MECHANISED BRIDGES: DEVELOPMENT OF A NOVEL, MULTIDISCIPLINARY, DESIGN AND BUILD PROJECT.

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ABSTRACT

We developed a new common core first-year “introduction to engineering” unit at Monash University, the number one Engineering school in Australia (THE, 2023). The requirements for the unit and its team-based project were to span multiple engineering disciplines, especially Civil and Mechanical, and to scale effectively for up to 900 students per offering. The relevant CDIO standards were applied in the unit design process to understand the context, ensure curriculum integration, devise appropriate learning outcomes, and develop a major team-based design-and-build project. The project was scaffolded via weekly active learning in-class activities and assessments. We had the advantage of delivering this new unit in brand new teaching spaces, which we designed specifically for first-year teaching. Our specialised learning spaces feature flexible, teamwork-configured furniture, ample power, secure storage and a large fleet of 3D printers. Students access Computer-Aided Design Software on their own devices, allowing them to continue working outside formal class time. These facilities and the project design allowed student teams to engage in a very practical and hands-on way with the unit content, via design, build and testing. Program evaluation following the first offering showed strong student satisfaction and development of skills in 3D printing and teamwork (Tong et al., 2022) associated with the new unit and the “bridge mechanism” design project.

KEYWORDS

Design project, first-year, 3D printing, Standards: 1, 2, 3, 4, 5, 6, 7, 8, 12

INTRODUCTION

This paper uses a CDIO framework to document the development of a new design-and-build, team-based project for a first-year introduction to engineering course at Monash University, Australia. The Faculty of Engineering has only recently joined CDIO, so this process familiarised many of our engineering design academic staff with the CDIO standards, stages and processes. Throughout this paper, we refer to the subject level as ‘unit’ and the program level as ‘course’, consistent with our university’s nomenclature.

CONTEXT

First-year engineering at Monash University consists of eight units of study, four each semester for two semesters (Monash University, 2023). Three of these units are reserved to allow students to catch up on any foundation maths, physics or chemistry they may have missed from their high school studies and to allow for electives. This leaves five common core units in the first year that all students must complete - four engineering units and one maths unit. Monash University offers a comprehensive range of engineering specialisations (ten in total) in a four-year Honours level program, with specialisations chosen by students from the second year onward. Our degrees, offered at both our Australian and Malaysian campuses, are accredited by Engineers Australia to the Stage 1 Competency Standard (Engineers Australia, 2019).

In 2018, the Faculty of Engineering embarked on a major review of our common-entry, first-year engineering program, which had not received any major revisions or updates since its first design in 2014. This review took in a wide and diverse range of stakeholder feedback, including that of academic staff, students, alumni, and local industry. Our common first year introduces the fundamental engineering concepts that underpin Sustainable Smart Cities and the critical engineering design processes required to solve related problems. Our first-year students are exposed to:

- the construction of safe and sustainable structures and mechanisms, and examining how complex problems can be addressed (in ENG1011);
- the design of critical water treatment processes and the ethical, environmental and sustainability considerations of such systems (in ENG1012);
- the software and electrical systems required to enable it all to work in a coordinated manner (in ENG1013);
- how to use computers to solve complex numerical problems that arise in engineering (in ENG1014);
- And how to use mathematics to model these problems and to be able to solve them (in ENG1005)

This paper will utilise the lens of CDIO (Malmqvist, J., 2019) to first consider all three of these new design units (ENG1011, ENG1012, ENG1013) in terms of their context, curriculum and integration (Standards 1 and 3). We will then focus on one unit (ENG1011) in greater depth and consider how we addressed Standards 2, 4, 5, 6,7, 8, and 12 in its design, delivery and initial evaluation.

STANDARD 1: THE CONTEXT AND STANDARD 3: INTEGRATED CURRICULUM

The basic introductory technical content for these three new design units was divided on the following basis in an attempt to group cognate subject areas while also covering the required breadth:

- ENG1011 - Engineering Methods (Civil, Mechanical, Materials, Computer-Aided Design, 3D Printing)
- ENG1012 - Engineering Design (Chemical, Materials, Sustainability, Humanitarian, Ethics)
- ENG1013 - Engineering Smart Systems (Electrical and Software)

The units are mapped below for a typical Semester 1 entry (see Figure 1). Due to our mid-year entry pathway (common for international students), these first-year units are not prerequisites for each other and are designed to be attempted in any sequence (bar engineering maths, ENG1005, which is a co-requisite for the numerical analysis unit, ENG1014).

