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Evaluating Outcomes in Two Engineering 'Clinic' Subjects

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ABSTRACT

CONTEXT
Project-Based Learning (PBL) is seen as a key pedagogical approach to address a widely acknowledged skills gap existing between the capabilities expected by employers and what is seen in engineering graduates. This enthusiasm stems from an understanding that PBL provides authentic learning experiences where students perform the very activities in which they will engage after graduation, as well as opportunities for "dual-impact" learning activities to build technical and professional skills simultaneously (Crawley et al., 2014). Moreover, open-ended projects can encourage students to develop capabilities for self-directed learning and application of knowledge, and the independence and initiative needed for a successful career.

PURPOSE
This paper details the creation of two project-based 'clinic' subjects within a traditionally taught Electrical Engineering master's program. Both subjects revolve around open-ended, semester-long design projects addressable through many plausible solution paths. The primary purpose of this paper is to evaluate the extent to which students were able to simultaneously integrate knowledge from prerequisite subjects and develop their professional engineering skills through dual-impact learning activities.

APPROACH
The design and implementation of the clinic subjects is informed by literature on project-based learning. In lieu of pending survey results, the approach taken to assess the success of students achieving defined learning outcomes is through observations of the instructors and analysis of recurrent themes expressed in self-reflection essays submitted by students.

OUTCOMES
Observations indicate students were highly motivated by the open-ended nature of the projects and considered gaining practical experience with hardware and software tools to be their most significant achievement from undertaking the subject. These experiences were indeed gained simultaneously with the development of professional skills; however, the instructors observed a deficiency in the rigorous application of theoretical engineering concepts from prerequisite subjects.

RECOMMENDATIONS
The next iteration of the subject will address the perceived lack of engineering rigour by exemplifying the expectation, while ensuring that such an example does not degrade the open-ended nature of the project. To that end, an adaptation of the project scope will be used to ensure that an off-the-shelf solution to the project does not exist and hence achieve the same ownership and engagement that was observed to drive students' skill development.

KEYWORDS
Project-based learning; integrative learning; professional skills.

Introduction

It has long been recognised that successful engineers possess not only solid theoretical knowledge but a strong aptitude in the practical application of that knowledge accompanied by numerous professional attributes that are non-technical in nature. Such professional attributes include generic and transferable competencies such as written and verbal communication skills, teamwork, self-management, innovation, and ethical conduct. It is common for studies on the attributes required of engineering professionals to report these non-technical and attitudinal competencies to be as important as technical competencies (Male et al., 2011). In its current phase (Crawley et al., 2014), engineering education has been on a path of continuous evolution to better deliver graduates with these attributes, as is clearly reflected in an increasing emphasis on such capabilities in accreditation standards (Engineers Australia, 2021).

The shift in emphasis in graduate attributes has naturally required a corresponding shift in pedagogical approaches and design of curriculum within engineering programs. Project-based Learning (PBL) is one approach widely promoted and deployed to better prepare students for the realities of the engineering workforce (Mills and Treagust, 2003). The enthusiasm for PBL, and its central role in many reform initiatives (CDIO, 2021), derives from its ability to provide authentic learning experiences where students perform the very activities in which they will engage after graduation. These activities can be ‘dual-impact’ in nature, simultaneously and efficiently allowing the development of both technical and professional skills (Crawley et al., 2014). Furthermore, the potential open-ended nature of project work encourages students to develop capabilities for self-directed learning and the application of knowledge while fostering greater independence and initiative, which is aligned with notions of life-long learning and sustainable assessment (Boud and Soler, 2016).

In this paper we reflect on the initial offering of two ‘clinic’ subjects within a Master of Electrical Engineering program which are structured around semester-long design projects in the areas of autonomous systems and communication systems. Here, the ‘clinic’ label is inspired by its use within the medical community to denote practical instruction and experience in the treatment of real patients. In a similar manner, we envisage an engineering clinic to be

> *a class of engineering students which takes place predominantly in a workshop setting where skills, knowledge, and understanding are gained through practical instruction in analysing and implementing solutions to a team-based design project.*

These subjects afford students the opportunity to integrate prerequisite knowledge, practice engineering design principles, and develop important professional attributes.

