

The global state of the art in engineering education

MARCH 2018

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Printed in the United States of America

First Printing, 2018

ISBN 13: 9780692089200

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Cambridge, MA 02139
USA

neet.mit.edu

Executive summary

The study considers the global state of the art in engineering undergraduate education. It was undertaken to inform Massachusetts Institute of Technology's (MIT) *New Engineering Education Transformation* (NEET), an initiative charged with developing and delivering a world-leading program of undergraduate engineering education at the university.

The study was structured in two phases, both of which used one-to-one interviews as the primary evidence gathering tool:

- Phase 1** conducted between September and November 2016, Phase 1 provided a snapshot of the cutting edge of global engineering education and a horizon scan of how the state of the art is likely to develop in the future. The analysis drew on interviews with 50 global thought leaders in engineering education and identified the most highly-regarded current and emerging university leaders in the field.
- Phase 2** conducted between March and November 2017, Phase 2 involved case studies of four selected institutions identified during Phase 1 as being 'emerging leaders' in engineering education: Singapore University of Technology and Design (Singapore), University College London (UK), Charles Sturt University (Australia) and TU Delft (Netherlands).

Together, the two phases of the study are informed by interviews with 178 individuals with in-depth knowledge and experience of world-leading engineering programs. As such, they paint a rich and diverse picture of the state of the art in engineering education as well as the opportunities and constraints facing the sector.

The report addresses five key questions, the first four of which are outlined below:

- 1. Which institutions are considered to be the 'current leaders' in engineering education?** Olin College of Engineering and MIT were both cited by the majority of thought leaders consulted in Phase 1 to be the 'current leaders' in engineering education. Other highly-rated universities including Stanford University, Aalborg University and TU Delft. Many interviewees noted that the engineering education sector was entering a period of rapid change, and they therefore anticipated considerable movement in global leadership in the coming years.
- 2. Which institutions are considered to be 'emerging leaders' in engineering education?** A number of institutions – including Singapore University of Technology and Design, Olin College of Engineering, University College London, the Pontifical Catholic University of Chile and Iron Range Engineering – were consistently cited by Phase 1 thought leaders as global 'emerging leaders' in engineering education.
- 3. What features distinguish the 'current leaders' and 'emerging leaders' in engineering education?** Institutions identified as 'current leaders' in engineering education tended to be well-established US and European research-led universities catering to large student cohorts. Good educational

practices highlighted at these institutions included user-centered design, technology-driven entrepreneurship, active project-based learning and a focus on rigor in the engineering ‘fundamentals’.

The group of ‘emerging leaders’ represented a new generation of engineering programs, many of which were developed from a blank slate or the product of systemic educational reform, and which were often shaped by specific regional needs and constraints. Distinctive educational features of the ‘emerging leaders’ include work-based learning, multidisciplinary programs and a dual emphasis on engineering design and student self-reflection. Case study evaluations suggest that the ‘emerging leader’ programs have benefitted from strong and visionary academic leadership, a faculty culture of educational innovation and new tools that support educational exploration and student assessment.

4. What key challenges are likely to constrain the progress of engineering education in the future?

A range of barriers that continue to constrain positive change in engineering education worldwide was identified. These include aligning government and higher education goals, the challenge of delivering student-centered active learning to large student cohorts, the siloed monodisciplinary structure of many engineering schools, and faculty appointment and promotion systems that are not perceived as rewarding teaching achievement.

The final question addressed by the study was **‘What is the future direction for the engineering education sector?’** Drawing on evidence from both phases of work, a horizon scanning approach was used to anticipate both the future trajectory of the engineering education sector and the profile of the leading engineering programs in the decades to come. It pointed to three defining trends.

The **first anticipated trend** is a tilting of the global axis of engineering education leadership. Evidence from the study pointed to a shift in the center of gravity of the world’s leading engineering programs from north to south and from high-income countries to the emerging economic ‘powerhouses’ in Asia and South America. Many among this new generation of world leaders will be propelled by strategic government investment in engineering education as an incubator for the technology-based entrepreneurial talent that will drive national economic growth.

The **second anticipated trend** is a move towards socially-relevant and outward-facing engineering curricula. Such curricula emphasize student choice, multidisciplinary learning and societal impact, coupled with a breadth of student experience outside the classroom, outside traditional engineering disciplines and across the world. While many of these educational features appear within engineering programs at the ‘current leader’ institutions, they are often “bolt-on activities” and are isolated within the curriculum. As a result, much of the benefit of these experiences remains unexploited because they are unconnected with other curricular components and students are not encouraged to reflect upon and apply what they have learned in other areas of the degree program. In contrast to the ‘current leaders’, many institutions identified as ‘emerging leaders’ in engineering education typically deliver distinctive, student-centered curricular experiences within an integrated and unified educational approach. In most cases, their curricula were designed from a blank slate or were the result of a recent systemic reform. Experiences such as work-based learning and societally-relevant design projects are

embedded into the programs in a way that provides a solid platform for student self-reflection and a pathway for students to both contextualize and apply the knowledge and skills they have gained elsewhere in the curriculum. However, many of these ‘emerging leader’ exemplars – such as at Olin College of Engineering and Iron Range Engineering – cater to relatively small cohort sizes. The key innovations that are likely to define the next chapter for engineering education are the mechanisms by which such features can be integrated across the curriculum at scale: delivered to large student cohorts under constrained budgets. In the words of one thought leader:

“The next phase in the evolution of engineering education is for the rest of us to figure out how we can offer this type of quality of education at scale.”

The **third anticipated trend** for the sector is therefore the emergence of a new generation of leaders in engineering education that delivers integrated student-centered curricula at scale. The case studies considered in Phase 2 point to a number of institutions that have developed such a model, where this curricular coherence and integration is delivered through a connective spine of design projects. For example, the Singapore University of Technology and Design curriculum is delivered through multidisciplinary design projects, which contextualize and integrate learning across courses and years of study. A second example is the UCL Engineering curriculum which structures the first two years of study in five-week cycles, where students spend four weeks acquiring a range of knowledge and skills that they subsequently contextualize and apply in a one-week intensive design project. Interviewees also suggested that, in the longer term, some of the world’s leading engineering programs would increasingly deliver student-centered learning to large student cohorts through a blend of off-campus personalized online learning and on-campus hands-on experiential learning:

“This is the future of the field, where you put the student at the center and use the resources to facilitate team projects and authentic experiences, and then put the taught curriculum online.”

A number of institutions are already moving forward with such an educational model. Most notable is one of the case study institutions, CSU Engineering in Australia. This newly-established five-and-a-half-year program combines an 18-month on-campus education, framed around a series of project-based challenges, with four years of off-campus, work-based learning. Almost all ‘technical engineering content’ – including both knowledge and skills – is delivered online and accessed independently by students, as and when they need it. This program was described as *“completely rethinking what engineering education ought to look like”* with the potential to be *“very influential, if they can pull it off.”*

Taken together, the study feedback suggested that the engineering education sector is entering a period of rapid and fundamental change, where the world’s most highly-rated programs would no longer be confined to global research leaders and small boutique programs. This sets the scene for the emergence of new players from all corners of the globe that will set the future benchmark for excellence in engineering education.

Acknowledgements

This report was commissioned and financially supported by MIT. I am particularly grateful to the students, faculty, university managers, industry partners, academic leaders, teaching and learning professionals, educational researchers, graduate employers and national government representatives from across the world who contributed so generously to the study by giving their time and sharing their experiences, knowledge and expertise.

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PART I Introduction to the study

Part I provides a brief introduction to the study. It discusses the study context, which is focused on identifying and exploring the global state of the art in engineering education. It then describes the approach taken to the study, which drew on interviews from global thought leaders and in-depth case studies of four 'emerging leaders' in engineering education.

Part I closes with a summary of the report's structure and focus.

1. Context

In June 2016, MIT launched the New Engineering Education Transformation (NEET), an initiative charged with developing and delivering a world-leading program of undergraduate engineering education at the university. Building on MIT's established educational strengths, NEET responds to the need for a focus on *'new machines and systems'* in engineering education.

The NEET vision is built upon three pillars:

- an educational approach that is underpinned by design synthesis and innovation;
- educational delivery that integrates effective and appropriate modern pedagogical approaches, supported by a flexible curriculum;
- an educational structure that reflects the challenges facing engineering in the 21st century.

To inform this program of reform, MIT commissioned a benchmarking study of the global state of the art in undergraduate engineering education. The study addressed five critical questions:

- 1. Which institutions worldwide are considered the 'current leaders' in engineering education?**
- 2. Which institutions worldwide are considered the 'emerging leaders' in engineering education?**
- 3. What features distinguish the global 'current leaders' and 'emerging leaders' in engineering education?**
- 4. What key challenges are likely to constrain the global progress of engineering education in the future?**
- 5. What is the future direction for the global engineering education sector?**

As well as supporting the ongoing curricular innovations and reforms at MIT, this study is designed to inform the global engineering education community and support positive educational change across the world.

The study focused on engineering education at the undergraduate level. Its scope did not include educational research/scholarship, postgraduate study or other factors not directly related to the quality of undergraduate education as experienced by the students enrolled.

The study was conducted by an independent higher education consultant. Further details of her background and experience can be found at her website, www.rhgraham.org.

2. Study approach

The study was structured in two phases, both of which used one-to-one interviews as the primary evidence gathering tool:

- Phase 1** used interview evidence from 50 global thought leaders in engineering education to provide a snapshot of the cutting edge of global engineering education and a horizon scan of how the state of the art is likely to develop in the future;
- Phase 2** involved a case study evaluation of four selected institutions identified during Phase 1 as being 'emerging leaders' in engineering education.

Together, the two phases of the study are informed by interviews with 178 individuals with in-depth knowledge and experience of some of the world's leading engineering programs. As such, they paint a rich and diverse picture of the state of the art in engineering education as well as the opportunities and constraints facing the sector.

During both phases of work, interviews were one-to-one, typically of one hour in duration and in English. Quotes from the study's 178 interviewees are used throughout the report to illustrate the common views and themes that emerged. Anonymity was protected; interviews took place on the understanding that information or opinions would not be attributed to named individuals in the report unless explicit permission was granted by the interviewee.

Further details of the approach taken in Phase 1 and Phase 2 are provided in the two subsections that follow.

2.1. Phase 1 approach

Conducted between September and November 2016, Phase 1 sought to identify the world's most highly-regarded engineering programs and characterize the approach taken by these top-ranked institutions. It focused on both 'current leaders' as well as 'emerging leaders' in the field and drew on interviews with 50 individuals recognized to be global thought leaders in engineering education. This set of opinion-leaders included pioneers in engineering education research, policymakers in the field, and university leaders with direct experience of delivering the world's most highly-regarded engineering education programs. By bringing together the perspectives and insights of this respected group of international experts, the study provided a map of global best practice in engineering education and the future direction of the field.

Initial targets for interview were identified through a review of the literature and the author's knowledge of the international engineering education network. A snowballing method was used to identify further individuals for consultation, with the initial group asked to identify other international thought leaders who should be consulted in the study. Priority was given to thought leaders recommended by three or more interviewees.

A total of 50 thought leaders from 18 countries were successfully interviewed. Their geographical location is indicated in Figure 1. US-based interviewees represented the single largest group of experts, a weighting that reflects the frequency with which US-based individuals were recommended as global thought leaders. A full list of the 50 individuals consulted in the study is provided in Appendix A.1.

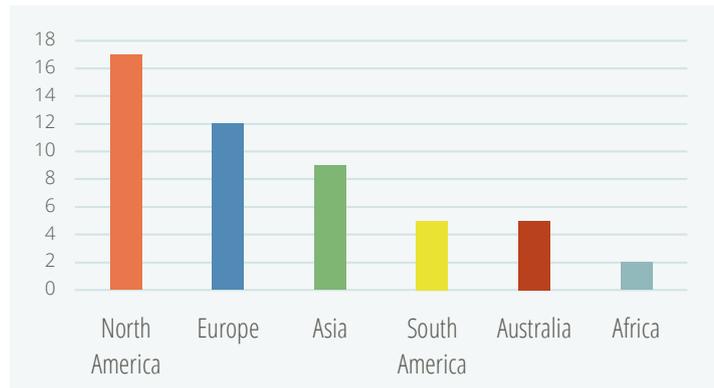


Figure 1. Breakdown of interviewees by location

A common set of questions was asked of all interviewees (as provided in Appendix A.2) with additional questions included for individuals with relevant specialist knowledge (in areas such as engineering design or the measurement of educational impact).

The interviews were complemented by a snapshot literature search and review on the state of the art in engineering education. This synthesis of current knowledge was used to provide contextual information about the best practice programs highlighted during the consultations. Additional consultations were undertaken with nine individuals to capture information about specific pedagogical approaches or programmatic details that had been highlighted as particular areas of interest during the interviews with thought leaders.

2.2. Phase 2 approach

The second phase of the study focused on four ‘emerging leaders’ of engineering education, as identified by thought leaders consulted during Phase 1. Section 7 of the report describes the criteria used to select the programs nominated as case studies – Singapore University of Technology and Design (SUTD), the engineering school at University College London (UCL Engineering), the engineering school at Charles Sturt University (CSU Engineering) and Delft University of Technology (TU Delft).

A formal invitation was submitted to each nominated university, seeking permission to proceed with the case study. These invitations stated that the completed case study evaluation would be held in confidence by its author pending their approval.

Each case study was undertaken over a six- to eight-week period between March and November 2017. The major data-gathering tool used for each case study was one-to-one semi-structured interviews with multiple stakeholders to the undergraduate program. A total of 133 one-to-one interviews were conducted across all four case studies, with between 31 and 37 one-to-one interviews conducted in each case.¹ The majority were one-hour interviews, conducted face-to-face during on-site visits to the

¹ It should be noted that five individuals consulted during Phase 1 of the study were interviewed on a second occasion in reference to one of the Phase 2 case studies. For this reason, the total number of interviewees listed for both phases of the study is shown as 178 rather than 183.

university. Where this was not possible, interviews were undertaken remotely, by telephone or Skype. Where requested, interview questions were supplied in advance.

An initial group of targets for interview was identified through a review of the literature as well as through recommendations from interviewees from Phase 1 and key contact points from the case study institution. Outcomes from this first wave of interviews were used to identify further interviewees, to ensure that a range of perspectives and roles was represented. Case study interviewees were drawn from four groups of stakeholders (see Figure 2):

- current and previous university academic leaders, including university presidents, deans and program leaders (as appropriate);
- current and previous university faculty, in both teaching-only and teaching and research roles, and representatives from the university teaching and learning functions;
- university students and alumni;
- external stakeholders, including members of the national government, peer regional and national universities, industry/university partners and graduate employers.

Stakeholder group	SUTD	UCL Engineering	CSU Engineering	TU Delft
University academic leaders	11	9	5	9
University faculty and educational professionals	10	12	9	13
University students and alumni	7	5	7	6
External stakeholders	9	5	11	5
TOTAL	37	31	32	33
<i>Additional faculty and students consulted in groups</i>	22	6	6	5

Figure 2. Distribution of interviewees by stakeholder group for each case study

To protect anonymity, the identities of interviewees consulted during Phase 2 remain confidential. During on-site visits to case study institutions, additional stakeholder feedback was captured from small groups of faculty and students, through informal focus-group style discussions. The number of individuals consulted during such group discussions is included at the bottom of Figure 2.

For each case study, the interviews and focus group feedback were complemented with:

- a snapshot literature search and review to identify pre-existing evaluations or documentation on the university or its educational approach;
- a review of any readily available institutional data relating to the university's undergraduate engineering program and/or the demographics of its engineering student populations;
- on-site observations of the university's courses, activities and events (as appropriate) as well as informal interaction with participating students.

Each case study was written up as a report and a two-page summary. Case study universities were given the opportunity to amend any inaccuracies or omissions in the draft documents prior to their subsequent inclusion in this report. Section 8 provides the two-page summaries. The corresponding full case study reports can be found in Appendices B, C, D and E. These reports all share a common structure, as outlined in Box 1.

Box 1. Common structure of case studies, each containing five sections:

1. **Context:** an overview of the national higher education landscape and the institutional context, including the university's size, focus and student demographic;
2. **Development of the engineering education program:** the key stages in the development of the university's undergraduate program from its conception, or from the time when the program started to evolve, through to the present day;
3. **Educational approach:** the defining features of the university's engineering program/s, the dominant pedagogical approach and the structures and processes that support it;
4. **Curriculum design:** the program's curricular design, providing information and examples of its key components;
5. **Review and concluding comments:** summary of the defining features of the engineering program, the factors that have underpinned its success and future challenges it may face.

3. Focus of the report

The structure of the report is outlined below:

- Part II The world's leading engineering programs:** outlines the universities considered to be the 'current leaders' and the 'emerging leaders' in engineering education, as identified by the 50 thought leaders consulted during Phase 1 of the study. Part II also describes the selection criteria used by thought leaders when identifying these two groups of institutions;
- Part III Case studies of 'emerging leaders' in engineering education:** provides a summary of the case studies undertaken during Phase 2 of the study, focused on four 'emerging leaders' in engineering education: Singapore University of Technology and Design (SUTD), University College London (UCL), Charles Sturt University and Delft University of Technology (TU Delft). The full case study reports are provided in Appendices B, C, D and E;
- Part IV Global engineering education – challenges and future directions:** brings together outcomes from Phase 1 and Phase 2, and outlines (i) features that distinguish the 'current leader' and 'emerging leader' institutions; (ii) major challenges facing the progress of the engineering sector; and (iii) major trends that are likely to define the trajectory of global engineering education in the future.

APPENDICES

Appendix A Background information from Phase 1 of the study: including (i) a list of the thought leaders consulted; (ii) the core interview questions asked of thought leaders; (iii) thought leaders' feedback on measures of quality and impact in engineering education; (iv) a summary of the feedback given by thought leaders on selected top-rated institutions; and (v) broad data to characterize the top-rated institutions.

Appendix B–E Case studies: from the universities selected for evaluation during Phase 2 of the study. These universities are:

Appendix B SUTD (Singapore)

Appendix C UCL Engineering (UK)

Appendix D CSU Engineering (Australia)

Appendix E TU Delft (Netherlands)

PART II The world's leading engineering programs

Part II presents outcomes from Phase 1 of the study, which canvassed the perspectives and experiences from 50 global thought leaders in engineering education. Thought leaders were asked to identify the universities that they considered to be (i) current world leaders in engineering education; and (ii) emerging world leaders in engineering education. In both cases, interviewees were asked to identify institutions rather than programs or courses, enabling their recommendations to be combined into institutional 'rankings' for both the 'current leaders' and 'emerging leaders', as presented in **Section 4** and **Section 5** respectively.

Section 6 explores the criteria used by the thought leaders in their selections of 'current leaders' and 'emerging leaders' and discusses how quality and impact in engineering education can be measured.

4. Who are the current leaders in engineering education?

The 50 thought leaders were asked to identify and describe the five or six universities they considered to be the current global leaders in engineering education.

In all, 81 universities from 22 countries were identified. The 10 institutions most consistently cited as ‘current leaders’ are presented in Figure 3. As it indicates, two US-based institutions were each identified by over half of those consulted – Olin College of Engineering and MIT. The universities that just fell short of this ‘top 10’ list included Harvey Mudd College, Singapore Polytechnic, Nanyang Technological University and Imperial College London.

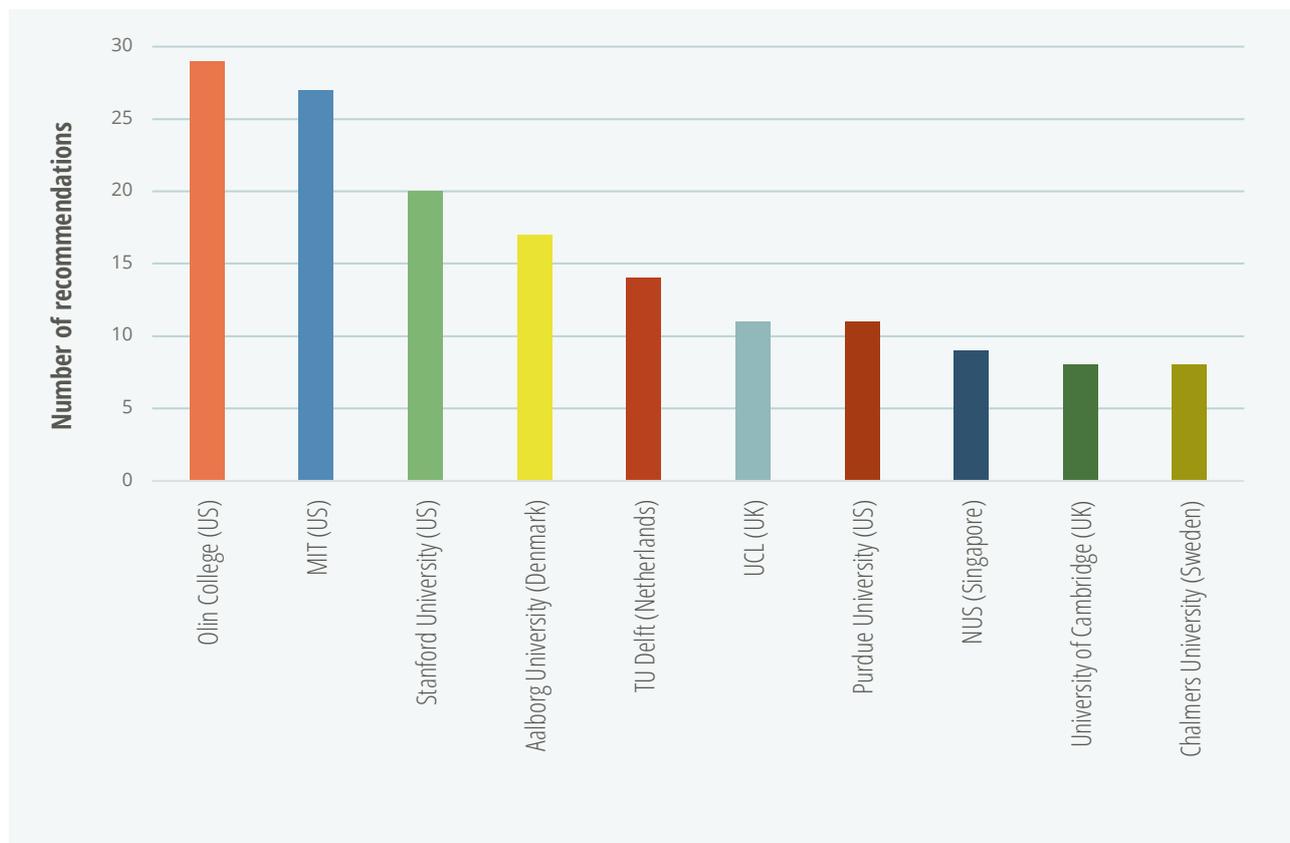


Figure 3. The 10 institutions most frequently identified as ‘current leaders’ in engineering education

An analysis of the selections revealed that US-based individuals were disproportionately likely to identify US-based universities as ‘current leaders’: 66% of the ‘current leaders’ selected by US-based interviewees were from the US. This pattern was not evident among interviewees from countries outside the US: only 18% of their selections were for institutions in the continent in which they were based.

