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Investigation of Design Skills Attained Through a First-Year Multidisciplinary Engineering Design Project

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ABSTRACT

CONTEXT

A new, core, first-year, engineering design and build unit was piloted at Monash University in Semester 1, 2022. A 9 week-long design project was developed with the aim of encouraging 5 member student teams to apply their new design, Computer-aided Drawing (CAD) and 3D printing skills. A competitive grading approach intended to reward innovation and optimisation of these deployable structures with static applied loads.

PURPOSE

The purpose of this study is to investigate quality of delivery and the attainment of selected engineering-design skills via a multidisciplinary design project relative to the selected benchmark; the Weir-WARMAN competition. This research is intended to provide recommendations for the further development of the project for successive offerings, and a reference for the implementations of similar projects.

APPROACH

Pre-existing survey instruments drawn from the literature and specific to design projects will be used to gauge the success of the project developed and the attainment of self-reported design skills. A survey will be developed and students will be invited to participate. Their responses will be analysed to discern the efficacy of the project in encouraging engineering-design skills. Follow-up interviews with the students and Teaching Associates (TAs) in the unit will be conducted to source additional qualitative insights. Student self-reflection is the primary tool for quantifying changes in student learning and design skill attainment.

RESULTS

Students responded positively to the project and the changes in their self-reported design skills were comparable to the benchmark of the Weir-WARMAN competition. However, reflections and observations from our TAs indicated that the students hesitated to utilise simple mechanisms, or to optimise their structures for self-weight as was intended for the project.

CONCLUSIONS AND RECOMMENDATIONS

This study was able to identify the strengths and weaknesses in the project related to design-skill developments. While surveys indicate an increase in student confidence in the use of engineering tools such as 3D Printing and CAD, observation of student outputs does not strongly support this. Therefore, several recommendations to address the weaknesses of the project for future offerings are provided.

KEYWORDS

Multidisciplinary Design, First-year, Engineering, Project

Introduction

Revision of common, core, first-year engineering units offered at Monash University occurs approximately every 5-7 years to address the changing needs of industry, the institution, and the students and provides an opportunity to take advantage of new technologies and teaching spaces as they become available.

A new “design and build” unit was commissioned for 2022 Semester 1. The curriculum for this unit included a Major In-Semester Assessment Task (MISAT) where teams of students would design and construct a deployable structure made from parts in a provided kit. Designs were required to fit inside a starting volume cube and deploy to a student-nominated span, supporting a nominated load. Teams were judged via a competition against their peers, with a formula and variables to determine their score, further details can be found under ‘Project Design’ below. An example of a collapsed and deployed student design is shown in Figure 1.

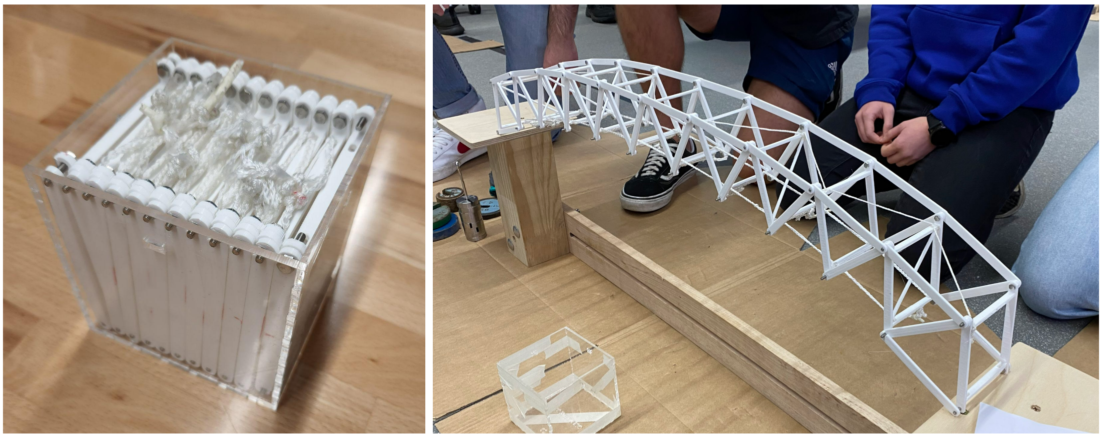

Figure 1: Examples of (left) a typical folded structure in the starting cube and (right) the same structure deployed to span a nominated length (but unloaded).

