomenological approach to investigate how team dynamics evolved over time. The findings reveal that early challenges often led to feelings of exclusion. However, as peer trust developed, many students transitioned from feeling isolated to forming meaningful friendships, especially with other women. These friendships provided emotional support, mutual recognition, and academic motivation.

The findings reveal that developing such friendships helped students feel valued and understood, navigate gendered barriers, and promote persistence in the engineering discipline. Through this lens, we gain insights into the dynamics of teamwork and its interplay in shaping students' emotional well-being.

This study underscores the need for greater institutional efforts to support peer connection and inclusive team environments. Ultimately, this research advocates for a culture of care within engineering education that prioritises inclusivity and emotional well-being as essential components of student success.

Keywords: Engineering Education, Collaborative Learning, Belonging, Gender Inclusivity, Persistence

1 Introduction

1.1 Background and rationale

Engineering education has increasingly adopted problem and project-based learning (PBL) as a pedagogical strategy to mirror real-world professional practices and foster technical and non-technical competencies. Although the benefits of collaborative learning are well recognized, unequal dynamics within teams—particularly dynamics tied to gender—can limit its potential (Aeby et al., 2019; Henderson, 2023). In this context, this paper reports findings regarding how female students navigate teamwork environments within PBL settings and what role peer relationships and friendships play in shaping students' academic and emotional experiences.

This study aims to contribute to the body of knowledge by examining the lived experiences of female engineering students using an existing longitudinal qualitative dataset, focusing on how their teamwork experiences evolve into friendships and how these friendships, in turn, affect their academic engagement and emotional well-being. Our analyses suggest that friendships may serve to protect female students against exclusion and foster a sense of belonging in engineering.

1.2 Research aim and questions

This research paper explores the following research questions:

a) What are the most common challenges that female engineering students face in PBL settings?
b) How do teamwork experiences in PBL settings evolve into friendships?
c) What impact do these friendships have on female engineering students' well-being?
d) How do friendships influence a sense of belonging and academic engagement?

1.3 Structure of the paper

Following the presentation of the rationale and objectives of the research paper, a brief literature review discusses the state-of-the-art regarding collaborative learning in engineering education, gender and

inclusivity in engineering, and the relationship between well-being and academic success in engineering education. Next, the methodology for this study is outlined, and then findings are reported and discussed to address the research questions. The paper concludes with key takeaways for educators and implications for future research.

2 Literature review

2.1 Collaborative learning in engineering education

Over the past five decades, problem- and project-based learning (PBL) and other collaborative learning approaches have become increasingly integrated into engineering curricula (Kolmos & de Graaff, 2014). These pedagogies are designed not only to support the development of technical knowledge and reasoning but also to enhance personal, interpersonal, and professional skills (Chen, Kolmos, & Du, 2021; Van Helden et al., 2023). Furthermore, collaborative learning as an active pedagogy is praised for emulating engineering practices, thus preparing students for professional collaboration in engineering contexts in professional settings (Mercier et al 2023). In this context, collaborative learning has been associated with academic achievement, improved learning outcomes, and increased student retention and persistence in engineering education (Du et al., 2020, p. 202; Stump et al., 2011).

However, while the benefits of collaborative learning are well documented, research has also drawn attention to its challenges and potential downsides. Some studies highlight the risk of marginalization within teams, where some students may feel excluded or undervalued (Mercier et al. 2023). Additionally, there is a need for a deeper understanding of how students experience collaboration in project teams and how team dynamics influence participation and engagement (Du et al., 2020; Henderson, 2023). These findings suggest that while collaborative learning fosters critical competencies, its implementation must be examined to ensure it promotes inclusive and equitable learning environments for all students.

2.2 Gender inclusivity in engineering

Masculinity in engineering extends beyond the numerical dominance of men, encompassing a deeply rooted culture (Aeby et al., 2019). Such cultural characteristics are often associated with competitiveness and technical dominance (Kamanda et al., 2022), which can influence how students experience teamwork. Gender stereotypes continue to shape role distribution and task allocation (Henderson, 2023; Svihla, Davis, & Kellam, 2023). For instance, Aeby et al. (2019) found that male students are more likely to take on tasks related to coding and maths, while female students more often handle report writing.

These dynamics are particularly challenging for female and underrepresented students, who may face barriers to participation, recognition, or leadership roles in teamwork settings (Isaac, Kotluk, & Tormey ,2023; Keough, Hirshfield, & Fowler, 2021). Being part of a numerical or cultural minority within a team has been linked to unpleasant or marginalizing experiences, which can affect students' academic motivation and confidence (Picard et al., 2022). In this context, there is a need to explore more inclusive and supportive approaches to teamwork in engineering education.

2.3 Well-being and academic success in engineering undergraduate programs

Well-being in collaborative settings often relies on peer relationships. Du and Kolmos (2009) found that students who engaged in collaborative learning formats reported feeling more motivated and perceived technical tasks as more manageable through peer-to-peer support than through individual study. Similarly, Stump et al. (2011) observed that women tend to be more inclined to collaborate than men, noting gendered differences in learning preferences.

Social capital—defined as the resources gained from interpersonal networks—has also been shown to play a key role in supporting students' persistence (Smith et al., 2021). For underrepresented students, such as

women and Black students, peer networks can be especially crucial in fostering confidence and retention, particularly by offering emotional support and access to academic resources (Henderson et al., 2023).

3 Methodology

3.1 Research design

This research is part of a larger project initiated in 2014, aimed at investigating the experiences of female students in Project/Problem-Based Learning (PBL) projects in engineering programs. A total of 72 individual and group interviews were collected at three universities across three European countries: the Technological University Dublin (formerly Dublin Institute of Technology) in Ireland, the Polytechnic Institute of Setúbal (IPS) in Portugal, and the Warsaw University of Technology (WUT) in Poland. The data collection was carried out by Professor Chance and her research team (Chance & Bowe, 2015; Chance & Williams, 2016; Chance, Williams, & Direito, 2021). In the years since, the research team conducted follow-up interviews with some of the participants. In the first year of interviews, the team sought to include all willing female engineering students at DIT and as representaative as possible a sample at IPS and WUT. However, follow-up were scheduled based on availability and opportunity (i.e., convenience sampling).

For this paper, the interviews used as data exclusively involve 32 interviews conducted with 13 students enrolled in engineering degree programs in 2014 in Dublin, Ireland, as this was the extent of our data showing change over time. These 13 students provided at least two interviews each, which facilitated identifying how participants' perceptions of teamwork and friendship had evolved.

The research adopted a phenomenological approach to understanding student experiences, and it encompassed two levels of analysis: (1) the exploration of individual women students' lived experiences in collaborative learning environments within engineering courses and (2) the role of peer support and friendship in promoting students' engagement in their courses and their sense of belonging in engineering.

The methodological approach we selected for this research places emphasis on women students' interpretation of experiences within collaborative learning environments. Ultimately, this examination is essential for understanding the extent to which these experiences are meaningful in fostering feelings of inclusion and belonging among participants in the field of engineering.

3.2 Participants and data collection

The study reports on the lived experiences of undergraduate engineering students at Technological University Dublin (TU Dublin) in Ireland. The longitudinal dataset comprised 32 interviews with 13 female engineering students from six countries. Group codes containing IR indicate Irish origin, ME indicates Middle Eastern origin, and FO indicates others (non-Irish, non-Middle Eastern).

Table 1. Overview of the 13 female participants interviewed

No	ID Group code	Country of birth	Years in Ireland*	Field of interest in engineering
1	IR02	Ireland	Since birth	Structural or manufacturing
2	IR07	Ireland	Since birth	Environmental engineering
3	ME01	Oman	2	Manufacturing and design engineering
4	ME02	Oman	3	Architectural engineering/civil engineering
5	ME03	Oman	1	Computer and communication engineering
6	ME04	Oman	3	Civil engineering
7	ME05	Kuwait	2	Mechanical engineering
8	ME06	Kuwait	5	Mechanical engineering
9	ME07	Oman	3	Civil engineering

No	ID Group code	Country of birth	Years in Ireland*	Field of interest in engineering
10	FO09	USA	3	Computer engineering
11	FO10	India	6	Mechanical engineering
12	FO11	Philippines	12	Mechanical engineering
13	FO12	Philippines	6	Mechanical engineering

* at the time of the first interview.

Interviews were conducted using a phenomenological approach. Each interview was 60 to 110 minutes long and occurred in a single sitting. They took the form of unstructured, open conversations regarding students' experiences in studying engineering, the pleasant situations and the more challenging ones, their experiences of working in teams, and their feelings regarding the predominance of males in the classes.

3.3 Data analysis

Based on the conceptual framework developed from a social phenomenological approach (Deep, 2020; Schutz, 1967a; Schutz, 1967b), we determined three general topics for description. Those topics were: (1) students' backgrounds, (2) students' experiences in engineering at college, and (3) students' plans. Within each of these topics, inductive coding was performed. Narratives with features in common were grouped as categories to help us identify patterns across participants (Saldaña, 2013). Within the second theme, seven subthemes were identified inductively. For this paper, only the subthemes about dynamics in formal study groups, informal collaborative support, and networking were considered; this allowed us to explore the team members' interactions and their development of friendships.

4 Findings

4.1 Challenging experiences for women students in PBL settings

In the early stages, the most common challenges for female students in PBL settings were related to group formation and being one of the few women—or even the only woman—on the team. The testimonies below indicate this is particularly problematic when a participant does not understand something but feels too shy to ask their teammates for help, or when they have an idea but feel ignored and must wait to suggest it again.

- "in the energy cube project, I was also in the boys' group. I couldn't say anything, maybe because I felt shy, don't know. And I can't connect with them." (ME02)
- "in semester one, and now also, I work with another group, with eight boys and just me. So… [laughs]. So, I should be, just like, I try to be fine with them and study. But… when I want to say a new idea for them about labs or experiments or anything, sometimes some of them…. When I speak, actually they say, 'No, this is a bad idea' or 'it's not strong idea. We just, we need another idea.' So when they start saying that, I feel like, inside me I, 'I will not say anything. I just, I will be quiet, and I will listen to them. And if there is something wrong, I can say my idea again'." (ME07)
- "in the bridge [project] I had three boys with me, and they were not listening to me as well. So I can't remember anything good about teamwork then as well." (ME03)

Another challenge mentioned by the participants was the distribution of roles and ensuring a fair workload for each team member. In the first-year interviews, we observed a bias among women, where they assumed that their male teammates knew more about the subjects, and as a result, they adopted follower roles. This may be linked to the perception that male students had prior exposure to engineering-related subjects at previous education levels.

In their testimonies, women participants:

1) joked around the secondary roles they could take: "[an Irish guy]'s a good drawer, so he did the drawings so then as well he did, you know, the dimensions on the cardboard. Like I was always joking,

like 'I'll make the tea!' Because they did Engineering for their Leaving Certificates, so they have a bit of knowledge about construction" (IR07)

2) noted they relied on male peers for technical explanations: "obviously, most of them have more knowledge on, I'd say, the technical stuff, or this and that. So, if I'm struggling with something, I ask them, and they'll gladly help me" (FO11); and
3) even relinquished leadership roles without questioning it. "I wanted to go for that [role], but [one of the male students] was very adamant about it. He really wanted to do that. So, I was just like, 'I'm not that enthusiastic about it, as much as he is, and it's a lot of responsibility'. So, I'll just let him have it. He likes to take charge!" (FO09)

Over time, this dynamic changed as women students realized that after some years in the major, most of them had similar levels of knowledge as the male students on their course. However, some participants felt that the bias against women persisted: "They knew that like, we've been in the same education and all that stuff to everyone perceives around the same level [… but] I noticed that some of them thought that I might not have known how to do it. I listen in class. I know how to do it." (FO11)

Over time, their self-confidence increased and that helped them navigate gender-based challenges.

4.2 Evolution from teammates to friends

Regarding the second research question – how do teamwork experiences in PBL settings evolve into friendships? – one apparent factor is the shared challenge of being one of the few women in engineering. Some students reported that their experience was more enjoyable when there was at least one other woman in the group, as it allowed them to support each other and speak up more confidently.

For example, student ME04 said: "In the Energy Cube [project] I had a Philippine girl. We were two girls and two boys. So whenever we have something, [we were] like 'let's tell them this or that'. It was much better. We were saying, 'Let's do this. Let's do that.' And we could understand each other better that way. I think that was a good group […] It was really good. Because we were all together, working together.

A student from the Middle East expressed the sense of empathy she felt when there was another woman in her team: "Sometimes you're saying: 'Why I'm doing the work with boys, and we don't have another girl in my group?' […] Maybe for girls, they can understand each other, you know – even if she's not Arab, not an Arabic girl, – but because she's a girl." […] Maybe she can understand your situation, being a girl in a group of three boys, so she can say, 'Oh, yeah, I can understand her feelings,' and so, we can offer and then help each other." (ME05).

Similarly, for Irish students, having another woman in the group also improved their performance: "I'm quite an anxious person. I don't particularly like standing up and talking in front of a large group. But I feel if I had to do that by myself, I wouldn't be nearly as confident. But working with [a Middle Eastern female teammate], bouncing ideas off each other, working off what each person said in the presentation, added a lot to it." (IR02)

Another factor that fosters friendships is vulnerability and reciprocity – expressed through asking for help to understand concepts or subjects and offering support in return. Participant F011 mentioned that in her first year, she hesitated to ask for help because she felt it would bother her teammates and she would be seen as less intelligent. Over time, she realized that everyone faced similar challenges and was willing to help each other: "In First Year, I had asked some people, but I didn't want to keep asking them because, for me, I felt I was just bothering them. One other thought I always had was, 'I don't want them to look down on me because I'm a girl. I don't want to sometimes ask them stuff because I don't want them to see me as below them or something like that'. Then, in the second year, I guess I carried on even though I did ask people occasionally, and if they explained to me and I didn't understand, I'd be like, 'Oh, okay.' Even though I didn't understand it because I felt bad having told them to explain it again. But then after that time where I was really frustrated […]. I started to ask more people like, 'Can you sit down and explain this to me because I

have no idea what's going on?' Then they're like, ''Yes, no problem.' They'd explain it. And I guess it's different when you're asking a lecturer and then you're asking your peers to explain it."

