Building towards better learning: Evolution of practical design, build and test activities in an introductory Mechanical Engineering Design course

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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.

6 References

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