E3001 Bachelor of Engineering (Honours) — Common first year

If no foundation units are required:

Year	Period	Units			
1	Sem 1 Feb	ENG1011 Engineering methods	ENG1005 Engineering mathematics Required: ENG1090 *	ENG1014 Engineering numerical analysis Corequisite: ENG1005	First Year engineering technical elective+ Or swap semester with an Elective unit
	Sem 2 July	ENG1012 Engineering design	ENG1013 Engineering smart systems	Elective	Elective

Figure 1. Revised first-year mapping showing three new core engineering design units.

These three design units were carefully planned to be complementary (rather than repetitive) in terms of their focus on professional skills development and their mode of assessment for team and project work. ENG1011 Engineering Methods was tasked with providing a particular focus on the following areas.

For professional skills:

- Development of team meeting skills: agendas, minutes, tasks, and progress tracking;
- Development of delegation skills: sharing of workload and scheduling work;
- Development of decision-making skills: considering, selecting, and justifying the best concepts;

For assessment modalities:

- Communication of project progress and outcomes using hand sketches, and Computer-Aided Design (CAD) modelling and drawings;
- Communication of project progress and outcomes using oral presentations, slide decks, animations, and multimedia (i.e. videos).
- Documentation of engineering analysis through report writing and calculations

STANDARD 2: LEARNING OUTCOMES

We operate in an outcomes-based education environment, whereby our Course Learning Outcomes align directly with the Engineers Australia Stage 1 Competency Standard graduate competencies. We utilise the SOLO taxonomy (Biggs, Tang & Kennedy 2022) to articulate the level of each assessed learning outcome and appropriately scaffold learning outcomes throughout the course, culminating in assessment pieces that are constructively aligned (Biggs, 1996). The ENG1011 team converged on six learning outcomes (LOs) for the unit.

1. Determine reactions and internal member forces in simple truss and beam systems and carry out limit state design to select appropriately sized members.
2. Determine the strength of structural materials to inform engineering designs with considerations to performance, cost, sustainability and societal impact.
3. Determine the steady-state performance of simple systems involving levers, gears, springs and pulleys using appropriate engineering problem-solving methodologies.
4. Propose concept designs that solve engineering problems and justify finalised design with considerations of key variables, assumptions and system boundaries.
5. Identify appropriate engineering tools and techniques to develop, validate and convey designs and solutions.
6. Identify roles and responsibilities within a team and reflect on self and team.

LOs 1-3 were allocated to each of the three major discipline areas covered by the unit (civil, materials, and mechanical engineering, respectively), and these were all pitched at a multi-structural level (level 2). The verb *determines* was used for all three of these LOs. The remaining three learning outcomes were allocated to design processes and methods (as per the title of the unit) at a multi-structural level using the verb *propose*; the identification and use of appropriate engineering tools (including CAD and 3D print slicer software) at a uni-structural level (level 1) using the verb *identify*; and teamwork roles, responsibilities, and behaviours, also at a uni-structural level also using the verb *identify*. The final LOs are presented in the unit handbook (Monash University, 2022).

STANDARD 4: INTRODUCTION TO ENGINEERING

CDIO Standard 4 recommends an introductory unit that *"provides the framework for engineering practice in product, process, system, and service building and introduces essential personal and interpersonal skills and the rationale of sustainability in the context of engineering."* As explained in the previous section, we took the approach of providing three units in the first year with such experiences. We balanced them with relevant fundamental technical knowledge in the spirit of Standard 7 Integrated Learning Experiences. We found this approach to be most equitable and politically expedient in our negotiations with discipline academics, some of whom favoured incorporating design and team project assessment elements, while others preferred to avoid any design or open-ended assessment elements. By approaching each unit (and engineering discipline) from a design and teamwork perspective, we hoped to avoid reinforcing unconscious biases that certain disciplines are more theoretical/individual and others are more practical/collective. First-year students tend to be inexperienced and often fearful about working in highly interdependent teams for any significant proportion of a unit's marks (Huang, 2021). In our anecdotal experience, early exposure to unfavourable teamwork experiences can negatively influence their opinions of the disciplines associated (Sekhar *et al.*, 2022). Given our students decide their disciplines at the end of the first year, these first impressions are critical as they impact student load, teaching revenue, and ultimately, department size, resourcing, and staffing.