It is common to find PBL employed in engineering curricula, particularly within introductory engineering subjects (Dym et al., 2005) and final-year capstone design projects (Heitmann 1996). It is less common to find PBL widely employed across a single master’s degree program, although there are examples (Kjersdam, 1994). PBL is not without its associated challenges; many of these issues have been identified or studied in the literature, including topics such as the hierarchical nature of engineering knowledge (Mills and Treagust, 2003), team formation (Rasul and Mandal, 2019), the assessment of individual contributions within team-based work (Holgaard and Kolmos, 2009), and the high time commitment for project-based work (Bédard et al., 2010).

In the remainder of this paper, we first describe the design and implementation of these two subjects. We then offer reflections based on instructors’ perceptions of student performance and attitudes. When relevant, we comment on how awareness of PBL-associated challenges informed design and implementation decisions and discuss how observations in our reflection may be related.

Subject Design

The primary motivation behind introducing the clinic subjects was to give students additional opportunities for completing domain-specific design projects, further developing important professional attributes, and integrating knowledge across prerequisite subjects. Both subjects are taught as electives and have master's level prerequisites as depicted in Figure 1. A key anticipated benefit of the subjects was that, by requiring students to draw on knowledge from multiple prerequisites, the 'silos of knowledge' that often exist between separately taught technical areas could be eroded. These silos are the unintended consequence of the semester structure and subject division within university programs and can conceal from students how closely related many subdisciplines are within practical engineering applications.

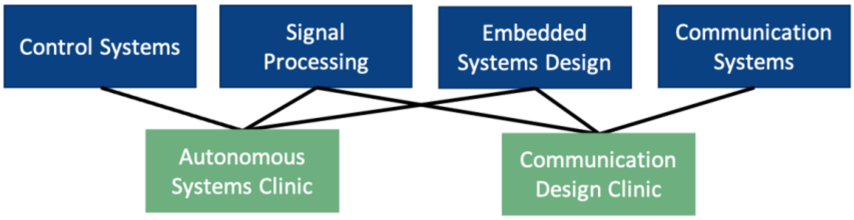

Figure 1: Prerequisite subjects (blue) for engineering clinic subjects (green) within the Master of Electrical Engineering program

Intended learning outcomes (ILOs) were formulated for the two clinic subjects to codify the high-level conceptual goals. ILOs for the clinic on autonomous systems are reproduced in Table 1 along with their mapping to Engineers Australia (2021) 'Stage 1 Competency Standard for Professional Engineer'. The 16 mandatory elements of competency are grouped into three categories, and from the mapping it can be seen the stated learning outcomes heavily focus on categories *2. Engineering Application Ability* and *3. Professional and Personal Attributes*. Less emphasis is placed on instructing students in new theoretical knowledge, as will be further evident in the discussion on subject implementation. Rather, the focus is on students applying prior theoretical knowledge and self-directing their study of advanced topics they identify as relevant to their proposed solution. This focus is similar to the year-long, team-based capstone design project completed by all students in the degree. In this way, the clinic subjects are intended to be 'mini-capstone' experiences and provide preparation and skill development relevant to students' future capstone efforts.

Following the well-established educational best practice of constructive alignment (Biggs and Tang, 2011), learning activities and assessments were designed with the outcomes of Table 1 in mind. We defer discussion of learning activities to the next section, but a summary of assessments employed is provided in Table 2. These included a mix of both individually and team assessed tasks with a heavy focus on the use of authentic assessments related to project work. A series of guided workshops, completed as a team but assessed individually, familiarised students with the software and hardware platforms used within the projects. A mid-semester exam was used to assess individual achievement of concepts relevant to the area of the respective design project.

Table 1: Intended learning outcomes for clinic on autonomous systems

	Intended Learning Outcome	EA Competencies
1	Apply established engineering design methodologies to assist in the design and implementation of autonomous systems.	1.5, 2.3
2	Analyse and devise solutions to autonomous systems design problems, drawing upon fundamental principles underpinning autonomous systems from areas such as embedded systems, control systems and signal processing.	1.3, 2.1, 3.3
3	Determine the integrity and reliability of structures, circuits, and algorithms, in order to robustly design against failure.	2.2
4	Demonstrate competency with modern hardware components and software frameworks for autonomous systems through hands-on engagement.	2.2
5	Apply systematic approaches to the conduct and management of a relatively complex electrical engineering design project in a small team.	2.4, 3.5, 3.6
6	Communicate effectively with professionals across different engineering disciplines, through media such as concise technical reports and informational videos.	3.2

