



Initial outcomes of the redevelopment of an integrated systems engineering curriculum

Jenny Simmons; Jeremy Smith, and Marnie Shaw.
School of Engineering, The Australian National University
Corresponding Author Email: jenny.simmons@anu.edu.au

ABSTRACT

CONTEXT

Bachelor engineering degrees at the Australian National University (ANU) include a compulsory systems engineering (SE) core. In 2018-2019, the SE core curriculum was redeveloped to create a more integrated series of courses focusing on SE as a framework for applying traditional engineering disciplines in interdisciplinary contexts to solve the complex global challenges of the future. The redesign had a strong emphasis on learning-by-doing and engagement with industry. The new courses have been progressively introduced; 2nd year courses in 2020, 3rd year in 2021 and 4th year in 2022.

PURPOSE OR GOAL

The goal of this study was to summarise the initial outcomes of the SE core curriculum redevelopment, highlighting achievements as well as challenges. We expected that the redesign would bring increased clarity and a shared understanding of the purpose of SE for the teaching staff across the degree and this in turn would result in improved student satisfaction. We expected that the project-based focus on important, real-world application of engineering would result in both increased industry engagement and a more diverse student cohort.

APPROACH OR METHODOLOGY/METHODS

The outcomes of the curriculum redevelopment were assessed in terms of student experience of learning and teaching (SELT) scores. We assessed the number of industry partners, student projects and student teams. The challenges associated with the roll-out of the new core design were also explored and summarised based on collaborative reflection.

ACTUAL OR ANTICIPATED OUTCOMES

Over 20 projects have been established with a range of partners including student teams, internal research groups and external organisations. We found that an administrative role was required to increase shared understanding of the curriculum and connection between the courses and convenors. In 2022, there was a substantial increase in SELT scores compared to before the redevelopment.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

We are seeing benefits from the redesign of the SE core curriculum in terms of student experience and collaboration across courses and convenors. An administrative role has provided increased consistency across courses and shared understanding of the curriculum across convenors. Future work includes completing an Engineering Learning Commons, self-study modules and increasing opportunities for peer-to-peer learning across year levels.

KEYWORDS

Engineering curriculum, systems engineering, project-based learning, industry engagement

Introduction

Engineers of the 21st century are increasingly required to work across multiple disciplines within engineering and beyond and incorporate social, economic, and environmental perspectives to address the complex and compounding challenges facing the Earth (ACED 2021, UNESCO 2021). Globally the engineering profession needs to expand not only its capacity and capability but its collaboration and inclusion (UNESCO 2021). To achieve this, transformations are required in engineering education to produce graduates with technical, disciplinary, and professional skills, and the ability to transfer those into industry (ACED 2021). A range of curriculum models beyond traditional lectures and exams are necessary to simulate contemporary engineering practice of working in multi- and cross-discipline teams on open-ended and emerging systems and challenges in order to develop the ability to work in complex and rapidly changing environments (UNESCO 2021).

The Bachelor of Engineering of the Australian National University (ANU) was established in the 1990's with some of these aims in mind. As it evolved the program developed an interdisciplinary system engineering core which ran through the spine of the undergraduate degree program (Blackmore et al 2019). This program, with its systems engineering focus and discipline integration, was highlighted as distinctive in the ACED 2035 study (Crosthwaite 2021), although as mentioned graduates still complete with a designated discipline major. However, over time due to several internal factors including re-organisations and resourcing, the envisioned integrated systems engineering core had become fragmented leading to a lack of consistency and a return to traditional curriculum approaches (Blackmore et al 2019). In 2017, a review of the systems engineering core at the ANU was undertaken with the intent of renewing the courses, and by 2019 a design of a redeveloped core completed.

The redeveloped core sought to create an integrated series of courses using project-based learning in real-world interdisciplinary contexts. Students would develop knowledge by applying breadth in professional skills alongside depth in technical skills, solving open-ended problems in multidisciplinary teams and working with partners to increase industry engagement and interactions from early in the program. The redevelopment sought to establish a consistent course structure and development of educator experience to ensure increased stability and consistency across the program. Taking lessons on implementation from similar efforts to create an integrated spine of connected courses (such as Mitchell et al 2019), a staged rollout of the redeveloped courses over three years was used.