The authors sought to investigate the students’ development of specific engineering-design skills via this multidisciplinary project. This was assessed through student MISAT results, two voluntary anonymous surveys to determine students' self-perception of their design skills, and an optional follow-up interview. The first survey examined 14 Engineering Design Skills identified by Churches and Smith (2016) and was selected due to the similar research aims and assessment contexts. An additional set of questions was developed from prior works within the sphere of engineering education (Dau et al. 2021 and Sanchez-Cambronero 2021), and added to this survey in order to gain further insight into MISAT and unit effectiveness. The second survey matched start and end of semester responses to determine individual changes in self perception of skills undertaken across the assessment task. This combination was used to evaluate the MISAT delivery, and to provide feedback and recommendations for subsequent deliveries.

Aims & Objectives

This study aims to provide recommendations for the further development of the MISAT such that it better meets the unit's learning outcomes and results in improved student self-perception of engineering design skills. As such, the following objectives were set to address the aims of this research.

1. Survey students to gauge student satisfaction with the delivery of the MISAT and self perception of design skills attainment.
2. Interview TAs to complement the students self perception of skill attainment.
3. Compare and contrast the results with the benchmark WARMAN Competition findings.

4. Produce a set of recommendations and improvements to be implemented in the next offering of the unit.

Approach

Project Design

This project was worth a total of 30% of the unit (inclusive of some in-class activities, a design report and final competition testing), and utilised a “project-based learning” approach. Teams of five students were challenged to design and build a “deployable structure”, capable of being expanded from a 100x100x100mm starting volume to span a team-nominated gap of between 200 and 1000mm, and then support a team-nominated weight (between 1 and 6 kg). Performance was assessed using a “structure score”; a formula incorporating factors based on the structure’s self weight, the maximum load carried (at midspan), and the gap spanned. This was all relative to the maximum performance achieved (for span and load) and the minimum self-weight achieved by any team. The span factor was given a squared weighting, to recognise the difficulty and non-linear nature of achieving spans up to ten times the starting volume. A schematic of the testing rig, starting volume and typical loading is shown below in Figure 2.

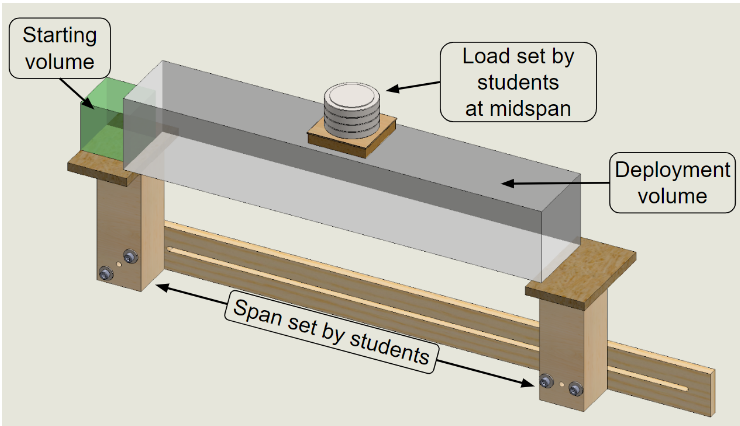

Figure 2: Schematic of testing rig and deployable-structure requirements

Teams were provided with a range of free resources to aid in the development of their structures:

- A kit containing: acrylic, laser-cut members; M3 nuts, lengths of threaded rod (50mm, 75mm and 100mm lengths), wrenches, builders’ stringline, safety glasses, a 120x120mm padded loading plate, digital scales, and a steel rule.
- Access to loading weights, testing rigs and 100x100x100mm starting-volume boxes.
- Access to 3Drinters (Prusa i3 Mk3s) and free PLA filament.
- SolidWorks CAD and Cura Slicer software (for installation on their own machines).