Similarly, participant ME05 explained how friendship developed through supportive teammates: "I was absent because I was sick. Then, when I came back to college and saw [my teammate]. I asked, 'What's missing, and what can I do?' And he said, 'If you want, we can go to the library, and then I can show you some works that you can do.' And then, we spent almost two and a half hours together, working on it because he wanted to help me catch up."

A crucial aspect of friendship is that, eventually, students develop trust in one another and attempt to solve their questions together by discussing them rather than always turning to the lecturer. In this way, having a circle of friends becomes a source of learning: "When I have a problem, I try to sort it out with my friends, sitting together and talking about how can I deal with this." (ME05)

Over the years, the reduction of the class size also fosters cohesion and friendships, not only because there are fewer students but also because of the working reputation of those who remain. The following student testimonies illustrate this:

- "I'm second year and the group's slowly been dropping. I think we're around 80 now because some people repeated, some people dropped out, [my female friend] as well. That's why now, one of the reasons I think that I got closer to other people is because it's a smaller class now compared to first year." (FO11)
- "[After] four years of working with the same people, you know who not to have in your group, as well [laughs]! A lot of those people that you don't want in your group didn't make it into Fourth Year anyway, so everybody is so driven this year. The issues of group work – of people not carrying their weight – you don't see it happening." (IR07)

4.3 Impact on self-confidence and emotional well-being

The third research question focuses on the impact of these friendships on the well-being of women students. Participants highlighted various aspects related to their self-confidence and emotional well-being. One key factor was receiving peer recognition for their technical competencies. When teammates valued their contributions and reassured them of their worth, they felt accepted – an experience that had a meaningful impact on their well-being.

For example, participant F011 described her emotional experience in completing a challenging group task: "It was in RoboSumo project. I was in charge of the programming and coding, and I was one of the first people to get the robot to move. So, when I got that done, everyone was like, 'How did you do that? Can you show us? Can you explain to us?' So, obviously, I felt kind of accepted.[…] Because I'm not trying to be sexist or anything, but guys are, most of the time, kind of prideful and they don't ask for help […] So, when I got the robot to move, and then everyone was asking for help, 'Will you show me how to do it?' And stuff like that, I felt like I belonged."

Another important aspect for participants is knowing that they have friends who genuinely want to be around them and offer support beyond the teamwork. Participant ME01 described it simply: "they take care of me, you know? If I'm stuck, they won't leave me like this".

The increase in friendships within the groups also leads to a shift from competitiveness to camaraderie, which may reduce emotional burden and stress. Participant IR07 explained: "In First Year I would have had a circle of friends, but now they're my circle of friends for three years and they're good friends, now. The competitiveness that I would have felt, probably directed to these people as well, is now very much like, 'well done. I'm proud of you for doing it too' […] So if, if I get 89% and my friend gets 90%, or whatever, I'm still really happy because I have got the first and I'm proud of her, or him, or whatever, for doing the same, you know what I mean? Because they are good friends now, like probably life-long friends.

Despite gaining self-confidence and a stronger voice in teams as they progress through the program, women students still struggle with self-doubt, which can prevent them from fully contributing to the team. Participant FO10 reflected on this and acknowledged that she sometimes perceives her teammates' feedback as a critique of her entire opinion, when it is perhaps just a disagreement with a specific aspect of her proposal. In her words: "I've more seen in other people's interactions that sometimes females tend to doubt themselves, even before someone says anything against their opinion. Say, for example, me or one of my female friends would be like, 'I think this is a good idea because of X, Y, Z.' Someone else says, 'I don't agree with Y.' My friend would doubt her entire idea rather than try and see if only Y was wrong. Correct Y, and then the whole thing will be correct. I tend to do that sometimes. If someone says anything against my opinion, I'm like, 'Yes, I'm wrong.' I need to tell myself, 'No, I might not be completely wrong. It may be half of it is wrong. I just correct it, and then, we're fine.' That is a big thing that I find myself doing, and I find other females doing. It's not really something I face from other people."

Conversely, losing friends who drop out of the program has significant implications for those who continue, particularly in finding a new group of friends. Participant F012, described her experience as follows: "Last year, we were together, so whenever we had an exam, she'd be like, 'Let's do this.' Or if she was feeling down, I would be like, 'Let's do this!'. But this year, she went back home because she said that she didn't like electrical engineering that much. So this year, it was kind of [sighs], but my classmates are really good. My Irish friends and my friends from Malaysia and China, we do work together and whenever we have questions we ask each other. They're very supportive."

4.4 Sense of belonging and academic engagement

The last research question centres on the influence of friendships on belonging to the field of engineering and academic engagement. In several instances, students described feeling encouraged when their contributions in group settings or peer interactions were heard, valued, and incorporated into the project, even when accompanied by constructive feedback. Furthermore, the testimony of participant FO11 offers insight into this sense of inclusion by highlighting the supportive nature of team interactions—not only when her peers offered help but also when she found that they respected her wish to try tasks independently first (instead of taking them over), so she could engage more actively in the learning process. She said: "I think when we're doing group work, and you can see that people are really taking into account your opinions, giving constructive criticism, and really applying it, it kind of makes you feel prideful, and then you feel like you belong. Obviously, it's a profession that's so dominated by men. And even it's seen in my labs, I'm the only girl there, everyone else is guys. I guess when we're doing stuff, and they ask for help, and then I ask for help, and then everyone kind of helps each other. In lab, I've never felt like I was pushed to the side, or by myself because the guys are very accommodating, and if they see that I'm struggling with something, they'll offer to help. They don't just take the stuff and do it for me. They are like, 'Do you want me to help you?' And then, at first, I'll be like, 'No, no, I'll try it first, and if I'm still struggling, then, I'll ask for your help.' And then they respect that. They know I'm like, 'No, let me do it first, let me do it first.' I kind of think that's where I feel I belong."

Finally, another key aspect is the role of emotional support from friends in academic persistence – and even in preventing dropouts. Participant FO09 described how the encouragement she received from friends and other students helped her reconsider dropping out of the program in her final year. The emotional support she received played a crucial role in her decision to persist. She expressed: "Well, I spoke with a lot of people – my friends here and other students. Obviously, I knew this in the back of my head, but to leave your final year is crazy. You commit to all these years, all the time spent studying, the money, whatever, the money that you could have made just working in whatever job, so it makes sense to stay. Somebody actually said to me 'You can't make decisions when you're emotional. Think about it, sit with it, drink over it, eat over it, think about it. Think about it for a few days, then make a decision'. That's stuck with me. It made sense. So, however, I feel, I'm still going to continue it. Do it. Do it to the best of my ability as well."

5 Conclusions and recommendations

5.1 Summary of key findings

Although many of the participants initially felt isolated or hesitant to speak up in male-dominated teams, based on the idea that their male peers were more knowledgeable on the subjects, their confidence grew over time, and they began to challenge the gender bias. However, subtle forms of exclusion still persisted and were acknowledged by them in the later stage of the engineering program.

Regarding the development of friendships, female students reported forming bonds with other women who shared similar challenges, offering mutual support and empathy. Additionally, asking for and offering academic help – through vulnerability and a commitment to reciprocity – helped build trust. Finally, sustained collaboration and smaller class sizes strengthened the group cohesion.

The impact of friendships on the self-confidence and emotional well-being of female students was strengthened by peer recognition, validation, and a sense of care. For the sampled women, friendships also contributed to reduced competitiveness and lower stress levels, easing the pressure to constantly prove themselves. Nonetheless, self-doubt and the experience of losing friends due to dropouts remained challenges in the later stages of the program.

Finally, the sense of belonging and academic engagement for these students was promoted by the validation and implementation of their contributions in team projects. Additionally, having the space to try out solutions independently reinforced the inclusive dynamic of the teamwork. Lastly, the emotional support from friends and peers proved effective in encouraging persistence.

5.2 Implications for educators and future research

Given the findings, we believe that educators should consider implementing strategies that foster meaningful peer interactions and collaborative support networks. Additionally, educators can play a key role in cultivating more inclusive and caring environments for learning that contribute to building a more equitable culture within engineering education. An example of this type of initiative is offered by Isaac et al. (2023).

Further research is needed to explore how friendships among female students can contribute to redefining the culture of engineering, particularly by creating environments where women's contributions to teamwork are recognized and valued rather than undermined. Additionally, future studies should investigate the role of social emotions in teamwork, including how feelings such as pride, frustration, empathy, and the like influence students' sense of belonging within engineering teams. Lönngren et al. (2023) provide valuable guidelines for researching emotions in engineering education. Finally, examining the long-term impact of friendships formed during engineering studies, particularly how they extend into professional collaborations and career development, could offer insight into the significance of peer networks promoted in PBL settings.

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Addressing wicked problems through empathy-enhanced design-based team learning: illustrating implicit and explicit approach

Jan Van Maele
KU Leuven, Belgium, jan.vanmaele@kuleuven.be

Diana Bairaktarova
Virginia Tech, USA, *dibairak@vt.edu*

Veerle Bloemen
KU Leuven, Belgium, veerle.bloemen@kuleuven.be

Inês Direito
University of Aveiro, Portugal; University College London, UK, *ines.direito@ua.pt*

Abstract

This practice paper aims at contributing to the conversation about caring pedagogies and sustainable engineering education by focusing on empathy, 'the ability to understand people by perceiving or experiencing their life situations'. Based on our experiences as engineering educators in Europe and North America, we offer examples of how design-based learning can be enhanced through the purposeful integration of empathy nurturing activities at every stage of the team project work. More specifically, we describe an approach in which empathy is an explicit focus of learning activities and an approach in which empathy is a more implicit learning outcome that is embedded within broader transversal learning goals. The design projects we offer as illustrations center on 'wicked problems' that affect various stakeholders beyond technical experts. By encouraging a decentralized, multi-perspective approach, wicked problems can enhance a caring pedagogy in project-based learning. By integrating empathy with technical expertise, be it explicitly or in more implicit ways, we highlight the crucial role of emotional intelligence, ethical decision-making, and interpersonal skills in engineering practice—an approach that cultivates responsibility and equips individuals to tackle real-world challenges with compassion and ethical insight.

Keywords: empathy, design-based learning, engineering education, wicked problems, project-based learning

1 Background and rationale

In this introductory section we sketch the rationale for structurally integrating empathy-nurturing learning activities in design team projects in engineering education to support students in addressing so-called wicked problems in the real world.

1.1 Wicked problems in design-based engineering education

Wicked problems have been defined as real-life issues that have no definitive formulation nor completion since they are both symptoms and causes of other problems (Rittel & Webber, 1973). The concept of wicked problems has facilitated discussions about the limitations of more traditional problem-solving approaches in which delineated puzzles are put to students, who are then expected to apply taught protocols and algorithms in order to arrive at a correct or optimal solution (Lönngren & van Poeck, 2020). Wicked problems do not lend themselves to such an approach, however. The tensions inherent in wicked problems are more suited to being approached as dilemmas or even more so as paradoxes that accommodate all sides of a tension in some synthesis (de Wit & Meyer, 2005; Van Maele & Vassilicos, 2013). In addition, wicked problems can enhance a pedagogy that fosters a 'caring community' (Rogers & Freiberg, 1994) by encouraging a decentralized, multi-perspective approach that calls for deep listening.

Design education offers a powerful platform for engaging with these wicked problems (Buchanan, 1992). In those complex, multifaceted challenges that resist straightforward solutions, empathy is emphasized as a core component of the creative process (Brown, 2009; Dorst, 2011). This is precisely because in design courses the design thinking philosophy serves as a foundation of the curriculum. Unlike traditional problem-solving approaches, which often seek linear solutions, the application of the design thinking framework encourages students to deeply understand the human context behind an issue, considering the lived experiences, needs, and values of diverse stakeholders (Kouprie & Visser, 2009). This empathetic grounding not only fosters more inclusive and sustainable solutions but also cultivates in students a mindset attuned to ambiguity, collaboration, and social responsibility (Mattelmäki & Sleeswijk Visser, 2011). As such, design courses are uniquely positioned to prepare learners to tackle wicked, global and societal challenges with creativity, critical thinking, and empathy.

1.2 Empathy-enhancing learning activities in engineering education

Empathy is defined as 'the ability to understand people by perceiving or experiencing their life situations' (Segal, 2011, p. 267). It involves putting oneself in someone else's shoes, seeing the world from their perspective, and sometimes experiencing their emotions as if they were one's own (Davis, 1994). In recent years empathy has been conceptualized as a concept for empowering engineering students to design and create solutions that are not only technologically sound but also ethically grounded and socially impactful (Bairaktarova, 2022; Walther et al., 2017). This has enabled educators to design a more structured pedagogical approach to nurturing empathy in engineering students through developing a variety of innovative learning activities, as the following resources illustrate.

Hermsen et al. (2023) apply 'perspective dialogue' techniques to support engineering students in dealing with wicked problems. In small groups students share how they would respond to authentic day-to-day situations that are provided by the instructors. Then they select 'guests' from a collection of well-known actual or fictional characters, represented by props - e.g., a Lisa Simpson doll, a poster of Nelson Mandela - and invite these 'guests' to participate in the dialogue and shed their light on the situation at hand. Adopting the perspective of these outsider guests provides an antidote to following familiar protocols and procedures, the authors explain. The activity aims to lead students to recognize their habits, perspectives and other underlying patterns as a first step towards valuing alternate ways of viewing and acting in day-to-day situations. In a similar vein, Walther and Sochacka (forthcoming) present various 'empathic imagination' exercises that can be used in the design phase of a study. These exercises allow students to become more keenly aware of one's own perspectives, assumptions and blind spots before gathering data through real-life interaction with the study participants. Examples include writing short vignettes about experiences that others who are very different from yourself may have; creating imaginary pieces of data (e.g., interview transcripts before the interview itself has been conducted); or role playing mock participant interactions. Each of these learning activities should be followed by guided reflection and is firmly geared at extending this empathic orientation into the actual data-gathering interactions. Sochacka et al. (2020), finally, provide probably the most comprehensive learning package for developing empathy in engineering education to date. The handbook includes 'empathic communication' learning modules on self and other awareness, emotion regulation and affective sharing, affective responding, and switching between analytic and empathic communication modes. In the module on affective responding, for instance, the authors highlight techniques as attending, paraphrasing, and reflective feeling, adding that teachers can heighten the learning effect by modeling affective responding themselves when facilitating plenary debriefs of learning activities.