Having three major team projects also gives us a greater opportunity to stimulate a student's interest and passion for a topic area or a particular approach to engineering practice. We believe that achieving such engagement is healthy for student confidence, well-being, and retention and is one of the first steps to helping them identify as engineers. This early sense of belonging within the profession is more important than ever, given the impacts on learning and student engagement resulting from COVID-19, which we are still experiencing.

STANDARD 5: DESIGN-IMPLEMENT EXPERIENCES

In ENG1011 Engineering Methods, students are introduced to fundamental aspects of civil, mechanical, and materials engineering. We selected static structural force analysis (equilibrium, reactions, truss and beam analyses) for the civil content, common mechanisms (springs, pulleys, gears, frames) for the mechanical content, and material properties (stress and strain) for the materials content. Considered together, we intended for students to have the theoretical foundations to design and analyse spaceframe-like structures to failure limits and to develop functional mechanisms. Computer-Aided Design (in our case, SolidWorks©) was taught in this unit to allow students to develop their ideas digitally and in three dimensions. The slicer software Cura© was also taught and utilised to enable students to 3D print their structures and mechanisms using twenty-four fused deposition modelling (FDM) 3D printers (Prusa i3 Mk3s+), which were supplied for exclusive use by students in this unit (more details in the Standard 6 section).

The major project spanned 5 weeks at the end of the semester. Teams of approximately five students were challenged to design and build a ***bridge mechanism*** that could:

- Fit within a restricted starting volume (a 100 mm sided cube);
- Extend/deploy/expand from its initial state, to span a gap several times its starting size (gap was 300mm);
- Support a specified mass at its mid-span (mass of 1kg).

Teams were provided with the following resources to prototype and realise their designs:

- an assortment of custom-designed “Meccano-like” structural members that were laser-cut from 3mm acrylic sheet, featuring 3mm holes at 10mm intervals;
- unlimited M3 nuts, washers and pieces of M3 all-thread rod in various lengths (50mm, 75mm and 100mm);
- unlimited use of elastic bands and tension and compression spring elements;
- unlimited builder’s string to use for tension-only members;
- unlimited PLA filament and regular access to FDM printers.

The requirements for the deployment of the bridge mechanism were strict to ensure teams created a mechanism with a single degree of freedom and to effectively outlaw the rapid assembly of disparate parts. These included:

- Mechanisms were to be deployed by the application of torque via a ¼” hex drive either in the form of an electric screwdriver or a hand-operated hex wrench.
- This action could power the deployment of the mechanism directly. i.e. via gears or linkages, or it could act to unlatch stored spring energy to power the mechanism.
- Deployment time was strictly limited to 30 seconds.
- Deployment was to be achieved via a single team member utilising one hand to support the mechanism and one hand to actuate the hew key or driver.
- The orientation of the mechanism was to be maintained consistently during deployment and when positioned to span the gap, to eliminate the input of gravitational potential energy via the operator during or after mechanism deployment.

Teams were explicitly required to incorporate at least one 3D printed component into their device due to the planned scaffolded class activities (CAD, slicing, and 3D printing) and the desired learning outcomes. Nearly all teams choose to 3D print at least the ¼" hex recess to accept the hex key to actuate or unlatch their device. Many teams designed and 3D printed the entirety of their mechanisms. Some example bridge mechanisms produced by teams are shown in Figures 2, 3, and 4.