The design of the core redevelopment was outlined in Blackmore et al (2019) at the beginning of its implementation. This paper will update the previous work to summarise the implementation of the new courses, initial outcomes from their delivery, challenges and lessons learnt along the way, and resources and support required. The intent is to provide our experiences with curriculum renewal designed to develop engineers more appropriate for contemporary and emerging practice. The broad context for engineering at the ANU will be outlined along with a summary of the motivations for redevelopment and key design features. An explanation of how the design has been implemented and results from the first years of delivery are provided, along with a summary of success, challenges and future work.

Context

Engineering programs at the ANU are housed within a single School of Engineering (SoEn). Since the 1990's a four-year Bachelor of Engineering (BE) has been offered (see Figure 1), with a higher entry requirement Bachelor of Engineering (R&D) introduced later (with additional research projects in second and third year). Students undertake an 8-course (one-year full time equivalent)

discipline major which appears in brackets on a testamur, for example, a graduate will complete a *Bachelor of Engineering (discipline major)*. Five-year double degrees are common among students. The BE consists of a common first- and second-year for all students of foundation courses, with the discipline major undertaken in third- and fourth-years. Across all four years runs a systems engineering spine, or core, with one course in semester 1 of first year then one course (a ¼ of a full-time load) each semester in years 2, 3 and 4.

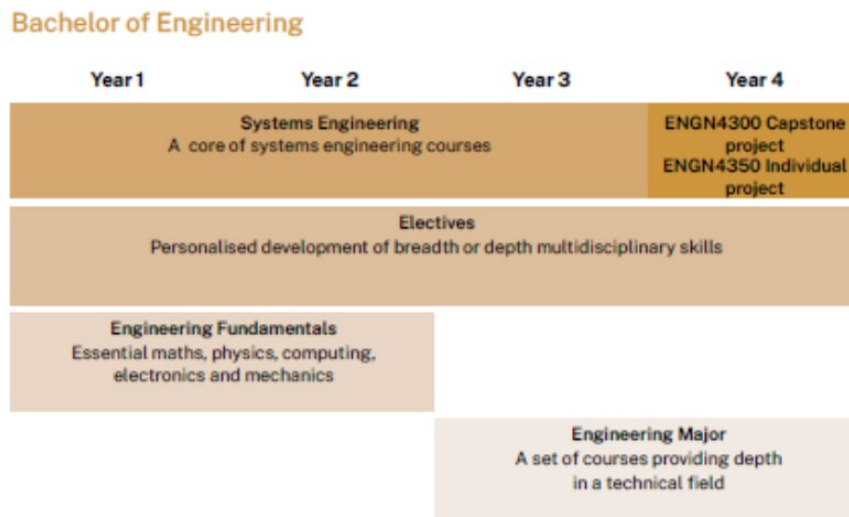


Figure 1: General structure of the BE program at the ANU

The core redevelopment outlined here focuses solely on the systems engineering (SE) core. Apart from one change in final year, the contribution and timing of the core courses to the overall program remained unchanged. The original final year consisted of all students completing a two-semester (25% of final year) individual project and a one-semester team capstone. As part of the redevelopment, this was changed to students electing to take either a year-long individual or team capstone project, each contributing to 25% of the load in final year (the other could be undertaken using elective slots if the student wished).

Motivation

Since 2010, the SE core courses received regular poor student experience feedback and outcomes, lower than the average for engineering courses as a whole. As there is no dedicated SE research group, core courses were delivered by a wide variety of staff, including academics from discipline-focused research clusters supplemented by external practitioners and sessional-staff; there were no dedicated staff to manage and delivery the core. Course creep was present leading to the SE core being a collection of individual courses rather than a cohesive program. As highlighted in Blackmore et al (2019) an external review of the core was completed which led to the redevelopment of the SE core courses. The goals of this were (Blackmore et al 2019):

- Increase engagement and interactions;
- Increase program stability, and;
- Enable opportunities for tailorable depth.

Design

Through research, engagement, and discussions with stakeholders at the ANU and externally, and conversations and workshops with staff, students and practitioners, a design for the SE core as a program, distinct from individual courses, was developed. The resulting design is captured in

Figure 2 below (see Blackmore et al 2019 for further description of the concept and design undertaking) with the key features consisting of:

- Courses each semester as part of an *Engineering Design* sequence. These are typically front loaded with 40% content, often taught in flipped-classroom delivery or active workshops, and 20% skills, developed through more specialised workshops or tutorials. The remaining 40% of each course (approximately the second) focuses on application of the content to a specific authentic project.
- Application streams, which serve as homes for projects in related, overarching areas. Projects could potentially sit across multiple years, such as vertically integrated projects (VIPs), and relate to research, industry partners, or student led (such as competitions). These generally related to *domains* common within SE such as transport, space, and healthcare, and emerging specialisations such as Humanitarian Engineering.
- An online asynchronous Engineering Learning Commons (ELC) containing material available to all students that could be applicable across multiple courses (such as design approaches, tools, and techniques) or that link to discipline majors or specific projects.
- Optional industry-based certificate frameworks which enable students to demonstrate specific learning or experiences as defined by external groups.