Adding to these existing resources, we now turn to a description of how we have integrated various empathy-enhancing learning activities in design-based team projects in our own teaching practice. We will illustrate the points at which and the ways in which empathy nurturing can be mobilized to support student teams as they handle the different stages of the design process.

2 Empathy-enhanced design-based team learning in practice

In this section we describe how empathy can be cultivated in design-based team projects at the undergraduate and graduate level in the context of two engineering programs at a North-American and a European institution (see Bairaktarova et al., 2024, for further specifics about these courses and their respective educational contexts). Both projects provide practical guidance on how to cultivate empathy through various learning activities as described below. The courses share a common orientation towards supporting students in applying empathy effectively in their personal and professional lives. They do so by integrating empathy-enhanced learning activities in a structured and purposeful way throughout the design cycle, driven by iterative movements of divergence and convergence in both the problem and the solution space (Elmansy, 2021). However, they differ in the pedagogical approach they take to reach this end. In the

former course empathy is an explicit focus of learning activities while in the latter it is a more implicit learning outcome that is embedded within broader transversal learning goals.

2.1 Design-based project in a multidisciplinary course at bachelor level

The course, titled "Create! Ideation and Innovation" offers a semester-long, project-based exploration of empathy within the design thinking framework at a technological university in North-America. It begins with an explicit introduction of empathy as a critical component of design and problem-solving, and then moves into hands-on activities that allow students to experience empathy in action. These are several activities mobilized to this end roughly in the order in which students conduct them:

- One of the early in-class exercises is called "The Human Face" activity. Adapted from UNESCO (https://worldslargestlesson.globalgoals.org/resource/the-human-face-of-food-investigations-in-social-science/), this is one of the core in-class activities, where students use various materials brought to class to construct a 'face' that represents the human element central to their project. This creative process challenges students to visually express the diverse attributes and emotions of the end user, fostering a deeper connection to the people they design for.
- Another exercise students engage with through the semester is to develop storyboards (Buxton, 2007) that map out user experiences, encouraging them to visualize and plan the narrative of how their designs can impact real lives. The workbook of Greenberg et al. (2011) offers hands-on exercises and templates, including storyboard activities that could be directly adapted for design studio classes. If instructors are looking for more classroom activities or guidance for students, the Hasso Plattner Institute of Design (https://dschool.stanford.edu/innovate/tools)) could be a fruitful site for classroom activities, including storyboard design activities as they often integrate storyboarding into empathy and prototyping phases. Those resources are good for engineering and interdisciplinary design courses.
- To further immerse themselves in the user experience, another key exercise involves role-playing, where students perform the same tasks as their intended users, thereby stepping directly into their shoes. For example, in a design course focused on improving patient experiences in a clinic, students might first visit a local clinic or simulate a visit—from entering the building to checking in, waiting, and finally receiving care.

After this hands-on role-playing experience, they are asked to create a storyboard that illustrates each stage of the user's journey. The storyboard might include sketches and captions showing:

1. A patient arriving and struggling to find parking.
2. Confusion about where to check in.
3. A long wait time in a crowded, noisy waiting room.
4. A brief, impersonal interaction with a nurse.
5. Relief after receiving help but lingering frustration with the overall experience.

Through this visual storytelling, students capture not only the sequence of events but also the emotions and pain points that users may experience. This exercise encourages empathy and helps students identify specific opportunities for design improvements. Storyboarding, paired with role-play, thus becomes a powerful tool for understanding context and shaping user-centered solutions.

Weekly reflections and targeted questions on empathy complement these hands-on activities and help students connect theory to practice, encouraging introspection about how their design choices can impact diverse stakeholders. Throughout the semester, students work on the real-world project, engaging directly

with community members and industry partners to gather insights and understand the needs and perspectives of those affected by design outcomes. This immersive approach not only teaches empathy as a professional skill but also fosters personal growth, equipping students with strategies to integrate empathetic thinking into their daily lives and future careers.

2.2 Design-based project in a biomedical engineering course at master level

This second example pertains to a semester-long course for master students in biochemical engineering with a biomedical focus at a comprehensive university in Europe. The project revolves around a real-world problem introduced by a civil society stakeholder, who acts as the commissioner of the project. For instance, the manager of a horse owners' association raises grave concerns about an equine chronic liver disease that is assumedly caused by ragwort poisoning and asks the students to come up with solutions. Or a firefighter instructor wonders about the potential health risk of gases released by protective clothing after exposure to fire ('off-gassing') at the firefighter academy. In each case students are asked to come up with low-fidelity prototypes that address an aspect of the problem. Typically, all students work on the same problem in teams of three or four during seven full-day sessions spread out over a semester. The approach to developing empathy is implicit in that the instructors do not mention this concept when they introduce the tasks that require empathizing on the part of the students to bring the task to a fruitful end. Instead, the various learning activities are presented as ways for students to better understand and interact with key stakeholders of the issue at hand so as to arrive at more effective designs. These are several activities mobilized to this end roughly in the order in which students conduct them:

- Identifying, analyzing, prioritizing and mapping the parties and people who have a stake in the issue. Estimated expertise, influence, and willingness the relative position of each stakeholder group (Taylor and Bancilhon, 2019).
- Developing *personas*, i.e. fictional yet plausible representatives, for the key stakeholder groups and giving them a voice by narrating in the I-form a day in the life of each persona. These activities can enable students to gain a more concrete, 'emic' understanding of the different stakeholder groups (https://www.mindtools.com/a9rsycl/developing-personas).
- Brainstorming solutions to the issue from the perspective of the stakeholder personas ('figuring storming', Hansen, 2022) and engaging in other lateral thinking activities (such as the 'six thinking hats' of de Bono, 1986) for generating and exploring ideas from a variety of perspectives.
- Defining suitable stakeholder engagement approaches (Taylor and Bancilhon, 2019) and engaging with real-life stakeholders for checking one's assumptions, validating the personas, and collecting feedback about proposed solutions.

In contrast to the earlier described design-based team project, the concept of empathy is not explicitly introduced in this course nor is it mentioned as a desirable learning outcome. This choice was made to avoid potential adverse reactions and rejection by some students, who until that moment studied in an educational program and culture that hardly draws upon empathy as a valued asset. Instead, the instructors situate the described activities as contributions towards developing transversal professional skills, mostly under the name of stakeholder interaction.

3 Conclusion

In this short practice paper we introduced several tested learning activities for nurturing empathy in engineering education, supplementing the activities that can be found in related resources (Hermsen et al., 2023; Sochacka et al., 2020; Walther & Sochacka, forthcoming). These learning activities are conducted in the context of design projects and are aimed at equipping students with core competences for tackling wicked problems that reflect the world outside the classroom. Taken together, the presented activities

illustrate how design-based learning can be enhanced through the purposeful integration of empathy nurturing activities at every stage of team project work. By integrating empathy with technical expertise, be it explicitly or in more implicit ways, we intend to draw students' attention to emotional intelligence, ethical decision-making, and interpersonal skills as vital elements of effective engineering practice in real settings. As student reflections attest (Van Maele et al., 2025), this has been no vain hope.

By way of envoi, we would like to share this work with the reader within a 'propagation' paradigm (Sochacka et al., 2020). This means that much more than as a showcase, we offer this paper as an invitation to fellow educators, especially on the African continent where this conference is organized, to engage in dialogue with us so that we can exchange ideas and experiences on how empathy-nurturing approaches can be adapted to fit an ever-widening circle of settings in design-based team learning.

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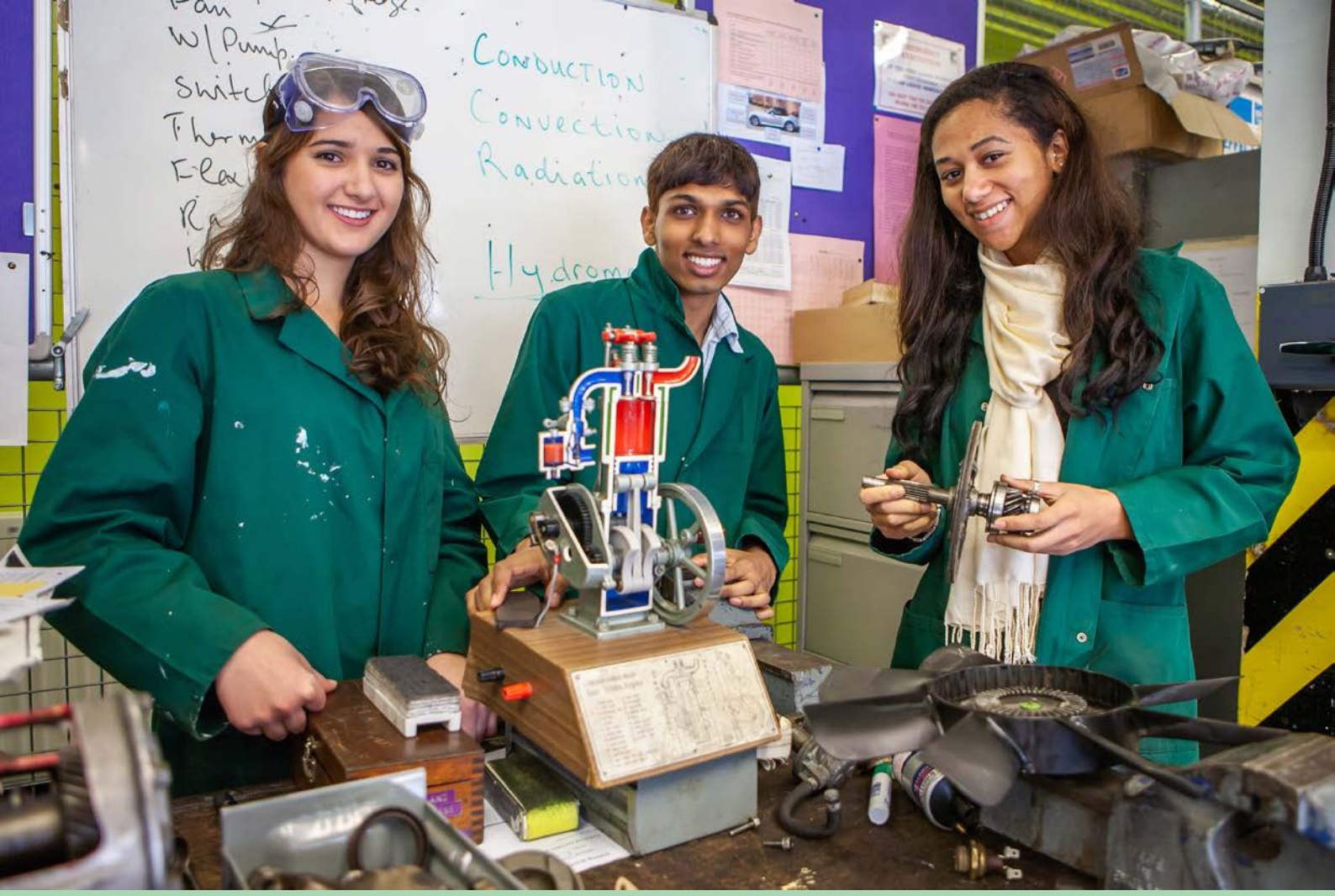

K12 & Vocational Education

Mapping High School Science Teachers' Approaches to STEMification: An Exploratory Cross-Case Analysis

Christian Skelmose Jensen
Aalborg University, Denmark, *christiansj@plan.aau.dk*

Søren Hansen
Aalborg University, Denmark, *sha@plan.aau.dk*

Bettina Dahl
Aalborg University, Denmark, *bdahls@plan.aau.dk*

Emilia Jun Nielsen
Aalborg University, Denmark, *ejni@admin.aau.dk*

Mette Møller Jeppesen
Aalborg Stadsarkiv, Denmark, *mette.moeller.jeppesen@aalborg.dk*

Camilla Guldborg Hundahl
Aalborg University, Denmark, *cgni@plan.aau.dk*

Sofie Otto
Aalborg University, Denmark, *sio@plan.aau.dk*

Jakob Farian Krarup
University College of Northern, Denmark, *jfk@ucn.dk*

Lars Bo Henriksen
Aalborg University, Denmark, *lbh@plan.aau.dk*

Lykke Brogaard Bertel
Aalborg University, Denmark, *lykke@plan.aau.dk*

Abstract

STEM teaching is a promising approach to increase student interest in science across educational levels as it integrates disciplines in engaging ways mirroring real-world applications, emphasizing practices such as problem-solving, critical thinking, and hands-on engineering design. However, teachers' approaches to implementing STEM teaching can vary significantly, depending on available resources, experience, subject, and contextual factors.

The STEMification model is a design and planning tool developed in the LabSTEM North project to support teachers´ professional development in STEM teaching. STEMification describes a teaching approach where students engage in science subjects and/or mathematics through inquiry-based learning (IBL) and/or problem-based learning (PBL) processes, involving experiential and collaborative STEM practices necessary to answer the students' own questions related to the topic. In this paper, we use the model as a mapping tool to explore ways in which high school science teachers apply PBL and IBL principles in their STEM teaching.

Applying the model as a mapping tool during interviews helped teachers visualize and compare different IBL/PBL principles combined with diverse approaches to develop STEM teaching. The mapping also helped in redesigning the STEMification model, aiming to make it more applicable as a STEM teaching design and planning tool.