To ensure that the top 10 list of ‘current leaders’ was not unduly influenced by this potential bias, the data were reanalyzed to take account of the individual’s country of residence. This second analysis, as presented in Figure 4, excluded recommendations made by interviewees within their own country of residence. To protect anonymity, only the top five institutions are listed in Figure 4. The top 10 institutions identified as ‘current leaders’ remained unchanged following this re-evaluation; however,

the ranking of Purdue University and Stanford University was lower. The premier positions held by both Olin College of Engineering and MIT remained unchanged, although their ranked order was reversed, perhaps reflecting the fact that non-US interviewees were more likely to identify Olin College as an ‘emerging leader’ rather than a ‘current leader’.

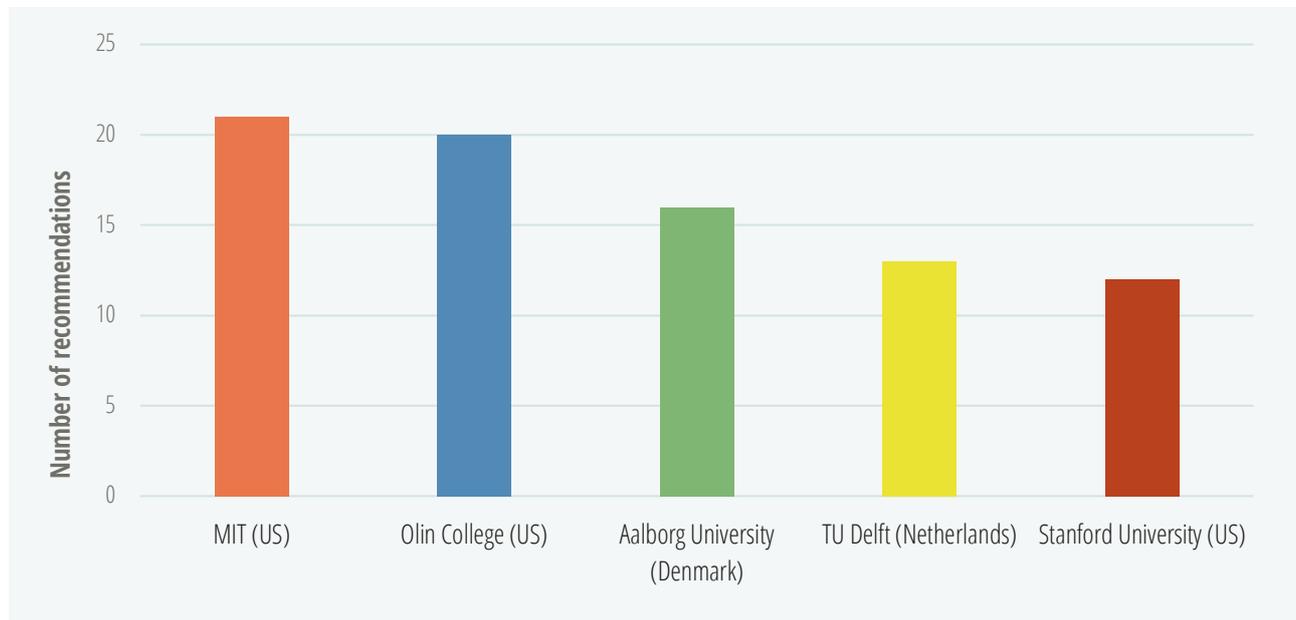


Figure 4. The five institutions most frequently identified as ‘current leaders’ in engineering education, with the results adjusted for the country of residence of the interviewee

In describing their institutional selections, around half of the interviewees went on to suggest that the engineering education sector was entering a period of rapid and fundamental change. As a result, many suggested that the universities they identified as world leaders were likely “to be quite different in five years’ time to what they are now, because the benchmark of what constitutes good practice is changing.” Interviewees also suggested that these changes were not confined to engineering: quality and impact in undergraduate education were increasingly becoming priorities across the sector. Some interviewees noted the increased emphasis given by university leaders, including presidents, vice-chancellors and senior managers, to their institution’s educational vision and strategy. For example, one interviewee reported that, in the past:

“the conversations I had with deans, with university presidents, started and ended with research... [but now] they are talking about their teaching: what they are doing, what they are changing.”

Others, however, also noted the difficulty in “knowing what really goes on in the classroom” at other institutions and being able to “distinguish the rhetoric from the reality.” As a result, it was suggested that most attention will continue to be paid to “universities at the top of the [international] rankings and the universities on the conference circuit” with good practice elsewhere often overlooked.

Further information on the common features of the ‘current leader’ institutions is given in Section 9.1. Feedback provided by thought leaders on top-rated ‘current leaders’ in engineering education is provided in Appendix A.4 and a broad comparison of the profile of 12 of the top-rated engineering programs is provided in Appendix A.5.

5. Who are the emerging leaders in engineering education?

Thought leaders were asked to identify and describe the five or six universities that they considered to be the ‘emerging leaders’ in engineering education: the institutions that look set to rise to the cutting-edge of engineering education worldwide in the decades to come.

In all, 89 universities from across 27 countries were identified. The 10 universities most frequently cited are presented in Figure 5. The group of universities that just fell short of this ‘top 10’ list included Monterrey Tech (Mexico), Hong Kong University of Science and Technology (Hong Kong), RWTH Aachen University (Germany) and Nanyang Technological University (Singapore).

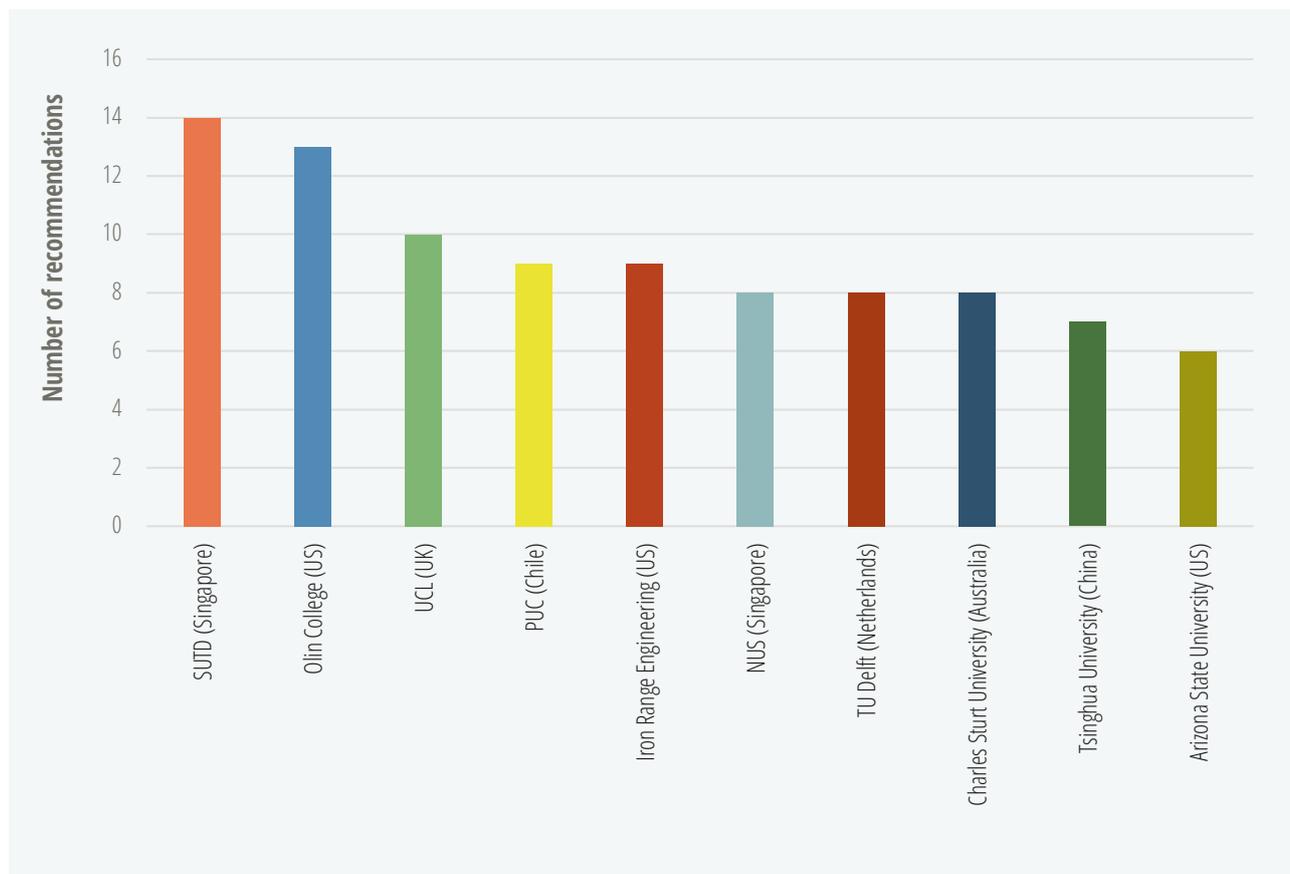


Figure 5. The 10 most frequently-identified ‘emerging leaders’ in engineering education

Four institutions feature prominently among both the current and emerging global leaders. While some interviewees identified Olin College of Engineering, the National University of Singapore (NUS), UCL and TU Delft as ‘current leaders’, others (particularly those based at institutions that were not national or regional peers to these universities) viewed them as ‘emerging leaders’. This suggests that the ranked position of these four institutions could have been even higher if their status as either a ‘current leader’ or ‘emerging leader’ had been allocated more consistently. Overall, however, SUTD and Olin College of Engineering were the institutions most frequently cited as ‘emerging leaders’ in engineering education.

Further information on the common features of the 'emerging leader' institutions is given in Section 9.2. Feedback provided by thought leaders on each top-rated 'emerging leader' in engineering education is provided in Appendix A.4.

As explored further in Section 11.1, a particularly striking feature of the 'emerging leaders' is how their geographical location contrasts with that of the 'current leaders' in engineering education. While the majority of 'current leaders' are based in North America or Europe, the institutions selected as 'emerging leaders' are drawn from a wider group of countries, with Asia and South America featuring prominently.

A number of institutions were also repeatedly discussed by interviewees as "*places to watch for the future*," but were seen to be at too early a stage of development to yet identify as 'emerging leaders'. Examples are given in Box 2.

Box 2. 'Places to watch' in engineering education, as identified by thought leaders

- NMiTE,² a teaching-only engineering and technology institution currently under development in the UK, with a focus on creativity, innovation and experiential learning. NMiTE aims to admit its first cohort of students in 2019. With no formal lectures, the curriculum will be developed in partnership with industry and will incorporate 6- to 12-month mandatory work placements;
- the Lassonde School of Engineering³ at York University (Canada), a new engineering school that aims to educate 'renaissance engineers'⁴ and admitted its first undergraduates to its programs in 2013;
- BVB College,⁵ based in Hubli, India, which transformed its undergraduate curriculum to focus on social and technological innovation in a multidisciplinary learning environment. One of the drivers for the educational reform was to advance the development of the regional entrepreneurial ecosystem. Around 1200 engineering students graduate from BVB College each year;
- new Boston-based institution in the US: a number of thought leaders spoke about the new university currently under development by Christine Ortiz, former Dean of Graduate Education at MIT;
- the new engineering school at Insper⁶ in Brazil which has developed a new hands-on, student-centered curriculum.

² New Model in Technology & Engineering (NMiTE), UK (<http://nmite.org.uk>)

³ Lassonde School of Engineering, York University (<http://lassonde.yorku.ca>)

⁴ Club Lassonde, Lassonde School of Engineering (<http://clublassonde.com>)

⁵ B. V. Bhoomaraddi College of Engineering and Technology, India (<http://www.bvb.edu>)

⁶ The new way to teach engineering, Insper, Brazil (<http://www.insper.edu.br/en/newsroom/insper-in-the-media/the-new-way-to-teach-engineering/>)

6. How should educational quality be measured?

Phase 1 interviews explored the thought leaders' views on how quality and impact in engineering education should be measured. They were asked to consider the criteria underpinning their selections of 'current leaders' and 'emerging leaders' and to note those institutions taking a robust approach to measuring the impact and quality of their undergraduate programs.

There was a clear consensus that:

"measuring the impact we have on our students, how much they are actually learning, is something that we as a community do very badly."

Indeed, the vast majority (over 80%) of thought leaders were unable to provide the name of one or more institutions that they believed were taking *"an effective approach to measuring the impact of their programs on student learning and/or measuring the impact of an educational change"* (see question 6 in Appendix A.2). Instead, interviewees spoke about the paucity of reliable and comparable data by which the quality of an institution's education could be assessed; an issue that both constrained their ability to make informed assessments of the quality of an institution's education as an external observer and restricted the evidence base upon which the engineering education community as a whole was able to move forward. International university rankings were widely recognized to provide very poor indicators of educational quality, often relying on proxy measures such as staff-to-student ratios and graduate employment profiles. In turn, scholarly activities in engineering education were widely regarded to be insufficiently related to overall program quality and impact: *"the scholarly work going on in engineering education is not translated back into the lecture room, it's always theoretical."*

One institution was repeatedly cited as an exception to this pattern: Aalborg University in Denmark. It was singled out as having taken a more coherent and robust approach to measuring its institutional impact on student learning. Indeed, interview feedback suggested that the systematic approach to assessing program impacts, the demonstrable quality of the programs and the external visibility given to the university's achievements all played a role in Aalborg University's identification as a 'current leader' in engineering education (see Figure 3). For example, in 2004, Aalborg University published a survey that captured employers' perspectives of the skills and capabilities of Aalborg University graduates compared to graduates from peer Danish institutions that had not widely adopted a problem-based approach.⁷ While all graduates were rated equally for their technical engineering knowledge, Aalborg University graduates were identified as demonstrating a superior range of personal and professional skills when compared to graduates from peer institutions. More recently, Aalborg University has developed the PROCEED-2-WORK study, capturing longitudinal data on the experiences and perspectives of Danish engineering students as they transition into the workplace.⁸

⁷ Kjærdsdam, F. (2004). Technology transfer in a globalised world: transferring between university and industry through cooperation and education. *World Transactions on Engineering and Technology Education*, 3(1), 63–66

⁸ PROCEED-2-WORK, Aalborg University ([http://ybn.aau.dk/en/projects/proceed2work\(12da3a74-9831-4e8d-9d52-27200206a6b6\).html](http://ybn.aau.dk/en/projects/proceed2work(12da3a74-9831-4e8d-9d52-27200206a6b6).html))

Overall, the thought leaders identified three broad types of informal indicators that they might use to determine the educational quality of institutions outside their own. Summarized in Box 3, these are: (i) the quality and impact of the university's graduates; (ii) the 'delta' added to the students during their studies; and (iii) the institution's capacity to deliver a world-class education. Feedback from thought leaders relating to each of the three groups of indicators is explored further in A.3.

Box 3. Informal indicators of quality in engineering education identified by thought leaders

- 1. The quality and impact of the graduates:** the career trajectory and impact of graduates was seen as an important indicator of the quality of an undergraduate program. Measures proposed included graduates' "*career prospects ten years out*" and the extent to which graduates "*have the capabilities that industry needs now and in the future.*" However, skepticism was expressed about the validity of such metrics for cross-institutional comparisons when seeking to identify the best programs worldwide. This skepticism stemmed from the influence of the quality of the student intake on graduate outcomes. Some thought leaders argued that the use of these 'output measures', both formally and informally, had secured a reputation of educational quality for many of the world's top-rated research universities – ones that receive an exceptional quality of student intake – that was not borne out in practice.
- 2. The 'value added' to students during their studies:** many interviewees suggested that "*the gold standard*" for measuring quality and impact of engineering programs was to capture the 'delta' or 'value added' to students during the course of their studies. It was acknowledged, however, that "*we just don't have anything like the quality and breadth of data that we need to make any objective assessments of the 'delta' in engineering programs. This is the next big frontier for engineering education.*"
- 3. The institution's capacity to deliver a world-class education:** the capacity of an institution to deliver a world-class education was identified by almost 90% of thought leaders as guiding their selection of 'current leaders' and 'emerging leaders'. This was in part due to the absence of other reliable and robust data relating to educational quality. Three dimensions of institutional capacity were emphasized:
 - *the institutional leadership in and commitment to education*, as evidenced, for example, through its processes for recognizing and rewarding teaching excellence and through its investment in support for teaching and learning;
 - *the educational culture*, as reflected by, for example, "*the willingness [of the school/university] to innovate and try new things*" and the extent to which faculty are "*informed and actively discussing teaching with colleagues*";
 - *the capacity of the institution to influence practice elsewhere*, as apparent through: (i) the university's active interventions to inform and improve educational practice at a regional/global level; and (ii) the transferability of the institution's practices to other universities across the world.

Most interviewees touched upon all three indicators during their interview. However, one indicator – the institution's capacity to deliver a world-class education, indicator 3 in Box 3 – was given particular weight and was consistently cited when identifying 'current leaders' and 'emerging leaders'. The thought leaders noted that institutional capacity was the only indicator where the evidence was readily available (unlike 'value added' data, indicator 2) and not distorted by the quality of the student intake (unlike indicators relating to the quality and impact of graduates, indicator 1).

PART III Case studies of 'emerging leaders'

Part III summarizes the outcomes from Phase 2 of the study, which focused on case studies of four of the 'emerging leaders' in engineering education:

1. SUTD (Singapore)
2. UCL Engineering (UK)
3. CSU Engineering (Australia)
4. TU Delft (Netherlands)

Section 7 provides background information on the scope and approach taken to the case studies. **Section 8** presents summaries of each case study. The full case studies are presented in the appendices: Appendix B (SUTD), Appendix C (UCL Engineering), Appendix D (CSU Engineering) and Appendix E (TU Delft).

7. Introduction to the case studies

7.1. The four institutions selected as case studies

Phase 1 identified a 'top 10' list of both 'current leaders' and 'emerging leaders' in engineering education. Each stands as an exemplar of excellence in engineering education and all could have been selected as case studies.

These top-rated institutions have typically followed one of three development pathways:

- programs established in recent years from a 'blank slate', such as CSU Engineering, Iron Range Engineering, Olin College of Engineering or SUTD;
- programs that are the product of ambitious systemic reform, such as PUC, UCL or Arizona State University;
- universities that have taken a continual and forward-thinking approach to the development of their educational provision, such as MIT, Stanford University or TU Delft.

The universities identified as case studies were selected to represent a balance of these three approaches. They were also selected to ensure that a range of geographical, economic and institutional contexts was represented. Guided by these criteria, the four universities/schools selected as case studies were:

SUTD (Singapore)

A recently-established engineering and architecture specialist university that offers a design-centered, multidisciplinary and project-based curriculum structured around small group learning. The SUTD case study report is given in **Appendix B**;

UCL Engineering (UK)

One of UCL's 11 Faculties, UCL Engineering recently implemented a root-and-branch educational reform, the *Integrated Engineering Programme*, across its nine engineering undergraduate programs. The UCL Engineering case study report is given in **Appendix C**;

CSU Engineering (Australia)

A new engineering program, established in regional Australia, that combines on-campus project-based learning with online learning and off-campus work-based learning. The CSU Engineering case study report is given in **Appendix D**;

TU Delft (Netherlands)

A university known for its egalitarian culture and spirit of inclusivity that has allowed bottom-up innovation to emerge in areas such as design-led curricula, student-led extra-curricular activities and online learning. The TU Delft case study report is given in **Appendix E**.

Summaries of each case study are given in Section 8.

7.2. Broad comparisons of the scale and focus of the case studies

The four case study programs vary considerably in their scale and approach. For example, two of the case studies focus on specialist engineering and technology institutions – SUTD and TU Delft – and therefore the case study covers all of the university’s undergraduate programs. The other two case studies – UCL Engineering and CSU Engineering – focus on the engineering school of a larger university. As a result, there is wide variation in the size of the case study programs; the CSU Engineering program currently caters to an annual intake of 28 students while the annual intake to TU Delft bachelor programs totals over 3700 students.

The case study programs also differ in their curricula design and focus. To enable broad comparisons, Figure 6 presents an overview of the four curricula side by side. Each curriculum is described in more detail in the case study reports (Appendix B–E).

When reviewing Figure 6, it should be noted that:

- only undergraduate programs are included. The master curriculum is only shown if the program is a combined bachelor/master, as with UCL Engineering and CSU Engineering;
- CSU Engineering is the only program where all participating students follow a single curriculum track. The other three curricula offer student choice in selecting their specialist majors. As such, the curricula shown for SUTD, UCL Engineering and TU Delft show a typical or sample program: the SUTD curriculum illustrates the Engineering Product Development specialism (from Year 2 to Year 3.5) and the TU Delft curriculum illustrates the Aerospace Engineering bachelor program;
- although not shown, the length of the academic year varies across the four institutions. For example, the TU Delft curriculum comprises two 20-week semesters; the SUTD curriculum comprises three terms of 14 weeks; and during 12-month work placements during the final four years of study, CSU Engineering students work 47 weeks per year;
- diagonal green shading used in the SUTD curriculum denotes multiple design projects that are integrated within and across courses;
- examination periods are only shown for UCL Engineering. The other three undergraduate programs either do not include examinations or the examination periods are too short to illustrate in the curricula summaries: CSU Engineering does not offer formal examinations; SUTD offers two–three day examination periods at the close of each term; TU Delft typically offers two weeks of examinations both at the midpoint and end of each semester.