Participants and Ethics

Participants for this research can be broken into two groups; students and staff (TAs) of the unit. The target population for this research was first-year engineering students enrolled in the unit and their participation was voluntary. Teaching Associates (TAs) were included as across the semester they observed the students' interactions with the MISAT and should be able to reflect on the success of the pedagogy utilised (Ivey et al. 2017). As identifiable data was collected, the chosen tools (MISAT results, surveys and interviews) were approved by the University’s Human Research Ethics Committee (Approval Number 32767).

Study Design

Data was collected via: two surveys; student and staff interviews; and the competition results for the two milestone assessments. The first survey was released in the penultimate week of semester and contained two parts. Part 1 was a self-reflection on attained design skills using a 5-point Likert scale with questions sourced from research by Churches and Smith (2016) due to the similar aims of assessing students' engineering design skill. The 14 key Engineering Skills identified align closely with the Engineers Australia Stage 1 Competencies (Engineers Australia, 2017) and are, thus, similarly aligned to the intended learning outcomes of this unit. Part 2 incorporated quantitative and open-response questions from literature (Dau et al. 2021 and Sanchez-Cambronero 2021) to gauge student satisfaction as a whole. This strategy, used in the work of Hall, Palmer & Bennett (2012), allowed students to provide general feedback and openly express how the project could be improved. In total this survey attracted 179 responses from a cohort of approximately 350, for a response rate of 51%.

Interviews were conducted to gather further, more specific sentiment. Students were able to opt-into the follow up interview within the first survey. In total, three student and four staff interviews were conducted. Informed consent was obtained before scheduling the interviews and verbally again before commencing and interviews were recorded for transcription purposes.

A second, follow-up survey was released to the same student population following completion of the unit. To take advantage of pre-existing data, four relevant questions relating to self-perception of the following skills were asked: 3D CAD modelling, design project experience, 3D printing and team-work were re-released after completion of the unit. 36 responses were matched to the initial questionnaire.

Results

Skills Attainment: Comparison to WARMAN Design & Build Retrospective

The Weir-WARMAN competition has been run in a broad range of Australian Engineering universities for more than 30 years and is widely utilised for mechanical and mechatronics degree programs. It is typically aimed at a second year engineering cohort and forms a major project in second year design units. It was chosen for comparison to this project as both represent students' introduction to complex engineering design.

To make a meaningful comparison, responses of both the MISAT and WARMAN data have been normalised by their individual mean. The MISAT data shows, on average, a higher level of *perceived* attainment compared to WARMAN. Results in Figure 3 have been ordered in descending order of difference between the normalised datasets, with areas where WARMAN has performed 'better' at the top. The top three and bottom three rows will be focussed on in this discussion, as those data points have the highest mismatch when making a comparison.

The skill "importance of cost considerations" (top row, Figure 3: left), scored very low with the MISAT students (-39). This was unsurprising since a project kit with unlimited replenishment and free PLA for 3D printing was supplied. As a consequence there were no cost implications for most MISAT students. In contrast, WARMAN students are typically required to spend their own funds for the majority of the project materials (~$AUD 200 per team). As such, the lower bounds have been changed to -15 to better represent the other skills under investigation.

The MISAT is also seen to under-perform in comparison to WARMAN on the skill "how to translate design into product" (second row, Figure 3: left). This is likely due to students not conducting design work, instead simply 3D printing the provided CAD files that resemble the provided acrylic parts with only slight modifications. This hypothesis is reinforced in Figure 3 (right) by comparing the growth of CAD and 3D printer skills across the semester. Figure 3 (right), shows a higher growth of student self-perception of 3D printing skills over CAD skills, despite the similar "before" mean scores. It was expected that students would do the bulk of their own design work; however, they bypassed this work and, thus, the skill attainment, by printing provided files rather than designing their own. This may be attributable to self-directed, and minimally pursued, CAD study. While it was expected that CAD would motivate students, leading to significant amounts of work outside of class, in practice this did not occur, and may have resulted in students unsure on how to translate an idea into a design.