Keywords: STEM Education, Problem Based Learning, Inquiry Based Learning, Creative Platform Learning, Teacher professional development

1 Introduction

Due to increasing demands from industry and society, European and American education systems share the common goal to develop pre-college students' (K12) knowledge, skills, and competencies in the fields of Science, Technology, Engineering, and Mathematics (STEM) (European Commission et al., 2015; National science & technology council, 2018). This interest in STEM education is also shared by researchers (Li et al., 2020). However, contemporary research depicts conceptual differences in the definitions of STEM teaching across science and engineering-related educations and highlights the need for a shared understanding of what STEM educations should contain (Holmlund et al., 2018). Even though businesses and governments are promoting STEM in the educational systems, new inquiries and recommendations are necessary to mitigate the expected lack of STEM graduates in the future and to increase diversity in engineering education and professions (European Commission, 2015; Pérez, 2021; Region North, 2019).

One major challenge is a measurable decrease in motivation for science, mathematics and engineering among pre-college (K12) students (Moskal & Skokan, 2011; Pleasants, 2020). Another challenge is supporting teachers to feel competent and confident in designing, executing and evaluating STEM teaching (Margot & Kettler, 2019). Thus, it is necessary to develop design and planning tools that better equip teachers to explore and apply STEM approaches in science and mathematics education.

An important attribute of STEM education is actively engaging students in learning science and mathematics (Holmlund et al., 2018). It is therefore vital to identify teaching practices that elicit student engagement and interest in science and mathematics teaching. Problem based learning (PBL) and Inquiry based learning (IBL), have been identified as promising teaching approaches that increase student engagement with both science, mathematics, and integrated STEM (Bybee, 2015; Holmlund et al., 2018; Minner et al., 2010; Portillo-Blanco et al., 2024).

Building on this, a central part of the LabSTEM North project is to gather knowledge of best practices from programmes or initiatives particularly successful in ensuring students' interest and diversity in STEM and science education (Bertel et al., 2022). Another central aspect is to develop new teaching approaches and practices through accessible and sustainable cross-institutional collaboration (Christiansen et al., 2022). An important aspect of development is to disseminate these practices to teachers in a way that allows for the

adaption to their own contexts and practices (Whitcomb et al., 2009). Even when teachers have similar learning experiences, they can have widely different ideas of what is important in STEM teaching and how to implement it (Holmlund et al., 2018).

To explore these differences in ideas and approaches, the STEMification model was co-developed by researchers and teachers throughout the LabSTEM North project as both a design and a planning tool for teaching in science subjects and mathematics while integrating STEM disciplines and practices (Lisborg et al., 2023). Based on interviews with 8 participating high school science teachers, the STEMification model was used to explore and map STEM-teaching developed by teachers in the project to better understand variations in their approach and potentials for further development. This mapping also contributes to further validate the model in how well it reflects this diversity in STEM teaching practices.

In the following, the theoretical background for and different aspects of the STEMification model will be explained, after which we present the research design and results from a cross-case analysis using the STEMification model as a mapping tool. Finally, we discuss how the mapping aligned with assumptions of teacher approaches, as well as future research.

2 The STEMification model: Background and theoretical underpinnings

The STEMification model (figure 1) was developed as part of the LabSTEM North project (Lisborg et al., 2023), in collaboration between Aalborg University and seven primary schools, ten high schools and one vocational school, with the aim to increase K12 students' interest in science and ease transitions in the STEM education system (Bertel et al., 2022).

The project uses a design-based research approach, where teachers design STEM teaching in cross-institutional and cross-disciplinary collaborations using a PBL and/or IBL approach. The STEMification model proposed in this paper is continually being tested and refined as the project progresses based on several iterations on developing and implementing teaching designs with participating teachers (Edelson, 2002).

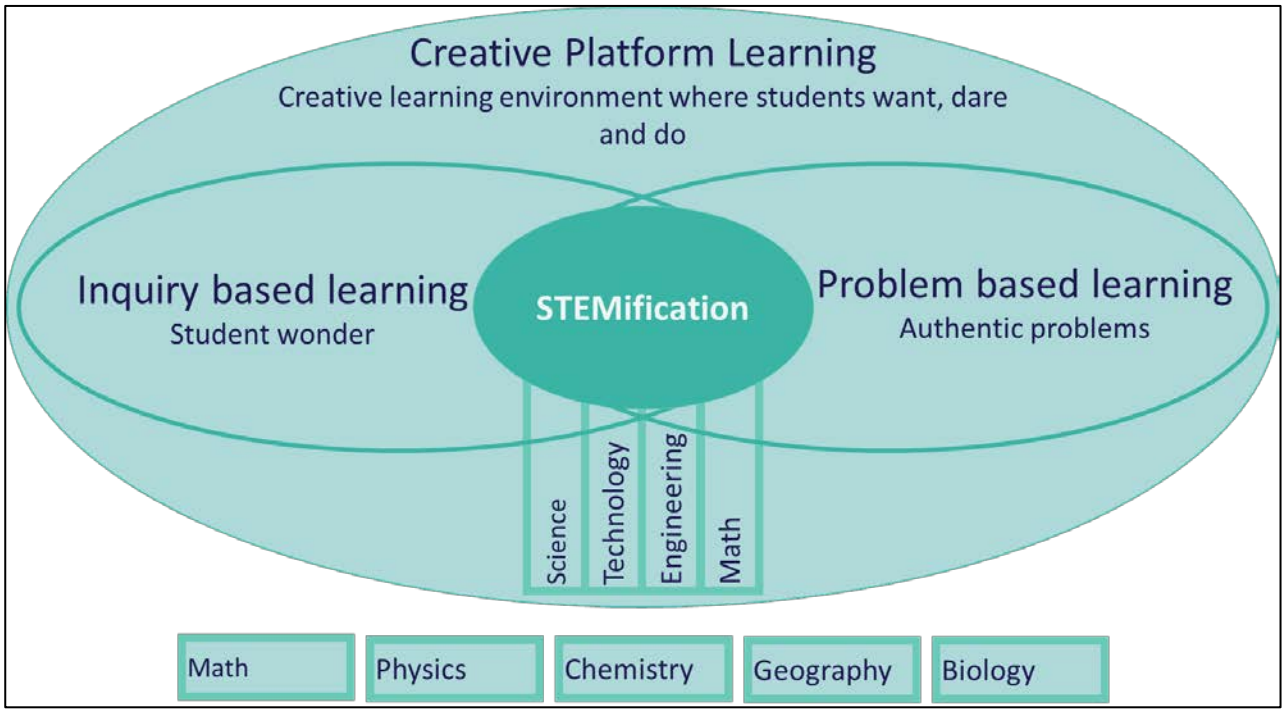

Figure 1: Model for STEMification of Science and Mathematics teaching

In the model, we understand S-T-E-M not as distinctly separate subjects or disciplines but rather as an integrated toolbox of knowledge, skills and practices that teachers and students can utilize and appropriate for particular purposes and learning processes (Lisborg et al., 2023).

This approach aligns with Bybee's (2013) ninth and most integrated model of iSTEM as transdisciplinary in which students can use *"the entire group of STEM disciplines, and perhaps others (e.g.: ethics, politics, economics) to understand a major contemporary challenge"* (Bybee, 2013, p. 78).

In this chapter we elaborate on each of the STEM practices and explain how we see these practices interact with PBL and IBL approaches in a creative learning environment.

2.1 Science practices

Science as a practice is focused on posing questions and constructing answers to these questions (National Research Council, 2012). The approach to answering these questions are also considered a part of scientific practice so developing models, analyzing data and engaging in argumentation has also been identified as important aspects of science teaching (Kloser, 2014; National Research Council, 2012).

In connection with STEM education, scientific practice has been highlighted as using and drawing on authentic practice of scientists (Kelley & Knowles, 2016; Roehrig et al., 2021). This approach is meant to increase students interest in science and give them the opportunity to engage in self-directed inquiry through construction of knowledge (Guzey et al., 2016).

We consider Inquiry based learning (Minner et al., 2010) and more specifically the 5E method (Bybee, 2015) as a didactical implementation of scientific method in a learning environment. The 5E method for example is exemplary in how it engages students in creating hypotheses and then constructing explanations.

2.2 Engineering practices

Engineering is a process or way to think about how to solve problems with a distinct purpose (Moore et al., 2014). Compared to the disciplines of S, T, and M, Engineering is described by specific processes that focuses on defining and solving a problem through iteration (National Academy of Engineering & National Research Council, 2014). Vries (2016) in trying to untangle engineering and technology specifies that engineering is the process of designing and manufacturing artefacts where it is essential to use theory and models.

As engineering works with solving problems it allows for integration of real-world problems and is considered an important aspect of STEM education (Moore et al., 2014; Roehrig et al., 2021). This integration has been shown to especially motivate female students (Miller et al., 2006). This also allows for the inclusion of ethics which has been highlighted as important aspect of engineering practice and engineering education (Roehrig et al., 2021; Vries, 2016). Ethics or compassion in engineering education is important to allow students to consider the social implications of their engineered solutions (Gunckel & Tolbert, 2018).

We define engineering practice as both one where problems are identified and analyzed with special attention to social aspects, and one where solutions to problems are constructed using theory and models.

With our definition of engineering practice above we consider the Problem-based learning approach as an implementation of the non-technical aspects of engineering practice. A didactical approach to engineering practice is for example the FITS model, which is an engineering design model that also focuses on content integration (Breukelen et al., 2016).

2.3 Technological practices

We apply a broad concept of technology, inspired by techno-philosophical approaches such as Carl Mitcham's distinction between technology as Knowledge, as Volition, as Artifact and as Activity (Mitcham, 1994), which signifies a shift away from the understanding of technology as merely "applied science" (de Vries, 2011).

Mitcham presents these four themes in a simplified causal relationship, illustrating how humans combine their technological volition with technological knowledge, thereby enabling technological activities that result in technological artifacts.

Technological knowledge, in contrast to scientific knowledge, is often context-dependent, non-propositional, normative, and socially embedded in practices involving both technical skill and ethical reflection, judgment and decision-making (Meijers & de Vries, 2009).

Thus, a technological artifact is "dual in nature", i.e. it has both a physical expression and an embedded intentionality that originates from the fact that it was created (designed and manufactured) by someone for a particular purpose (Nia & de Vries, 2016). However, this intentionality does not have a fixed relationship with the physical design and is overlaid by the users' interpretation of what purposes it can serve – technology is something we create, shape, and live with.

Thus, technological practice in teaching should reflect this duality, and include both the use of technological tools to enhance learning in an authentic manner that is similar to that of STEM professionals (Ellis et al., 2020). This could be using scientific measurement and computer programs to process and model the scientific phenomena. But understanding technology and its impact on the world around us is equally important, e.g. through teaching the history of technology (International Technology and Engineering Educators Association, 2022) or by fostering thinking skills such as systems thinking (Lavi & Bertel, 2024), design thinking (Ejsing-Duun & Hanghøj, 2019) or creativity (Hansen & Bertel, 2023).

2.4 Mathematical and modelling practices

Mathematics is an ancient discipline which involves both an abstract world of concepts but at the same time, a discipline applied in other fields as argued by Wigner (1960) who talks about "The Unreasonable Effectiveness of Mathematics in the Natural Sciences" Wigner here referred to the, perhaps surprising, fact that mathematical concepts and theories, abstract in nature and developed sometimes 100s years ago have application and predictive power beyond the context in which they were developed originally. In the US, the National Council of Teachers of Mathematics (2000) described mathematics using both process and content standards. The former here mentions problem solving, reasoning, communication, and connection as core aspects of mathematics. Likewise, OECD PISA writes about both content as well as mathematical reasoning, and the relationship between mathematical reasoning, the problem solving (modelling), mathematical contents, context and selected 21st century skills.

In this paper, we have a focus on the modelling and problem-solving aspects of mathematics, which invites extra-mathematical subjects such as science subjects. Andresen & Dahl (2023) described how problem solving is essential in mathematics, including problem solving from a creative angle. Hence, problem solving is not just about solving standard problems, but also open, or ill-structured problems which is aligned with both PBL and IBL. In addition, problem solving does not need to always involve extra-mathematical subjects but both PBL and IBL can occur within a pure mathematical realm finding patterns or solving theoretical problems as argued by Dahl et al. (2023).

2.5 Problem- and Inquiry Based Learning approaches

Working with real-world problems has been identified as an important aspect of integrated STEM education (Roehrig et al., 2021). In a literature review by Portillo-Blanco et al. (2024), real-world problems had been a central element of 26 of 27 articles that revolved around integrated STEM-education. The "real world" has been argued to work as a context for learning that provides motivation and purpose for learning STEM content (Kelley & Knowles, 2016).

PBL is a specific approach to using authentic problems and groupwork to enhance learning through solving these specific problems (Kolmos, 2016; Smith et al., 2022). In the STEMification model, the use of PBL as a concept is less focused on specific PBL models, and more on the principle of working with authentic problems as the point of departure for learning and a motivation for students to actively engage with science.

Inquiry-based learning invites students to ask questions and construct evidence-based knowledge in relation to these questions (Minner et al., 2010). It is often centered around students' self-directed examination of a question, and in this context, it would be a scientific or mathematical question. Inquiry contains many different models and approaches most notable being Inquiry based science education (IBSE) (Bybee, 2015). An Inquiry approach to teaching has shown to increase students interest and engagement in education (Friesen & Scott, 2013; Minner et al., 2010).

Specific instructional models and approaches have been developed for both PBL and IBL. In the context of this paper, we view them more broadly as guidelines for the teachers' approach to create more degrees of freedom for the students. Simply put; if students work within IBL, the students pose questions. They wonder about an aspect of science or mathematics that they can answer through experiments or research. If they work within the auspice of PBL they work with authentic problems, ideally identified by themselves, and attempt to propose and construct solutions to these problems using STEM knowledge and practices.