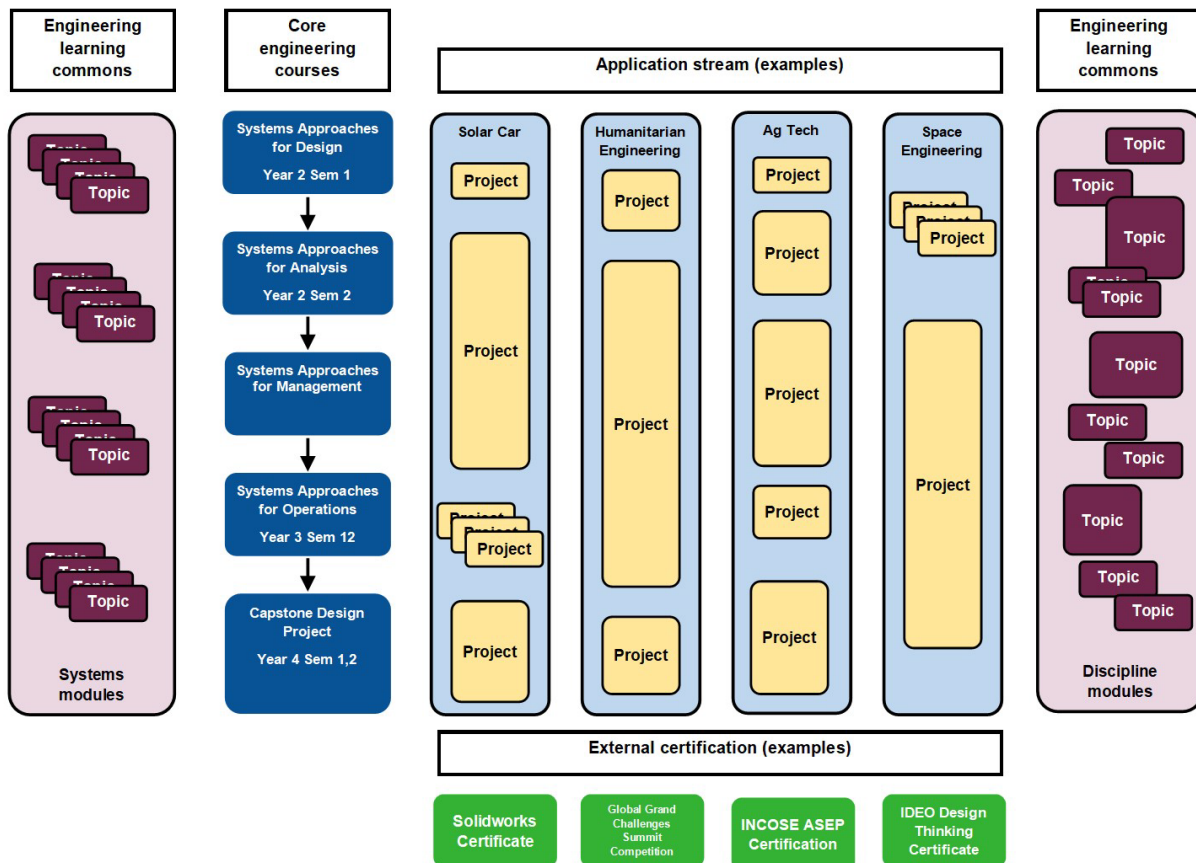


Figure 2: Design of the systems engineering core highlighting courses (dark blue), asynchronous material available through an Engineering Learning Commons (purple), project areas (light blue and yellow) and professional certifications (green) (Blackmore et al, 2019).

