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).

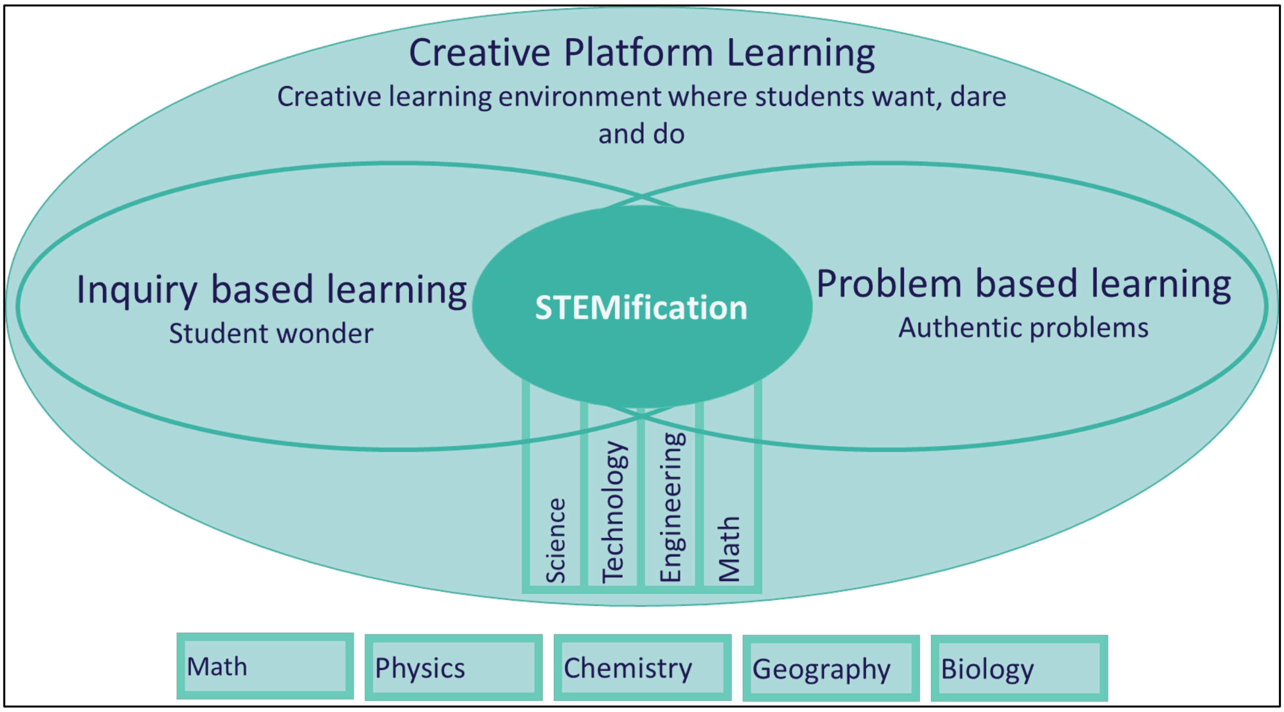

Figure 1: Model for STEMification of Science and Mathematics teaching

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

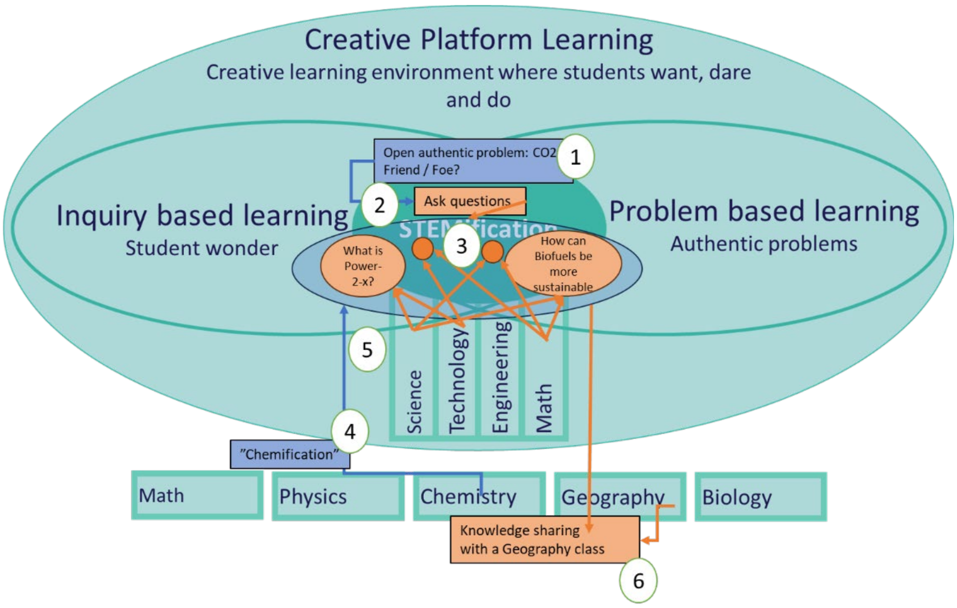

Figure 2: Mapping of Case A STEM teaching module

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

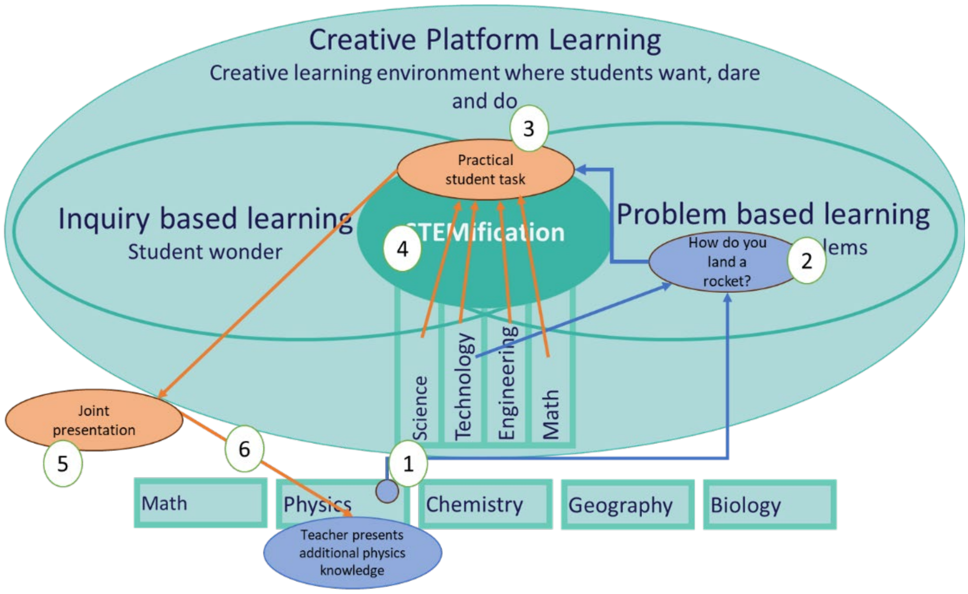

Figure 3: Mapping of Case B STEM teaching module

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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