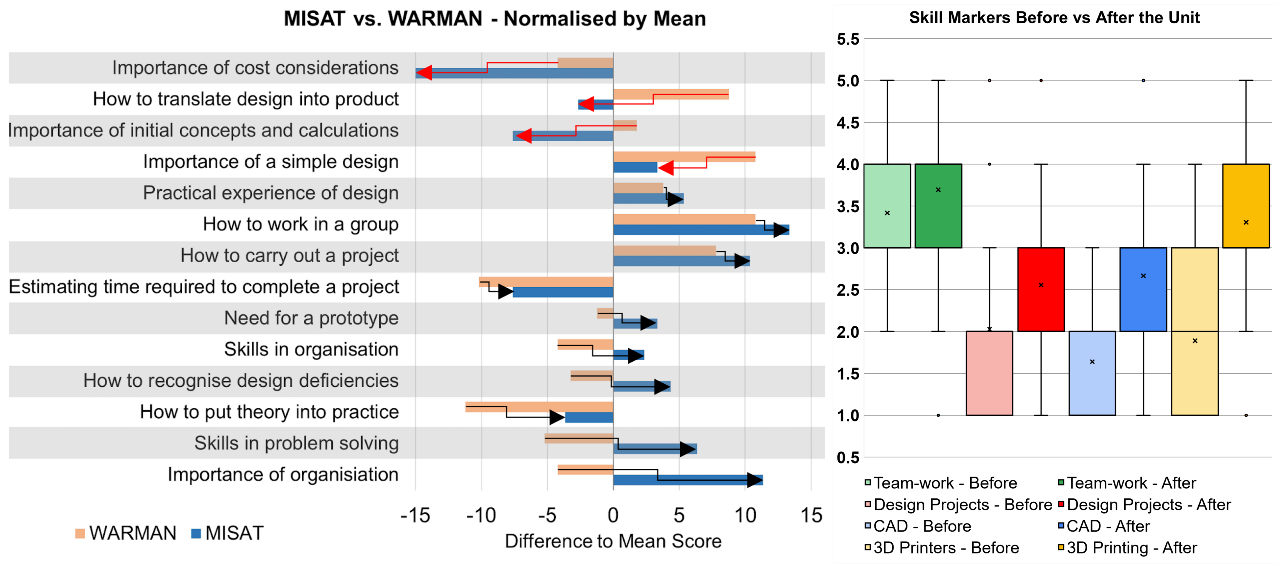

Figure 3: Left - Normalised by individual mean, combined survey responses of “some" and “significant” to “Did your experience in WAMAN/MISAT result in significant learning in each aspect listed?” (WARMAN n=1248, MISAT n=179, responses). Right - Comparison of four key skills from before and after completion of the MISAT (36 matched responses).

The MISAT students are also seen to underperform in row 3 “Importance of initial concepts and calculations”. The students were taught basics of materials science, with a dedicated practical activity on tensile and buckle testing to encourage an approach where concepts were developed using stress modelling. Unfortunately, this was largely not seen in practice. Students instead largely choose to make a heavy structure, and increase the load carried until failure, rather than refine their member geometry for an overall lower self-weight. While one team (see Figure 4, overpage) did optimise their cross-sectional geometry, this was not the norm. This intended learning outcome has not been realised by the students as hoped.

The largest point of difference in favour of the MISAT was the skill “Importance of organisation”. This could be due to the students being overly positive in their self-assessment. The MISAT students are new to university and no longer provided the same level of scaffolding as high-school. They may be confronted, in this project, by the realisation of how important organisation is. While this is a favourable result for the unit, it should be noted that the MISAT students have limited exposure to team work in a University setting and therefore their responses may not be as mature as the WARMAN students, who are typically second or third-year engineering students.