Implementation

Planned

To implement the design as captured in Figure 2 the following elements were undertaken in parallel as part of the overall redevelopment which commenced in 2018:

1. Curriculum renewal. New course codes, names, learning outcomes, descriptions, and assessment were developed for all the new core courses from 2nd to 4th year (the first-year course retained its course code, name and learning outcomes). In second- and third-year, a range of projects were offered in each course, between 3-5, within application themes, to match a greater range of student interests and motivations. The new courses were rolled out with a new cohort, so new 2nd year courses in 2020, 3rd year courses in 2021, and the 4th year courses in 2022. Support for the development of the first of the new courses (ENGN2300 in semester 1 2020) was provided by the university central teaching and learning centre.
2. Space. New dedicated and fit for purpose teaching and learning spaces were required. These needed to support active workshops, provide flexibility for class sizes and activities, and provide a physical home for core courses, which had previously used general locations across the campus which were not suited to small-group or design/prototyping activities. The core redevelopment overlapped with a major building redevelopment allowing direct input into the design of new spaces which were available from mid-2021.
3. Expertise and personnel. A key issue with the core delivery is that most conveners are coming from discipline specific groups or clusters i.e., there were no dedicated staff within the core. This had a number of responses; 1/ building a sense of community for core conveners; 2/ a dedicated professional staff role to support conveners, particularly during their first engagement with core courses, and to ensure consistency of material including Learning Management Sites (LMS), student facing material, assignment sheets, and assessment feedback; 3/ a pathway to support and nurture tutors, where current undergraduates and recent graduates could be involved in delivery and bring their experiences particularly in relation to projects.
4. Partnerships. A range of internal and external partnerships were required to scope, offer, and support authentic projects within application streams across the core courses. This focused on a small number of locally based companies, existing community-focused partners (such as Engineers Without Borders-Australia – EWB-A), student associations (particularly involved with student competitions such as the ANU Rocketry and World Solar Car teams), and multi-disciplinary research centres at the university. This was also to ensure projects beyond just discipline-based research projects would be available, to explore and experience the multi-disciplinary nature of systems engineering and contemporary engineering practice.

Completed Changes

Not all the elements of the design and implementation captured above have been completed (see discussion), however the following elements have been completed at time of writing in mid-2022 against the four elements identified for implementation above:

1. Curriculum renewal:
 - a. All the new courses have been developed and delivered using the general structure identified. Student numbers are typically 130-150 students per course.
 - b. While some material has been shared between courses, a dedicated ELC has not been established.

- c. One certificate program, the National Academy of Engineering (NAE) Grand Challenge Scholars Program (GCSP), is in place as an option for students who met the criteria associated with the program.
 - d. Project application streams have been completed although projects involving students from different year levels has not been done. Authentic projects linked to research, student competitions or scoped by external partners are offered in each course.
2. Space:
- a. New teaching spaces were available for the start of semester 2, 2021, although with a lock-down during that semester, semester 1, 2022, is the first time they have been available un-interrupted. These allow teaching to a large cohort (up to 100 students) in one space or sub-dividing into two or three smaller cohorts of 20-30 students to support project and application streams and/or skills sessions.
 - b. Dedicated storage is available, and two purpose-build MakerSpaces are across the corridor.
3. Expertise and personnel:
- a. A dedicated permanent professional staff position has been created to support the development and delivery of courses.
 - b. Three convener workshops are run per year covering not only course design and delivery but systems engineering approaches and methodologies
4. Partnerships:
- a. New formal project application stream partnerships are not in place although projects linked to the pilot set of application areas are used across multiple courses.

Results and Outcomes

Common course structure

A similar course structure is used through the second- and third-year courses with content delivered by flipped-mode classes and active workshops towards the beginning of the course. During this time a specific skills module is taught within each course (for example rapid prototyping in semester one second year, statistics in semester two second year). Following the delivery of the content, the focus switches to the application of the content to the project.

The courses follow a similar assessment structure with content quizzes, individual skills module assignment, project assessment and an individual reflection at the conclusion of each course.

Number of projects, sources of projects

Eight occurrences of the redeveloped second- and third-year courses have been delivered since 2020 with a total of 255 student project teams (varying in size from 4-6 students). Application steam, project partners and project counts can be seen in Table 1.

Offering a range of projects is important, to give students the opportunity to apply systems engineering concepts and approaches to an area of interest to them, which can foster great motivation, learning and outcomes (Smith et al, 2019). Project Streams enable a broader communication of engineering, providing an alternative vision beyond simply disciplines to areas of application and impact, which has been shown to enhance diversity within engineering programs (Smith et al 2019). Project streams in more human-centred areas, such as Humanitarian Engineering, AgTech and healthcare were particularly important and anecdotally had greater female involvement than the overall average in engineering at the university.