In practice, the two approaches overlap. While working on a problem, students may encounter questions of scientific nature that are necessary to investigate as part of understanding or solving the problem. Likewise working with inquiry can uncover new problems, ideas and solutions that the students had not previously identified.

2.6 A Creative Learning Environment

As mentioned above the IBL and PBL approaches are based on students working with self-identified questions and problems. It is therefore important that students can ask and pose interesting, creative and meaningful questions and problems. When students in an IBL or PBL learning process are encouraged to ask questions about something they do not understand or to pose problems for which they do not know the solution, they naturally experience uncertainty and maybe even anxiety. This calls for a psychologically safe learning environment, where students feel safe voicing questions and ideas, taking risks and experimenting without risking negative consequences for their self-image or social status (Edmondson, 1999; Edmondson & Bransby, 2023). A suggested learning environment for the STEMification model, where students feel safe to use their creativity is found in a process model called The Creative Platform (Byrge & Hansen, 2009; Byrge & Hansen 2014). The Creative Platform scaffolds a creative and psychological safe learning environment by facilitating a strong task focus in an evaluation free environment, where the students can participate as themselves without the risk of making mistakes or being excluded (Hansen & Bertel, 2023).

3 STEMification as a reflective mapping tool

While co-developing STEM teaching with teachers in the LabSTEM North project, it became clear that most teachers do not consider themselves STEM teachers, but solely teachers of mathematics or their specific science subjects. This could be emphasized by the fact that science in Denmark is primarily taught as separate subjects, e.g., biology, physics, chemistry, geography etc. rather than one common "science" subject. In high school, in particular, this separation is exacerbated further by the fact that high school science teachers major in their science subject first, with pedagogical training as an add-on rather than integrated throughout their education. Thus, for science to share experiences with STEM teaching, we first need to create a shared language for this practice. As part of this process, we wanted to explore the application of the STEMification model to understand the steps involved when a teacher STEMifies a learning process.

For instance, can the STEMification model be used to visualize how the teacher fosters students' initial curiosity, e.g. do they formulate a guiding question (inquiry) related to a science subject, or present an

authentic problem for students to solve? Or do they co-create the learning process by inviting students' own questions and concerns into the classroom? Can the model help illustrate how teachers bridge science subjects such as physics, chemistry, geography or biology, and the role mathematics play in their STEM teaching? What version of Bybee's nine STEM-integrations is most prominent in their teaching; are S, T, E and M considered overlapping disciplines, separate silos, or all encompassed in one over-arching 'S'?

4 Method

To explore these questions further, we selected two cases in conjunction with a teaching development process that was facilitated by the LabSTEM North project at a high school in northern Denmark.

The cases are built on an initial workshop that served as a starting point for the teaching design process introducing the STEMification model and the fundamental aspects of the model i.e. IBL, PBL and STEM-education, followed-up by a guidance session with each teacher of 30 minutes and a group-based exercise where four teachers shared their teaching design and the accompanying thoughts and reflections on the process up to that point. Two months after the initial workshop, a reflective meeting was held, where the teachers shared experiences and feedback with each other and participated in individual semi-structured interviews with a researcher, reflecting on their experience with developing and carrying out STEM teaching. While the interviews contained more data pertaining to other aspects of the process, for example efficacy of the modules, needs of students and ideas about specific STEM disciplines, the data analysis in this paper focuses specifically on mapping the STEM modules according to the STEMification model.

3.1 Mapping approach

This paper uses a descriptive case study methodology (Priya, 2021) to map how the teachers develop STEM-teaching modules within the LabSTEM-North project using the STEMification model. For the analysis of the data sets, a deductive meaning condensation was used (Brinkmann & Kvale, 2018). This was performed by identifying the sections of the interview that describe or discuss the development of the teacher's STEM teaching and describing them with a short instructional design and action description.

The mapping is then done by arranging the instructional design and action descriptions identified by the meaning condensation analysis method, so that they show the timeline of the teaching module from beginning to end. The beginning of the narrative of the module has been chosen to be the teachers' reasoning for creating the teaching module. In the coding, a teacher-led action was colored blue and a student-led action colored orange. An action is defined by going from one step of the module to the next.

4 Results

In this section we will present the two cases selected for mapping in this paper. The analysis of each module and the following visual mapping with the STEMification model is described below.

4.1 Case A: CO_2 – Friend or foe?

This module was developed and implemented with a second-year high school chemistry class. The teaching goal for the module is addressing core curricular goal for chemistry called Inorganic chemistry, this is introduced with the initiating question "CO_2 – Friend or foe?" following the 6 steps outlined below (see mapping in figure 2):

	Instructional design	Teacher/student actions	STEMification
1	Present guiding question	Introducing CO_2 as a substance, why it is harmful/posing exploratory questions: *"What can be done to mitigate the effects of CO_2 or reduce emissions?" "Can CO_2 be harnessed for good purposes?"*	Engage through curiosity/ dilemma
2	Initiate students' open-ended questions	Initiating an open-ended process, where students in groups pose questions or identify problems within the initiating question.	Collective inquiry
3	Collecting questions/ problems	Students identify varied questions and problems that they want to work with, not necessarily strongly linked to the chemistry curriculum.	Collective exploration of problem space
4	Connecting with core concepts	Meet with every group to connect their focus of interest to chemistry knowledge and curriculum and guide them in this process. The teacher called this process "Chem-ification". This guiding process also include changing the students' questions if they were too difficult to integrate the subject knowledge.	Subject/ curriculum anchoring Containing of curiosity.
5	Research	Students research their problems/questions themselves with guidance from the teacher, e.g. one group researched Power-2-X technology and associated chemistry knowledge, while another group analyzed the issue of using arable land for growing biofuels, otherwise useful for food production.	IBL/PBL Apply Technology and Math practices
6	Share / discuss	Students present their work to a group of geography students to create knowledge sharing between the two classes and create motivation for the students. The teachers from each subject circulated between the mixed groups. The chemistry teacher reported good engagement and discussion between the groups and the students expressed that this activity was meaningful to them.	STEM-integration by overlapping

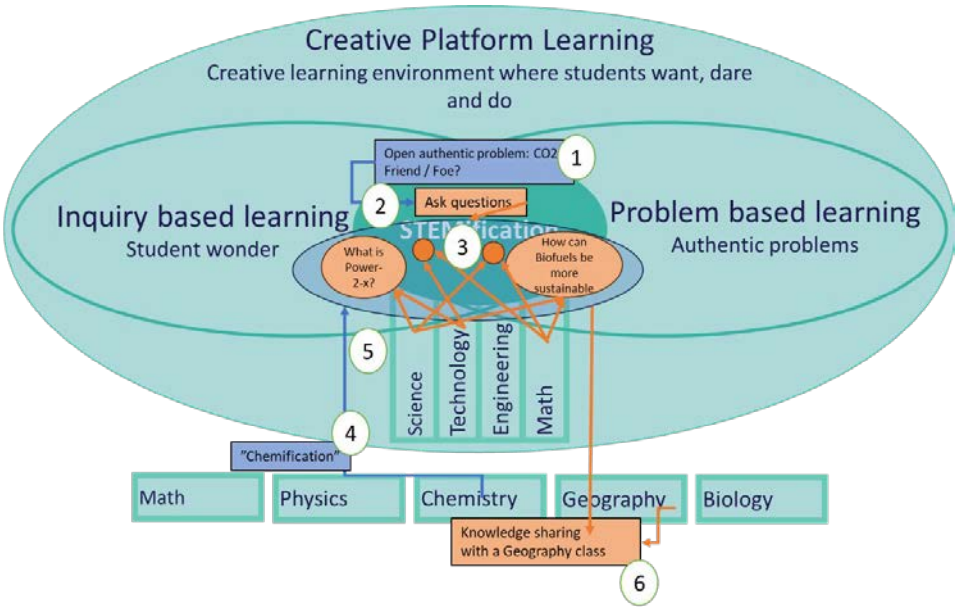

Figure 2: Mapping of Case A STEM teaching module

In this case the students expressed frustration with the module as they felt it needed more structure and a clearer goal of what they had to achieve coming from the teacher. When asked, the students would have preferred a stricter module with specific tasks and questions they could easily answer. This frustration could indicate two things, the teacher needed to be clearer about what the product was supposed to be and how the students got there, it could also indicate that students in this class were uncomfortable with self-directed learning since they would have preferred a teacher directed module.

4.2 Case B: SpaceX & Blue Origin – How can we safely land reusable rockets?

This module was developed and implemented in a second-year high school physics class. The teaching goal for the module was related to the curricular core goal for physics of mechanical forces along with the requirement that students had to do some form of experimentation. The module followed the 6 steps outlined below (see mapping in figure 3):

	Instructional design	**Teacher/student actions**	**STEMification**
1	Visualize relevance of problem	Initiating with short video of reusable rockets exploding on landing, and authentic framing problem *"How can we safely land these reusable rockets?"*	Engage through problem
2	Open-ended engineering design process	Students have to engineer a lander and find a method for measuring the mechanical forces that affected the lander. All groups apply a similar approach involving a parachute to slow down an object	Apply Technology, Engineering practices
3	Experimentation and documentation	Students record the landing experiments, calculating to estimate the speed and forces involved.	Apply Science and Math practices
4	Presentation of product and process	Groups present their findings, and the methods applied.	STEM-integration by overlapping
5	Share/discuss	These presentations lead to a realization among the students that they had not all used the same calculations, thus inquiring about more ways of calculating.	Collective reflection on learning goals and knowledge gaps
6	Follow-up lecture	Teacher presentation of the additional physics formulas.	Subject/ curriculum anchoring

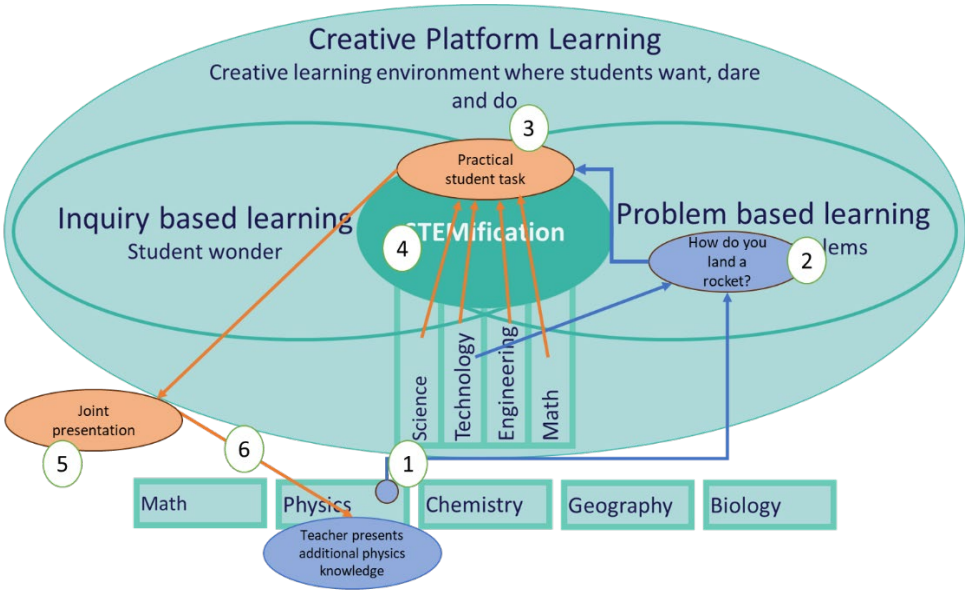

Figure 3: Mapping of Case B STEM teaching module

In this case, the physics teacher expressed some disappointment in the interview with the uniformity of the students' solutions and experiments. From the perspective of the STEMification model, this conformity could perhaps be mitigated by facilitating more of a creative process between Step 1 and 2, using CPL to ideate different ideas to solutions prior to the open-ended part of the task.

5 Discussion

While the participating teachers in the LabSTEM North project identified as science subject teachers more than STEM teachers, the STEMification model helped make explicit the distinction between science subjects and STEM practices while also highlighting the potential of STEM disciplines and practices to enhance the learning of science subject content and mathematics.

The mapping is part of our design-based research approach to co-creating STEM teaching together with participating teachers and exploring the model's applicability as a teaching design and planning tool. It is an iterative process, and these mappings should be seen as part of an ongoing development in improving and validating the model as a tool for teachers.

Our initial assumption was that teachers would begin the design of a module by deliberately choosing appropriate STEM practices relevant to the subject and defined learning goals and afterwards choose an IBL or PBL approach based on what the module required. However, the integration of STEM practices in the mapped modules seem to be less structured and are applied by the students on a basis of what they consider is needed to answer their questions or solve their problems, with little guidance from the teachers. A similar observation was made by Andresen & Dahl (2023) in mathematics class, who suggest students that are not sufficiently guided by the teacher in working with creative and independent work, will choose less complicated methods for problem solving. This is potentially also one of the reasons why all the students in Case B used the same engineering method for solving the problem of landing a rocket. It suggests that to properly support students in creatively integrating STEM-practices in open-ended IBL or PBL processes in science teaching, the teacher needs to clearly scaffold creative thinking. Thus, this too needs to be explicit in the STEMification model for it to be useful as a design and planning tool.

5.1 Limitations and future work

The project design has focused on teachers' perspectives on designing and co-creating IBL/PBL approaches in STEM teaching using the STEMification model with the purpose of increasing K12 students' interest in science subjects and mathematics as well as STEM professions, however we did not investigate the impact of these designs on student learning and level of interest in STEM. This perspective could be included in future research to contribute to a deeper understanding of the model's impact on STEM teaching and student engagement in STEM education.

The model suggests supporting the STEMification process with a safe and creative learning environment to support students' confidence in exploring problems and posing questions as part of their participation in a student-centered learning environment. The mappings show, however, that this aspect was not explicitly incorporated into the teaching designs or learning goals, thus this will need more attention in future iterations of the STEMification model.