The global state of the art in engineering education

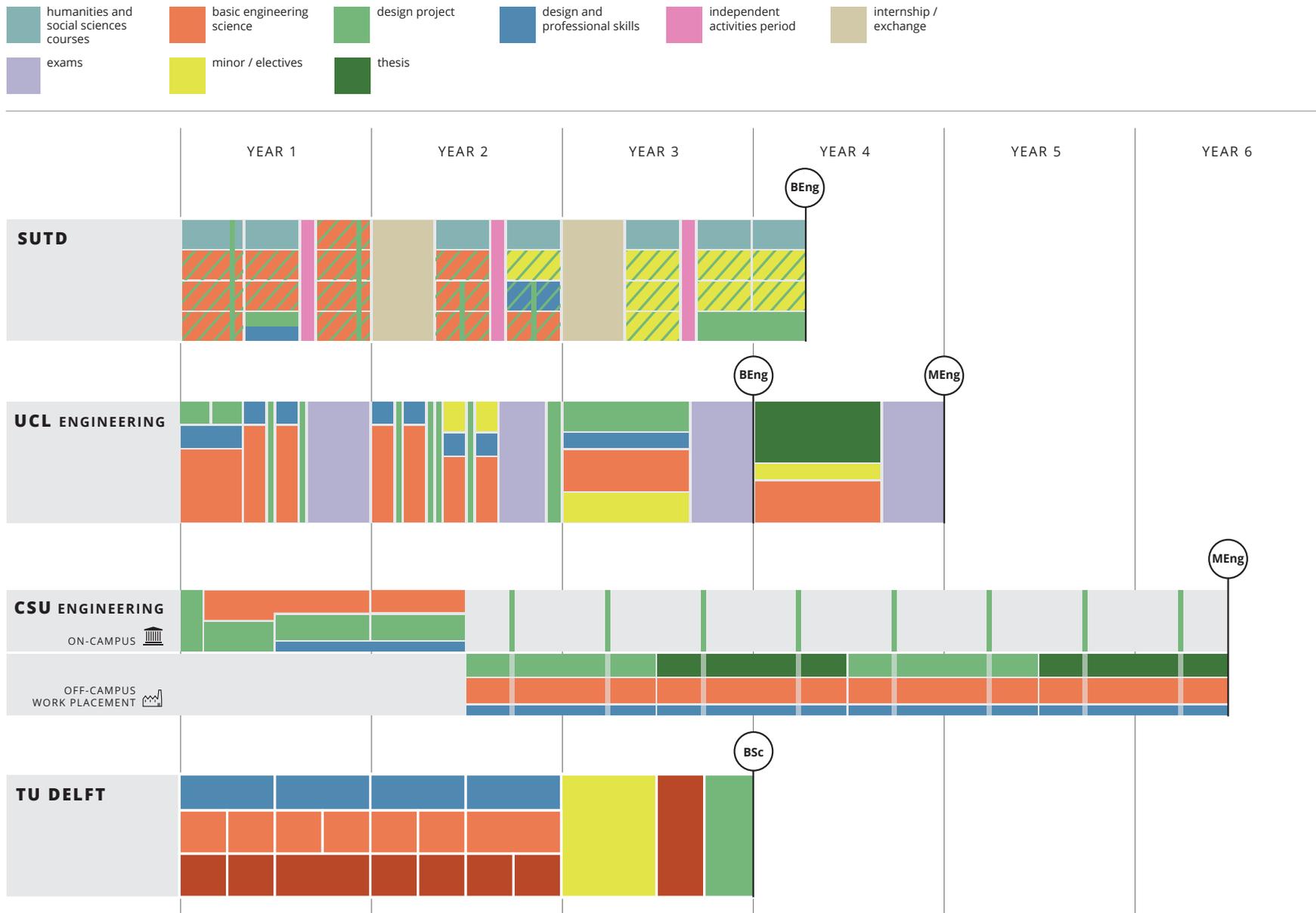


Figure 6. The curricula structure and content for each of the four case study engineering programs

8. Summaries of the four case studies

Summaries of each case study are provided in the subsections that follow:

- Section 8.1** provides a summary of the **SUTD** case study (full report in Appendix B). SUTD was identified by Phase 1 thought leaders as the foremost ‘emerging leader’ in engineering education;
- Section 8.2** provides a summary of the **UCL Engineering** case study (full report in Appendix C). UCL was identified by thought leaders in Phase 1 as both a ‘current leader’ and ‘emerging leader’ in engineering education;
- Section 8.3** provides a summary of the **CSU Engineering** case study (full report in Appendix D). CSU was identified by thought leaders in Phase 1 as an ‘emerging leader’ in engineering education;
- Section 8.4** provides a summary of the **TU Delft** case study (full report in Appendix E). TU Delft was identified by thought leaders in Phase 1 as both a ‘current leader’ and ‘emerging leader’ in engineering education.

Details of the case study approach taken are given in Section 2. However, key points to note are:

- the case studies are built from one-to-one interviews, which captured the experiences and perspectives of key stakeholders. Between 31 and 37 stakeholder were interviewed for each case study;
- anonymized quotes from the 133 interviewees consulted as part of the case studies are used to illustrate common views and themes;
- each case study report shares a common structure;
- reflecting the focus of the report, the case studies only consider undergraduate education. Graduate education or research activities at the case study institutions are not considered unless specifically linked to undergraduate programs;
- the case studies are forward-looking assessments of programs at the cutting edge of practice; as such, limited evidence of their impact on student learning and outcomes was available.

It should also be noted that the terminology used for each case study is consistent with that used by its institutional stakeholders. This convention was used to avoid confusion caused by the dual use of the word ‘faculty’, which can mean ‘*a member of academic staff*’ at one institution and ‘*one of the university’s schools*’ at another. In particular:

- university ‘faculty’ or ‘academic staff’ are described as ‘teachers’ at TU Delft and ‘academics’ or ‘staff’ at UCL;
- discipline-specific Schools are referred to as ‘Faculties’ at both UCL and TU Delft.

8.1. Summary of the SUTD case study

In August 2007, Singapore's Prime Minister announced government plans to increase national participation rates in publicly-funded higher education from 25% to 30%. At the time, Singapore was home to only three publicly-funded universities. The government's vision called for an increase in the capacity and diversity of Singapore's higher education landscape through establishing a fourth university. This new institution was to be an engine for national economic growth, fostering talent and applied research in three critical sectors: (i) engineering and applied sciences; (ii) business and information technology; and (iii) architecture and design. With an emphasis on interdisciplinary, hands-on learning and a strong connectivity with industry, the university would also offer "*a new future-oriented [educational] approach*" designed to nurture technology-driven entrepreneurs and inspire future generations to follow careers in science and engineering. Following a call to the global higher education community, the government selected MIT as the major partner in its establishment.

MIT developed a blueprint for the new university that placed design at its heart. The design focus would also be reflected in the name of the institution, the "Singapore University of Technology and Design" (SUTD), carrying the motto, "a better world by design." In May 2012, SUTD welcomed the first cohort of students to its undergraduate program.

The university's educational structure and approach are distinctive in a number of respects, including:

- **design- and maker-based learning:** the SUTD pedagogy is underpinned by design-based active learning. Open-ended design activities and projects are integrated throughout the curriculum to help students explore, integrate and reinforce their ongoing learning. Many take a hands-on approach, asking students to deliver a working prototype;
- **a collaborative culture:** faculty and student interviewees alike pointed to "*a flat hierarchy*" and "*a 'start-up' atmosphere*" at SUTD. This "*camaraderie and community spirit*" among the student population is supported by SUTD's extensive use of small group learning;
- **a multidisciplinary approach:** SUTD is not structured around "*traditional engineering siloes*" and does not offer conventional engineering disciplinary degrees. Instead, students study a common first year and then specialize within one of four multidisciplinary 'pillars' – such as Engineering Systems & Design – for the remainder of their studies;
- **a breadth of education:** SUTD offers a breadth of experience not traditionally associated with engineering undergraduate study, including research opportunities, industry internships, undergraduate teaching opportunities and courses in humanities and social sciences;
- **academic rigor in the 'engineering fundamentals':** most of SUTD's courses take their content directly from MIT, with the majority retaining equivalent expectations for student achievement. As a result, the academic rigor of the SUTD curriculum is unquestionably high.

Despite being co-designed by a team working across two continents – from MIT and SUTD – each of these distinctive features is embedded in a thoughtfully-designed curriculum that allows students to contextualize and assimilate their learning across courses and between years of study. Indeed, what is most striking about SUTD's approach is its connectivity: connectivity between cross-disciplinary faculty

teaching teams, connectivity between courses in the curriculum and connectivity between students, within and outside their formal studies.

This connectivity plays a major role in shaping the distinctive characteristics of SUTD's student and graduates. Interviewees consistently pointed to two distinctive attributes that set them apart from peers:

- **intrinsic motivation:** the experience of working in small-group learning communities on immersive real-world projects was understood to have been instrumental in nurturing students' intrinsic motivation and *"shaking them out of chasing the paper grade"*;
- **adaptability:** the adaptability to tackle ill-defined problems that *"spill over the boundaries of ... disciplines"* and to address the changing needs of projects and/or professional roles.

Much of the success of the SUTD education rests on the commitment and vision of its leaders and faculty. Supported by its partnership with MIT, the university has appointed a world-class, hand-picked leadership team and a cadre of outstanding young faculty that together will undoubtedly enable SUTD to continue to push the boundaries of design-focused research and innovation in science and technology. Alongside its stellar research credentials, the university also offers a deep commitment to its educational mission. Indeed, one of the most striking features of the interview feedback from SUTD's academic leaders was their shared educational vision and their clear personal commitment to establishing a new paradigm for engineering education.

Two additional factors have been integral to the success of the SUTD education:

- the Singapore government's investment in and commitment to the university. At the same time, the government has also offered SUTD's leadership the autonomy and flexibility needed to establish an educational culture and approach that is both unique and world-class;
- the MIT partnership, which has been instrumental in both co-designing a world-class curriculum and instilling a culture of innovation among SUTD students and faculty.

As SUTD moves beyond its educational partnership with MIT, it faces two important challenges. The first concerns building the size of its undergraduate population in the face of a declining Singaporean prospective student population, an increasingly competitive national higher education landscape and the reluctance of many prospective students and their parents *"to take the risk of choosing a university that is still so young."* The second challenge concerns preserving SUTD's collaborative, student-centered culture and distinctive educational approach as the institution grows. The university recognizes the challenges faced. It will welcome a new president in 2018 to lead a university that has embraced and championed design-led, student-centered education and is well-placed to continue to define best practice in engineering education for many years to come.

8.2. Summary of the UCL case study

Based in the UK, UCL is one of the world's leading research-led universities, consistently positioned within the top 10 in global university rankings. The university supports a wide range of disciplines, from fine art to medicine and from astrophysics to anthropology. UCL Engineering is one of the university's 11 Faculties. It comprises 11 departments, of which nine offer degree programs at the undergraduate level.

Before 2010, the undergraduate programs in UCL Engineering were unremarkable from their peers, and characterized as *"very engineering science-focused, very traditional, with very little group work or practical work."* In addition, while *"we have been incredibly good at working in an interdisciplinary way in our research portfolio,"* departments were reported to have operated *"in independence, in very traditional silos"* in the educational domain. The seeds of reform were sown in early 2011, when the then Dean of UCL Engineering became increasingly convinced of the need for the Faculty to adopt a radically different approach to undergraduate education. As he commented:

"Our programs looked pretty much like the engineering education I had experienced and I wasn't satisfied with that. I wanted something that looks like UCL, like our spirit, our values and our vision of engineering."

In the three years that followed, the Faculty designed and delivered a root-and-branch reform to its undergraduate curriculum. Called the *Integrated Engineering Programme (IEP)*, the new Faculty-wide program was launched in September 2014. It brought together two major components:

- **a common curricular structure applied across all engineering departments:** although all engineering students continued to be based within discipline-specific departments from entry to the university, a common Faculty-wide curricular structure was adopted during the first two years of study. A centerpiece of this curriculum was the *Scenarios*: a series of five-week curricular cycles where students would spend four weeks building critical engineering skills and knowledge that they would subsequently apply in a one-week intensive design project. These experiences were designed to help students to contextualize and reinforce their learning throughout the program by applying their knowledge to authentic engineering problems.
- **multidisciplinary experiences that bring together most or all engineering students:** students from across UCL Engineering would come together to engage in a series of multidisciplinary projects and modules during the first two years of study. The experiences were designed to allow students to *"break out from their disciplinary silos,"* offering them critical insight into the role and place of their own engineering discipline, as well as the tools *"to work effectively with people from a range of backgrounds and perspectives."* One example is *How to Change the World*, an intensive two-week project at the close of Year 2 where students work in multidisciplinary teams to solve open-ended humanitarian problems.

When asked to describe its defining features, interviewees consistently pointed to the IEP's emphasis on: multidisciplinary learning; the application of knowledge to practice; the framing of engineering as a vehicle for positive world change; and the development of students' professional skills and attitudes. UCL Engineering is not alone in driving forward an educational agenda that is underpinned by these

features; some or all appear in the mission statements of many engineering schools worldwide. Where UCL Engineering stands apart, however, is in the scale of their application and in their integration across the programs. Where peer engineering programs may offer multidisciplinary, project-based experiences, they often cater only to small student numbers or are isolated from the rest of the curriculum, with students struggling to connect these experiences to their learning in the 'core' engineering modules. In contrast, the IEP education is integrated across the core curriculum for all engineering students. UCL Engineering engages a thousand incoming engineering students each year, from across eight departments, in immersive and authentic engineering projects that are integrated into a coherent curriculum structure.

Interviewees consistently attributed the success of the IEP reform to a number of factors. These included the flexible and responsive leadership approach provided by the Faculty's senior managers that offered *"a balance between vision and ambition with a pragmatism about how we can make this work."* It was a leadership style that was to be seen to empower departments to drive change from the bottom up in a way that reflected their particular needs, interests and culture.

The IEP also faces some important challenges. Two, in particular, were singled out by interviewees. The first relates to maintaining an effective balance between, on the one hand, establishing a cross-Faculty educational model that is coherent, ambitious and evidence-informed, and, on the other hand, ensuring that each department retains ownership of their disciplinary curriculum and is able to shape its development according to their own strategic priorities. The second relates to the roles and focus of academic staff. Interviewee feedback suggested that the introduction of the IEP has led to a bifurcation of academic staff roles: that the transition away from teacher-centered delivery of 'engineering content' and towards project-centered learning had left *"research-focused staff, who would have taught the traditional lectures, doing less teaching"* and *"staff that are more interested in teaching taking on a much greater load."* Where this reshaping of academic roles reflects the interests and priorities of staff members, such diversification may not necessarily present a problem. However, its success rests on the capacity of the recently-reformed UCL promotion system to appropriately recognize and reward the contribution of academics in the educational domain.

Despite the challenges faced, however, the IEP offers a world-class model, and both the Faculty and university have been explicit about their commitment to sustaining and strengthening these educational reforms. At the same time, the growing educational expertise embedded in the departments, the IEP team and the newly established *Centre for Engineering Education* ensure that UCL has a solid platform on which to continue to advance its innovative and evidence-informed curriculum.

8.3. Summary of the CSU case study

Charles Sturt University (CSU) is located in regional south-eastern Australia, in an area marked by low population density, away from the country's major metropolitan hubs. Rooted in a mission to *"support our regions and the professions that sustain our regions,"* CSU has built its disciplinary base around the economic and social needs of regional New South Wales. Building on these established strengths in professions *"that are the lifeblood of the regional economy"* – such as nursing, teaching and accountancy – the past 20 years has seen the university diversify further to include disciplines such as dentistry and veterinary science.

One discipline that had proved difficult to *"get off the ground,"* however, was engineering. The rationale for establishing an engineering program at CSU was widely acknowledged, with growing calls from industry and local councils to increase the regional talent pool of skilled engineering professionals. However, concerns remained about the viability of a new engineering program within the CSU regional setting:

"...we would be the 37th engineering school in Australia. We had no reputation in engineering... The big question is why would people want to come to us?"

The conclusion reached was that if CSU was to establish an engineering program, it must offer prospective students *"something completely unique, something they could not get anywhere else."* In the four years that followed, the university's first engineering school was established – CSU Engineering – and a diverse team was assembled to design and build a distinctive new engineering undergraduate program.

What was created was a five-and-a half-year joint bachelor/master program in Civil Systems Engineering that was launched in February 2016. Its student intake number would be small; the first cohort joining CSU Engineering was just 28 students. The curriculum is structured in two distinct phases. The first phase – comprising the first 18 months of the program – is based on campus and structured around a series of project-based design *challenges* that immerse students in the broader societal context of engineering. The second phase – comprising the last four years of the program – is based off-campus and structured around a sequence of four paid 12-month work placements.

CSU Engineering's educational approach offers three distinctive features:

- **a professional, work-ready environment:** the close industry partnerships that lie at the heart of the CSU Engineering program were noted to be *"engrained in the culture and the expectations on students"* enrolled in the program. This culture is reflected in the curricular *"focus on practical engineering and preparing people for the workplace,"* where students are able *"to work on real engineering problems and are treated like professionals"* from the point of entry to the program.
- **underpinned by self-directed learning:** the program takes a student-centered, experiential approach that emphasizes self-directed learning. Students are confronted with a series of on-campus *challenges* and work-based problems and are expected to identify, master and apply the knowledge and skills necessary to tackle them, as well as reflect upon their learning. Students are also encouraged to direct and manage their own learning goals.

- **embedding flexible, state of the art online learning:** arguably the most distinctive element of the CSU Engineering education is its approach to online learning. Almost all ‘technical engineering content’ – including both knowledge acquisition and skills development – is disaggregated into a set of ‘topics’ that are delivered online for students to access independently, when and how they wish.

CSU Engineering brings together many of the features that the thought leaders in Phase 1 of the study identified as likely to distinguish the world’s leading engineering programs in the decades to come. However, when asked to identify the characteristics that set CSU Engineering apart on a global stage, many external observers pointed to its blend of face-to-face project-based learning with student-directed online learning: *“the first 18 months is exceptional, it embodies all aspects of best practice that I have seen.”* One observer characterized CSU Engineering’s online platform for flexible *“just in time”* learning as *“the most innovative thing I have ever seen in pedagogy.”*

Despite these clear strengths, this newly-established program faces major challenges, the most pressing of which will be meeting its annual student recruitment targets. As one external observer commented:

“the biggest challenge facing CSU is exposure. If future Australian engineers and their families were aware of and actually understood the CSU model... the enrolments would sky-rocket. The difficulty is in creating the awareness.”

Much of the early success of the CSU Engineering program rests on the expertise, energy and leadership of the CSU Engineering team; it is a team that combines strong industry connectivity, hands-on experience with major curricular reform and expertise in pedagogical scholarship. The program’s success has also been underpinned by two additional factors:

- the *“unwavering support”* offered from the university’s senior management that has ensured that the vision and design of the program has remained largely uncompromised by institutional constraints or protocols;
- the ability of the program’s leaders to draw upon external expertise and goodwill from across both the university and the country, which has proved invaluable to the design and delivery of the engineering program: *“there has been a real sense that they are all working for a common good and there is a genuine academic and intellectual honesty about how they all try to share that.”*

CSU Engineering, however, is a young program and evidence of its impact on student learning will not be available for a number of years. Nonetheless, interview feedback from external observers was universally positive, as one noted: *“... I’ve never seen anything like it before, but I am really excited by what I see. It is a new chapter in engineering education.”*

8.4. Summary of the TU Delft case study

Established in 1842, TU Delft is the oldest and largest of the three technology-specialist universities in the Netherlands. It is formed of eight Faculties that encompass engineering, applied science and design.

TU Delft featured among the top 10 'current leaders' and 'emerging leaders' in engineering education, as compiled in Phase 1 of this study. Its reputation derives from a blend of factors which have enabled it to remain at the forefront of educational practice. Key among these is what interviewees referred to as "*the Delft spirit*." It is an ethos of openness and inclusivity that enables new ideas and innovative approaches to emerge from across the university community, from students and teachers as well as university leaders and managers. The egalitarian principles that inform this ethos are embedded in Dutch society and, consistent with these principles, interviewees described how TU Delft has nurtured an environment where creativity can flourish. The quality of its students bears testimony to the success of its approach. So too does the university's growing reputation as "*a global thought leader in engineering education*," a position which has undoubtedly been advanced by influential reports such as *Engineering Education in a Rapidly Changing World*.⁹

Unlike the other three institutions considered for case study evaluation in this MIT-commissioned report, TU Delft does not offer a single overarching model for its engineering education. Instead, its programs are characterized by their diversity. The 17 bachelor programs and 33 master programs at TU Delft are designed and delivered relatively independently and considerable variation in curricular design and pedagogy exists between them. However, they share common characteristics.

In addition to its egalitarian culture, interviewee feedback suggested that four features of the TU Delft education set it apart from national and global peers:

- **deep disciplinary knowledge:** all interviewees highlighted the technical rigor of the TU Delft education, with its students graduating with "*a solid background in maths, mechanics and the engineering fundamentals*";
- **design-centered learning:** the design-centered curriculum established in a number of the university's Faculties – including Industrial Design Engineering and Aerospace Engineering – was seen to provide opportunities for students to apply and contextualize their learning;
- **an ambitious student culture of initiative and hands-on learning:** the culture of TU Delft was seen to promote ambition and leadership among its student population, with significant opportunities to apply their knowledge to real engineering problems. Much of this activity is driven and supported by the student-led extra-curricular activities, which operate relatively independently of the university;

⁹ Kamp, A. (2016) *Engineering education in a rapidly changing world*, second revised edition (<https://www.4tu.nl/cee/en/publications/vision-engineering-education.pdf>)

- **a pioneering approach to blended and online learning:** many interviewees noted the university's growing strength in online learning and the positive impact this has had in recent years on student learning, both on- and off-campus.

TU Delft's position among the 'emerging leaders' in engineering education is not the result of systematic reform or a blank-slate development. Instead, its strength lies in its capacity for incremental change, and, in particular, for maintaining its reputation for academic excellence while embracing educational innovations that subsequently become sector-wide. Vital to the process of incremental change has been cross-campus consultation and consensus-building, centrally supported by the provision of "*opportunities and space*" for teachers and Faculties to drive educational reform from the bottom up. One interviewee characterized this process of teacher-led educational reform to be:

"like the way oil spreads on water,... change happened slowly – by consensus, in small steps, letting people get used to the idea all the time."

A crucial factor underpinning the success of TU Delft's education has been the quality of its educational leadership. The educational approaches for which TU Delft is internationally recognized – design-led curricula, student-led activities and online learning – have been given targeted support when and where needed. In TU Delft's decentralized environment, the groups leading each of these initiatives have also been given the freedom to be creative without the structural and regulatory constraints found in many academic institutions.

The university's approach, however, was also seen to present inherent tensions. While many of the successes of TU Delft's educational approach are associated with its decentralized institutional structure, so too are many of its challenges. Interviewees from both within and outside TU Delft referred to the university as "*a collection of islands and small kingdoms,*" where "*the bright spots are scattered*" and pedagogical practice varies considerably across the institution. Limited program connectivity appears to exist between Faculties, and few structural changes have been imposed on teachers that were not mandated by the national government.

The university is now, however, at a turning point. It has developed a draft vision statement containing a number of radical ideas for educational change, including the introduction of greater student flexibility and choice and the integration of new multidisciplinary, active learning experiences. For many Faculties, these proposals would require significant educational change, both pedagogical and curricular. The proposals would also require significant cross-Faculty cooperation and institution-wide changes. As this suggests, a bottom-up approach to reform is unlikely to be sufficient if these proposed ideas are to be successfully implemented. The realization of the reforms proposed in the university's 'vision' document is also likely to require a step change in TU Delft's culture.

These and other challenges face the university as it seeks to pilot and develop its new vision in teaching and learning. However, its history of delivering high-quality engineering education suggests that TU Delft will be able to build upon its culture of engagement in educational change and retain its position among the global thought leaders in engineering education.

PART IV Global Engineering education: challenges and future directions

Part IV provides an assessment of the state of the art in engineering education and a horizon scan of the future direction for the global sector. It draws on the two phases of the study: the consultations with 50 thought leaders in engineering education (Phase 1) and the case studies of four 'emerging leaders' in engineering education identified through the consultations (Phase 2).