Table 1: Application streams, project partners and number of projects per application stream of redesigned second- and third-year courses since the restructure

Application Stream	Project partner(s)	Number of teams	% of project teams
Humanitarian Engineering	EWB-A	51	20%
Space and Aerotech	ANU Rocketry Society	40	16%
Electric Vehicle Fleets	ANU Battery Storage and Grid Integration Program (BSGIP)	38	15%
Transport Systems	ANU World Solar Car (WSC) and ANU Formula SAE	36	14%
Agri-technology	Centre for Entrepreneurial Agri-Technology (CEAT), Australian Pork Ltd	34	13%
Security and Resilience	ANU-Optus Bushfire Research Centre of Excellence	32	13%
Healthcare	ANU John Curtin Medial School (JCSM)	24	9%

Student Experience Survey Results

The outcomes of the curriculum redevelopment were assessed in terms of student experience of learning and teaching (SELT) scores. SELT surveys are run at the end of each teaching session at ANU. Figure 3 shows the average overall satisfaction in the seven core courses from 2010 to 2018. In 2019 the survey was altered to measure the overall teaching experience. SELT were not completed during semester 1 of 2020 due to the transition to remote learning during the first ACT lockdown for Covid-19. Prior to the restructure, the core courses did not score well and were on a downward trend. SELT results indicate greater student satisfaction since the restructure began. The second delivery has always scored higher than the first for all second- and third-year courses as seen in Figure 3.

Dedicated Professional Staff Support

A permanent professional role has been created within the School to support the development and delivery of the SE core courses to ensure consistency and connection between the courses and the convenors. This staff member works closely with the conveners, particularly during their first engagement with core courses and is responsible for maintaining online course content, standardisation of processes, managing assessment and tutor mentoring. This role helps to ensure consistency of material including Learning Management Sites (LMS), student facing material, assignment sheets and assessment feedback. This consistency has helped to demonstrate the connection between the SE core courses to the student cohort.

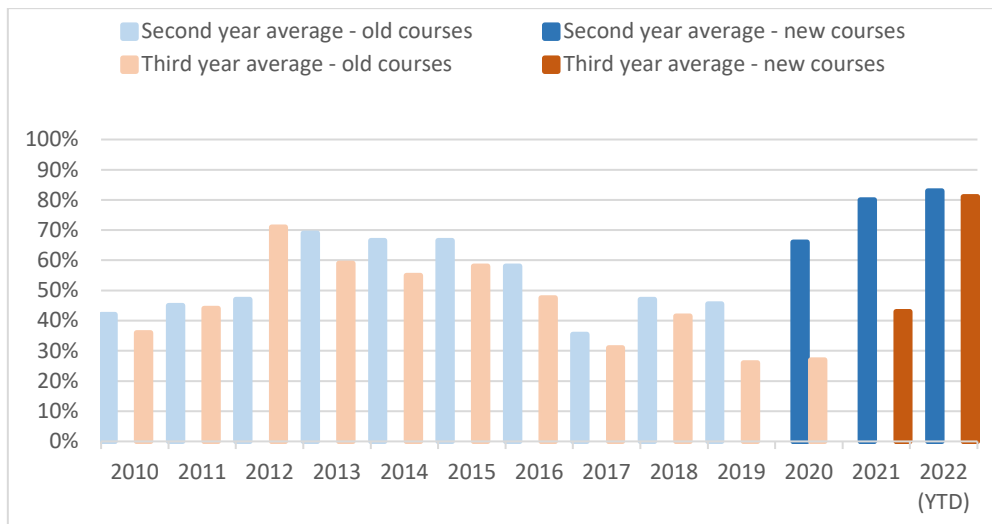


Figure 3: Average SELT scores for 2nd and 3rd year SE courses, pre-year. Note: pre-2019 overall satisfaction, from 2019 overall learning experience. SELTS not completed during Semester 1 2020.

Convenor Workshops

As staff are from different discipline clusters, it is important that they come together regularly to maintain a shared vision for the SE core and avoid course creep. A core convenors workshop is held three times a year, providing an opportunity to develop a shared understanding of the SE core. Workshops are used to review content, share successes, failures and lessons learnt, and continue with longer term planning. The workshops can also be used to seek further ways to link between the courses, particularly relating to the development of students' professional skills over the program.

Discussion

Successes

Program changes can be ambitious, involving rapid change and uncertainty which could have made implementation of a re-developed core difficult. However, due to the consistent general structure of the second- and third-year courses, along with the staged roll out over several years and support from the School in terms of resourcing, the program change has been successful.