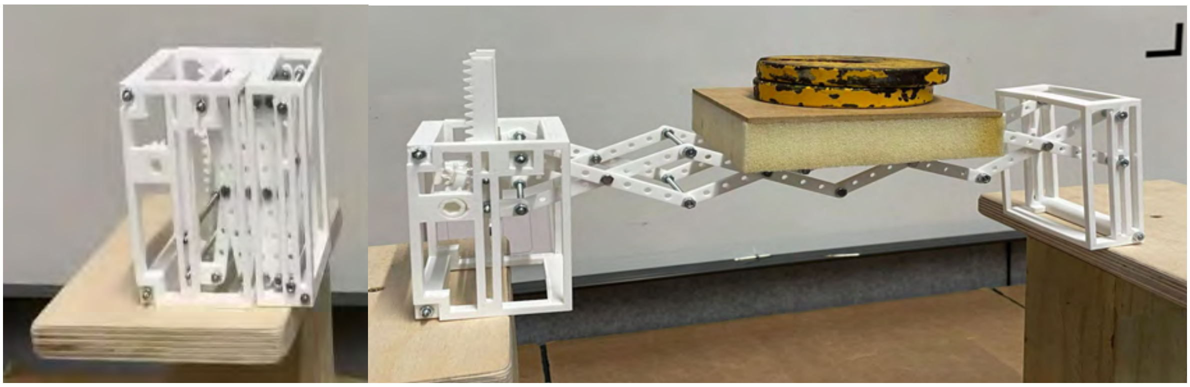

Figure 2: A bridge mechanism featuring rack-and-pinion and scissor elements prior to (left) deployment, and (right) the mechanism deployed to span the 300mm gap, supporting 1 kg.

Figure 3: CAD of a bridge mechanism utilising a threaded power screw, scissor elements and tension locking top panels in (left) pre-deployment and (right) post-deployment.

Figure 4: An elastic-powered bridge mechanism with hex-drive operated latch in its (left) pre-deployment and (right) post-deployment states.

STANDARD 6: ENGINEERING LEARNING WORKSPACES

A specialised "flat-floor" space with seating for 120 students was designed and built (as part of a large new building) for the weekly 3-hour practical sessions and associated project work in this unit. This venue is equipped with dry-erase tables on wheels that can be quickly folded and stowed, overhead power, audio-visual equipment, and large areas of the floor that can be easily cleared to make room for project testing (see Figure 5). The connected storeroom was used to stow the 24 dedicated 3D printers mounted on six rolling workbenches outside of class time. Each team was provided with a small combination locker to enable them to store their project kits close to the teaching space, allowing any subset of team members to access the materials and work on the project fluidly throughout the semester. Our students are required to provide their own laptop device, which meets a minimum performance standard required to install and run the required CAD and slicer software in class.

The venue's facilities allow students to present physical and digital media of their choice. Presentations are often performed in up to three streams, aided by the provision of mobile audio/visual solutions in the form of Mobile Computers on Wheels (MoCoWs) to handle the demands of large cohorts (850+ students per semester, 120 students and 24 teams per session).

Figure 5: Our 120-seat, flat-floor teaching space (left). Two of our six mobile 3D printer workbenches, each featuring four Prusa i3 Mk3 printers and a ducted HEPA air filter (right).

STANDARD 7: INTEGRATED LEARNING EXPERIENCES AND
STANDARD 8: ACTIVE LEARNING

Each week of the project represents a phase of the design process and moves closer to the ultimate goal of a realised product. The type of informal reporting typical of the engineering workplace is used for assessment early in the project, and a more substantial formal, summative presentation with a supporting slide deck is made at its conclusion. Different team members are required to present each week to ensure shared participation. Practical learning activities and assessment details are shown in Table 1.

Table 1: Project Assessment

Week	Primary Activity	Practical Learning Activities	Assessment (%)
1	Concept Ideation	Working in your team, develop one unique idea per team member that satisfies the project brief. Describe using hand sketches, or build a prototype using the kit parts.	Two team members present the team's three best ideas and describe relative merit. (1%)
2	Part/Assembly CAD	Two high-potential concepts are developed into functional CAD assemblies.	Two team members present CAD models and describe mechanism function and merit (1%)
3	Additive Manufacturing Study	Key details (fits, tolerances, critical geometry, print orientation, etc.) are prepared for 3D printing and test parts are manufactured.	Two team members present and justify their parts and additive manufacturing strategy. (1%)
4	Preliminary Testing	Teams manufacture prototype assemblies and are provided access to testing equipment. Instructors are available for consultation.	Peer assessment of design brief satisfaction and performance test criteria against a provided rubric. (1%)
5	Final Test	Teams demonstrate the function of their mechanism and present slides which explain their design, development and testing.	Two team members present and demonstrate their mechanism and critically analyse the entire design process. (9%)