Table 2: Assessment structure for engineering clinics

Assessment	Type	Weight	ILOs
Guided Workshops	Individual	12.5%	3
Mid-semester Exam	Individual	10%	1-3
Project Plan	Team	10%	2, 3, 5
Project Review Meeting	Team	15%	2, 6
Project Demonstration	Team	2.5%	4
Final Team Report	Team	30%	2-3, 6
Team Video Presentation	Team	10%	6
Self-reflection	Individual	10%	5

Team assessment tasks reflected the philosophy of the subject being a ‘mini-capstone’ with students completing in sequence: a project plan, a project review meeting, a project demonstration, and a final technical report. Teams were not required to strictly follow their submitted project plan but needed to benchmark their progress against previous expectations. The project review meeting, in which student teams orally presented their progress and defended design decisions made up to that point, was intended to model such meetings as are typically held on industry projects. It was the most significant formative assessment task in the subject and an opportunity for instructors to give teams direct feedback on their verbal communication abilities and planned technical solutions.

A small percentage of the overall subject marks (2.5%) were allocated to a competitive project demonstration at the end of the semester. Team solutions were compared by their ability to meet announced performance requirements with the strongest team in each category awarded additional marks. The competition was intended to motivate students by providing a product-delivery element to the subject as well as a sense of achievement for the winners. It is important to note that instructors repeatedly emphasised the primary evaluations of the subject would assess the process taken in solving the project rather than performance in the end-of-semester competition.

The final team report was a 30-page document in which students were expected to provide rigorous evidence of the engineering analysis, design, and implementation methods employed to produce their solution. Students were not explicitly reassessed on theoretical knowledge from the prerequisite subjects; instead, assessment focused on their application of said theoretical knowledge to the project. This approach differs significantly in nature and scale to the problem set and workshop assessments found in prerequisite subjects. Specifically, students were expected to describe over-all system architecture, explain how subsystems were to interact, report multiple solution approaches considered for each subsystem, and justify design decisions made throughout the project. They were expected to make clear connections across their 'silos of knowledge'.

Students completed three self and peer assessments (SPAs) through the semester associated with the project plan, project review, and final report, respectively. These assessments allowed students to provide each other with formative feedback on their performance, identified issues in team dynamics so that they could be addressed, and provided appropriate scaling of team marks based on individual contributions. The first SPA for the project plan was strictly formative with only the project review and final report SPAs impacting marks.

Finally, students completed a 1500-word individual self-reflection at the end of the semester in which they reflected on the experience of working as a member of a project team and the relevance of various professional attributes to the achievements made on the project. This self-reflection was intended to drive deeper student awareness of and appreciation for how their professional attributes had developed through the dual-impact activities of the subject. Additionally, the self-reflection provided valuable feedback to instructors for assessing the efficacy of subject design in meeting the stated high-level goals.

Implementation

Central to the implementation of any PBL subject is the selection and parameterisation of an appropriate project that enables students to achieve the defined learning outcomes. Based on the goals set for the clinics, this required selecting projects that were open-ended in nature, addressable by a diverse set of solutions, exercised concepts from all prerequisite subjects, and lent themselves to exploration of advanced domain topics through self-study.

For the clinic on autonomous systems, students were tasked with delivering

> *a working prototype of a robot that operates autonomously in a warehouse environment to repeatedly perform the task of collecting items from various locations in the warehouse and delivering those items safely to other parts of the warehouse.*

As the mechanical design was not a focus of the subject, a baseline differential-drive robot was given to each team composed of a chassis, wheels, motors, and a single-board computer. A variety of potentially useful sensors (distance, proximity, encoder, camera, IMU, colour) were made available to each team for integration into the baseline platform. The necessary code libraries were pre-installed and skeleton code was provided for retrieving the raw data from each sensor separately and for commanding the input voltage to each motor. Students were responsible for designing and implementing all additional features and algorithms that they determined to be necessary for achieving the task, including processing the raw sensor data, localisation, path planning, and motor control for path following.

For the clinic on communication systems, students competed in a spectrum challenge in which they were tasked with

> *designing, implementing, and verifying a secondary communication link capable of opportunistically communicating using spectrum shared with an incumbent user without significantly degrading the incumbent's communications.*

Spectrum challenges (DySPAN 2017, ShaRC) are a common way to motivate the learning of digital communications and drive research in related areas such as software-defined radio (SDR) and cognitive radio (CR). Clinic students developed solutions on an SDR platform (GNU Radio and Nuand bladeRF), which presented a lower barrier to entry as compared to traditional hardware-based platforms and great freedom in the design of communication protocols. Workshops guided students through the development of a reference narrowband communication link useful as a baseline for their project. Students were responsible for designing and implementing the secondary link's spectrum access strategy and any improvements to the baseline link.