Part IV addresses three questions:

1. What are the distinctive features and strategies of the world's top-rated programs? **(Section 9)**;
2. What key challenges are likely to constrain the global progress of engineering education? **(Section 10)**;
3. What is the future direction for the global engineering education sector? **(Section 11)**.

Anonymous quotes from interviewees consulted in Phases 1 and 2 are used to illustrate the views expressed.

9. What features distinguish the top-rated programs?

Both phases of the study explored the features and experiences shared by the world's top-rated 'current leaders' and 'emerging leaders' in engineering education: the Phase 1 feedback from thought leaders was used to characterize and profile these top-rated programs and the Phase 2 feedback from stakeholders was used to identify the facilitators of positive educational change.

Drawing on this evidence, this Section explores three questions in turn:

1. What is the common profile and approach of 'current leaders' in engineering education? (Section 9.1)
2. What is the common profile and approach of 'emerging leaders' in engineering education? (Section 9.2)
3. What are the common factors that facilitate educational excellence among the 'emerging leaders' selected for case study evaluation? (Section 9.3)

9.1. Profile and approach of the 'current leaders' in engineering education

The institutions identified by interviewees as global 'current leaders' in engineering education (as presented in Figure 3, page 9) share a number of common features:

- **established international profile:** the majority of the 'current leaders' are well-established public universities catering for relatively large cohorts of undergraduate engineering students. A significant overlap is apparent between the institutions most frequently cited by interviewees to be 'current leaders' in engineering education and the international university rankings – indeed, four of the universities identified as 'emerging leaders' (MIT, Stanford University, UCL and the University of Cambridge) also appear in the top 10 of the 2018 QS World University Rankings.¹⁰
- **educational excellence often confined to 'pockets':** many Phase 1 thought leaders noted that the good practice that helped to make a university world-leading in engineering education was rarely institution-wide: *"so much of these things are pockets, it is one program or one department. Unless it is a new university, like Olin, there are not many places where the whole university is a leader."* Another described the educational practices at the 'current leader' institutions as *"a lot of bright spots of activity, but nothing coherent."* Educational cohesion was seen as a particular challenge in countries such as the US where individual faculty autonomy plays a significant role. Indeed, a number of interviewees noted that *"European universities, like Aalborg, Delft, Chalmers and KTH [Royal Institute of Technology, Sweden] seem to have been able to take a more coordinated approach, a more consistent approach."* However, feedback – both from interviewees based at the top-cited 'current leader' institutions and external observers –

¹⁰ QS World University Rankings 2018 (<https://www.topuniversities.com/university-rankings/world-university-rankings/2018>)

suggested that, regardless of location, most are “*finding it difficult to propagate the ideas, the culture, the good practice out from the pockets of excellence. This is going to take some time and a lot of effort.*”

- **emphasis on external engagement and educational collaborations:** the majority of the ‘current leaders’ – particularly the five most frequently cited universities – have been actively engaged in disseminating their ideas and practices across the international higher education community. In addition, most have strategic global partnerships to support the development of undergraduate engineering programs elsewhere. Examples include: (i) the *Collaboratory*¹¹ at Olin College of Engineering; (ii) the *Conceive, Design, Implement and Operate (CDIO)*¹² initiative established and co-led by MIT; (iii) *Epicenter*,¹³ operating until recently at Stanford University; and (iv) the *UNESCO Centre for Problem-Based Learning*¹⁴ at Aalborg University.

In addition to these commonalities in profile and structure, similarities in educational approach were also apparent among the ‘current leaders’, as outlined in Box 4.

Box 4. Distinctive pedagogical features of the ‘current leaders’ in engineering education:

- pathways and linkages for students to engage with the university’s research activities, often building upon rigorous, applied teaching in the engineering fundamentals;
- a wide range of technology-based extra-curricular activities and experiences available to students, many of which are student-led;
- multiple opportunities for hands-on, experiential learning throughout the curriculum, often focusing on “*problem identification as well as problem solution,*” and typically supported by state of the art maker spaces and team working areas;
- the application of user-centered design throughout the curriculum, often linked to the development of students’ entrepreneurial capabilities and/or engaged with the social responsibility agenda;
- emerging capabilities in online learning and blended learning;
- longstanding partnerships with industry that inform the engineering curriculum as well as the engineering research agenda.

¹¹ Collaboratory, Olin College of Engineering (<http://www.olin.edu/collaborate/collaboratory/>)

¹² CDIO (Conceive, Design, Implement and Operate) (<http://www.cdio.org>)

¹³ Epicenter, Stanford University (<http://epicenter.stanford.edu>)

¹⁴ Aalborg Centre for Problem Based Learning in Engineering Science and Sustainability under the Auspices of UNESCO (<http://www.ucpbl.net>)

9.2. Profile and approach of the 'emerging leaders' in engineering education

The institutions identified by interviewees as 'emerging leaders' in engineering education (as presented in Figure 5 on page 11) share a number of common features.

The **first feature** that connects most 'emerging leader' institutions is their systemic and unified educational approach. The majority of 'emerging leaders' fall into one of two categories:

- new start: a university or engineering school established from a blank slate with a distinctive and integrated educational approach, such as SUTD, Olin College of Engineering, Iron Range Engineering and Charles Sturt University (CSU);
- systemic reform: a university or engineering school that has engaged in systemic educational reform to implement an integrated and unified educational approach across engineering disciplines, such as UCL, PUC and Arizona State University.

Interviewee feedback suggests that such a unified and consistent educational approach – one reaching across all engineering programs – is not a feature of the majority of the 'current leaders'.

The **second feature** connecting many of the 'emerging leaders' is the extent to which their development has been shaped by regional needs and constraints. For example:

- the educational reforms in the School of Engineering at the Pontifical Catholic University of Chile (PUC)¹⁵ have been advanced by significant government investment aimed at catalyzing a new generation of technology innovators to drive the economy and improve social mobility;
- the new engineering school at CSU¹⁶ (Australia) was established in response to the regional shortage of engineers with transferable and entrepreneurial skills;
- the educational transformation in the engineering school at Arizona State University¹⁷ (US) has been focused specifically on supporting the health, opportunity and economic development of the state of Arizona.

Interview feedback suggests that the clarity of educational goals among these institutions – be that of national economic development, improving the regional engineering skills base or tackling societal inequalities – has enabled them to take a more visionary and innovative approach, one that would not have been possible if the focus of reform had simply been on "updating the catalog."

The **third feature** common to the 'emerging leaders' is an educational approach that distinguishes them from the 'current leader' institutions. While the elements of this approach varied across the 'emerging leaders', they included at least three of the following:

¹⁵ Clover 2030, Pontifical Catholic University of Chile (<http://www.ingenieria2030.org>)

¹⁶ CSU Engineering, Charles Sturt University (<http://www.csu.edu.au/go/engineering>)

¹⁷ Ira A. Fulton Schools of Engineering, Arizona State University (<https://engineering.asu.edu/#>)

- non-conventional student entry requirements or selection processes;
- the increasing integration of work-based learning;
- the blending of off-campus online learning with on-campus intensive experiential learning;
- the establishment of student-led, extra-curricular activities in contexts and cultures that are not typically associated with non-curricular experiences;
- a dual emphasis on engineering design and student self-reflection.

These elements combined in ways that marked a distinctive break with the educational approaches of the 'current leaders'. The educational features anticipated to define the next generation of leaders in engineering education are explored further in Section 11.2.

9.3. Facilitators of best practice in engineering education

The case studies of four 'emerging leaders' of engineering education (summarized in Section 8 and presented in full in Appendices B–E) provide insight into the common factors that facilitate best practice in engineering education. Four common features were particularly evident:

- **strength of academic leadership:** a prominent theme that linked all case study institutions was their academic leadership. It was a leadership style that articulated a clear educational vision and demonstrated a personal commitment to establishing a new paradigm for engineering education at the institution. The leadership approaches were also highly inclusive, drawing on feedback, evidence and ideas from across the university hierarchy and beyond the institution. For the cases of UCL Engineering and CSU Engineering, strong and consistent support from university senior managers for the development of their non-traditional educational models appeared to be a critical factor in their success. For example, at CSU Engineering, the university senior management was understood to bring "*no expectations or preconditions about what [the program] should look like*" and, instead, "*allowed us to break the university's rules*" in order to accommodate the program's unconventional timetabling, staffing, budgeting and on-campus space requirements. As a result of this "*unwavering support,*" the vision and design of the CSU Engineering program was not "*watered down along the way*" and has remained largely uncompromised by institutional constraints.
- **a collegial and exploratory educational culture:** interviewees at each of the case study institutions repeatedly pointed to a distinctive 'spirit' or culture of collegiality and common purpose that pervaded the faculty. In each case, this culture was identified as an important mechanism to allow ideas and practice to emerge from the 'bottom up'. For example, at TU Delft, interviewees spoke about "*a Delft spirit and attitude, where they are forward-thinking, ambitious and entrepreneurial and committed to education.*" This egalitarian culture and spirit of inclusivity has allowed bottom-up innovation to emerge in areas including design-led curricula, student-led extra-curricular activities and online learning. For both CSU Engineering and SUTD, the universities were able to hand-pick faculty who brought a commitment to the universities' educational mission. For example, many of the SUTD interviewees spoke about the empowerment of faculty to collaborate and innovate in teaching: "*the management is giving*

[us] flexibility to try new ideas... they just want to know how the students benefit, but the openness is there."

- **student engagement in and understanding of new educational approaches:** one of the most striking features of the on-site visits to the case study institutions was the high level of student engagement apparent: engagement in the student-led extra-curricular activity DreamTeams¹⁸ at TU Delft and engagement in the student-centered and active curricula at CSU Engineering, SUTD and UCL Engineering. It is interesting to note that this latter group of engineering programs – at CSU Engineering, SUTD and UCL Engineering – all faced early resistance from the student population to the introduction of the new curricula. The new programs called upon students to engage in exploratory and open-ended problem-solving and address challenges that spanned multiple disciplines. In the early months and years, some students were left overwhelmed by the challenges posed and skeptical about the relevance of such experiences in an engineering program. In each case, these barriers were overcome through improved and targeted communication with the student body, focused in three areas: (i) conveying the major challenges facing the engineering sector in the 21st century and the key capabilities that will allow engineering graduates to contribute most in this environment; (ii) explaining how the program's distinctive pedagogy would help students to nurture these competencies; and (iii) articulating a clear set of expectations and deliverables for each course or activity.
- **in-house development of new tools and resources to support and advance the educational approach:** all of the case study institutions have developed in-house tools and mechanisms to support and advance their distinctive educational approach. For example, UCL Engineering, SUTD and CSU Engineering have all developed, or are developing, tools for student assessment that are compatible with their own distinctive pedagogical approach. For UCL and SUTD, these tools are designed to ensure that individual student contributions to group projects are appropriately recognized; for CSU Engineering, online tools support the assessment of students' 'mastery' of topics. Three of the four case study institutions are also building significant capacity in engineering education research, to create an evidence base from which to inform and advance the undergraduate programs. It is also interesting to note that each case study institution has strengthened its capacity to deliver authentic on-campus engineering challenges through establishing new teaching roles, such as *Undergraduate Teaching Assistants* (at SUTD and TU Delft), *Engineers in Residence* (at CSU Engineering) and *Teaching Fellows* (at UCL Engineering).

¹⁸ TU Delft DreamTeams (<https://www.tudelft.nl/d-dream/>)

10. What challenges constrain progress of the sector?

During Phase 1 of the study, thought leaders were asked about the key challenges facing the global progress of engineering education in the coming decades. Four issues were consistently identified:

1. the alignment between governments and universities in their priorities and vision for engineering education;
2. the challenge of delivering high-quality, student-centered education to large and diverse student cohorts;
3. the siloed nature of many engineering schools and universities that inhibits collaboration and cross-disciplinary learning;
4. faculty appointment, promotion and tenure systems that reinforce an academic culture that does not appropriately prioritize and reward teaching excellence.

These issues are discussed in turn below.

10.1. Alignment of goals between government and higher education

Phase 1 thought leaders noted that government funding, support and interventions are likely to play an important role in driving change in engineering education in the coming years. They pointed to the growing number of national governments – such as Chile, the Netherlands, Singapore, South Korea and China – that were strategically investing in engineering education as an incubator for a new generation of talent in technology innovation and a springboard for economic growth. Many reported that such investments are having “*a transformative effect*” on the capacity for “*visionary and ambitious reform in engineering education.*” In contrast, interviewees based outside these national contexts were more likely to point to perceived conflict between universities and governments in their priorities for engineering education. As outlined below, concerns typically fell within three broad categories.

The **first** set of concerns related to a perceived tension between “*what engineering science professors want to teach engineers to do, so that they can become young scientists and PhD students, and the needs of government and society, which is to create engineers to contribute to economic development and growth.*” Some commented that this tension “*will either progress or be resolved in the next decade.*” Nevertheless, interviewees suggested that such a conflict – and a broader lack of consensus about the purpose of engineering undergraduate education – lies at the heart of why many faculty and engineering schools are reluctant to engage in curriculum reform.

Secondly, some interviewees highlighted the restrictions imposed by national accreditation requirements, “*the expectations of local governing bodies*” and government higher education regulations. The impact of these restrictions on the structure, content and delivery of undergraduate programs was particularly noted in countries such as China, India, Brazil and Canada; in consequence, they “*leave little room for experimentation and new ideas.*” For example, one interviewee described the challenges of creating cross-disciplinary engineering programs within an accreditation system that was intrinsically monodisciplinary in approach: “*when you try to be innovative, try to work in a cross-disciplinary way, you*

see the long arm of the professional accreditation societies that prevent engineering schools from doing this.” It is interesting to note, however, that all four case study institutions reviewed as part of this study had either been, or were on track to be, awarded accreditation for their engineering programs.

Thirdly, concerns were raised about the unpredictable nature of government higher education funding, which *“makes it difficult to plan for the future”* and often *“derails or restricts what it is possible for [engineering] schools to do in practice.”* For example, some US-based interviewees expressed concern about reductions in state funding for public universities:

“[there are] increasing expectations for the number of graduates we can produce... expectations of access to an affordable education but without a solid economic basis for how that happens. This commodification works against innovation and is a real concern for the future. The large public universities are the places that really interesting things can happen [in engineering education] at scale, but finances will play a role.”

Other interviewees highlighted countries such as the UK and Australia, where recent changes in government policy had the potential to restrict educational innovation and the establishment of regional networks of support. For example, interviewees pointed to the recent decision of the Australian government to cease distributing grants to support innovation in university education through the *Office for Learning and Teaching*. One interviewee suggested that, over many years, these grants *“have impacted almost every one of the 35 [engineering school in Australia]. The amount was trivial – around AUS \$8 million – but they would have been matched by the university and they have been very influential... We have already lost momentum.”* Concerns were expressed that the strong national network of support and expertise in engineering education that has developed in recent decades across Australia may *“start to fade”* as the lack of educational grant opportunities constrains the pool of new engineering faculty willing to specialize in teaching and learning.

10.2. Adapting to larger and more diverse student cohorts

Phase 1 thought leaders reflected on the worldwide trend towards the integration of active, student-centered learning into engineering curricula and the benefits that this brings to students. It was noted that *“early pioneers like Aalborg have been an inspiration to many”* since their establishment of a new problem-based engineering curriculum in 1974.¹⁹ The widespread influence of the CDIO initiative¹² was also noted to have *“spurred a lot of changes in a lot of countries across the world: new introductory engineering courses, industry-linked projects and learning through doing.”* The interview feedback made clear that the majority of thought leaders anticipated that *“team-based, hands-on student learning that responds to the needs of society and industry”* would underpin the world's leading engineering programs in the decades to come. However, concerns were repeatedly expressed about the capacity of large, publicly-funded institutions to deliver such educational programs to large student cohorts, particularly when operating under limited budgets. In particular, interviewees pointed to the increasing cohort

¹⁹ Problem-Based Learning at Aalborg University (<http://www.en.aau.dk/about-aau/aalborg-model-problem-based-learning/>)

sizes at many large public universities and the challenges that this poses to educational quality. The views of this interviewee were typical of many of the thought leaders:

“How do we deal with this expansion [of student numbers]? How do we still engage students early on with the world of engineering? How do we show them the messiness of engineering, the political and social aspects? ... How do we do this beyond the capstone project? This type of education, the type of education we want to have, is expensive. So how do you do this for all students, large cohorts of students, without compromising on everything?”

Interviewees from institutions experiencing a rapid increase in student numbers were particularly aware that there were few ‘role model’ institutions delivering high-quality student-centered education at scale. Indeed, many of the educational features common to the ‘current leaders’ and ‘emerging leaders’ in engineering education – including entrepreneurial or authentic industry experiences – are, in practice, only available to relatively small student cohorts.²⁰ As one interviewee commented:

“places like Olin and Iron Range are early development models – high cost, low volume – but the economically feasible version will come next.”

It was also recognized that increasing student numbers would inevitably bring a greater diversity in student demographics and background. Although it was noted by many that *“we cannot continue to cater to the same type of students, we need to attract the students that would not normally think of engineering,”* it was also suggested that a more diverse student body was not well served by current engineering curricula. Many of the engineering schools and universities identified as ‘current leaders’ and ‘emerging leaders’ have, in recent years, pioneered changes specifically aimed at increasing the diversity of their student populations. Some of these interventions have involved adapting the entry criteria to undergraduate programs. For example, CSU Engineering and the Department of Civil, Environmental and Geomatic Engineering at UCL do not require prospective students to have studied mathematics and physics as prerequisites for entry, as is typical for most engineering degree programs, but rather have a selection process open to candidates from all disciplinary backgrounds. In addition, Olin College of Engineering uses residential ‘selection weekends’ to shortlist potential candidates, and PUC has developed a dedicated *Talent and Inclusion* entry route for under-represented groups, with dedicated mentoring and support offered to this group of students.

²⁰ For example, the National University of Singapore was singled out by many for the quality and influence of its programs in engineering design education. However, the *Innovative and Design-Centric Programme* at NUS is an invitation-only program that caters to 100 students per year-group, representing less than 10% of the engineering student cohort.

10.3. Disciplinary and educational siloes

The discipline/department-based structure of many engineering schools and universities was seen to be holding back innovation and excellence in engineering education. As discussed further in Section 11.2, multidisciplinary learning and increased student choice were predicted to be key features of the best engineering programs over the coming decades. It was acknowledged, however, that such developments would be constrained by the structural separation that often exists between and beyond engineering disciplines and the lack of informal interaction across these boundaries, particularly in teaching and learning. For example, one thought leader noted that the provision of curricular flexibility was significantly constrained by:

"impenetrable departmental silos that make it almost impossible to offer students real choices that are not completely disconnected from the rest of their curriculum."

Interviewees also noted the difficulty in reforming the 'fundamental' courses that are often *"bought in from the [university's] science school,"* and ensuring that their approach, content and focus formed a coherent and consistent part of the engineering degree program as a whole. As one explained:

"if a department equals a program, there is no way that you can discontinue a program [Instead] you need to create a strong power base around the [cross-disciplinary] programs, so that departments are not only interested to offer their own standard courses, so that you are not coming with your hat in your hand begging the maths department to change anything."

In this respect, Chalmers University of Technology in Sweden was noted by a number of interviewees to be *"a real beacon for their interdisciplinary programs... they have created a good power balance [between the departments and the programs] with mutual commitment from both sides."*

Many of the high-profile engineering and technology universities established in recent years (including SUTD in Singapore, Skoltech²¹ in Russia and Olin College of Engineering in the US) have been created without traditional engineering disciplinary boundaries. Feedback from representatives from these institutions suggests that this approach has:

"meant that we could focus on what capabilities we wanted for our graduates, what types of experiences we wanted them to have, rather than arbitrarily bounding them by a set of disciplines that are no longer relevant to the types of problems that they will need to solve in their careers."

Other highly-rated institutions such as UCL in the UK and PUC in Chile have made important strides in recent years to *"soften the [existing] boundaries"* between engineering disciplines and create more opportunities for cross-disciplinary collaboration and learning.

²¹ Skoltech (<http://www.skoltech.ru/en/>)

10.4. Faculty engagement with and university rewards for education

Phase 1 interviewees consistently pointed to the lack of faculty engagement and recognition as a major barrier to the progress of engineering education globally. Some spoke about *“the disconnect between the academic and the world of [engineering] practice”* as well as the lack of formal and informal support available to faculty to reflect upon and improve their teaching practice.

However, the major focus of interviewee feedback was on *“the reluctance of faculty to change because they are in an environment where education is not rewarded by their university.”* In particular, the criteria by which faculty are appointed and promoted were repeatedly cited as a major inhibitor to educational excellence and capacity to reform:

“Most engineering programs are at research-led institutions. [Faculty] are ultimately being judged on being an excellent researcher... tenure is based on research, so you do enough teaching to tick the teaching box. [Educational] reform is focused on teaching people to teach more efficiently so that you can spend more time on research.”

As another interviewee put it, *“the relative thresholds for being an adequate teacher and an adequate researcher are very different.”* It was also suggested that the lack of appropriate metrics for evaluating the quality and impact of teaching was an important barrier to improving its reward and recognition in faculty careers:

“I have great ways to measure a great researcher. I don't have the same indicators that someone is a great teacher. This makes it very difficult to endorse them for [promotion] and all we have to give them is a teaching prize.”

Many noted that the greater weight given to research over teaching in faculty promotion reflected perceptions more broadly across higher education: *“what determines reputation [of a university] continues to be research. Unless this changes, it is difficult to see how there will be an extensive change to teaching across the [sector]... it will continue to be the outliers, the mavericks.”*

It is interesting to note that this issue was equally apparent at most of the case study institutions. Despite delivering globally renowned undergraduate programs, a major concern consistently raised by faculty and academic leaders alike was the lack of appropriate reward for contribution to education in faculty career progression. In the words of one academic leader at a case study institution:

“The desire exists among senior managers to change [the promotion system], but it has not been enacted. Implementing it is a different thing because we want to attract the best [faculty] and they know that their future and reputation among peers depends on their research... so we do not reward teaching in the way we should.”

Many interviewees went on to note the potential long-term damage that such inequitable reward systems may have upon faculty and their willingness to devote time to advancing the curriculum and supporting a breadth of student learning.

11. What is the future direction for the sector?

This Section takes a horizon scanning approach to anticipate both the future trajectory of the engineering education sector and the profile of the leading engineering programs in the decades to come. It draws upon evidence from Phases 1 and 2 of the study and the wider literature.

Evidence from the study pointed to three trends likely to define the future of the engineering education sector:

- a **tilting of the global axis of engineering education leadership**, from north to south and from high-income countries to the emerging economic powerhouses in Asia and South America. Many among this new generation of world leaders will be propelled by strategic government investment in engineering education as an incubator for the technology-based entrepreneurial talent that will drive national economic growth. This theme is explored further in Section 11.1;
- a move towards **socially-relevant and outward-facing engineering curricula**. These curricula will emphasize student choice, multidisciplinary learning and societal impact, as well as expose students to a breadth of experiences outside the classroom, outside the traditional engineering disciplines and across the world. This theme is explored further in Section 11.2;
- the emergence of university leaders that **deliver an integrated and world-class curriculum at scale**. The next generation of world leaders in engineering education is unlikely to be distinguished by specific classroom techniques or student experiences. Rather, they are likely to be institutions that deliver an integrated and coherent student-centered curriculum to large student cohorts under constrained budgets. This theme is explored further in Section 11.3.