The second skill that MISAT students self-reported higher over the WARMAN students was “Skills in problem-solving”. Majority of students conducted an iterative test-to-failure approach to problem solving rather than using calculations to inform their designs as discussed above, likely leading to the students rating this skill highly. This was reflected in excerpts from students where they cited it “was a good introduction to what real life engineers would do and what problems they would face”.

The third-most skill that the MISAT students self-reported higher in was “How to put theory into practice”. It is thought that students have interpreted this as completing calculations on their final designs, rather than applying the theory to inform their design. All students were required to conduct a member force analysis after-the-fact. This was reflected in open response questions in Survey 1 with several students commenting it was good “seeing theory put into practice”.

The remaining half of surveyed skills (see Figure 3: left) aligned similarly between WARMAN and the MISAT, suggesting that a similar experience is being delivered to students. This is positive, as an initial intention of the MISAT was to provide a ‘stepping-stone’ learning experience to WARMAN. However, the deviations discussed show that elements of the MISAT still require refinement, which will be addressed by the recommendations below.

Survey 2 (Figure 3: right, ordered by increasing change in perception) indicated that, of the 4 skills areas interrogated, 3D printing skills saw the most growth during this project, with CAD skills second in this regard. This growth was expected given that it was the first time most students were exposed to these technologies, this was supplemented by the need to incorporate 3D printing to achieve high-scoring designs. Design project skills saw less improvement than expected, this could be indicative of future adaptations required in the delivery of course content. Team-work outcomes were previously rated highly, so did not see significant growth, although the students did work in teams, specific resources and learning outcomes relating to team-work were not part of this unit. The overall positive change across all skills is a good outcome for the MISAT, indicating positive individual growth across key skills across the semester.

Student Competition Results

The MISAT was introduced to teams in week 3, with a preliminary test in week 6 and final testing in week 11 of the 12-week semester. The underlying assumption was that teams would iteratively improve their designs using engineering design tools and analysis techniques introduced in the unit’s content. Teams were shown to have made significant progress from the preliminary to final rounds of testing, with an 172% improvement to their average structural scores. Teams that initially performed poorly, showed on average significant improvement to their design with structural scores, while those that performed well were still able to advance their design but to a lesser extent. Results indicate an overall leveling of team performances as expected owing to the convergence of solutions through the iterative process and diminishing returns. However, the minimal improvement amongst higher achieving students would indicate that this MISAT could benefit from adjustments to better engage these higher achieving teams. Figure 4, shows the progression of different students' designs.