Enrolment consisted of 33 students and 12 students for the autonomous systems and communication systems clinics, respectively. Students completed the projects in teams of three and were allowed to choose their teammates. Team formation was completed by the fourth week, prior to which students were encouraged to work in a variety of constellations and discuss compatibility for discerning their teams.

As the focus of the clinics is on integrating existing theoretical knowledge and gaining new knowledge through self-directed study, the subjects utilised a non-traditional format of contact hours. The first four weeks of semester were an intensive period of instruction, having students attend three hour-long lectures and one three-hour guided workshop each week. The focus of instruction was introducing students to the design project, familiarising them with the software and hardware tools, motivating a range of viable solution paths for applying prerequisite knowledge, and scaffolding the independent teamwork that would form the remainder of the semester. A fallow period of reduced contact hours followed in which students worked independently on their design projects. Three-hour, optional workshop sessions were scheduled each week to allow students access to the hardware and to engage instructors for assistance with ad hoc questions. Project-related assessment tasks took place throughout this fallow period. See Figure 2 for the sequencing of contact hours and assessment tasks within the clinics.

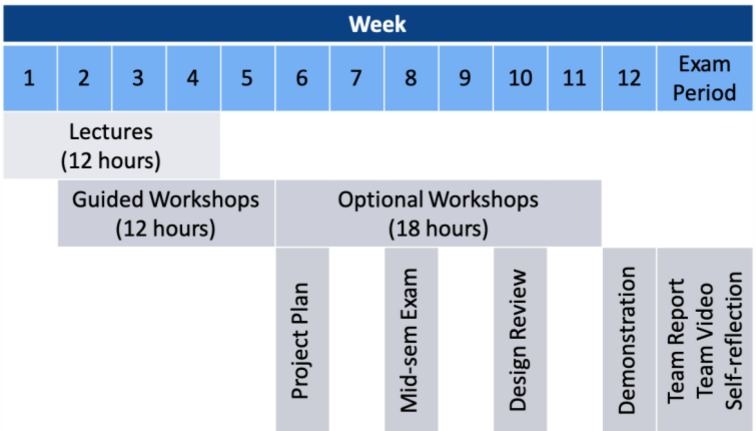

Figure 2: Engineering clinic contact hours and assessment structure

As a learning resource, students were provided with a set of video interviews conducted with instructors of prerequisite subjects and relevant industry experts. These videos were a way of framing the content studied in the prerequisites for the project at hand and gave helpful hints about potential advanced topics to explore. Additionally, discussion with industry experts demonstrated the real-world relevance of the projects and contextualised the importance of professional attributes to the success of an engineer.

Reflections

A quantitative and qualitative survey of students is underway to evaluate learning outcomes, with a focus on the perceived efficacy of dual-impact activities on professional skills development and students' experience of the project-based pedagogy. Results were unavailable at the time of writing; here we offer reflections based on the experience of creating and delivering these subjects and recurrent themes in student self-reflections.

Project scope, rigour, and ownership

A common theme raised in student reflections was that the size and scope of both projects was of sufficient scale to necessitate both efficient teamwork and a methodical design approach. Multiple students observed that these were the first projects they had completed not addressable in the given timeframe working individually. The inability for one individual to carry an entire team drove a greater appreciation among students for the importance of core skills around project work, such as the use of system-level thinking, documentation, distribution of workload, coordinating individual efforts, and managing team dynamics. These insights likely would not have been as strong if projects were of a smaller scope. The use of semester-long projects with a significant fallow period clearly has strong advantages in this regard and was made possible by focusing on the integration of existing theoretical knowledge.

Both instructors observed that the balance of student effort spent on the rigorous application of engineering design methods and the focus placed on implementation was heavily skewed towards the latter. Prerequisite subjects provided students with ample theoretical and analytical tools to apply but few teams fully utilised such tools, instead electing more ad hoc design approaches. Learning outcome 1 in Table 1 makes clear that applying engineering design methodologies was a key goal for the subjects. One approach to address this imbalance would be to give students a refined project platform to reduce time spent on implementation. A more promising alternative would be to include concrete examples of applying design methodologies within the guided workshops to prompt a more balanced approach. Care must be taken in any redesign of workshops that students do not simply see an example design approach as a prescriptive model directly applicable to the larger project without intelligent modification.