One particular case study institution, SUTD in Singapore, exemplifies each of these three themes, as outlined in Box 5 and explored further in Appendix B.

Box 5. The SUTD undergraduate education

SUTD was born out of the Singaporean government's vision to establish a new university that would be an engine for national economic growth, fostering talent and applied research in engineering, architecture and design. Over the coming years, SUTD's annual undergraduate intake is set to increase from 450 to 1000.

Established in 2009, the university's educational approach and structure are distinctive in a number of respects. For example, with no departments or schools, SUTD offers a multidisciplinary education built on a rigorous grounding in the fundamental engineering sciences. The curriculum is immersed in design-centered active learning that allows students to connect and integrate their learning between both courses and years of study. Many of these projects have a hands-on component and are supported by open-access state of the art maker spaces. Indeed, it is estimated that by completion of the degree program, every SUTD student will have participated in 20 to 30 intensive design projects. SUTD also offers a breadth of experience not traditionally associated with engineering undergraduate study, including research opportunities, industry internships, undergraduate teaching opportunities and courses in humanities and social sciences.

11.1. Tilting of the global axis of engineering education leadership

Interview feedback from both phases of the study suggests that the engineering education sector is entering a period of rapid and fundamental change. As one Phase 1 interviewee commented:

"... for years and years, there was endless talk about why engineering education needed to change, lots of statements and reports about what needed to be done. And nothing changed, give or take a few electives and new mission statements ... [but in recent years] something has happened, things are happening in places you have never even heard of, all over the world. Doing the same old thing is suddenly not going to be good enough."

Echoing this observation, thought leaders in the field did not just anticipate rapid change among institutions that have hitherto taken a leading role in driving the debate and shaping best practices in engineering education – typically research-led institutions located in North America and Europe. Their feedback also pointed to a fundamental change to the profile and geographical location of the institutions that will be defining and advancing the state of the art in engineering education in the future. This geographical shift of focus can be seen by contrasting the location of the institutions identified by Phase 1 thought leaders as both ‘current leaders’ and ‘emerging leaders’ in the field.

Figure 7 presents data for all recommendations made by Phase 1 interviewees, in the categories of ‘current leaders’ and ‘emerging leaders’, by global region. As this data illustrates, institutions identified as the world’s ‘current leaders’ in engineering education are predominantly based in the US or Europe (representing 54% and 29% of the total recommendations made, respectively, and totaling 83% in all). In contrast, the ‘emerging leaders’ are much more likely to include Asian-based universities (increasing from 13% to 32% of the total selections made) and South American-based institutions (increasing from 3% to 11% of the total selections made). The geographical center of gravity of the world’s leading engineering programs may therefore be undergoing a fundamental shift, from north to south and from established high-income countries to the emerging economic ‘powerhouses’ in Asia and South America.

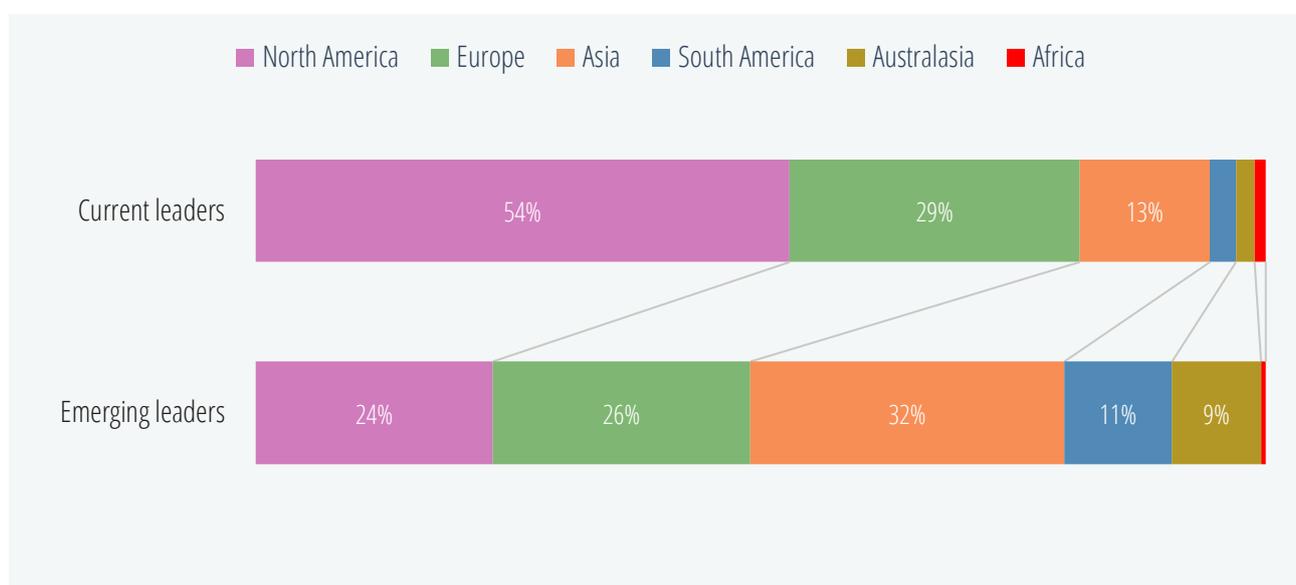


Figure 7. The locations of all recommendations made for ‘current’ and ‘emerging’ leaders

This global trend is illustrated in Figure 8. It highlights the regional shift from North America and Europe to Asia, South America and Australasia, as indicated by the direction of the arrows. It also turns a spotlight on the particular countries that were highlighted among the ‘emerging leaders’ from across the world. Many of the developments in these countries are propelled by strategic government engagement in engineering education and supported by strategic investment in undergraduate engineering programs to drive national economic growth. It is also interesting to note that the countries consistently represented among the ‘emerging leaders’ include those which are relatively small, such as Singapore (population: 5.6m), Chile (population: 18m) and the Netherlands (population: 17m).

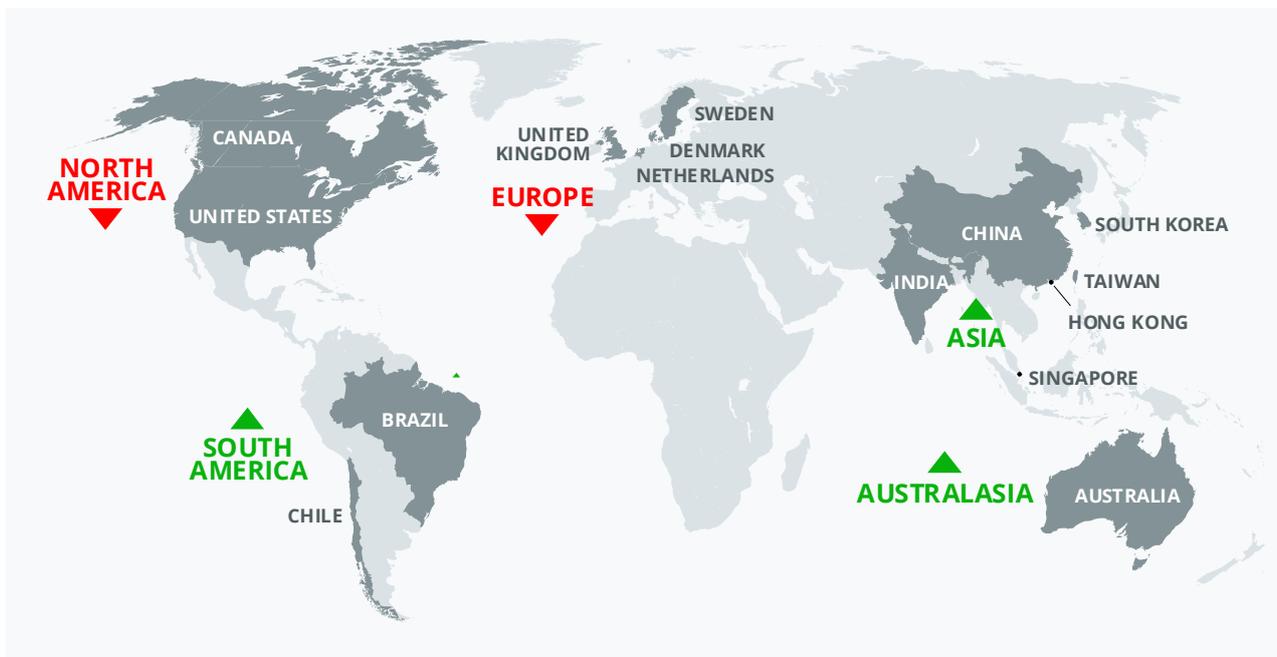


Figure 8. Global patterns of the ‘emerging leaders’ in engineering education

Although only one South American university features among the top 10 of ‘emerging leaders’, a range of other institutions in Brazil, Colombia, Mexico and Chile were consistently identified by Phase 1 interviewees. The transformations underway in Chile were particularly noted:

“what I see universities doing across Chile – from the most elite research universities through to mid-range regional universities – is just phenomenal ... It is an all-out effort, implemented with not only a vision, but with what people are doing on the ground.”

Almost a third of universities identified as ‘emerging leaders’ were based in Asia. As one thought leader noted: *“there has been an unprecedented expansion of higher education in South East Asia, and engineering education is at the core of that. There is going to be interesting things coming out of those parts of the world.”* Indeed, interviewees at a university senior management or dean level often spoke about:

“... spending quite a lot of time in the Asian part of the world recently ... Other countries are not losing momentum, but there is a strong realization in many Asian universities that strength in research needs to be balanced by strength in education and there are real opportunities there.”

A theme repeated by thought leaders was that, while *"the teaching and the curriculum is not yet what I would call cutting edge,"* it was the speed and direction of travel in many key Asian universities that was the source of particular interest. Many noted the significant investment in engineering education in both China and South Korea and the potentially disruptive influence of new private universities in India. However, it was Singapore that was discussed most frequently. Over 60% of interviewees identified at least one of four Singaporean institutions – SUTD, NUS, Nanyang Technical University and Singapore Polytechnic – either as a 'current leader' or an 'emerging leader' in engineering education. Benefitting from considerable government support and investment in higher education, Singapore was seen as *"a country with a history of having to innovate"* where universities offered a unique *"willingness to collaborate with others in a forward-thinking way."*

In addition to this geographical shift in the location of many future leaders, some thought leaders also suggested that the engineering education landscape would see an increased diversification in the coming years, particularly outside *"prestige brand"* universities. Some anticipated that institutions would seek to establish more distinctive and focused institutional profiles, catering to a more clearly-defined market both for prospective students and graduate employers: *"to compete, you need to know what niche you are filling."* As another interviewee commented:

"there are choices that universities are going to be making – whether they are a science/technology or an engineering/design oriented university, whether they are online or on-campus, whether it is about practice or about research."

It was recognized that such developments may be particularly evident among universities operating in competitive markets for prospective students. In this context, it is interesting to note that many of the institutions identified as the 'emerging leaders' (Figure 5, Section 5) would be considered to offer a 'niche' engineering education, with respect to their student intake, educational focus and/or graduate profile. Examples would include SUTD (see Appendix B), Olin College of Engineering, IRE and CSU (see Appendix D). Some interviewees suggested that such developments were unlikely to spread to large, research-led institutions: *"[university] rankings are a big impediment to diversification. Universities clamor for prestige and prestige comes from research. You cannot do this and be too focused."*

11.2. Educational focus of future leaders in engineering education

The evidence gathered from both phases of the study was used to anticipate the distinctive curricular experiences that would be shared by the world's best engineering programs in the future. The curricular emphasis in areas already evident among many of the 'current leaders' in engineering education – such as user-centered design, technology-driven entrepreneurship, active project-based learning and a focus on rigor in the engineering 'fundamentals' – are likely to continue to be prominent features. In addition, five curricular themes appear likely to become increasingly prominent:

- **student choice and flexibility:** interviewees suggested that, as *"engineering schools start to move away from seeing engineering students only as scientists, future PhD students,"* a range of different learning pathways for students will be offered, *"to educate students in the profile that is more oriented to their future career."* As one interviewee put it:

"Beyond the fundamental core, there are so many competing topics that we could include – entrepreneurship, service learning..., internships, research methods – we need to allow the students to explore these things and then let them choose a pathway that suits their talents and interests."
- **multidisciplinary learning:** interviewees noted that the ability to integrate knowledge and to work effectively across disciplines, both within and beyond engineering, is increasingly seen as a fundamental skill that all engineering graduates should possess;
- **the role, responsibilities and ethics of engineers in society:** interviewees spoke about the key role that engineers will increasingly play in tackling the challenges facing society, including water scarcity, air pollution and the shift to non-carbon-based industries. It was anticipated that this emphasis would increasingly be reflected in engineering curricula and *"a greater focus on solving human challenges and the problems facing society"* would emerge as hallmarks of the world's best engineering programs;
- **global outlook and experiences:** it was anticipated that engineering schools would increasingly focus on the development of *"skills to be effective in a global environment,"* providing students with a range of opportunities to work across nationalities and cultures. It was noted, in particular, that *"most US [engineering] schools have a long way to go on the global side. We don't give our students the kind of global exposure they need and [we] are way behind some other countries";*
- **breadth of student experience:** interviewees anticipated that engineering students would be offered greater choice in their studies, allowing them to add breadth to their learning outside the traditional engineering disciplines. Interviewees also pointed to an increasing emphasis on experiences outside the classroom, such as work-based learning.

The five themes listed above are distinctive features of many of the 'emerging leader' institutions and often go hand in hand within their curricula. Examples include the emphasis on multidisciplinary learning, user-centered design, entrepreneurship and societal impact in the new undergraduate programs at PUC in Chile (see Appendix A.4.7) and the student-centered, project-based approach

adopted at Olin College of Engineering in the US (see Appendix A.4.1) which offers a multidisciplinary student-centered education that extends across and beyond traditional engineering disciplines and is anchored in issues of ethics and social responsibility. A further example, taken from one of the case study institutions, UCL, is provided in Box 6 and explored in Appendix C.

It should also be noted that the educational features and approaches listed above are not radically new: societally-oriented, multidisciplinary curricula that expose students to a breath of experiences, for example, are established features of many engineering programs worldwide. When discussing the pedagogies that would characterize the best engineering programs worldwide in the decades to come, many Phase 1 thought leaders commented that:

"I don't see any brilliant new techniques down the pipe. We already have the ideas. We are rich in theory. What we will need to get better at is pulling them together."

This key challenge – the ability of engineering programs to ‘pull together’ and integrate best practice experiences at scale – is discussed in the Section that follows.

Box 6. The integrated Engineering Programme at UCL Engineering

Established in 2014, the *Integrated Engineering Programme*²² (IEP) represented a root-and-branch reform of the undergraduate curriculum across UCL's school of engineering, UCL Engineering.

The IEP incorporates a common school-wide curricular structure that has been adopted by all engineering departments for the first two years of undergraduate study. A centerpiece of this curriculum is a series of *Scenarios*, operating in five-week cycles, where students spend four weeks building critical engineering skills and knowledge that they subsequently apply to tackle a one-week intensive design project. Often drawing on external partnerships with industry, charities and the regional community, the *Scenario* projects ask students to “solve real engineering problems.” As students progress through their studies, the *Scenarios* are designed to become increasingly complex and open-ended.

The IEP is also interspersed with a series of team-based projects that draw together the full student cohort of almost 1000 students from across the engineering school. These multidisciplinary projects are notable for their global, societal and ethical focus, challenging engineering students with questions such as “How can engineering contribute to global TB (Tuberculosis) vaccines?” For example, at the close of the second year of study, all engineering students come together to participate in *How to Change the World*,²³ a two-week intensive team-based project to devise practical solutions to real societal and environmental problems from across the world. Provided with an open-ended brief from external clients such as the World Bank and Arup, mixed student teams drawn from different disciplines are asked to consider not just a technical solution, but also the societal, environmental and public policy implications of their approach.

²² Integrated Engineering Programme, UCL (<http://www.engineering.ucl.ac.uk/integrated-engineering/>)

²³ How to Change the World, UCL (<http://www.engineering.ucl.ac.uk/industry/change-world/>)

11.3. Scaling-up and integrating good practice

Feedback from the Phase 1 thought leaders and outcomes of the Phase 2 case studies suggest that the key innovations that will define the next chapter of global engineering education are unlikely to be new teaching techniques or curricular components, but rather **how programs are managed, structured and delivered** in practice. In particular, and echoing a theme highlighted in Section 10.2, Phase 1 thought leaders anticipated that the next generation of leaders in the field would be those that incorporated best practice into a coherent and integrated curriculum that could be successfully delivered to large cohort groups and under constrained budgets.

A striking feature of many of the universities identified as 'current leaders' is that good practices in engineering education are often isolated, confined to 'pockets', with limited connectivity to the rest of the curriculum. For example, although an increasing number of leading universities are including enriching student-centered experiences into their programs – such as user-centered design projects, work placements or community-based social entrepreneurship – many are characterized as *"bolt-on activities."* Phase 1 thought leaders repeatedly noted that, in engineering schools across the world, much of the benefit of these experiences often remains unexploited because they are unconnected with other curricular experiences; in consequence, students are not encouraged to reflect upon and apply what they have learned in other areas of their degree program. In the words of one interviewee: *"the learning is not contextualized and the student does not get the maximum benefit"* from the experience.

In contrast to the 'current leaders', many institutions identified as the 'emerging leaders' are distinguished by their integrated and unified educational approach. In most cases, their curricula were designed from a blank slate or were the result of a recent systemic reform. Experiences, such as work-based learning and societally-relevant design projects, are central to the program, and provide a platform for students to contextualize, reflect upon and apply the knowledge and skills they have gained elsewhere in the curriculum. However, many of these educational exemplars – such as at Olin College of Engineering and IRE – cater to relatively small cohort sizes. The key innovations that are likely to define the next chapter for engineering education are the mechanisms by which such features can be integrated at scale: to large student cohorts under constrained budgets. As one thought leader put it:

"the next phase in the evolution of engineering education is for the rest of us to figure out how we can offer this type of quality of education at scale."

The case studies considered in Phase 2 point to a number of institutions that offer such a model, where this curricular coherence and integration is delivered through a connective spine of design projects. Examples include the SUTD curriculum (summarized in Box 5) that is anchored in multidisciplinary design projects which contextualize and integrate learning across courses and years of study. A second example is the UCL Engineering curriculum (summarized in Box 6).

In the longer term, Phase 1 thought leaders suggested that an increasing number of the world's leading engineering programs would deliver student-centered learning to large student cohorts through a blend of off-campus personalized online learning and on-campus hands-on experiential learning.

Through such an approach, *“most of the [engineering] fundamentals will be learned online”* with *“a greater sharing of materials between universities”* to reduce costs. As Phase 1 thought leaders noted:

“this is the future of the field, where you put the student at the center and use the resources to facilitate team projects and authentic experiences, and then put the taught curriculum online”;

“these new players are going to change the landscape. With an online component and a unique model, they will be a disruptive force that will cause the whole landscape of engineering education to change. I didn't feel that way five years ago.”

Despite some doubts expressed about the capacity of the current generation of online tools to offer *“individualized pathways for each student,”* a number of institutions are already moving forward with engineering education models that blend off-campus online learning with on-campus active learning experiences, on the assumption that *“the technology will very quickly catch up with us.”* One notable example from the case study institutions is the new program at CSU Engineering in Australia, as outlined in Box 7 and explored further in Appendix D. Box 8 provides three further examples of top-rated universities that are currently preparing to develop online platforms to deliver engineering ‘content’ in conjunction with intensive on-campus challenges and projects to apply, embed and contextualize this learning.

Box 7. CSU Engineering, Australia

Launched in 2016, the new engineering undergraduate program at Charles Sturt University was described by thought leaders as *“completely rethinking what engineering education ought to look like,”* with the potential to be *“very influential, if they can pull it off.”* Amongst those that cited CSU Engineering as an ‘emerging leader’ in engineering education globally, almost all spoke about their particular interest in the potential transferability of its blended on-campus and online approach to their own institutions.

The five-and-a-half year-program combines an 18-month on-campus education, framed around a series of project-based challenges, with four years of off-campus, work-based learning. Almost all ‘technical engineering content’ – including both knowledge and skills – is delivered online and accessed by students as and when they need it. Fundamental engineering courses have been disaggregated into a set of online ‘topics’, offered in *“small bite-sized chunks rather than semester-long courses, giving people freedom in how they learn.”* In collaboration with a commercial company, CSU Engineering has created a bespoke online platform that provides students with a visual map of the relationships and dependencies between topics, and allows them to identify new topics they wish to target based on their own interests and/or specific problems encountered in their project-based *challenges* or work placements.

Box 8. Three engineering programs preparing to blend online and on-campus learning:

Iron Range Engineering (IRE), in the US, is an example of an engineering program that is adapting its existing curricula to embrace blended online and on-campus learning. IRE was highlighted as an 'emerging leader' in engineering education for its problem-based, hands-on approach, which was described as "*a truly innovative program and an amazing thing to watch.*" The second generation of IRE is currently under development and will launch in 2019. It will be designed as "*a low cost model which will cost less than tuition.*" Rather than bringing industry-sponsored projects to the students on-site, the new program will embed students in industry to work on dedicated authentic projects. A significant proportion of the learning and support will be supplied online. To be established as a four-year bachelor degree program, Iron Range Version 2 plans to admit 125 students per year in its steady state, a significant increase from its current intake of 25.

Aalborg University, in Denmark, was identified as a 'current leader' in engineering education. The university is investing over 9 million Danish Krone (Approx. US\$1.5m) over the next three years to develop "*new models of problem-based learning for the digital age*" with a view to implementing such approaches at the university. The model is likely to bring mixed method approaches to problem-based learning that will be supported by virtual projects, international linkages and online learning.

Monterrey Tech, in Mexico, which just fell short of the top 10 of the 'emerging leader' institutions, has recently developed the *Tec21*²⁴ curriculum that is structured around a series of design-based challenges. Each challenge is associated with a set of 'prior competencies', with the onus placed on the student to develop these competencies through self-directed research, engaging with the challenge user group and registering for modules linked to the challenge, many of which will be online.

This Section has identified three defining trends that are likely to play a critical role in shaping the future of engineering education: a tilting of the global axis of leadership in the field; a move towards socially-relevant and outward-facing curricula; and the emergence of university leaders that deliver an integrated and world-class curriculum at scale. While the study focused only on engineering education, these trends are likely to be evident across the university sector. Engineering education therefore has a pivotal role to play in addressing the major challenges facing universities in the 21st century. It has the opportunity to be the catalyst and standard bearer for excellence in higher education, and the incubator from which best practices will develop and spread.