The proposed mapping methodology utilizing the STEMification model was found to be useful in articulating the different intentions and steps in the teaching designs and how they link with particular STEM practices. However, the model needs further refinement particularly as it relates to IBL and PBL processes to provide practical and structured guidance for each step, to support the design and implementation of science teaching that actively engage students in open-ended student-centered STEM practices that reflect and increase their interest in STEM professions. In future work, integrating tools such as generative AI to provide such structured guidance will be explored.

Finally, to assess the efficacy of the model in teacher development, future research will examine how teachers can utilize mapping techniques to support not only planning processes, but also a community of sharing and continuous evaluating STEM teaching, in Denmark and in other countries and contexts.

6 Conclusion

In this article we have applied the STEMification model as a mapping tool to visualize STEM teaching designs in two cases of science teaching in a Danish high school context. The mappings show two different approaches to developing and integrating inquiry- based and problem-based learning with STEM practices. inspired science teaching in a Danish high school context. A commonality of the two approaches is a student led integration of STEM practices to answer the students' questions or solve problems. One of the biggest differences was that the chemistry teacher approach was open ended in inviting the students to freely ask questions or identify problems. The physics teacher started with a more closed problem that all the students in the class had to work with but elicited an environment that allowed them to draw practices from all four STEM disciplines.

The model distinguished between what actions and processes were performed by the teachers and which ones were performed by the students. This approach results in mappings that visualize to what degree the modules are student or teacher centered.

6.1 Acknowledgements

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Working in a problem-based manner with mathematics and crafts gives meaning to mathematics at Danish vocational schools

Bettina Dahl
Aalborg University, Denmark, bdahls@plan.aau.dk

Søren Hansen
Aalborg University, Denmark, sha@plan.aau.dk

Jette Schaarup
Hillerød Technical School UNord, Denmark, jets@unord.dk

Lena Lindenskov
DPU Aarhus University, Denmark, lenali@edu.au.dk

Frank Justesen
Tradium Technical School, Denmark, frju@tradium.dk

Abstract

Students at Danish vocational schools often struggle with learning mathematics and finding it relevant. In response to this, the project KLUMP ("competence lifting of mathematics teachers at vocational schools") offered professional development of mathematics teachers and craft teachers through facilitating collaboration on creating teaching materials bridging mathematics and the craft. Five teams were established consisting of one mathematics and one craft teacher in the following areas: carpenter, blacksmith, mason, mechanics, and electrician. The teachers joined KLUMP voluntarily, and the school management supported KLUMP by coordinating time schedules and joining project seminars. The teachers selected relevant topics, where they developed, tested, evaluated, and refined their teaching material. The teachers received inspiration in workshops on, e.g. emergent modelling, inquiry- and problem-based learning, and concepts such as self-efficacy. A central theme is Jaworski's notion about learning communities. KLUMP found that the frameworks of a "bridge" between mathematics and crafts and emergent modelling were easy for the teachers to use. The students were happy when they experienced the bridge. Structures such as timetable planning, teacher allocation, and institutional support were essential for KLUMP to become successful.

Keywords: Mathematics, Vocational education, Teacher professional development, Upper secondary, Learning Community

1 The need for mathematics understanding and vocational education in Denmark

In Denmark, major technological developments have intensified the need for craftsmen to have more skills in mathematics. For instance, a mechanic connects electric cars to a computer to find the fault. It is no longer enough to open the bonnet or look at the mechanical parts. The soil and concrete worker has now replaced the shovel with large, expensive excavators. Therefore, today's craftsman is required to be both a theorist and a craftsman. This technological development alongside retirements from the workforce due to age means that by 2035, Denmark lacks around 150,000 people with a vocational degree, out of a population of 6 million (DA Analyse, 2023). Therefore, a high level of mathematics as well as a propensity for learning a STEM-subject, particularly in vocational fields is more important than before. Sadly, it is going the wrong way with the mathematics achievements in the Danish compulsory school system. The OECD PISA investigation from 2022 showed that mathematics achievement is falling, and there is now a larger proportion of low performers and smaller a proportion of high performers than before (Christensen et al., 2023). The written school leaving exam grades (9th grade) has also dropped (Bjerril & Fahrendorff, 2024). The TIMSS study for 2023, in addition, found that the students' motivation for mathematics has declined since 2015 as well as their self-confidence in mathematics (Kjeldsen et al., 2023). Good mathematics grades (minimum '7', equivalent to grade 'C' on the European ECTS-scale) reduce the likelihood of dropout from a vocational education, while age and wellbeing are also important (EVA, 2023). Thus, the need for raising the level of mathematics understanding and the students' desire to study a vocational STEM subject is urgent.

Professional development of teachers is therefore essential. Only a few research and development projects in Denmark have explored these issues (Lindenskov, 2014; Lindhardt et al., 2025). Our project, KLUMP, focuses on professional development of teachers in various STEM vocational programmes, particularly for first-year students. The Danish education system consists of a 10-year compulsory unit school from grades 0 (aged 6 years) to grade 9. After this, youth can choose between a variety of general academic high schools (*gymnasium*) and a variety of vocational education and training (VET) programmes (Eurydice, 2024). The four main vocational fields are: (1) Care, health, and pedagogy, (2) Administration, commerce, and business service, (3) Food, agriculture, and hospitality, and (4) Technology, construction, and transportation. This paper focuses on programmes within the latter.

2 The diverseness of vocational teachers in Denmark

Teachers at vocational schools have very different backgrounds. The craftsmen teachers who teach in the workshops where the craft is being learnt prior to and parallel with apprenticeships, usually have a craft or vocational background, but little didactical training. The subject teachers, like mathematics, have the 4-year Professional Bachelor's Degree aimed for teaching in the compulsory school, but with typically no craftsman experience. Craftsmen teachers must take a full Professional Diploma (PD) in teaching, which corresponds to two years within a 6-year time limit. Hence, the teachers have a very diverse background.

Based on Jaworski's (2005) concept of "Learning Communities" (LC), we see a potential strength in the diverse backgrounds of the vocational teachers. Both types of backgrounds are valuable, and the teachers can learn from each other – and from educational research. A distinctive feature of LC is that all members are considered equal and learners in professional discourse. Mutual respect is essential. Another distinctive feature is a recognition that teachers do not only "receive" information from experts (e.g. researchers) and then simply implement these ideas. Teachers are seen as translators and interpreters of the knowledge presented to them by researchers into the practice they teach. Teachers have central knowledge of their practice, both in terms of students, the subject matter, and the subject area, and they are therefore also inventors of teaching methods and materials. This means that VET teachers in KLUMP are considered as experts in their own practice, and with unique insight into their subject area. Similarly, researchers and consultants participate on an equal footing with teachers as sparring partners in the process - not as judges.

3 The KLUMP project

The purpose of KLUMP ("competence lifting of mathematics teachers at vocational schools", an acronym in Danish) is to find and communicate answers to how mathematics and craft teachers can achieve professional teacher development through collaborating on teaching, particularly on developing joint teaching material.

3.1 Organisation of the KLUMP project

KLUMP consisted of a consortium of Aalborg University, NCUM (National Centre for the Development of Mathematics Teaching) at Aarhus University, and Tradium Vocational School in Randers. KLUMP took place with teachers and students from Tradium. Teacher teams (pairs) consisted of a craft teacher in a VET programme with a considerable mathematics content, and the same programme's mathematics teacher. Five teams completed the tasks. The carpenters' mathematics teacher was on the KLUMP steering board representing Tradium (fifth author). Each team selected relevant areas in their teaching and analysed, developed, tested, evaluated, and refined the lessons. This included co-teaching, hence being in each other's room (workshop versus classroom), for some for the first time. The new lessons were intended to make mathematics more accessible and relevant for vocational students by creating a bridge between mathematics and crafts. The teams got feedback for further reflection from consultants, where one was a university researcher (second author), the other a VET teacher from another vocational school (third author). The consultants also documented the project through interviews and observation of the students' reception of the new teaching, as well as the teachers' experience with participation in the LCs. The evaluation primarily consisted of a combination of qualitative interviews and observations of students and teachers (Kvale & Brinkmann, 2014; Robson, 2002). The analysis uses Bishop's (1988, 2017) framework on the interactions of mathematics education with culture, where culture is understood broadly to include occupational cultures. A central idea here is that mathematics is practiced differently in different cultures.

KLUMP ran August 2023 – May 2025 and was funded by the Novo Nordisk Foundation with DKK 1,423,948 (ca. 190,000 EUR). The autumn of 2023 consisted of establishing the teams, providing the teachers with an Inspirational Workshop, beginning the work with developing the lessons, and interviews with teachers and students. The interviews were done by the consultants and focused on how the students viewed the relevance of mathematics and finding out what challenges the teachers experienced. During the spring of

2024, the last lessons were developed, tried out, evaluated, and revised. To do this, KLUMP organised an Inspiration and Knowledge Sharing Seminar with KLUMPs Advisory Board. Unfortunately, some of the developments were delayed due to, e.g., teachers leaving the school for other jobs, and therefore, some of the final development and trying out of the lesson were postponed to the autumn of 2024. In November 2024, KLUMP held its Final Conference sharing its results with vocational teachers, developers of teaching materials, and researchers in VET from the whole country. About 35 people participated. The spring of 2025 focused on the documentation and dissemination of the results and lessons.

3.2 Theoretical underpinning

At the Inspirational Workshop in the autumn of 2023, researchers (first and fourth authors) and consultants in KLUMP presented some theoretical frameworks for inspiration. One was “emergent modelling” (EM) by Gravemeijer and Stephan (2002). In EM, the focus is on four stages of the students’ learning. At the beginning, the situatedness is in focus, i.e. the students’ own informal strategies, later comes a specific reference to a subject, after which comes the general, formal, and generic. The model creates a connection from practice to the formal mathematics. We, however, extended the model to create a connection both ways, namely also creating a connection from formal mathematics to practice, i.e. a bridge between practical knowledge and formal mathematical knowledge. Teachers were also introduced to principles and examples of inquiry-based learning (IBL) and problem-based learning (PBL). These teaching methods have in common that the teaching is based on a specific problem in context, where students acquire mathematics through problem solving and modelling (Artigue & Blomhøj, 2013; Kolmos et al., 2004). Finally, teachers were also made acquainted with the concept of “self-efficacy” (Bandura, 1997) which means that if students believe that they can handle a challenge, they will be motivated to get started and to overcome any difficulties along the way.

4 The case of blacksmiths

Due to page limitations, we can only provide details from one of the teams. However, in Section 5, we summarise some of the overall findings across teams. The blacksmith team moved the mathematics teaching to the workshop. The classes were co-taught, and the teachers had several meetings developing the material. The example in Figure 1 is an explanation of what they did with the students when teaching them some mathematics calculations prior to plate rolling.



Figure 1: Blacksmith-Mathematics in the workshop. Here the mathematics teacher (white sweater) illustrates to participants at the KLUMP conference the plate rolling calculations he did with the students. The craft teacher stands next to the mathematics teacher. Conference participants are around the table. The first author took the picture.

The mathematics teacher explained that he normally does the standard generic mathematics formula with the students in the classroom, but that the collaboration with the craft teacher taught him that since material expands during plate rolling, his calculation would be wrong. He should not use the diameter when calculating, but the mean diameter. Then all would be correct. The mathematics teacher taught this in the

workshop, with the craft teacher telling the students, that they should now listen to the mathematics teachers, as "what he is saying is very important". By doing that the craft teacher also acknowledges mathematics and the mathematics teacher as important and valuable in the education as blacksmith, which can increase students' motivation for mathematics.

From the interviews with the blacksmith-students and teachers, we learnt that overall, the students are positive towards bridge-building between mathematics and the craft. However, it was not without practical problems moving the mathematics teaching to the workshop. One problem was that using a black/white board is not always easy in a workshop. This was solved by putting up chairs in a half-circle. Another problem was disturbances such as noise from other people working in the large workshops. This clearly presents a dilemma: By moving mathematics into the crafts, a multitude of distractions appear, which may hamper the students' learning. Both the mathematics and the craft teacher learnt a lot from each other's field.

Two concrete observations: One blacksmith student who according to his teacher usually did not like mathematics, discovers that the mathematical calculation with the mean diameter makes his plate rolling fit perfectly. It became very motivating for him to get useful mathematics competencies. This also contributed to the self-efficacy of the student. It was also observed that it was literally "hands-on" when some of the students put their hands around the cylinder to get an approximate measurement of the diameter, and when they used a string for the circumference and then suddenly grasped what diameter means. Concretely, the students said (all quotes are translated by the authors to English): "Mathematics in the classroom is boring – much better in the workshop where one can see the meaning of it"; "Like the mathematics that is useful as a craftsman", "Would like more mathematics in the workshop". However, we also learnt that some of the students hated being filmed, which meant that on the days when we were filming, which the students knew in advance, less students were present.

5 Overall results for all teachers and students

From the interviews and observations, it was evident that collaboration between a mathematics teacher and a craft teacher is efficient and enjoyable for both. Mathematics aimed at the craft is central for the students who like that the mathematics teacher also teaches in the workshop and the craft teacher also teaches in the mathematics classroom. Mathematics gives meaning for the students when it is relevant and interesting to them, and when the mathematics language is understandable. This was regardless of mathematical level being targeted in class. The students remember mathematics better and they did not get so tired. These findings are in line with the theoretical frameworks of problem- and inquiry-based learning in which relevant problems are motivating to students.

The table below gives an overview of some general experiences across the five teams.

Table 1: The experience of KLUMP on several factors.