In line with the open-ended project philosophy of the subjects, a conscious choice was made to not give an example solution for the project task but instead be confident it was achievable starting from the skeleton hardware and software provided. In this way students were likely to have an experience more closely mirroring that of a professional engineer, i.e., needing to carefully consider the applicability of solutions from similar problems before adopting and combining. This differs from project experiences in other subjects, apart from capstone, and instructors observed a shift in student mentality during semester to a greater sense of project ownership. A number of students expressed in their self-reflection that this ownership over the project combined with the assessment emphasis on engineering process gave them confidence to pursue solutions despite uncertainty in the outcome and hence learn from the subsequent 'failure' of a given approach.

As this was the first time both clinics were taught, students naturally encountered multiple software and hardware issues throughout the semester. The need to independently identify and resolve such issues had a different impact on students of the two subjects. Within the clinic on autonomous systems, it was generally observed that students were highly motivated by the chance to engage with software and hardware tools to resolve such bugs. Within the clinic on communication systems, however, students seemed to be more discouraged by such issues, with some teams focusing on resolving a given issue rather than continuing to make progress in other areas. A key takeaway inferred is that students can gain valuable insight and motivation from addressing software and hardware issues that arise during PBL, but this must be carefully balanced to prevent students from becoming discouraged.

Team dynamics and influence on future project-work

Several students made thoughtful observations about different learning approaches taken by teammates and demonstrated an appreciation for the relative strengths and potential complementarity of such approaches. Particularly notable were observations reported in individual reflections that agreed within a team. Usually, students who made the keenest observations about their teammates were best able to identify the underlying emotional attitudes that drove their own behaviours and learning approaches and whether those had positive or negative aspects. Such self-knowledge and emotional intelligence are important professional attributes and fall under EA elements of competency *3.5 Orderly management of self, and professional conduct* and *3.6 Effective team membership and team leadership.* Again, it is believed the large scope of the team projects undertaken by students was a contributing factor to enabling these types of insights.

Many students made clear connections in their reflections between the nature of the project work in the subject and what their likely experience of industry work will be. This led students to express an appreciation for the chance to practice communication skills, develop greater expertise in computer programming, and apply engineering knowledge in a practical setting. Some students reported such opportunities were a strong contributor to an increase in self-confidence in their ability to function as professional engineers in the future. The required prerequisites for each clinic meant most students had either already commenced their final-year capstone project or would begin in the next semester; multiple students expressed an expectation that experiences in the clinic would boost the success of their capstone project.

Collaboration and workload

Despite the competitive end-of-semester demonstration, a collaborative atmosphere was encouraged between teams during the guided and optional workshop sessions, for example by guiding students with certain questions to ask others in the cohort who had encountered a similar question. Students highlighted in their self-reflection that the act of providing explanations to others and asking questions of others was mutually beneficial. Additionally, the optional workshops fostered a collaborative atmosphere through engagement with instructors, which enabled just-in-time and highly tailored learning opportunities. Even if such a discussion was with an individual student, the learning was observed to flow back to both their team and the cohort at large through the collaborative atmosphere.

Student self-reflections indicated a keen interest and preference for more experiential learning approaches to be incorporated into the program. This is in part attributable to continuing pandemic restrictions on in-person instruction creating a strong appreciation for the return to working in a practical lab setting and face-to-face interaction with peers. Six students concurrently enrolled in both clinics and commented on the challenge of managing the high workload entailed by project work, which was exacerbated by similar assessment due dates for the two clinics. A high workload is a well-known challenge of PBL as compared to traditional pedagogies but can also be viewed as a good opportunity for students to practice planning ahead and managing stress levels. A wider-scale adoption of PBL in the master's program would require careful coordination and execution to address this challenge.

Conclusion

According to the observations of instructors and the reflections of the students, the clinic subjects described in this paper, which employed PBL pedagogies, did indeed achieve the high-level goal of simultaneously improving students' technical and professional engineering competencies. For the technical skills, a major dissatisfaction among instructors was an imbalance between engineering rigour and implementation work, with the latter being the major focus of the students' efforts. For the professional skills, a clear theme in student reflections was that the dual-impact activities of the subjects raised student awareness of the importance of these skills to their future endeavours as professional engineers. In particular, teamwork was seen by the students as contributing positively to both the technical and professional skills development aspects. Pending survey results are expected to provide a better understanding of these aspects, including the students' perception of the balance between engineering rigor and implementation work.

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