²⁴ Tec21, Monterrey Institute of Technology (<http://modelotec21.itesm.mx/index.html>)

APPENDICES

APPENDIX A PHASE 1 BACKGROUND INFORMATION AND FEEDBACK

Appendix A provides background information from Phase 1 of the study. It is structured in five sections:

- A.1** The names and affiliations of the 50 thought leaders consulted during Phase 1
- A.2** The core interview questions used during Phase 1
- A.3** Phase 1 feedback on informal measures of educational quality and impact
- A.4** Feedback from thought leaders on the top-rated universities
- A.5** Data to characterize 12 of the top-rated universities

A.1. Thought leaders consulted during Phase 1

Listed below are the 50 thought leaders consulted during Phase 1 of the study. For each individual, the roles and institutional affiliations presented below are taken from the time of their interview for this study; interviews were held during September and October 2016.

Amon, Cristina	Dean of the Faculty of Applied Science & Engineering, University of Toronto, Canada
Andersson, Pernille	Senior Executive Educational Development Officer, LearningLab DTU, Technical University of Denmark, Denmark
Atman, Cynthia	Director, Center for Engineering Learning & Teaching and Professor, Human Centered Design & Engineering, University of Washington, US
Baillie, Caroline	Chair of Engineering Education, University of Western Australia, Australia
Besterfield-Sacre, Mary	Associate Professor and Director of the Engineering Education Research Center (EERC), University of Pittsburg, US
Bhattacharyya, Souvik	Vice-Chancellor and Senior Professor, Birla Institute of Technology & Science (BITS Pilani), India
Case, Jenni	Professor of Academic Development, Centre for Research in Engineering Education, University of Cape Town, South Africa
Cha, Jianzhong	Professor and UNESCO Chair on Cooperation between Higher Engineering Education and Industries, Department of Mechanical Engineering, Beijing Jiaotong University, China
Childs, Peter	Head of the Dyson School of Design Engineering, Imperial College London, UK
Chou, Shuo-Yan	Distinguished Professor of Industrial Management and Director of the Center for Internet of Things Innovation, National Taiwan University of Science and Technology, Taiwan
Clark, Robin	Associate Dean for Learning and Teaching, School of Engineering and Applied Science, Aston University, UK
Crawley, Edward	Professor of Aeronautics and Astronautics, MIT, US
Cukierman, Uriel	IFEES President and Professor, National Technological University, Argentina
de la Llera Martin, Juan Carlos	Dean, School of Engineering, Pontifical Catholic University of Chile, Chile
Edström, Kristina	Associate Professor in Engineering Education Development, The Royal Institute of Technology (KTH), Sweden
Felder, Richard	Hoechst Celanese Professor Emeritus of Chemical Engineering, North Carolina State University, US
Fortenberry, Norman	Executive Director, American Society for Engineering Education (ASEE), US
Froyd, Jeffrey	TEES Research Professor, Dwight Look College of Engineering, Texas A&M University, US
Garza, David	Academic Vice-President, Monterrey Institute of Technology and Higher Education, Mexico
Goodhew, Peter	Emeritus Professor of Engineering, School of Engineering, University of Liverpool, UK
Hadgraft, Roger	Director, Educational Innovation and Research, Associate Dean (Teaching & Learning), University of Technology Sydney, Australia
Hosoi, Anette	Associate Department Head and Professor of Mechanical Engineering, MIT, US
Jamieson, Leah	The John A. Edwardson Dean of Engineering, Purdue University, US

Kamp, Aldert	Director of Education, Aerospace Engineering, Delft University of Technology (TU Delft), Netherlands
King, Robin	Emeritus Professor, University of South Australia and Adjunct Professor, University of Technology Sydney, Australia
Kolmos, Anette	Professor in Engineering Education and PBL and Chairholder, UNESCO Chair in Problem Based Learning in Engineering Education, Aalborg University, Denmark
Koo, Benjamin	Associate Professor, Department of Industrial Engineering, Tsinghua University, China
Kozanitis, Anastassis	Professor at UQAM, University of Quebec in Montreal, Canada
Lindsay, Euan	Foundation Professor of Engineering, Charles Sturt University, Australia
Litzinger, Tom	Director, Leonhard Center for the Enhancement of Engineering Education, Penn State University, US
Magnanti, Thomas	President, Singapore University of Technology and Design (SUTD), Singapore
Malmqvist, Johan	Dean of Education, Chair Professor of Product Development, Chalmers University of Technology, Sweden
Miller, Rick	President, Olin College of Engineering, US
Mitchell, John	Vice-Dean (Education), Faculty of Engineering Sciences, University College London (UCL), UK
Mohd Yusof, Khairiyah	Professor and Director, Centre for Engineering Education, University of Technology Malaysia, Malaysia
Morell, Lueny	Principal of Lueny Morell & Associates and Director of InnovaHiED, Puerto Rico
Müller, Gerhard	Chair of Structural Mechanics, TUM Department of Civil, Geo and Environmental Engineering, Technical University of Munich, Germany
Natera, Angélica	Executive Director, Laspau, Harvard University, US
Puri, Ishwar	Dean of Engineering, Faculty of Engineering, McMaster University, Canada
Ramakrishna, Seeram	Professor and Director of Centre for NanoFibers & Nanotechnology, National University of Singapore, Singapore
Sheppard, Sheri	The Burton J. and Deedee McMurtry University Fellow in Undergraduate Education and Professor of Mechanical Engineering, Stanford University, US
Shettar, Ashok	Principal, B. V. Bhoomaraddi College of Engineering and Technology, India
Song, Sung Jin	Dean of College of Engineering and Director of Center for Innovative Engineering Education, Sungkyunkwan University, South Korea
Tadesse, Tareegn	President of Addis Ababa Science and Technology University, Ethiopia
Torero, José	Head of the School of Civil Engineering, University of Queensland, Australia
Ulseth, Ron	Director of Curriculum, Iron Range Engineering, US
Van der Veen, Jan	Chairman of 3TU Centre for Engineering Education and Associate Professor, University of Twente, Netherlands
Vedula, Krishna	Executive director, Indo Universal Collaboration for Engineering Education (IUCEE) Professor and Dean Emeritus, UMass Lowell, US
Vigild, Martin	Senior Vice President and Dean, Technical University of Denmark, Denmark
Yutronic, Jorge	Consultant on Science, Technology, Innovation and Higher Education, Chile

A.2. Phase 1 interview questions

Provided below are the core questions used to frame each interview during Phase 1 of the study. All interviewees were sent questions in advance of the consultation.

1. *Which 5–6 universities do you consider to be the current global leaders in engineering education, in terms of educational design, quality and influence? For each, what factors do you feel are most responsible for their success?*
2. *Which 5–6 universities would you consider to be emerging global leaders in engineering education, that have the potential to be at the cutting-edge of educational practice in the decades to come? For each, what impresses you most about their approach?*
3. *What criteria/metrics are you using to identify these global leaders?*
4. *How do you expect engineering education worldwide to change in the coming decade? What common features/themes do you expect to be evident among the world's leading engineering education programs in 2025?*
5. *What do you consider to be the major challenges or barriers that will constrain the progress of engineering education reform over the coming decade?*
6. *Which universities, from across the world, would you consider to have taken an effective approach to measuring the impact of their programs on student learning and/or measuring the impact of an educational reform?*
7. *Could you recommend any other individuals whom you feel should be consulted as part of this study?*

For around half of the interviews, additional questions were included in this list. As appropriate, these additional questions were designed to (i) explore the educational vision and approach at the interviewee's own institution; and/or (ii) discuss specific topics relating to the expertise of the interviewee (such as engineering design, online learning or the measurement of educational impact).

A.3. Informal indicators of quality in engineering education

During Phase 1 of the study, thought leaders were asked to identify the types of informal indicator they might use to determine the educational quality of institutions outside their own. Thought leaders consistently pointed to three broad types of indicator that they might use to evaluate educational quality:

- the quality and impact of the university's graduates;
- the 'delta' added to the students during their studies;
- the institution's capacity to deliver a world class education.

These three types of indicator are discussed in turn in the subsections that follow (and summarized in Box 3, Section 6). It should be noted, however, that the third of these indicators – a university's capacity to deliver a world-class education – was the one most consistently used by thought leaders to identify both 'current leaders' and 'emerging leaders' in engineering education.

A.3.1. The quality and impact of university graduates

The career trajectory and impact of graduates was regarded as an important indicator of the quality of an undergraduate program. Measures proposed included:

- *"their impact on the social and economic situation of their own country";*
- the extent to which graduates *"have the capabilities that industry needs now and in the future";*
- graduates' *"career prospects ten years out."*

Simplified versions of such metrics, including graduate employability and earnings, are often included in national university rankings, and were seen to enable external observers to distinguish the quality of peer institutions.

However, skepticism was expressed about the validity of such metrics for cross-institutional comparisons when seeking to identify the best programs worldwide. Skepticism stemmed from the influence of the quality of the student intake on graduate outcomes. Some thought leaders argued that the use of these 'output measures', both formally and informally, had secured a reputation of educational quality for many of the world's top-rated research universities – ones that receive an exceptional quality of student intake – that was not borne out in practice. As one interviewee observed:

"Is the graduate [from such institutions] coming out distinctive because of who the graduate was when they came into the institution, or is the graduate coming out distinctive because of the transformation that the institution helps them to achieve while they were there?... We don't know because we have no instruments to look seriously at that question."

Another simply commented, *"it is not clear if the 'elite' universities are playing a bigger role than just taking the cream from the top."* It was suggested that measures of 'output quality' may have been appropriate in an era where there was little differentiation – in the engineering education market – *"where the*

curriculum in most engineering schools was roughly the same" – and where there was limited visibility of educational practice and priorities at institutions beyond your own. However, interviewees noted that the engineering education landscape had changed dramatically in the past five years, with the emergence and increased visibility of cutting-edge education practice from outside of the top-ranked research universities. As one interviewee commented:

"The next generation of [leading universities in engineering education] won't be just the places that take the best students – and do whatever they like with them because, let's face it, they were always going to be good – they are also going to be the places that might be lower down in the research rankings, may not have exceptional students, but are really doing something quite special ... with the students they have. Those are the places that people want to find out about, because they are doing the real trick!"

In this context, interviewees noted their interest in institutions – such as Aalborg University in Denmark, CSU in Australia and Iron Range Engineering in the US – that were understood to be catering to *"a more typical type of engineering student."* For example, one interviewee explained that his selection of CSU as an 'emerging leader' was influenced by the fact that *"their entry cohort are not those deemed as having the greatest skills. If you are looking for intrinsic motivation when you are talking about MIT, it is straightforward, because people who go to MIT have those qualities already. But Charles Sturt are [seeking to develop] intrinsic motivation... in the people that walk through the door, people that don't necessarily have any at the start."*

A.3.2. The 'delta' of student learning provided by the university

Many interviewees suggested that *"the gold standard"* for measuring the quality and impact of engineering education programs was to capture the 'delta' or 'value added' to the students during the course of their studies. These views were informed by the wider debate on 'value added' measures in higher education.^{25,26,27}

However, it was widely acknowledged that *"we just don't have anything like the quality and breadth of data that we need to make any objective assessments of the 'delta' in engineering programs. This is the next big frontier for engineering education."* Another interviewee noted that 'value added' impact measures *"are the big missing link in higher education, because to do such a thing, you need a steady hand and you need to collect a base line and you need a continuity of the data collected. The question is, who is going to do such a thing in engineering education?"*

²⁵ McGrath, C. H., Guerin, B., Harte, E., Frearson, M., & Manville, C. (2015). Learning gain in higher education, RAND Corporation (http://www.rand.org/pubs/research_reports/RR996.html)

²⁶ AASCU. (Spring 2006). Value-added Assessment. *Perspectives*. Washington, DC: American Association of State Colleges and Universities. ([http://www.aascu.org/uploadedFiles/AASCU/Content/Root/PolicyAndAdvocacy/PolicyPublications/06_perspectives\(1\).pdf](http://www.aascu.org/uploadedFiles/AASCU/Content/Root/PolicyAndAdvocacy/PolicyPublications/06_perspectives(1).pdf))

²⁷ Nusche, D. (2008), *Assessment of Learning Outcomes in Higher Education: A Comparative Review of Selected Practices*, OECD Education Working Papers No. 15, OECD Publishing (http://www.oecd-ilibrary.org/education/assessment-of-learning-outcomes-in-higher-education_244257272573)

A.3.3. The institution's capacity to deliver a world-class education

The capacity of an institution to deliver a world-class education was identified by almost 90% of thought leaders as guiding their selection of 'current leaders' and 'emerging leaders'. As noted above, this was in part due to the absence of other reliable and robust data relating to educational quality.

Three dimensions of institutional capacity were given particular emphasis:

- the institutional leadership/commitment to education;
- the educational culture;
- the capacity of the institution to influence practice elsewhere.

These dimensions are discussed below. The subsections should be read alongside feedback relating to the educational approach of the 'current leaders' and 'emerging leaders' (see Section 9).

A.3.3.1. Institutional leadership in and commitment to education

Institutional commitment and leadership were identified as cornerstones of a university's capacity to provide a world-class education. Many interviewees reflected upon the institutional features that could be seen as indicators of an institutional commitment to education. These included:

- processes for supporting, informing and recognizing teaching excellence, such as the quality and pervasiveness of faculty training in education or the extent to which education is recognized in faculty career progression. Chalmers University of Technology, TU Delft and NUS were repeatedly noted for their strength in this regard;
- investment in learning spaces that support and progress student-centered pedagogical approaches. Examples repeatedly cited by interviewees included the investments in 'Engineering Practice Centres' in Tsinghua University (China) and the new flexible classroom spaces at DTU (Denmark).

Many interviewees also spoke at length about what was understood to be "*a direct connection between the vision and ambition of a small number of individuals*" in leadership positions and the capacity of the university to develop and maintain world-class engineering education. At a time of significant worldwide change in engineering education, such leadership was regarded as crucial. As one interviewee commented:

"I am getting encouraging messages from across the world – the idea that something needs to change [in engineering education] is taking hold. There is still a slight fear, but the prerequisite for change is becoming universal. But it takes a leader to do it – not many people are that brave and that charismatic."

As this implies, many also noted that a university's prominence as a world leader was often closely tied to the continued tenure of one or two change champions:

"institutions don't cause change, it is people ... for any institution, if two or three key people were to leave, the university might continue to do what it is doing, but they would not continue to move forward."

Indeed, the success of many of the 'current leaders' and 'emerging leaders' was repeatedly attributed to the caliber of specific leaders: examples included Stanford University, CSU, DTU, TU Delft, Chalmers University of Technology, PUC and UCL.

A.3.3.2. Educational culture

When identifying an institution as a 'current leader' or 'emerging leader', interviewees often spoke about the university's *"unique culture in teaching."* Three elements of this culture were repeatedly emphasized:

- **innovative and forward-thinking approach:** *"the willingness [of the school/university] to innovate and try new things."* Many noted that a pervasive culture of educational innovation was required at both faculty and institutional level: a faculty that are *"prepared to take risks in their teaching"* and a university management that *"are willing and able to change the rules and regulations accordingly."* Institutions repeatedly highlighted in this regard were Arizona State University, CSU, Olin College of Engineering, UCL, PUC and IRE.
- **faculty attitudes towards education:** the extent to which engineering faculty are *"informed, engaged and actively discussing teaching with colleagues."* A culture where a critical mass of faculty were *"enthusiastic and knowledgeable about engineering education"* was repeatedly identified at institutions such as Olin College, TU Delft and Chalmers University of Technology.
- **evidence-based approach:** the extent to which the undergraduate engineering program was *"built on educational scholarship, not just doing what they think seems like a good direction"* and driven forward by *"an evidence-based examination of what is working and what is not"* and by *"responding to valid critique."* Institutions such as Purdue University, Aalborg University and the University of Technology Malaysia were consistently singled out as taking an evidence-based approach to their educational provision and practice.

A.3.3.3. The capacity of the institution to influence practice elsewhere

The majority (78%) of interviewees cited the capacity to influence practice elsewhere as a key factor in their selection of 'current leaders' and 'emerging leaders'. Two elements were particularly highlighted:

- **the university's active interventions to inform, influence and improve educational practice at a regional and global level:** an institution's *"outward-looking culture and commitment to external engagement"* in engineering education was seen as a key marker of current and future leadership in the field. A number of institutions were repeatedly highlighted in this regard (see the box below).
- **the transferability of the institution's ideas and practices to other universities across the world:** an approach to engineering education that was *"scalable, transferable and a role model to other programs"* was regarded by some as an important foundation of international leadership.

While noting that *“there should always be a place [among the world’s leading institutions] for boutique programs, where you can incubate new ideas,”* many interviewees suggested that *“world class, to me, means that the university is responding to the issues that other engineering programs are faced with and they are doing something about it. This means that they are operating at scale, with a diverse student [cohort] and with a tight budget.”* Many interviewees concluded that a position as global leader in engineering education should favor institutions whose conditions – student profile, resourcing and cohort size – reflected the ‘norm’ worldwide, thus allowing their ideas and practices to be portable elsewhere. For this reason, many thought leaders were particularly interested in PUC, UCL, Arizona State University, Purdue University and Aalborg University.

Institutions engaged in activities to influence educational practice elsewhere:

- Tsinghua University for its emerging role in informing and supporting educational reform in engineering schools across China;
- Stanford University, Olin College of Engineering and MIT for formal and informal university partnerships and outreach activities that have influenced practice in engineering education across the world;
- Aalborg University and Purdue University for a quality of educational research in engineering that has informed and inspired reform elsewhere;
- Institutions such as NUS, NTU and PUC that have taken an *“open-minded and inclusive attitude towards international [university] partnerships”* to support the delivery of globally-focused student projects and opportunities.

A.4. Feedback on the top-rated institutions

Provided below is a summary of selected interviewee feedback on institutions most frequently cited as 'current leaders' or 'emerging leaders' in engineering education (see Section 4 and Section 5):

1. Olin College of Engineering (US)
2. MIT (US)
3. Stanford University (US)
4. Aalborg University (Denmark)
5. Purdue University (US)
6. National University of Singapore, NUS (Singapore)
7. Pontifical Catholic University of Chile, PUC (Chile)
8. Iron Range Engineering (US)
9. Tsinghua University (China)

While the summaries generally reflect the balance of views expressed by interviewees and focus on the feedback most commonly given, critical feedback has not been included. For newer institutions, or those that have recently implemented a program of educational reform, some contextual information is also included in the descriptions. Information on the four case study institutions included in this report – SUTD, UCL Engineering, CSU Engineering and TU Delft – is not given below. The case study reports for these four institutions are provided in the appendices that follow (Appendix B–E).

A.4.1. Olin College of Engineering (US)

Established in 1997, Olin College of Engineering²⁸ is a small private university focused on undergraduate engineering education. Its student-centered educational approach is underpinned by experiential learning, where students draw inspiration from across a wide disciplinary base to tackle design-based challenges. The themes of entrepreneurship, self-directed exploration and social responsibility are particularly evident in the educational approach. With no tenure or departments, Olin College has a very unconventional culture and resource-base. It is home to a very selective and small student cohort – annual student intake is 80, leading a number of interviewees to comment that *"Olin's reputation is disproportionate with its size."* Many noted that Olin College *"embodies everything I think we have learned in engineering education in the past 30 years."* In this context, a number of interviewees anticipated Olin College's *"evolution from a 'boutique institution' to an institution oriented to massively support the engineering reforms throughout the world."*

Olin College was identified as a 'current leader' in engineering education by more than half of interviewees (particularly those based in North America and Europe) and an 'emerging leader' by over a

²⁸ Olin College of Engineering (<http://www.olin.edu>)

quarter of interviewees (particularly those from Asia and South America). Seven individuals identified Olin College as both a 'current leader' and an 'emerging leader'.

A.4.2. MIT (US)

MIT²⁹ was widely reported to offer an *"outstanding engineering education that provides students with so many opportunities to build and integrate knowledge"* supported by *"a high exposure to cutting-edge research and researchers."* A number of interviewees suggested that *"the sheer quality of staff and students that MIT attracts means that it is a self-generating model, and one which ensures that MIT graduates are the best in the world."* In particular, many pointed to the *"array of experiences open to students to use technology in entrepreneurial ways."* MIT's influence on engineering education globally was also described by some to be *"unparalleled,"* which has been further strengthened by its leadership in the CDIO¹² initiative and edX.³⁰

A.4.3. Stanford University (US)

Stanford University³¹ was identified by 40% of interviewees (and over a third of non-US interviewees) to be a 'current leader' in engineering education. The focus on design and entrepreneurship was singled out as a prominent and highly-influential feature of its approach. In particular, many interviewees pointed to the increasing size of the engineering student population, which now represents 39% of undergraduates at the university. This expansion was attributed, by some, *"to the prominence of design and entrepreneurship across the campus. It has changed hearts and minds."* Interviewees consistently pointed to the *"playful, experimental quality"* of the engineering programs at Stanford University *"that fosters freedom for the students."* Many also suggested that the engineering programs benefitted from *"being embedded in a full-service, liberal arts university where students have experiences in humanities, learn foreign languages and can get involved in being activists."*

A.4.4. Aalborg University (Denmark)

From its establishment in 1974, the educational programs at Aalborg University³² adopted a purely Problem-Based Learning (PBL) approach. The university was described by interviewees across the world as *"a really mature [educational] model that is powerful and transformational. They should be on everyone's list of places to benchmark"* in engineering education. Many interviewees commented on Aalborg's effective use of *"real or realistic industry problems in their projects"* and their success in *"getting students into action mode rather than transmission mode."*

A key feature of the Aalborg approach that appeared to influence its identification by interviewees as a 'current leader' or 'emerging leader' was its evidence-informed educational approach and willingness to

²⁹ MIT (<http://web.mit.edu>)

³⁰ edX (<https://www.edx.org>)

³¹ Stanford University (<https://www.stanford.edu>)

³² Aalborg University (<http://www.en.aau.dk>)

collaborate with partners across the world. Many cited the quality of educational research from the *UNESCO Centre for Problem Based Learning*¹⁴ – either in PBL, educational change or in program evaluation – as a key pillar of the university's leadership and influence in engineering education.

A.4.5. Purdue University (US)

A number of factors appeared to support Purdue University's³³ identification as a 'current leader' in engineering education. Some cited the *"quality of the first year programs"* that are delivered by the School of Engineering Education, as well as the EPICS³⁴ program that was reported to have had significant influence on engineering undergraduate programs across the world. Other interviewees pointed to Purdue's leadership in *"figuring how you can do hands-on learning at scale."* For example, all of Purdue's 2000 engineering students *"will have had a substantial experiential experience in their four years – like internships, coops, extended service learning, undergraduate research or study abroad – of at least one semester or more."*

Across the engineering education community, however, it is probably the School of Engineering Education³⁵ with which Purdue University is most strongly associated. Many noted the quality of the scholarly research conducted by the School and the influence this has had on attitudes towards and practices in engineering education, both across Purdue University and the rest of the world.