A significant advantage of the staged rollout and convenor workshops has been the collaborations between the teaching teams. This has resulted in a strong shared vision of the SE core and motivation for continuing collaboration. The staged rollout has allowed the teaching team to gather feedback from students and reflect on the roll out of each course. The feedback has been used to improve individual courses but also shared across the SE core to increase the connection between the courses and assist with planning course structure and management. This is seen through the SELTs scores, where the further into the redevelopment, the better the responses.

The delivery of the first restructured course coincided with the first lock-down of the Covid-19 pandemic in the first-half of 2020. The design of the delivery, working with front loading of course content and teaching activities that encouraged peer engagement, proved to be an adaptable and flexible design which was beneficial in a time of rapid change. A common pedagogical approach and course delivery processes through most of the program, in addition to administrative support, has allowed convenors to focus on course content creation and reduced the impact of the additional overhead created by the transition to online and hybrid delivery.

The range of project application streams available across the engineering core have made it possible for students to continue working within an area of personal interest (depth of expertise) or swap between applications to provide them with an increased breadth of experience.

A goal of the new design was to increase program stability. The support role has been critical, in achieving this, partly as academics sit within discipline-based clusters, with no dedicated academic staff within the core.

Challenges

Although the program change has been successful, there have been challenges. Many of these were the result on the covid-19 pandemic and could not have been foreseen during the planning of the program change. The priority has been to work on the structure, content, and processes, keeping the aims of the overall design in mind so that this work can be continued later. The pandemic resulted in significant organisational change at the ANU which included re-organisation and change management seeing the core change Schools three time over the course of the redevelopment. This restructure also resulted in the disestablishment of several Engineering majors for which we had aligned project streams. Staff changes within the school had significant impacts on the first delivery of the third-year courses.

Whilst the establishment of integrated project hubs has not been realised, the SE core has been able to offer a range of authentic projects across a variety of domains. The initial plan was to connect projects teams in concurrent courses in third year. However, it was found that this did not account for the significant number of students completing double degrees, or the disruption to patterns of enrolment due to Covid-19 and students navigating the resulting program changes because of the disestablishment of majors. A significant proportion of students are not completing the third-year courses in concurrent semesters. The proportion of students wanting to transfer between project application streams to achieve a more varied experience through the core, was higher than expected. Therefore, the connection between the third-year course projects has been removed from the design.

A limitation of our assessment of the outcomes of the redevelopment of the SE core is the change in the student survey (SELT) design in 2019. Pre-2019 the main outcome of the survey was 'overall satisfaction', whereas post 2019 the main outcome was 'overall learning experience'. For the current analysis, we assume a 1:1 correspondence between these two outcome measures. However, we acknowledge this is a limitation and may have impacted our results and conclusions.

Future directions

Many of the elements of the design yet to be realised will further develop student motivations and the connection between the courses. These include:

- 1) Project Hubs. Stronger establishment of project hubs with increased opportunities for peer-to-peer learning across year levels. This will include the establishment of staff leads for the hubs to facilitate this and identify further opportunities for case studies, and future projects linking out of previous work.
- 2) Engineering learning commons (ELC)
 - a) The creation of the ELC to provide students with continued access to course materials across the program.
 - b) The introduction of Self-study modules, homed within the ELC, to enable students to upskill in areas relevant to their project as needed.

Conclusion

This paper describes the progress of the redevelopment the SE core at the ANU focusing on the achievements and successes to date and reflecting on the challenges. Prior to the restructure, the core courses did not score well in student evaluations. We expected that the redesign would bring a shared understanding of the purpose of SE for the teaching staff across the degree and this in turn would result in improved student satisfaction. Student evaluation results indicate this with greater student satisfaction since the restructure began. Average evaluation results in the 2020/2021 financial year were 5% higher than the average results for 2010-2019. In the 2021/2022 financial year, average evaluation results were 47% higher than average results for 2010-2019.

We expected that the project-based focus on important, real-world application of engineering would result in both increased industry engagement and a more diverse student cohort. We have seen an increase in industry engagement with now over 20 projects with a range of partners across students, research, and industry, with multiple projects on offer within each course to meet diverse student interests.

Important factors in the success of the redevelopment have been the common structure between second- and third-year courses, workshops to create a shared vision amongst convenors and the introduction of an administrative support role. Covid has created additional work and organisational change, slowing down elements of the intended restructure but as the initial role out of each year level is nearing completion, this will provide additional capacity to realise the future improvements such as the ELC.

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