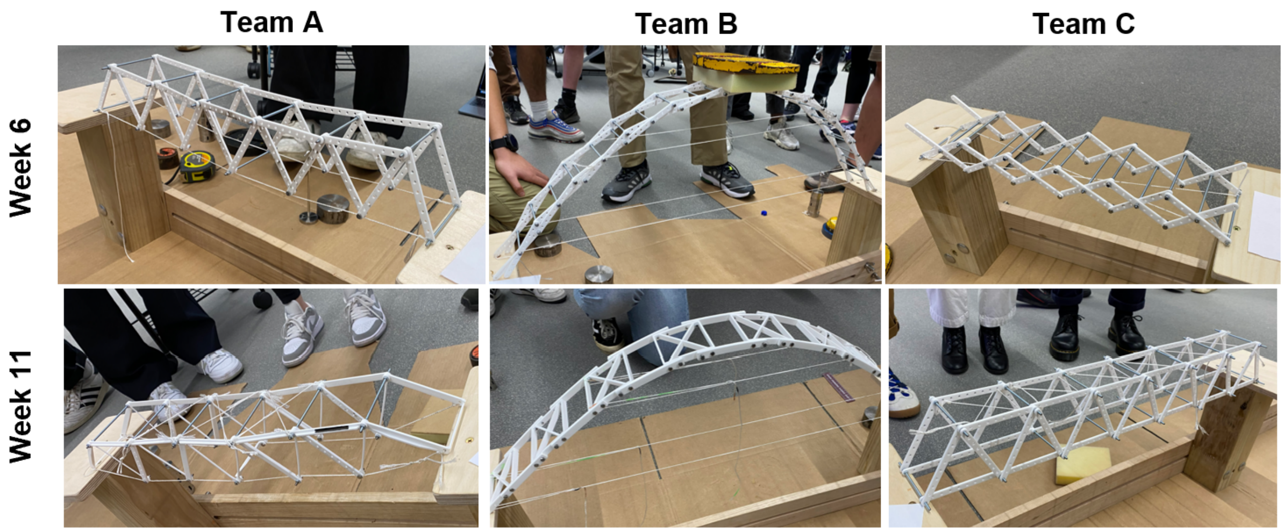

Figure 4: Student Structures from Week 6 (Top Row) vs Week 11 (Bottom Row) MISAT competitions. Left: truss design type; Middle: arch design type; Right: scissor design type.

There was an observed lack of originality in student output; many teams adopted a scissor type mechanism during the week 6 preliminary testing, even after the inherent inefficiency of this design was emphasised. Another common design were typical truss structures taught in the unit's course work adapted with members that rotate and clipped in place to meet the folding requirement. Although, this is a first-year unit, so reliance on provided designs is expected to some extent. To assist students in the design process, it is recommended that a concept development activity is incorporated into the early stages of the MISAT to promote divergent solutions. After preliminary testing, many teams elected to optimise their design by supplementing acrylic members and substituting with lighter 3D printed PLA parts. By using 3D printing teams were able to create customised members of sizes and shapes that are not achievable otherwise. Many teams realised inadequacies within preliminary design electing to transition to a different fundamental concept such as a truss; there was however an observed reluctance to abandon their initial existing designs.

Use of engineering tools (3D-printers)

Utilisation of 3D printing in the project was below expectations. In the majority of cases where 3D printing was used, students simply printed weight-reduced versions of the laser-cut acrylic members that were provided in their kits. Some students went further and supplemented their designs with unique 3D printed elements with improved structural properties as shown in Figure 5; however, this was not common. There were only a handful of teams that created unique 3D-printed designs.

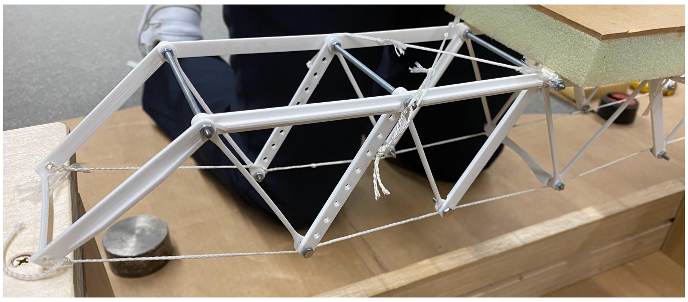

Figure 5: 3D printed component integrated with provided acrylic members with holes (close up of Figure 4 left, bottom)

Most students that chose to invest effort into 3D printing did so late in the project. Some teams did not start their 3D-printing designs until 2-3 weeks prior to the submission deadline (5 weeks into the MISAT). The level of 3D printing was given a ranking based on either "none", "low" or "high" before competition testing. As seen in Table 1 (overpage), students from categories of "high" and "low" achieved higher scores than their peers who chose not to 3D print at all. However, the difference is not significant enough to determine that there was a strategic benefit. From in-class observations, it can be noted that the "high" category mean score was likely brought down due to 3D-printed designs taking on more risk with their designs, and thus had a higher chance of failure.