A.4.6. National University of Singapore (Singapore)

The feature of the engineering undergraduate program at the National University of Singapore³⁶ (NUS) most commonly highlighted by interviewees was the *Innovation & Design-Centric Programme*.³⁷ Established in 2009, this invite-only program within the Faculty of Engineering provides hands-on opportunities for students to work on authentic, multidisciplinary design challenges and develop entrepreneurial, creative and leadership skills.

Other aspects of NUS's engineering undergraduate programs that were repeatedly highlighted by interviewees included their flexibility – *"there are a huge number of options and electives that students can take"* – and their *"commitment to offering their students a truly global experience... 70% of their undergraduates spend at least one semester at a university abroad."* Indeed, the openness of the university *"to engage in international collaborations"* was a topic repeatedly discussed by interviewees, as was the university's ability *"to get some of the best students and teaching staff from across the world."* The educational developments implemented across the engineering school at NUS over the past decade were described as a *"bold and impressive experiment,"* in an institutional environment that *"is deeply committed to supporting quality teaching."*

³³ Purdue University (<http://www.purdue.edu>)

³⁴ EPICS, Purdue University (<https://engineering.purdue.edu/EPICS>)

³⁵ School of Engineering Education, Purdue University (<https://engineering.purdue.edu/ENE>)

³⁶ National University of Singapore (<http://www.nus.edu.sg>)

³⁷ Innovation & Design-Centric Programme, NUS (<http://www.eng.nus.edu.sg/edic/dcp.html>)

A.4.7. Pontifical Catholic University of Chile (Chile)

The Pontifical Catholic University of Chile³⁸ (PUC) is one of South America's most highly-ranked research-led institutions. In 2011, the Engineering School at PUC launched a significant program of reform – *Clover 2030*¹⁵ – that cuts across all of its operating functions: research, education and technology transfer. This ongoing systemic reform has been accelerated over the past three years by a major government investment in selected Chilean engineering schools, *Engineering 2030*, aiming to drive national capacity in technology innovation and entrepreneurship. Interviewees noted, in particular, the "*pioneering vision of the school... [that is] poised to become a prominent engineering leader, regionally and internationally.*"

Moving away from a traditional Chilean engineering education model – that was largely teacher-centered and six years in duration – the educational pillar of the *Clover 2030* program seeks to establish a student-centered education that emphasizes multidisciplinary, user-centered design and social responsibility as well as student flexibility and choice. Interviewees also noted the curricular focus on "*building deeper relationships with industry and society*" both within and beyond Chile, which is reflected in many of the projects and experiences offered to students. Entrepreneurship and innovation are also prominent themes within and beyond the curriculum. One such experience is the *Research, Innovation and Entrepreneurship*³⁹ course. It challenges cross-disciplinary teams of students in their third year of study to develop technology-centered solutions to key challenges facing Chile in areas such as housing, waste and health inequalities. Students take a user-centered approach to tackling the challenge, and engage extensively with user groups, before designing and prototyping their solution. The school is also investing in a range of new multidisciplinary learning spaces and maker spaces as well as a department of engineering education to provide an evidence base for its curricular developments.

A.4.8. Iron Range Engineering (US)

Catering largely to the Community College student market, Iron Range Engineering⁴⁰ (IRE) is an upper-division program, comprising the final two years of a four-year engineering bachelor's degree. Although based on a Community College campus, IRE degrees are certificated by Minnesota State University, Mankato. The program first opened its doors to students in 2009 and its annual intake is currently fixed at 25. The two-year program is entirely structured around semester-long industry-sponsored projects using a PBL approach, with no traditional courses. At the start of each semester, students are expected to define their own learning goals and outcomes relating to each project as well as determine how these will be achieved. At the close of each project, students are asked to submit both a design report and a learning report. All exams are conducted orally, before a mixed panel. Self-directed learning is a critical element of IRE, which is supported by a significant focus on student self-reflection. Indeed, students are asked to document and submit around 150 structured self-reflections

³⁸ Pontifical Catholic University of Chile (PUC) (<http://www.uc.cl/en>)

³⁹ Research, Innovation and Entrepreneurship course, PUC (<http://www.ingenieria2030.org/outcome/research-innovation-course/>)

⁴⁰ Iron Range Engineering (<http://ire.nhed.edu>)

during the two-year program. With a strong program focus on *“supporting the unique trajectory of every student,”* the continuous process of self-reflection also helps to guide and inform student decision making in their choice of projects, competencies, specialisms and ways of working. Professional expectations are also strongly emphasized in the IRE program, with a dress code, a professional code of conduct relating to student and staff communication and a learning environment that *“emulates professional practice.”*

A number of interviewees commented that IRE was *“a truly innovative model, based on good scholarly work, that doesn’t get the press and the accolades that it deserves.”* As one interviewee commented, *“they are not starting with any cream-of-the-crop students. They take students that wouldn’t make it into outstanding engineering departments and they turn them into independent learners in two years. It is really very different.”*

A.4.9. Tsinghua University (China)

Many of the interviewees that identified Tsinghua University as a global ‘emerging leader’ in engineering education commented that *“I would not have given you Tsinghua’s name a few years ago – they have changed a lot in the past five years.”* It was noted that the university’s status as a global research powerhouse in engineering was *“starting to be balanced by their thinking about engineering education.”* In particular, it was reported that Tsinghua University has taken a national leadership position to drive educational reform in engineering schools across China, as part of the government-supported program to build *“the technology and innovation skills of the country.”* Such national leadership will be further reinforced by the recent establishment of the UNESCO Centre for Engineering Education⁴¹ that will be based at Tsinghua University.

Many interviewees, particularly those based within Asia, commented upon the bold and inclusive position that Tsinghua had taken in enabling educational reform: *“it is adventurous and it is new. Though it is a top-down change, if [faculty] come up with good ideas, they will try it. I am impressed with the kind of support that they are willing to put into different ways of teaching ... and it is very well supported by the Chinese government.”* Interviewees highlighted a number of aspects of this emerging strength in engineering education. Most notable was the investment in new buildings and maker spaces, reflecting an increasingly strong focus on technology-driven entrepreneurship and innovation across and beyond the curriculum. A number of interviewees also spoke about the *“explosion of extra-curricular activities at the university,”* which, for some, reflected a shift towards a more student-centered and experiential educational approach where *“some professors are allowing students to become more adventurous, helping them to be leaders, not just engineers.”* As one interviewee commented, *“what inspires me most about Tsinghua is the student groups – the Innovation Club, the Entrepreneurship Club, the Flying Club – students are moving so fast and they are calling the shots. It is strong and passionate... and it is changing.”*

⁴¹ International Center for Engineering Education (http://www.unesco.org/new/en/media-services/single-view/news/unveiling_of_international_centre_for_engineering_education/)

A.5. Data to characterize top-rated institutions

This Appendix section provides broad data on the top-rated engineering programs identified by thought leaders in Phase 1 of the study, as presented in Table 1.

The 12 universities considered are: Aalborg University, Charles Sturt University, Minnesota State University (Iron Range Engineering), MIT, National University of Singapore (NUS), Olin College of Engineering, Pontifical Catholic University of Chile, Purdue University, Stanford University, Singapore University of Technology and Design (SUTD), TU Delft and University College London (UCL).

For each institution, data was gathered for each of the following metrics:

- **the university name and country location;**
- **the unit under consideration:** whether the data relates to the engineering school/department or whether (in the case of specialist engineering and technology institutions) it relates to the entire institution;
- **duration of the undergraduate degree:** the number of years to completion of the undergraduate engineering degree (either to bachelor or combined bachelor/master, as indicated);
- **undergraduate student intake:** the number of students in the incoming (typically first year) engineering cohort. As the top-rated programs vary in duration from two to five-and-a-half years, it was decided that the student population in a single year group would offer more insight to the program size than the total undergraduate population. Given that a number of the programs highlighted are either newly established or have experienced recent increases in student numbers, the incoming student cohort (or the first cohort to declare an engineering major) was selected as the most appropriate sample year-group to include;
- **the number of faculty:** the total number of tenure and tenure track faculty (professor, associate professor and assistant professor) or equivalent in engineering;
- **data source:** sources of the data presented. Most data have been gathered from publicly available sources, for which web hyperlinks are provided. Where not available in the public domain, data was requested directly from the universities concerned.

National and institutional difference in data collection procedures and disciplinary boundaries encompassed by the term 'engineering' mean that the data are unlikely to be strictly comparable. With that caveat, the table presents a broad overview of the profiles and scale of the 12 top-rated universities.

Unless otherwise stated, all data relate to the 2016/17 academic year.

University name	Country	Unit under consideration	Duration of undergraduate degree	Undergraduate student intake	Number of faculty	Data source
Aalborg University	Denmark	Faculty of Engineering and Science	3 years (to BSc)	1945	713	Data source: correspondence with institution
Charles Sturt University	Australia	CSU Engineering	5.5 years (to MEng)	28	7	Data source: correspondence with institution
Minnesota State University	US	Iron Range Engineering	2 years (final 2 years of BSE)	25	4	Data source: correspondence with institution
MIT	US	School of Engineering	4 years (BSc)	839	379	Data source: ASEE College Profiles: MIT - 2016
NUS	Singapore	NUS Engineering	4 years (to BEng)	1400	291	Data sources: NUS Engineering Annual Report 2016 and Summary of undergraduate student enrolment , NUS Registrar's Office
Olin College of Engineering	US	<i>Full institution</i>	4 years (to BSc)	80	45	Data source: correspondence with institution
Pontifical Catholic University of Chile	Chile	UC Engineering	5.5 years (to BSc)	761	181	Data source: correspondence with institution
Purdue University	US	College of Engineering	4 years (to BS)	2706	452	Data source: Purdue University, College of Engineering, Facts and Figures
Stanford University	US	School of Engineering	4 years (to BS)	947	249	Data source: ASEE College Profiles: Stanford University - 2016
SUTD	Singapore	<i>Full institution</i>	3.5 year (to BEng)	439	110	Data source: correspondence with institution
TU Delft	Netherlands	<i>Full institution</i>	3 years (to BSc)	3749	930	Data source: TU Delft Facts and Figures (data from 2015/16)
UCL	UK	UCL Engineering	4 years (to joint MEng) (3 years to BEng)	959	302	Data source for faculty numbers: correspondence with institution. Source for student data: UCL student statistics

Table 1. Comparative information to characterize the institutional profile and scale of 12 top-rated engineering programs. All data refers to the 2016/17 academic year unless otherwise stated

APPENDIX B CASE STUDY – SINGAPORE UNIVERSITY OF TECHNOLOGY AND DESIGN (SUTD), SINGAPORE

Reasons for selection of SUTD as a case study

Singapore University of Technology and Design (SUTD) was identified as the foremost 'emerging leader' in engineering education by the thought leaders consulted during Phase 1 of the study.

SUTD is a research-intensive university, established in 2009 in collaboration with MIT and Zhejiang University. Its educational approach and structure are distinctive in a number of respects. For example, with no departments or schools, SUTD offers a multidisciplinary education that helps students to connect and integrate their learning between both courses and years of study. Building upon a rigorous grounding in the fundamental engineering sciences, the curriculum is immersed in design-centered active learning which is supported by state of the art maker spaces. SUTD also offers a breadth of experience not traditionally associated with engineering undergraduate study, including research opportunities, industry internships, undergraduate teaching opportunities and courses in humanities and social sciences.

As MIT's only major university partner in the undergraduate space, SUTD was seen by some thought leaders as providing a window into how the undergraduate programs at MIT might evolve in the future. This feature appears to have further supported SUTD's global profile and recognition.

B.1. Context

B.1.1. The university context

Singapore University of Technology and Design (SUTD) was established in 2009, in collaboration with MIT and Zhejiang University. It is a research-intensive university with a mission⁴² to: “... *advance knowledge and nurture technically-grounded leaders and innovators to serve societal needs, with a focus on Design, through an integrated multidisciplinary curriculum and multidisciplinary research.*”

Broadly focused on engineering and architecture, the university is not structured around traditional disciplinary departments. Instead, both its research and educational activities are integrated within a multidisciplinary institutional structure. While already attracting an annual research income of SIN\$50m, SUTD does not yet feature in the global university rankings; a greater number of student cohorts must graduate before it is eligible for inclusion. To date, three cohorts of SUTD students have graduated from its eight-term bachelor program. Tuition fees – which for home students are currently SIN\$5700 per term – are heavily subsidized by government support.

Five years since welcoming its first cohort of undergraduates, in 2012, the student and faculty populations at SUTD are still growing. As illustrated in Figure 9, the undergraduate intake in the university’s first year of operation was 344, and it had risen to 439 by the 2017 academic year. The university’s target for its undergraduate student intake is 1000; on-campus accommodation is currently available for 600 of this cohort. Female participation is relatively high for a technology-focused university: women represent 40% of the undergraduate population overall and 30% of those based in engineering-focused disciplines.

The university is currently home to 143 faculty, of which 110 are on a tenure track and 33 are in teaching-focused positions. SUTD faculty are a highly international group, with around a third (30%) originated from Singapore, 25% from the rest of Asia, and 40% from Europe and the US. Over the coming years, faculty numbers will be increased in line with the growth of the student population.

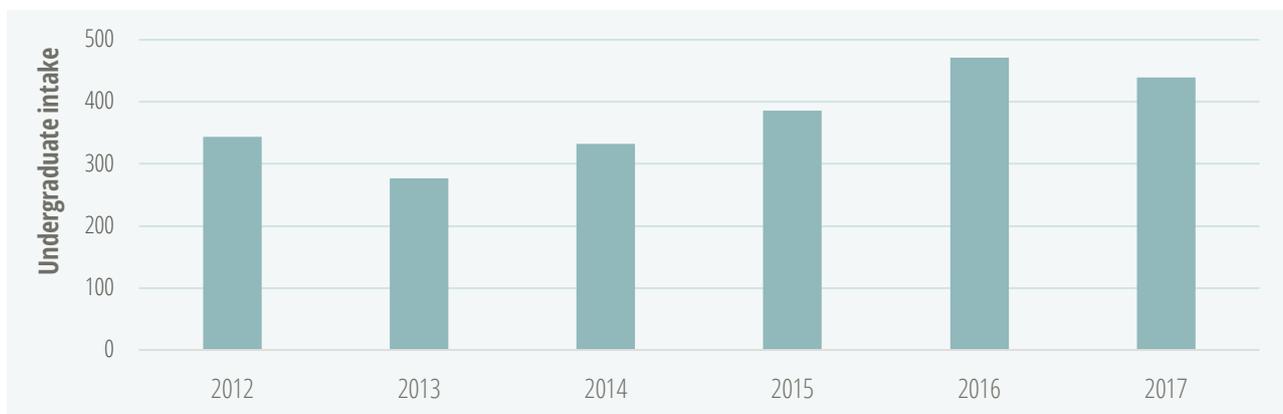


Figure 9. Annual undergraduate intake at SUTD (2012–2017)

⁴² Singapore University of Technology and Design (SUTD) (<http://www.sutd.edu.sg>)

B.1.2. The national context

Singapore was established as a republic in 1965. With an average annual GDP growth of 7.7%,⁴³ the last 50 years have seen the island nation transition from a developing economy to a leading global hub for finance, manufacturing and education. Today, Singapore is characterized by low unemployment, low crime rates, and the ethnic diversity of its population. Indeed, it is now identified as the world's second most competitive economy, behind only Switzerland.⁴⁴ Singapore is also the third most densely populated country in the world: its population of 5.5 million resides in an area less than half the size of Rhode Island. With limited natural resources, the government has invested heavily in its human resources to drive economic growth, most notably through education.

These investments have yielded impressive results: Singapore is globally recognized for its educational performance, both at primary and secondary levels. For example, in the most recent *Trends in International Mathematics and Science Study* (TIMSS),⁴⁵ Singapore students topped the world rankings in both mathematics and physics at primary and secondary level.

As with the primary and secondary education sectors, the Singapore government has invested strategically in higher education. Indeed, the government has committed SIN\$19.2b in research funding between 2016–2020⁴⁶ to support the national research and innovation infrastructure, extending across and beyond the country's six autonomous universities.⁴⁷ The past decade has also seen the country's most established universities – NUS and NTU – rise rapidly up the global university rankings, which are now placed in 15th and 11th position respectively.¹⁰

Against this backdrop of government investment and world-class educational performance, interviewees also pointed to a number of challenges facing Singapore's higher education sector. Two in particular stand out. Firstly, it was suggested that the deeply-embedded societal emphasis on educational performance has led to an extrinsically-motivated culture of "*chasing the paper grade*" among Singapore's school-aged children, as well as "*high levels of competition and stress*" among students entering higher education. Secondly, interviewees highlighted the issue of Singapore's low birth-rates,⁴⁸ which has significantly reduced the pool of prospective undergraduates in the city state: between 2012 and 2017 alone, the population of young people graduating high school fell by 21%.

⁴³ The World Bank in Singapore (<http://www.worldbank.org/en/country/singapore>)

⁴⁴ World Competitiveness Report 2016-17: World Economic Forum (<https://www.weforum.org/reports/the-global-competitiveness-report-2016-2017-1>)

⁴⁵ Trends in International Mathematics and Science Study (<http://www.iea.nl/timss>)

⁴⁶ Research, Innovation and Enterprise 2020 Plan (<https://www.nrf.gov.sg/rie2020>)

⁴⁷ Singapore's six autonomous universities are National University of Singapore (NUS), Nanyang Technological University (NTU), Singapore Management University (SMU), Singapore University of Technology and Design (SUTD), Singapore Institute of Technology (SIT) and Singapore University of Social Sciences (SUSS)

⁴⁸ Singapore has the world's lowest fertility rate at 0.82 children born per women. Source: Central Intelligence Agency World Fact Book (<https://www.cia.gov/library/publications/the-world-factbook/rankorder/2127rank.html>)

B.2. The development of the SUTD education

The development of the SUTD education can be structured around three broad time periods:

- the vision for a new university in Singapore (2007–2010);
- co-designing SUTD's undergraduate education (2010–2012);
- launching and advancing the SUTD education (2012–present).

The timeline is informed by interviews with 37 stakeholders and focus group discussions with 22 stakeholders consulted for the case study. It reflects a development process forged through collaboration between the Singapore government, MIT and the newly-appointed team at SUTD.

B.2.1. The vision for a new university in Singapore (2007–2010)

In August 2007, Singapore's Prime Minister outlined government plans to increase national participation rates in publicly-funded higher education from 25% to 30%. At the time, Singapore was home to only three publicly-funded universities: NUS, NTU and SMU.⁴⁷ The government's vision called for an increase in the capacity and diversity of Singapore's higher education landscape through establishing a fourth university in the country. This new institution was to be an engine for national economic growth, fostering talent and applied research in three critical sectors: (i) engineering and applied sciences; (ii) business and information technology; and (iii) architecture and design. With an emphasis on interdisciplinary, hands-on learning and a strong connectivity with industry, it would also offer "*a new future-oriented [educational] approach*" designed to nurture technology-driven entrepreneurs and inspire new generations to follow careers in science and engineering.

In August 2008, the Singapore government issued a call for collaborators from the global higher education community to establish the new university. MIT registered an interest, which built upon its long history of partnership with Singapore through initiatives such as the *Singapore-MIT Alliance (SMA)*⁴⁹ and later the *Singapore-MIT Alliance for Research and Technology*⁵⁰ (SMART). MIT's interest was also driven by:

"a core group of faculty that were passionate about new modes of teaching in engineering... [who] saw the collaboration as a way to put these ideas into practice using a green field, a 'fresh start' curriculum."

During the 18 months that followed, a *Faculty Advisory Group* from MIT developed and submitted a series of proposals that delineated the distinctive features of the new university and articulated the role MIT might play in its establishment, if selected as a partner. MIT put forward a vision for a small interdisciplinary university, with an intake of 1000 undergraduates per year and no traditional

⁴⁹ SMA (<http://web.mit.edu/sma/>)

⁵⁰ SMART (<https://smart.mit.edu>)

disciplinary departments. The proposal also placed design at the heart of the new university. As one member of the *Faculty Advisory Group* explained:

“If you look at wealth creation – what are US companies doing that have the greatest market capitalization, like Apple – is it almost certainly due to a certain approach to design ... We live in an innovation economy and innovation happens through design.”

Inspired, in part, by its experience with *TEAL*,⁵¹ MIT’s vision for the new university incorporated a design-centered curriculum that was underpinned by active learning in small cohort groups. The design focus would also be reflected in the name of the new university, the “Singapore University of Technology and Design” (SUTD), carrying the motto, “a better world by design.”

In October 2009, a key player in the development of the MIT proposal was appointed as President of SUTD. A former Dean of Engineering at MIT, he had also spent much of the past decade in Singapore in roles that included the founding director of SMART.⁵⁰ Many interviewees noted that, in consequence, he brought a deep understanding of the Singaporean culture, research portfolio and economy, and was “*well known and well respected by government, business and university leaders*” across the country.

In January 2010, the President of MIT and the newly-appointed President of SUTD signed a collaboration agreement for the foundation of the new university. The education and research components of the agreement were to run to 2017 and 2020, respectively; its major features are outlined in Box 9. Soon after, a second collaboration agreement was signed with Zhejiang University in China: this partnership would offer SUTD a significant student exchange program and several elective courses that would allow “*students to explore the Chinese culture and economy.*”

Box 9. Support provided to SUTD by MIT through the MIT–SUTD collaboration:

- **institution-building:** including support for (i) the development of SUTD’s institutional policies; (ii) the hiring of early faculty and academic leaders; (iii) the marketing of the institution; and (iv) recruitment of early cohorts of undergraduate and graduate students;
- **research collaboration:** including a major program of collaborative research and the establishment of a design-focused research center co-located between SUTD and MIT;
- **curriculum development:** including (i) secondments of senior MIT faculty to SUTD to co-design the curriculum; and (ii) the development and review of 93 SUTD courses (over 90% of the undergraduate curriculum) by specialist MIT faculty in the relevant fields;
- **faculty development:** providing SUTD faculty with a range of opportunities including (i) participation in *Teach the Teacher* program involving up to a year’s residency at MIT; (ii) 2-4 week co-teaching residencies at MIT; and (iii) one-to-one mentorship by MIT faculty;
- **dedicated programs to nurture students’ leadership and innovation skills:** including (i) the 10-week *Global Leadership Program* for SUTD and MIT undergraduates, involving 155 participants, between 2013 and 2017; and (ii) the 3-week *SUTD Winter Abroad Program* for SUTD undergraduates, involving 156 participants, between 2015 and 2017.

⁵¹ Technology Enabled Active Learning (<http://web.mit.edu/edtech/casestudies/teal.html>)

B.2.2. Co-designing SUTD's undergraduate education (2010–2012)

When the MIT-SUTD collaboration launched in January 2010, SUTD was reported to be “*more concept than reality.*” The concept was founded on the government’s vision for Singapore’s new university and articulated in a set of principles developed by MIT, outlined in Box 10. These principles included multidisciplinary, as represented by four pillars: Architecture and Sustainable Design (ASD), Engineering Product Development (EPD), Engineering Systems and Design (ESD) and Information Systems Technology and Design (ISTD).