Teaching	Collaboration	Frames	Students and classes
We experienced:	Teachers said:	We experienced:	We experienced:
- Craft-related math is the only right thing - Using the hands makes math easier - More motivating than traditional teaching - Bridge-building can happen everywhere - Positive to see the two teachers together, ping-pong between them	- Collaboration is the only right thing with crafts math - Requires joint meetings - Requires management and schedule planning on board - Would be useful with a common teacher room - Know each other's schedule - Develop a mutual language - Respect for each other's fields	- The workshop gives more differentiated teaching - The classroom gives a shared presentation for all students at the same time - Difficult to get access to the workshop as a math teacher without a craft	- The math content should give meaning and be relevant to the students - Prefer classes with only one craft, not mixed - Prefer teaching the same formal level of math in a class - Good if math classes are located in the crafts

Building bridges worked both when mathematics was taught in the workshop, and when crafts were taught in the classroom. The two teachers in each team met more frequently about the development of the teaching material compared to before. A collaboration like this, however, demands time, overview, and resources. It is not enough to encourage teachers to collaborate if teachers in practice are busy, located in different buildings where it takes time to move to and from. In a busy daily life, collaboration does not happen. Operation trumps development, which is seen if, e.g., a teacher is sick, and another teacher needs to take over, and this will always have priority. A part of the KLUMP budget gave release to the participating teachers, so they had less teaching than normal to be able to develop the teaching materials for KLUMP.

6 Conclusion – and some how-to suggestions

The five teams chose different approaches for collaboration which all seemed to work. This means that one does not have to choose among (1) mathematics entering the workshop, or (2) the craft entering the mathematics classroom. KLUMP shows that teachers are motivated by spending professional time with other teachers and sharing experiences, and teachers are motivated by seeing more mathematics in the profession.

Students supported what happened in KLUMP as it created meaning with mathematics. Motivation is promoted when students discover that they use mathematics skills to find solutions and streamline their craft. It is essential to create situations in the teaching where the students experience that they are successful. This creates learning and helps the students' self-efficacy. Wellbeing and feeling safe are also essential in order for the teachers to enter into such a collaboration. Teachers open their classrooms/workshops to someone else, and they go into unknown territory.

Teachers supported KLUMP but they were challenged by the difficulty of finding meeting times in a very full teaching schedule. Better scheduling, allowing for teacher meeting times, stable employees so the "investment" in the development can be applied many years ahead, and shared teacher rooms are desired. It is therefore necessary to have a system perspective on teacher development. Without the practical support from the administration in terms of actual planning of when the teachers could meet, including release from teaching/time to do the development, it is not possible. Also, there needs to be facilitators to inspire and push the project to give inspiration and feedback to the teachers on how the implementation goes.

KLUMP found that the frameworks of (1) a "bridge" between mathematics and the crafts and (2) emergent modelling were easy and intuitive for the teachers to use. But the bridge-metaphor can also be discussed. It was an advantage that the metaphor focused on the fact that mathematics and vocational subjects can and should meet, as well as the fact that they can meet many places on the bridge, including at the ends. It may be a disadvantage of the metaphor that it leaves the two places 'mathematics' and 'craft' untouched, and that the bridge itself remains at the same level. Something happens at both places when you collaborate with each other and when you have 'raised your skills'.

Learning mathematics is much more than cognitive and learning to manipulate symbols, as described by Bishop (1988, 2017). Learning mathematics is to become 'enculturated', i.e., through broad learning processes becoming part of a mathematics culture with specific norms and responsibilities. Bishop (1988) recognised many different mathematics cultures from around the world, with these having common grounds based on six fundamental mathematical activities: counting, locating, measuring, designing, playing, and explaining. Bishop saw modern symbolic mathematics as a tool to communicate experiences from such fundamental activities. In KLUMP we find that Bishop's ideas suit vocational education well as the crafts are filled with fundamental mathematical activities and as mathematics is about modern symbolic representations and communication.

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Transitioning to Project-Based Learning in Data Science Education: An Action Research Study at a Danish Vocational School

Nicolaj Riise Clausen
Aalborg University, Denmark, Nclausen@plan.aau.dk

Søren Hansen
Aalborg University, Denmark, sha@plan.aau.dk

Kim Guldholt
Mercantec, Denmark, kigu@mercantec.dk

Bjarne Poulsen
Mercantec, Denmark, bjpo@plan.aau.dk

Lykke Bertel
Aalborg University, Denmark, lykke@plan.aau.dk

Abstract

This paper presents an action research study on the transition from a traditional subject-based teaching model to project-based learning (PjBL) in data sciences at a Danish vocational school. The shift was primarily motivated by the need to create a more coherent learning experiences and better alignment between school-based instruction and workplace learning. The new model integrates multiple subject areas into holistic, continuous projects spanning up to ten weeks. Teachers and industry representatives participated as co-researchers to examine (1) the transition process, identifying areas for improvement, and (2) the benefits, challenges, and developmental potential of this new pedagogical model and students were interviewed on many of the same subjects. The study was conducted in three phases: exploratory focus group interviews with students, semi-structured interviews with teachers, and a workshop with teachers and industry stakeholders. Results indicate strong support from both students and staff, with notable improvements in student engagement and perceived relevance of learning. However, challenges related to logistical constraints, teacher adaptation, and balancing student autonomy with necessary instructional guidance were also highlighted. These findings provide valuable insights for other vocational schools considering similar pedagogical transformations and informs the further pedagogical development at the vocational school in question.

Keywords: project-based learning, Vocational education, Action research, Curriculum development

1 Introduction

The rapid evolution of technology necessitates continuous adaptation in educational practices to ensure students acquire the competencies needed for future employment. At Mercantec, a Danish vocational school, the previous curriculum structure consisted of week-long, single-subject courses with frequent teacher changes. Recognizing issues related to this fragmented structure, the school for data-sciences under Mercantec initiated a transition to project-based learning (PjBL) to foster deeper learning, strengthen relationships, and improve the relevance of educational experiences. Project-based learning at Mercantec involves students engaging in extended projects that integrate multiple subject areas and encourages self-directed learning, collaboration, and critical thinking, which are crucial competencies for modern industries. While PjBL has been widely adopted in higher education fields such as medicine and engineering, its implementation in vocational education remains less studied. Therefore, this practice paper aims to explore the transition process, assess the benefits and challenges encountered, and provide recommendations for optimizing the implementation of PjBL in vocational settings.

1.1 Background

In recent decades, Problem-Based Learning (PBL) has gained significant popularity as a pedagogical approach in higher education, particularly within medical and engineering programs. Over time, more variations, especially project-oriented adaptations of PBL have gained traction, not only in engineering education but across a broad range of disciplines (Chen et al., 2021; Leary, 2012; Servant-Miklos, 2019; Walker & Leary, 2009). Although PBL can take many different forms depending on the context in which it is implemented, there are core characteristics that define the approach. In many PBL models, there is a shift away from broad theoretical orientation through traditional courses in favor of a greater focus on specialized and applied knowledge in project work (de Graaff & Kolmos, 2003). Such a transition often means that students do not cover as extensive a theoretical foundation as in more traditional teaching models, where theoretical courses constitute a larger part of the curriculum. To compensate for this, PBL places great emphasis on developing students' ability to work independently and autonomously so that, both during their education and in their later careers, they are better equipped to identify and seek out the knowledge they need to solve given problems (Clausen, 2023). Self-direction and self-regulation are therefore both outcomes of and prerequisites for PBL as a teaching method (de Graaff & Kolmos, 2003; Ge & Chua, 2019).

Studies have shown that PBL students become better at using information-seeking strategies, setting learning goals, and developing a stronger belief in their own learning abilities (self-efficacy) compared to students from more conventional learning environments (Evensen, 2000). They have also been found to achieve better "library skills" and generally adopt a more proactive approach to literature searching, moving beyond the readings assigned by their instructors and seeking out alternative sources of information (Blumberg, 2000; Blumberg & Michael, 1992; Blumberg & Sparks, 1999; Loyens et al., 2008). Furthermore, research has shown that PBL students are often more self-driven and less dependent on instructor guidance, which supports their ability to work autonomously both during their studies and in their future careers (Clausen, 2021; Dolmans & Schmidt, 2000; Kivela & Kivela, 2005). At the same time, studies indicate that, compared to similar students in other programs, PBL students perceive themselves as better prepared in terms of generic and contextual competencies such as collaboration, problem-solving, and reflective thinking (Kolmos et al., 2021).

1.2 PBL in Vocational Education

In vocational education and training (VET), findings from previous studies indicate that implementing project-based learning (PBL) can have a positive effect on students' development of key competencies. PBL appears to be particularly effective in strengthening VET students' critical thinking, problem-solving skills, communication, collaboration abilities, and creativity—competencies that are also highlighted as essential in the 21st-century labor market (Geisinger, 2016; Megayanti et al., 2020). Other studies have shown that PBL can increase VET students' motivation, as they take on a more active role in their educational journey through

project work (Bagheri et al., 2013). Additionally, research has demonstrated that PBL in VET strengthens the connection between theory and practice (Chiang & Lee, 2016), that students working with contextualized problems are motivated to develop original and innovative solutions (Fitri Rahmawati et al., 2018), and that it improves students' communication and collaboration skills, as they continuously explain their work processes, discuss solutions, and present results, becoming better as asking questions, analyzing information and making well-founded decisions (Sasson et al., 2018).

However, research also highlights several challenges associated with implementing PBL in VET. For instance, a successful implementation of PBL in VET requires adequate resources, access to relevant technologies, and a learning environment that supports independent work and collaboration (Liu, 2018). Furthermore, instructors are required to have a deep understanding of the learning process and be capable of guiding students through the complexities of working with problems (Pinho-Lopes & Macedo, 2014). Thus, to enhance the chances for a successful implementation of PBL in VET, challenges such as the altered role of the instructor and the framework for project work must be continuously developed (Megayanti et al., 2020).

2 Methodology

With this in mind, the study employed an action research framework to examine the transition to PjBL with different phases, including a pre-planning and design phase, a piloting phase, and a formative evaluation and future directions phase. In this paper we present results from the formative evaluation and future directions phase. The research design in this phase included three data sources:

Student Focus Groups: Students participated in 5 semi-structured focus group interviews to share their experiences with both the traditional and PjBL models. Discussions focused on perceived benefits, challenges, and their overall experiences with the new model.

Teacher Interviews: Six teachers were interviewed using a semi-structured format. Initial interviews took an inductive approach, identifying emerging themes related to instructional challenges, knowledge-sharing needs, and adaptation to the new model but also implemented findings from the student interviews.

Industry Workshop: A workshop was held with teaching staff and industry stakeholders to explore strategies for improving collaboration between schools and workplace internships. Discussions included the alignment of school projects with industry needs and mechanisms for strengthening communication.

To analyze the interview data, a thematic analysis was conducted, inspired by the six phases outlined by Braun and Clarke (2006), in this case adapted to three distinct phases. The purpose of the thematic analysis is to identify, analyze, and present patterns and themes that represent significant aspects of the participants' narratives, without seeking to quantify the occurrence of a given theme (Braun & Clarke, 2006; Patton, 1990). The inductive and constructivist approach emphasizes that the data is not treated in an epistemological vacuum but is analyzed and interpreted in relation to the context in which it was produced (Braun & Clarke, 2006; Galletta & Cross, 2013). Each analytical process following the interviews was structured into the following three phases:

Phase 1: Coding and identifying themes

The data analysis began with listening to all interviews and reviewing all notes taken during the interviews, where notes and preliminary reflections on patterns and themes were recorded and revised. This process enabled the identification of recurring topics and statements that could form the basis for subsequent coding.

In this phase, key statements from the interviews were coded and categorized into smaller units of meaning. The coding was carried out with a focus on analytical relevance rather than frequency, ensuring the complexity of the participants' statements was preserved. Additionally, preliminary connections between different codes were noted and tentative overarching themes were produced, based on the relationships

between students' statements, aiming to capture the central experiences and challenges described in relation to the new teaching model.

Phase 2: Review and validation

In this phase, themes were evaluated in terms of their coverage of the data material. First, they were compared with the original interview excerpts to ensure they remained faithful to the participants' experiences. Subsequently, all interviews and interview notes were reassessed to examine whether the identified themes adequately represented the participants' statements or adjustments were needed.

The final themes were formulated and described based on their analytical contribution to understanding the study's research aims. Throughout this process, emphasis was placed on clarifying how each theme related to the students' experiences.

Phase 3: Reporting of results

In the reporting, themes were selected to create a coherent and nuanced representation of students' and staff members' experiences while preserving an understanding of their practices and context. Based on the inductive approach, a central goal was to ensure that the participants' voices were clearly represented in the presentation of results.

3 Findings and Discussion

Student Perspectives

Students generally expressed strong support for the new model, citing several key benefits. One of the most frequently mentioned advantages was the continuity of having a consistent instructor throughout the up to ten-week long periods, which helped foster stronger student-teacher relationships and ensured more personalized feedback due to enhanced insights of the teachers into the individual students. Additionally, students appreciated the real-world relevance of project work, as it provided a clearer link between theoretical concepts and practical applications and simulated their apprenticeship test which the students in general were quite concerned about being ready for.

However, challenges were also identified. Some students struggled with the increased emphasis on written documentation, particularly those who were more accustomed to practical, hands-on learning. Additionally, logistical constraints, such as hardware access for extended projects, were raised as concerns. Despite these difficulties, most students felt that the new model better prepared them for their final assessments and future employment.

Teacher Perspectives

Teachers also largely endorsed the transition to the new model, recognizing its potential to enhance student engagement and learning outcomes, although they faced significant challenges in adapting to their new roles. One of the primary difficulties was the lack of structured onboarding, leaving some educators feeling unprepared to navigate the new system. Several teachers described the transition as "laying the tracks while the train is moving" highlighting the difficulty of implementing the new model while actively teaching, although they also recognized that it was difficult to implement the model in any other way.

Another challenge was balancing student autonomy with structured guidance. Some educators developed strategies such as "minimum viable project templates" to provide students who wanted it with a baseline structure while other students were encouraged to be more self-directed if they felt up to the challenge. Additionally, the autonomous nature student projects in the new model required teachers to broaden their expertise beyond their traditional subject areas, underscoring the need for ongoing professional development.

Industry and teacher workshop

A key outcome of the industry workshop was the recognition that stronger collaboration between schools and companies is essential for the success of the new model as well as to ensure that school-based learning aligns more closely with industry expectations, improving student preparedness for the workforce.