STANDARD 12: PROGRAM EVALUATION

The success of this new team project was initially evaluated based on both quantitative and qualitative feedback collected as part of our university's Student Evaluation of Teaching and Units (SETU), summarised in Table 2. Overall, students were satisfied with the unit (3.83/5, above the university average score). This level of overall unit satisfaction was the highest among the three new design units. The survey results showed strong performance compared to previous semesters in criteria related to the mix of theory and practical application, engagement, learning activities and assessment. Students also self-reported growth in their skills relating to design project experience, CAD, 3D printing, and teamwork (Tong *et al.*, 2022). A large number of anonymous written comments were also received, and a couple of interesting ones relating to the project and scaffolded activities included:

"I really enjoyed the process of creating Solidworks models using the theory taught, 3D printing them, and testing. I found this prototyping loop to be a very effective way to teach the fairly abstract theoretical concept in a very hands–on way."

"There was a good aspect of practical application, when it came to the practical classes, and the group work was challenging, but doable. This allowed for great student discussion and teamwork, which is the perfect environment for learning engineering."

Table 2: Student Evaluation of Teaching Units Survey Results - ENG1011, S2 2022

University Wide Items (Summary)

	Responses	Median	%Strongly Agree/Agree
The Learning Outcomes for this unit were clear to me	133	4.10	78.95%
The instructions for Assessment tasks were clear to me	133	4.08	78.20%
The Assessment in this unit allowed me to demonstrate the learning outcomes	133	4.02	73.68%
The Feedback helped me achieve the Learning Outcomes for the unit	133	3.90	66.17%
The Resources helped me achieve the Learning Outcomes for the unit	132	4.00	68.18%
The Activities helped me achieve the Learning Outcomes for the unit	133	4.08	79.70%
I attempted to engage in this unit to the best of my ability	129	4.29	83.72%
Overall, I was satisfied with this unit	133	3.83	62.41%

Faculty Wide Items (Summary)

	Responses	Median	%Strongly Agree/Agree
The assessment tasks helped me to develop the knowledge and skills required for this unit	132	4.02	73.48%
I understood the grading criteria used in assessing my work	132	4.05	76.52%
This unit contained a good mix of theory and practical application	132	4.44	86.36%
The Moodle site was engaging and enhanced the learning experience	133	3.87	65.41%
The lectures were valuable for my learning	131	3.95	70.23%

Some comments included valuable recommendations for future improvements, including:

"Have smaller teams, 4 – 5."

"One major issue throughout the semester was the lack of printers available. I think obtaining more printers or setting aside more time would make the process much more enjoyable… It felt like there was very little time and if a single print failed or a single idea failed, then there would not be enough time to complete another."

RECOMMENDATIONS AND FUTURE WORK

For future iterations of the project, the following improvements will be made:

- Make 3D printers available on weekends and after hours. Limited access hours and competing with class time in other units of study may have limited the number of design iterations.
- Increase the weighting of the project assessment. The percentage of the total grade allocated was not seen to represent the time required to complete the project compared to other assessment tasks, as evidenced by students' comments in SETU.
- In 2023, we will implement a First-Year Learning Centre - an informal space for first-year students to work on their projects, attend unit helpdesks and be referred to study support where necessary.

Recommendations to others pursuing a similar project implementation:

- Pedagogically speaking, high expectations of student output can be set as long as learning is scaffolded appropriately. We recommend regular design reviews with skilled

teaching staff to provide timely feedback, motivate regular progress towards the goal (rather than a sprint at the finish), and help detect teamwork problems early.
- Teams of 4-5 students are preferable for first-year projects, given the students' inexperience in managing engineering teamwork dynamics.

CONCLUSIONS

A design project was implemented in the unit ENG1011 Engineering Design, integrating elements of civil, mechanical, and materials engineering. The project required students to propose a range of solutions to a complex, open-ended problem and justify their chosen solutions with engineering reasoning. Students developed a bridge mechanism according to the given constraints for starting size, deployment span and structural strength. This type of open-ended project has traditionally been challenging for first-year students. However, students were encouraged to pursue novel and/or non-obvious solutions, which was assisted through the stages of conceiving, designing and implementing an engineering solution. This scaffolding allowed students to feel confident to 'have a go' and awarded students for exploration and decision-making. By giving first-year students the tools to identify a complex problem, break it into manageable stages and prototype a solution, we believe we have set them up for success in their future years of study as they tackle more open-ended, engineering problems.

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