Table 1: Mean structural score for each category of 3D printing

Mean Project Structural Score, by level of 3D printing	
High	8.73
Low	9.77
None	7.18

For future deliveries of this project, changes should be made to highlight the potential benefits of 3D printing to the students. In particular, the 3D printer induction session should be updated to showcase the weight and strength benefits available via 3D print settings. This, in combination with a reframed project that further rewards reduction of self-weight, will encourage higher student uptake of 3D printing. The large number of performance variables (span, load and self-weight) may over-complicate the optimisation and prioritisation process for this cohort. Many teams were observed to chase and fall short of designs that could achieve the maximum span. Those that achieved maximum span then chased maximum loading. Few that achieved both those maxima pursued optimising variable three, structure weight. The ease of construction and design changes with the supplied acrylic kits acted as a significant barrier to use of the 3D printers, which required more design work and a long wait time for part printing.

Limitations

The imperative for students to seek design solutions that involved mechanisms for deployment was not achieved as intended. This is likely due to the availability of a 2-minute deployment time, with no personnel or tool limitations during the deployment phase. This encouraged more of a rapid assembly of partially attached parts by multiple students simultaneously, rather than elegant linkages as originally hoped. The low uptake of the provided 3D printing resources accentuated this, limiting the students' ability to deploy their designs. A lack of guided class time was allocated for students to generate concepts, as it was expected that students would conduct a mostly self-directed learning approach to CAD and 3D printing. However, they did not appreciate this “hands-off” approach with several commenting that “more training in SolidWorks” is needed and that the “teaching of SolidWorks” needs improvement.

Similarly, learning objectives associated with materials science, in particular the optimisation of member cross sections, were not achieved to the intended degree. Tensile and buckle testing were taught to encourage the students' to iterate member design. However, they instead chose to increase the borne weight of their structures until failure rather than refine their structures for lower self-weight. This can be addressed by minor rule changes as outlined in the next section.

Students found the project to be too abstract and “didn’t see any real world applications”, a relevant backstory for projects is recommended to create relevance as . Appropriate framing of the project in future with real-world context would help students understand the relevance of this engineering project.

The relatively small enrollment for the pilot offering limited the number of survey responses. The optional nature of the survey also contributed to the low response rate. Additionally, the response rate for interviews was low relative to survey engagement as interviews were conducted during the SWOT-VAC period, when participants were busy studying.

Recommendations and Future Work

It is recommended that teaching staff who wish to create a similar multidisciplinary project for first-year students significantly simplify the project’s performance variables, to allow for a greater variety of viable concepts and to allow for more direct optimisation. For example, setting a (significantly reduced) specific span and load would promote a more singular focus on self-weight reduction once teams had converged on a range of basic concepts that could achieve the task. This might drive demand for CAD usage and the associated 3D printing. Similarly, mechanism design could be further encouraged by modifying the deployment ruleset. For example, limiting team member participation, or duration of the deployment phase.

To take a more extreme approach, the performance metrics and competition basis could be completely removed, and the focus shifted to breadth and creativity of concepts developed and the successful delivery of any concept, regardless of its ultimate efficiency or engineering elegance, which might yield more Rune-Goldberg-like machines. Such contraptions are a celebration of simple tasks performed in overly complex ways, and first year engineering units at other Australasian institutions have reported employing design projects with similarly open bounds in the recent past (Mahinroosta and Lindsay, 2016), with mixed success.

It is recommended that weekly milestones are created for the students to gauge their progress relative to the expectations. It was apparent that the first-year students were not yet familiar with the expectations of self-directed learning and open ended projects. Additionally, they lacked the higher-order skills of directing and collaborating with their newfound peers in a team-based project.

Conclusions

The implementation of a first-year multidisciplinary design project has been investigated within this paper. The results from the investigation indicate a positive response to the project; self-reported design skills were comparable to WARMAN competition, the benchmark of the unit. However observations show that the teams of students hesitated to utilise simple mechanisms or optimise their structures for self-weight as intended, due to shortfalls and oversights in our project brief. Several suggestions are proposed to modify the project in the next offering of the unit. These changes hope to encourage students to design structures with linkages and use 3D printers for optimisation.

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