Participants proposed several initiatives to enhance integration, including: 1) Increasing direct communication between teachers and industry mentors, 2) Developing structured feedback mechanisms where industry representatives provide input on student projects, 3) Facilitating guest lectures and industry visits to expose students to real-world challenges.

Based on ideas from the workshop, scenarios for possible collaborations between schools and companies was developed. For instance, in one scenario, the teacher would organize a guest presentation from a relevant internship company. The purpose of the scenarios was to crystalize ideas into concrete actions that could improve the collaboration with the company. In addition, scenarios could be used as a a way to pass on experiences from previous to future teachers and perhaps even to other schools.

As part of the future directions phase, the results from interviews and initiatives from the workshop are discussed regularly in weekly follow-up pedagogical staff meetings. In these meetings, various current didactic topics and issues are discussed in the teaching group, including internship collaboration.

4 Future work

The transition to PjBL at Mercantec represents a significant pedagogical shift, bringing both advantages and challenges. Students and teachers generally view the model favourably, acknowledging its potential to enhance learning, student-teacher relations and real-world applicability. However, the success of this transition could be improved by focusing on sustained professional development, structured onboarding, logistical planning, and stronger collaboration between educational institutions and industry partners. At Mercantec they, to some degree, already started this work. One finding from interviewing teachers is that the classroom teacher role previously has been too demanding. To accommodate this, teachers now work in teams of 3 sharing two classes. The idea is that, besides reducing the workload for each teacher, the third teacher in this team is meant for new teachers being onboarded by two colleagues. Besides, weekly meetings among teachers are assigned for sharing and discussing subjects like lesson plans and classroom management. In addition to these changes, the following actions could be considered. Training sessions and professional development workshops can help teachers adapt to their evolving roles, shifting from traditional instruction to guiding student-driven learning.

The school prioritise building stronger relations, both among students and between students, teachers and companies. To accommodate this a student's advisory board together with an online communication platform has been developed. Another recommendation is strengthening industry partnerships by increasing direct communication between teachers and industry mentors, facilitating guest lectures, and implementing structured feedback mechanisms will better align school-based learning with workplace expectations. To meet this an Mercantec so far established an education committee with representatives from companies to ensure practice anchoring of student's projects has been launched.

Lastly, continuous assessment and refinement of the new model will be essential. Regular evaluations incorporating student, teacher, and industry feedback are already ongoing and will help identify areas for improvement and ensure that the model remains responsive to both educational and industry needs.

By taking these findings into account, Mercantec can create a more sustainable and effective PjBL framework, fostering deeper student engagement, better student-teacher relations, stronger educator collaboration, and improved alignment with industry demands. The lessons learned already spreads both internally to other departments at Mercantec and potentially also external to other schools as visits to learn from Mercantec has already been planned.

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List of Authors

(In alphabetic order)

Name	Country	Affiliation
Abrie Oberholster	South Africa	University of Pretoria
Ada Dienga	South Africa	Engineering Council of South Africa
Adri van Nieuwkerk	South Africa	Opti-Num Solutions
Adriaan de Villiers	South Africa	University of Cape Town
Aida Olivia Pereira de Carvalho Guerra	Denmark	Aalborg University
Alexandra Halligey	South Africa	University of the Witwatersrand
Alison Gwynne-Evans	South Africa	University off Cape Town
Alison Reddy	United States	University of Illinois
Amos Adeniyi	South Africa	Cape Peninsula University of Technology
Ana Rubio Denniss	United Kingdom	King's College London
Ana Valencia Cardona	Netherlands	Eindhoven University of Technology
Anders Rosén	Sweden	KTH, Royal Institute of Technology
Andrew Valentine	Australia	University of Melbourne
Anita Campbell	South Africa	University of Cape Town
Ann Kathrin Meilandt Bygholm	Denmark	Aalborg University
Ann Lourens	South Africa	Nelson Mandela University
Anna Overgaard Markman	Denmark	Aalborg University
Anne Nkoidila	Kenya	university of Nairobi
Anne Verhoef	South Africa	North-West University
Anthony Perry	United States	University of North Dakota
Antonia Scholkmann	Denmark	Aalborg University
Arnold Pretorius	South Africa	University of Cape Town
Avela Mqhakama	South Africa	University of Cape Town
Avinita Gautam	India	MIT Vishwaprayag University
Ayesha Reiners	South Africa	Cape Peninsula University of Technology
Baatseba Ramushu	South Africa	University of Johannesburg
Bárbara Gabriel	Portugal	University of Aveiro
Bart Johnson	United States	Minnesota North College
Beatrice Ndaisi	Kenya	university of Nairobi
Bente Nørgaard	Denmark	Aalborg university

Bernard Shibwabo	Kenya	Strathmore University
Bettina Dahl	Denmark	Aalborg University
Bill Williams	Portugal	Universidade de Lisboa
Bjarne Poulsen	Denmark	Mercantec
Bonolo Mokoka	South Africa	University of Pretoria
Brandon Collier-Reed	South Africa	University of Cape Town
Brandt Klopper	South Africa	Faculty of Engineering, North-West University
Brenda Nkhumise	South Africa	Engineering Council of South Africa
Brett Pyper	South Africa	University of the Witwatersrand
Bronwyn Swartz	South Africa	CPUT
Calayde Davey	South Africa	University of Pretoria
Camilla Guldborg Hundahl	Denmark	Aalborg University
Carin Zvandasara	South Africa	University of Cape Town
Carla Ferreira	Portugal	University of Aveiro
Clara Kansiime	Uganda	Gulu University
Carola Hernandez	Colombia	Facultad de Ingeniería Universidad de Los Andes
Cecile Uwimana	Rwanda	Institution of Engineers Rwanda
Cedrick Kwuimy	United States	UNIVERSITY OF CINCINNATI
Celeste Combrinck	South Africa	University of Pretoria
Chantal Brans	Netherlands	Eindhoven University of Technology
Charity Ampomah	Ghana	Ashesi University
Charlotte Palmer	United Kingdom	King's College London
Chiara Treglia	Netherlands	Eindhoven University of Technology
Chikondi Gurira	South Africa	EWBSA
Christian Skelmose Jensen	Denmark	Aalborg university
Christopher Smith	United Kingdom	Glasgow Caledonian University
Cila Botha	South Africa	North-West University
Clint Alex Steed	South Africa	Stellenbosch University
Clint Steed	South Africa	Stellenbosch University
Cody Mann	United States	Minnesota State University
Comfort Musiimenta	Uganda	University of Cape Town
Corrinne Shaw	South Africa	University of Cape Town
Curwyn Mapaling	South Africa	North-West University
Dan Jiang	Denmark	Aalborg University
Daniel Salau	Nigeria	University Of Lagos
Darcie Christensen	United States	Minnesota State University

David Andrew	South Africa	University of the Witwatersrand
David Ross Olanya	Uganda	Gulu University
David Kariuki	Kenya	university of Nairobi
David Okot Pakono	Uganda	Gulu University
Dennis Friedrichsen	Denmark	Aalborg University
Diana Bairaktarova	United States	Virginia Tech
Diana Martin	United Kingdom	University College London
Disaapele Mogashana	South Africa	University of Pretoria
Dominique Fürst	Netherlands	Eindhoven University of Technology
Doris Chasokela	Zimbabwe	University of Cape Town
Ellen Sjoer	Netherlands	The Hague University of Applied Sciences
Emanuela Tilley	United Kingdom	University College London
Emilia Jun Nielsen	Denmark	Aalborg university
Emma Crichton	United Kingdom	Engineers Without Borders UK
Erin Brady	United Kingdom	University of Bristol
Esther Matemba	Australia	Curtin University
Esther Osho	Nigeria	University Of Lagos
Euan Lindsay	Denmark	Aalborg University
Eunice Mureithi	Tanzania	University of Dar es Salaam
Eva Shayo	Tanzania	University of Dar es Salaam
Fiona Truscott	United Kingdom	University College London
Francesco Ciriello	United Kingdom	King's College London
Frank Justesen	Denmark	Tradium Vocational School
Gavin Ninshaba	Uganda	University of Cape Town
Geoffrey Tabo Olok	Uganda	Gulu University
Giajenthiran Velmurugan	Denmark	Aalborg University
Gopalkrishna Joshi	India	MIT Vishwaprayag University
Gosiame Noge	South Africa	NWU
Gustav Potgieter	South Africa	Faculty of Engineering, North-West University
Guttorm Alendal	Norway	University of Bergen
Heather Beem	Ghana	Ashesi University
Heillyn Camacho	Denmark	Consufe
Helen Inglis	South Africa	University of Pretoria
Iben Jensen	Denmark	Aalborg
Inês Direito	Portugal	University of Aveiro & Centre for Engineering Education (CEE), University College London

Irene Magara	United States	University of Nebraska-Lincoln
Isabelle Reymen	Netherlands	Eindhoven University of Technology
Izhar Mithal Jiskani	Denmark	Aalborg University
Jackson Maalu	Kenya	university of Nairobi
Jacoba H Bührmann	South Africa	Faculty of Engineering, North-West University
Jakob Farian Krarup	Denmark	University College Nord
James Huff	United States	University of Georgia
Jamie Bok	South Africa	University of Cape Town
Jan Van Maele	Belgium	Katholieke Universiteit Leuven
Janine Hechter	South Africa	University of Pretoria
Jarrett Odwallo	Kenya	university of Nairobi
Jean du Toit	South Africa	North-West University
Jenna Carpenter	United States	Campbell University
Jens Frederik Dalsgaard Nielsen	Denmark	Aalborg University
Jessica Swenson	United States	University at Buffalo
Jette Schaarup	Denmark	Hillerød Technical School UNord
Jicheng Gong	United Kingdom	King's College London
Johan Holmén	Sweden	Chalmers University of Technology
Johanna Lönngren	Sweden	Umeå University
John Batani	Lesotho	Botho University
John Magero Mango	Uganda	Makerere University
John Mitchell	United Kingdom	University College London
Jonathan Lee Montoya	United States	University of California
Jonathan Truslove	United Kingdom	Engineers Without Borders UK
Josias Mamabolo	South Africa	Engineering Council of South Africa
Josua Wesch	South Africa	University of Johannesburg
Juebei Chen	Denmark	Aalborg University
Jyoti Bali	India	MIT Vishwaprayag University
Kapil Moothi	South Africa	North-West University
Karabo Sitto-Kaunda	South Africa	University of Pretoria
Karin Wolff	South Africa	Stellenbosch University
Kate Bernberg	South Africa	University of the Witwatersrand
Katerina Pia Günter	Sweden	Umeå University
Katherine Ulseth	United States	Minnesota North College
Katlego Lokhele	South Africa	University of Johannesburg

Katriina Schrey-Niemenmaa	Finland	HRPLUS
Kim Guldholt	Denmark	Mercantec
Krishnendu Jana	India	MIT Vishwaprayag University
Krista Steele	United States	University of North Dakota
Kristo Kotsi	United Kingdom	University College London
Lars Bo Henriksen	Denmark	Aalborg university
Lehlohonolo Lefalatsa	South Africa	Engineering Council of South Africa
Lelanie Smith	South Africa	University of Pretoria
Lena Gumaelius	Sweden	KTH, Royal Institute of technology
Lena Lindenskov	Denmark	Aarhus University
Liandi Van den Berg	South Africa	Faculty of Economic and Management Sciences
Liesel Ebersöhn	South Africa	University of Pretoria
Liezl Van Dyk	South Africa	Faculty of Engineering, North-West University
Lilian Ganduri	South Africa	Cape Peninsula University of Technology and University of Cape Town
Liliana Maritza Melo Ramos	Colombia	Universidad de Los Andes
Linae Baron	South Africa	Engineers Without Borders South Africa
Loïs Vanhée	Sweden	Umeå University
Lone Dirckinck-Holmfeld	Denmark	Aalborg University
Louise Møller Haase	Denmark	Aalborg University
Luvuyo Kakaza	South Africa	Cape Peninsula University of Technology
Lykke Brogaard Bertel	Denmark	Aalborg University
Maiken Winther	Denmark	Aalborg University
Maj-Britt Quitzau	Denmark	Aalborg University
Makoena Sebatjane	South Africa	Stellenbosch University
Manimagalay Chetty	South Africa	Cape Peninsula University of Technology
Marc Zolver	Kenya	university of Nairobi
Marcello Sala	Netherlands	Eindhoven University of Technology
Margaret Namubiru	Uganda	Gulu University
Maria Berge	Sweden	Umeå University
Markus Löchtefeld	Denmark	Aalborg University
Mateus Halbe Torres	Denmark	Aalborg University
Matheus de Andrade	United Kingdom	University College London
Meelan Roopa	South Africa	Stellenbosch University
Meng Yuan	Denmark	Aalborg University
Mette Møller Jeppesen	Denmark	Aalborg university

Mia Mangaroo-Pillay	South Africa	Stellenbosch University
Mian Xie	United Kingdom	University College London
Michelle Maphosa	South Africa	University of Cape Town
Mohammad Pourbehi	South Africa	Cape Peninsula University of Technology
Morena Nkomo	South Africa	University of Johannesburg
Morney Mostert	South Africa	University of Cape Town
Moses Ismail	Tanzania	University of Dar es Salaam
Moses Olayemi	United States	University of Oklahoma
Munyaradzi Maravanyika	Namibia	Namibia University of Science and Technology
Naadhira Seedat	South Africa	University of Johannesburg
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Yuezhou Wang	United States	Minnesota State University
Zachary Simpson	South Africa	University of Johannesburg
Zinhle Mvelase	South Africa	University of the Free State

Acknowledgements

List of Reviewers

(In alphabetic order)

Name	Country
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Savita Hanji	MIT Vishwaprayag University, India
Shannon Chance	TU Dublin & University College London, Ireland
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Søren Hansen	Aalborg University, Denmark
Stine Ejsing-Duun	Aalborg University, Denmark
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Zachary Simpson	University of Johannesburg, South Africa