As the fledgling university had no campus and just a handful of employees, the early phases of SUTD’s curricula development were primarily driven by the MIT side of the partnership. A team of senior MIT faculty drove the design of SUTD’s common first year and pillar specialisms, while MIT faculty with expertise in specific domains were engaged to develop individual courses. As SUTD’s capacity grew, however – through the appointment of academic leaders, faculty and student pioneers – so too did its influence over the university’s evolving curriculum and pedagogy.

Following the appointment of the university President, the Singapore government made three further appointments during the turn of 2010 that would prove critical to establishing SUTD’s distinctive educational approach and culture: the university’s Provost, Vice-Provost for Education and Chairman of

Box 10. The broad principles around which SUTD would be built:

- 1. World-class:** Attracting the best faculty and student talent regionally and globally, SUTD would be world-class and research intensive while also delivering a cutting-edge student-centered education;
- 2. Multidisciplinary:** Instead of single-discipline departments, SUTD would be structured around four multidisciplinary pillars that are “*organized around what the world fundamentally consumes: products [architectural and engineering], services and systems.*” SUTD’s four pillars are: Architecture and Sustainable Design, Engineering Product Development, Engineering Systems and Design and Information Systems Technology and Design;
- 3. A blend of ‘East’ and West’:** SUTD would provide a learning environment that offers students immersive experiences in and perspectives from both Eastern and Western cultures;
- 4. Small and student-centered:** SUTD would be small – similar in undergraduate size to MIT – with a low staff-to-student ratio and a pedagogical approach that emphasized self-directed and small group learning;
- 5. Design-centered:** Technically-based design would be infused into all aspects of the university’s activities, with an emphasis on the use of design and technology to drive positive societal change;
- 6. Fostering leadership and innovation:** Using what was termed an ‘outside in’ approach, SUTD’s educational and research priorities would be shaped by the needs of industry and society, with a focus on nurturing a new generation of technology leaders and entrepreneurs;
- 7. A broad-based education:** In contrast to its Singaporean peers, SUTD’s curriculum would offer a common first year and would expose students to experiences beyond the scope of traditional engineering programs, including industry internships and courses in humanities and social sciences.

the Board of Trustees. Each was reported to bring a deep *“understanding of the Singapore culture and [a] sensitivity to the local environment.”* Many interviewees, internal and external to the university, noted that, together with the university’s President, these three appointees *“understood what the government was trying to achieve”* with the establishment of SUTD. Following these appointments, the government was reported to have given the MIT–SUTD collaboration significant autonomy and to have entrusted this group of university leaders *“to shepherd the project.... [and] make all of the decisions on how the university would take shape.”*

An early priority for SUTD was *“appointing a cadre of faculty and pillar heads so that they could have curriculum development from both the SUTD-side and MIT-side.”* The first cohort of faculty appointees joined the university shortly after it took residence in a temporary campus in West Singapore in March 2010. Many of the new recruits were high-potential early-career faculty that came to SUTD direct from post-doc positions in high calibre universities, both regionally and globally. Although few had experience or training in student-centered learning, they were reported to be *“exceptional young researchers”* who brought *“an open-mindedness and commitment to the [educational] vision at SUTD... they were not tied to the old ways of doing things.”* On joining SUTD, many faculty took residencies at MIT and engaged in professional development in student-centered, active learning both in Singapore and at MIT. At this time, the SUTD President also approached some of the world’s leading thinkers and practitioners in design. The result was a set of high caliber appointments to the university, both as pillar leaders and as leaders of the new *International Design Centre*,⁵² co-located between SUTD and MIT.

Alongside building its faculty and academic leadership, SUTD also admitted an early cohort of 30 students to help build the university’s profile, campus and curriculum, as well as shape its culture. This cohort, working in partnership with counterparts at MIT, quickly established a student culture of *“risk-taking, creativity and innovation.”* This spirit was most evident in the array of innovative, student-led extra-curricular activities that were soon established by this *“small group of student pioneers.”* Indeed, *“setting the culture, the tone of the university from the first day”* for staff, faculty and students was a strategic priority of SUTD’s academic leadership; in the words of one, *“we wanted to create a ‘we are all in it together’ culture, an informal atmosphere.”* This was an ethos that ran counter to traditional Singapore culture, described as *“very managed, very hierarchical.”* It was to be a culture that embraced and celebrated innovation, including in the curriculum.

Interviewees engaged in this period of SUTD’s development consistently noted that its pioneering ethos, supported by the collaborative MIT–SUTD partnership, enabled new and *“incredibly exciting”* advances to be made to the evolving SUTD curriculum: *“it was like a startup, we had a great idea and we just did it!”* For example, SUTD’s final year capstone projects were originally pillar-specific. As new ideas emerged, the team expanded the scope of the capstone projects to

⁵² SUTD-MIT International Design Centre (<https://idc.sutd.edu.sg>)

make them truly multidisciplinary, bringing together final year students from across the university's four pillars.

By the fall of 2011, the team began to think more strategically about the question, *"what does it mean to be a design university?"* in the context of the draft SUTD curriculum. In particular, concerns were raised that *"the courses [under development] were too content-centric. There was very little active learning, very little design in the curriculum."* In the months that followed, SUTD's Provost for Education and the newly appointed Head of the EPD pillar started to develop a new pedagogical model, called the '4D' approach, that would enable student-centered design experiences to be embedded across and beyond the SUTD curriculum. As described further in Box 11 (page 76), a crucial element of the 4D approach was the application of design experiences to both explore concepts within courses and also connect learning between different courses and years of study.

By early 2012, six months ahead of the launch of the undergraduate programs, 4D design experiences were being integrated throughout the SUTD curriculum. For example, immersive, integrative projects were designed for each term of Year 1 of the program. The first such project – a week-long experience midway through Term 1 – was designed to connect students' learning from courses in advanced mathematics, physics, chemistry, and humanities. The project would call upon student teams to *"design a device, a [chemically-powered] potato cannon, that could deliver food to a medieval castle that was under siege."* A number of SUTD-based interviewees pointed to *"the uncommon interactions"* formed between the diverse faculty teaching teams established for such projects, that, in turn, helped to foster new inter-disciplinary spheres of research for the university. In the words of one SUTD academic leader:

"One of the most exciting parts of SUTD is the connections between research and teaching that would not have been possible in a traditional university. The way the teaching team comes together. So a robotocist and a biologist teach [the first year course] 'Introduction to Design', and now they have a research project together [developing an] autonomous robot to find mosquito nests to destroy them."

B.2.3. Launching and advancing the SUTD education (2012–date)

In May 2012, SUTD welcomed the first cohort of students to its undergraduate program. Many interviewees pointed to the distinctive and *"quirky"* character of the student cohort. As one observer from outside SUTD commented:

"SUTD attracted a very particular type of student, not the typical Singapore student. They were dynamic, entrepreneurial – willing to take a risk on coming to a university that didn't even exist yet – a little bit geeky, full of ideas."

Student interviewees among this inaugural group pointed to both *"the MIT connection"* and SUTD's educational approach – framed around problem-based and small group learning – as motivating their choice of university. In the words of one, *"it offered something different to the other [Singaporean] universities, it is problem-based, collaborative, a place you can make things happen."*

SUTD's launch year was a challenging period for the university's faculty and academic leaders. As well as driving forward new research groups and the IDC,⁵² the university was also rolling out a unique design-centered, hands-on undergraduate curriculum that remained untested at this scale.

The first major test of the SUTD curriculum came in August 2012, with the rollout of the flagship Year 1 course, *Introduction to Design*. Interviewees from across SUTD pointed to the foundational importance of this course for introducing students to the principles of design as well as nurturing a culture of collaborative and active learning among the cohort. However, as one faculty member noted, *"in this first run [of the course], we had a lot of problems ... students were telling us 'we cannot cope with this thing'... instead of spending 12 hours per week on this course, they were spending much more."* Interview feedback suggested that the problems centered on two challenges. The first related to course management, where students were confronted with a *"confusing mix"* of definitions of 'design' and of teaching styles. As a result, students were unclear about course expectations and deliverables. The second challenge was the difficulty students faced in adjusting to a self-directed and exploratory learning style and in tackling the open-ended problems posed. As one course leader explained:

"Students in Singapore come from a very controlled environment in Junior College that is a bit top-down. They do the test and know exactly what they need to do to get an A ... [In this course] the set of instructions is minimal and they hated the uncertainty. There is no right or wrong answer... They were writing 100-page reports when they were only asked for 20. They didn't know how to manage their time."

In response, SUTD faculty and academic leaders called a *"town hall meeting"* with students to address the problems faced. As a result, a number of new measures were introduced to the *Introduction to Design* course. These included: (i) establishing a coordinated and consistent definition of 'design'; (ii) articulating a clear set of course expectations and deliverables; (iii) creating new classes in 'time management'; and (iv) the appointment of senior-level SUTD students as teaching assistants to provide support and advice in *Introduction to Design* as well as other first-year courses. Interviewees suggested that, by the third iteration of the course in 2014, many of the initial problems had been resolved. The move to SUTD's permanent university campus in the Changi region of Singapore in January 2015 also supported students' transition to a self-directed and active learning approach; among other facilities, the new campus provided dedicated classrooms for first year and capstone cohorts and the IDC, a 5000m² facility that includes open-access prototyping facilities. At the same time, the SUTD program was awarded provisional professional accreditation. With the university's curriculum and pedagogies *"pushing at the boundaries"* of innovative engineering education, this award represented a major milestone for SUTD, which was credited to the powerful educational vision articulated by the MIT-SUTD partnership.

In the months and years that followed, the collaborative culture of educational experimentation and innovation at SUTD continued to support a process of curricular development and renewal. A number of these developments were undertaken as collaborations between faculty, academic leaders and students from both SUTD and MIT. For example, the 2D 'potato cannon' project originally set during Term 1 of the curriculum had been replaced with a project framed around a fuel cell vehicle. However, concerns were expressed by both faculty and students that *"the fuel cell car was too slow – it was not*

exciting for the students – and the project was not using the content from all of the courses in the way we liked.” In consequence, the faculty teaching team invited second- and third-year SUTD students to redesign the project. In collaboration with faculty leaders from MIT, a completely new project was developed – framed around a sugar-propulsion rocket – which offered students a clearer connection to the linked Term 1 courses.

The formal educational partnership between MIT and SUTD ended in 2017. Interviewees from both MIT and SUTD made clear, however, that informal educational connections will continue between the two institutions. Interviewees attributed this commitment to a continuing collaboration and to sharing *“ideas and experiences in the classroom”* to the mutual benefits the partnership offered both universities. Indeed, a number of MIT-based interviewees pointed to their experience with SUTD as a major inspiration for change to their own courses and curricula. For example, the recent educational reforms in MIT’s Department of Nuclear Science & Engineering were described to be

“directly influenced by SUTD. The Freshman design course and in the capstone... [were] based on the SUTD design principles.”

The end of the educational partnership with MIT heralds a new phase for SUTD, one where its brand and profile must flourish independently. The university is putting in place new in-house mechanisms to support ongoing educational development, such as the SUTD *Learning Sciences Lab*,⁵³ which opened its doors in July 2016. The university’s evolving curriculum and pedagogy will also be propelled by its growing expertise and evidence base in educational research, and is being driven forward by a core group of SUTD academic leaders and faculty. Some among this group are exploring the experience of creating SUTD’s distinctive curriculum from the ground up. Others are responding to some of the challenges and opportunities associated with delivering a design-centric project-based education, addressing questions such as:

- *to what extent does SUTD’s integrative curriculum equip students to identify and apply concepts learned in previous courses to new problems or topics?*
- *how can SUTD assess individual contributions to group project work in an equitable way?*
- *how can SUTD ensure that contributions to group projects are spread evenly across its members, with no student relying on the efforts of others?*

A group of SUTD faculty recently submitted a SIN\$1m research proposal to the Singapore government to address these questions with a view to incorporating the lessons learned into the university’s educational design.

⁵³ Learning Sciences Lab, SUTD (<https://sutd.edu.sg/learningsciences>)

B.3. SUTD's educational approach

Interviewees were asked to identify the distinguishing features that set SUTD apart from its national and global peers. Noting *"the foundations of the curriculum that came from MIT"* and *"the rigor and academic standards"* that this implies, four features were consistently highlighted:

- **design- and maker-based learning:** the SUTD pedagogy is underpinned by design-based active learning. Throughout all years of study, students engage in multiple design projects and experiences on a range of scales, durations and areas of focus. Some are located within single classes or courses, while others span multiple courses and years of study. This distinct multi-layered approach to design-centered education – termed '4D' – is described further in Box 11. Very few of SUTD's classes are lecture-based, and many, particularly in Year 1 of study, adopt an experiential and/or 'flipped classroom' approach. Hands-on learning is also a major feature of the SUTD curriculum. With largely unrestricted access to state of the art workshop and 'fab lab' facilities, many projects, courses and non-curricular activities call upon students to develop and refine physical prototypes of their design ideas.
- **a collaborative culture:** faculty and student interviewees alike pointed to *"a flat hierarchy"* and *"a 'start-up' atmosphere"* at SUTD: *"the culture here is just so open, you can talk to anyone, no matter who they are."* This *"camaraderie and community spirit"* among the student population is supported by SUTD's extensive use of small group learning. Throughout the first year (three terms) of study, students work exclusively within cohort groups of 50, with whom they interact in all curricular classes and projects within a dedicated classroom: indeed, class size rarely exceeds 50 in all years of study.
- **a multidisciplinary approach:** SUTD is not structured around *"traditional engineering siloes"* and does not offer conventional engineering disciplinary degrees. Instead, students study a common first year and then specialize within one of four multidisciplinary pillars – such as Engineering Systems & Design – for the remainder of their studies. Each pillar brings together faculty from across and beyond engineering disciplines:

"our students don't think of themselves as a mechanical engineer or a civil engineer. Real problems sit across these [disciplinary] boundaries... they tackle the whole problem."

- **a breadth of student experience:** the SUTD curriculum offers a breadth of education not traditionally associated with engineering undergraduate study. For example, over a fifth (22%) of the curriculum is dedicated to humanities and social sciences (HASS). Non-curricular experiences are also emphasized, with two afternoons per week and one month at the beginning of the year dedicated to student-led activities, which may include teaching opportunities, student-led clubs and research projects. In addition, by their graduation, all SUTD students must have completed at least one 16-week industry internship, and are encouraged to spend time abroad on study exchanges or organized summer programs.

Box 11: The '4D' educational approach at SUTD

Design projects are a familiar feature of engineering curricula worldwide. Most, however, follow a similar structure, often in the form of a single, semester-long capstone-style project designed to consolidate learning from across the undergraduate program. SUTD takes a very different approach. Open-ended design activities and projects are integrated throughout the curriculum to help students explore, integrate and reinforce their ongoing learning. Many take a hands-on approach, asking students to deliver a working prototype. The scale and focus of these design experiences vary enormously: at the smallest scale, short, in-class design exercises allow students to apply and contextualize new ideas or concepts as they are being taught; at the largest scale, immersive project experiences spanning multiple years of study are used to consolidate and reinforce learning across a range of topics. SUTD has coined the term '4D' to describe this distinctive, multi-layered approach to design-centered learning.

The four layers of the '4D' approach are outlined below:

- **1D design activities, within a single course:** 1D activities apply and explore concepts learned within a specific course. Some 1D experiences may be short, discrete exercises, confined to a single class. For example, in the Year 1 *Physics II* course, students spend one afternoon designing and constructing speakers from a paper plate using the principles of electromagnetism. Other 1D exercises may be more immersive and span a full semester. For example, the *Data and Business Analytics* course in the ESD pillar embeds a semester-long 1D project where students work in teams to tackle real problems posed by industry partners.
- **2D design activities, spanning multiple courses:** 2D projects integrate and apply concepts from across two or more courses that are studied concurrently. The project themes often draw together a diverse range of subject areas; for example, the 2D project in Term 3 of Year 1 focuses on growing algae for biofuels, and draws together learning from the courses in biology, chemistry, technical systems, optimization and programming. In some cases, all relevant courses are suspended for one week so that students can engage full-time on their 2D project. In other cases, 2D projects run across the entire term. The themes for 2D projects are often student-directed, with teams asked to formulate a suitable project brief that encompasses concepts from each of the linked courses.
- **3D design activities, building progressively over time:** 3D activities allow students to repeatedly revisit a single project over time; with each iteration, the project is advanced using the new techniques and concepts learned by students in their most recent courses. For example, in the EPD pillar, during courses in three separate terms, student teams build a windmill and progressively improve its efficiency and performance. Details of another 3D project, also from the EPD pillar, which focuses on a radar gun, are given in Box 13 (page 83).
- **4D design activities, outside the curriculum:** 4D activities are student-led, allowing them to explore and apply design principles through participation in, for example, competitive teams, community projects, cultural studies, athletics, undergraduate research and entrepreneurial activities.

By graduation, each SUTD student will have participated in 20–30 substantial design projects. The themes explored during many of these projects are redesigned regularly, keeping the challenges 'fresh'.

Key features of SUTD's educational approach are outlined below, in Table 3. The data included in the table is distilled from interviews with stakeholders to SUTD's undergraduate program.

Educational feature	Details
Criteria for selection of student intake	In 2017, SUTD received 3700 applications from prospective undergraduates, from which 900 were shortlisted and 439 enrolled. Although no fixed entry criteria are specified, most shortlisted candidates are expected to bring strong qualifications in mathematics and physics. SUTD is the only university in Singapore where all shortlisted candidates are interviewed. Interviews are used to identify candidates with, in the words of one SUTD academic leader, <i>"passion for technical design, aptitude for multidisciplinary learning and a willingness to take risks."</i> The proportion of overseas students that SUTD is able to accept is capped at 30% of the cohort. Of the Singaporean student intake, around 80% have a Junior College background; the rest studied at Polytechnics or took an International Baccalaureate.
Flexibility and student choice	Year 1 of SUTD's program is common for all students. Students then select their pillar specialism, which is studied from Year 2 onwards. Except ASD, electives make up over half of the pillar curricula. Students are also given significant choice and flexibility over the focus and scope of projects, which are embedded throughout the eight-term curriculum.
Opportunities to work across disciplines	With no traditional discipline-specific departments or degree programs, the SUTD education is intrinsically multidisciplinary. The programs span science, engineering and architecture and encourage students to look beyond the purely technical dimensions of engineering problems through, for example, HASS courses and design projects.
Pedagogical approach	Much of the SUTD curriculum is delivered through design-centered active learning, with a particular focus on hands-on learning and prototyping, as well as through group discussion and problem-solving. Some of the specialist courses and electives in the pillar years, however, were reported to use <i>"extended lectures"</i> alongside projects and problems.
Assessment and feedback	In order to support the development of students' intrinsic motivation early in their studies, the first term of the SUTD program is not graded. Thereafter, students sit two–three days of exams at the end of each term. However, much of the assessment is continuous and linked to students' team projects. Indeed, 70% of the marks awarded for the final year capstone project is based on products submitted by student teams, such as prototypes and reports.
Teaching and learning support	In the early development phases of SUTD, much of the professional development and support in teaching and learning was provided by MIT, with 40 SUTD faculty participating in the <i>Teach the Teacher</i> program at MIT. A number of ad hoc pedagogical training workshops were also organized on the SUTD campus, in areas such as active learning, facilitation, design-based learning. In 2016, SUTD established the Learning Science Lab, ⁵³ an in-house center to support educational development among the university's faculty.
Reward and recognition of teaching	SUTD currently employs 33 'lecturers' and 110 tenure-track faculty. Interviewees suggested that SUTD has adopted <i>"the US promotion system"</i> for its tenure-track faculty which focuses almost exclusively on research outcomes, where <i>"teaching is not rewarded in any exceptional way unless you mess up like crazy."</i> Some noted, however, that as <i>"we have only had three years of promotion"</i> rounds, scope exists to rebalance the priorities of these reward systems.
Educational research activities	Interviewees suggested that, at SUTD, <i>"educational research is more prominent than at most research intensive universities."</i> Many of the educational papers published by SUTD faculty and academic leaders are focused on the themes of <i>design education</i> and <i>active learning</i> . A team from SUTD have also recently submitted a proposal to the Singapore government to conduct a major study to evaluate student learning in the SUTD curriculum and develop new assessment tools for group design projects (see Section B.2.3).
Extra-curricular opportunities	Student-led extra-curricular learning is a major element of the SUTD education, with dedicated time periods set aside for students to engage in these activities. Since the early 'student pioneers' joined SUTD in 2010, over 90 clubs and societies have been formed at the university, the same number as found at NUS, which is home to 27 times more students.

Table 2. Key features of the SUTD education approach and support systems

B.4. Curriculum design

An overview of the SUTD curriculum is provided in Figure 10. It comprises three major components:

1. **Freshmore year:** the first year of study is common to all students and provides foundational courses in mathematics and science as well as introductory courses in design, HASS and the engineering pillar themes. The Freshmore year is explored further in Section B.4.1.
2. **Pillar years:** students continue their SUTD education within one of four multidisciplinary pillars: ASD, EPD, ESD and ISTD. The pillar curriculum illustrated in Figure 10 is taken from EPD. The pillar years are explored further in Section B.4.2.
3. **Capstone project:** during the final two terms of study, students from across SUTD engage in a team-based multidisciplinary capstone project, as described further in Section B.4.3.

The SUTD academic calendar is unusual in a number of respects. The bachelor program is three and a half years (eight terms) in duration and starts in May – five months before peer Singaporean universities – during what would traditionally be considered the ‘summer’ break. The academic year is also long compared to national and global peers, comprising three terms of 14 weeks each.

Each term of the curriculum is built from four equally-weighted courses. Beyond these timetabled courses, SUTD places considerable emphasis on non-curricular activities offered both between and during terms. Two types of non-curricular activity are given particular prominence:

- **summer internships and overseas experiences:** the two ‘summer’ terms at the start of Years 2 and 3 are left open for students to engage in internships, overseas exchanges, summer programs or other “*broadening experiences.*” Internships are typically 16 weeks in duration and are supported by over 700 industry partners. Summer programs include the *Asian Leadership Program*, during which around 100 SUTD students each year spend 13 weeks at the university’s Chinese partner, Zhejiang University, and regional companies in Zhejiang to participate in a bespoke hands-on leadership program. Other summer program partners include Stanford University, the University of California, Berkeley and TU Berlin.
- **independent, student-led activities:** student-led activities are a major part of university life. No classes are scheduled on Wednesday or Friday afternoons to enable students to devote this time to “*extra-curricular passions.*” Activities extend beyond student clubs and societies. For example, many students take up roles as teaching assistants, to support and guide the learning of their peers in lower year groups. Around a half of undergraduates also engage in non-curricular research projects with SUTD faculty and researchers. In addition, the month of January each year is assigned as an *Independent Activities Period*, where students may engage full-time in non-curricular pursuits, which might include courses or overseas field trips linked to particular courses of study. During this period, the university also runs training courses to prepare students for their internships.

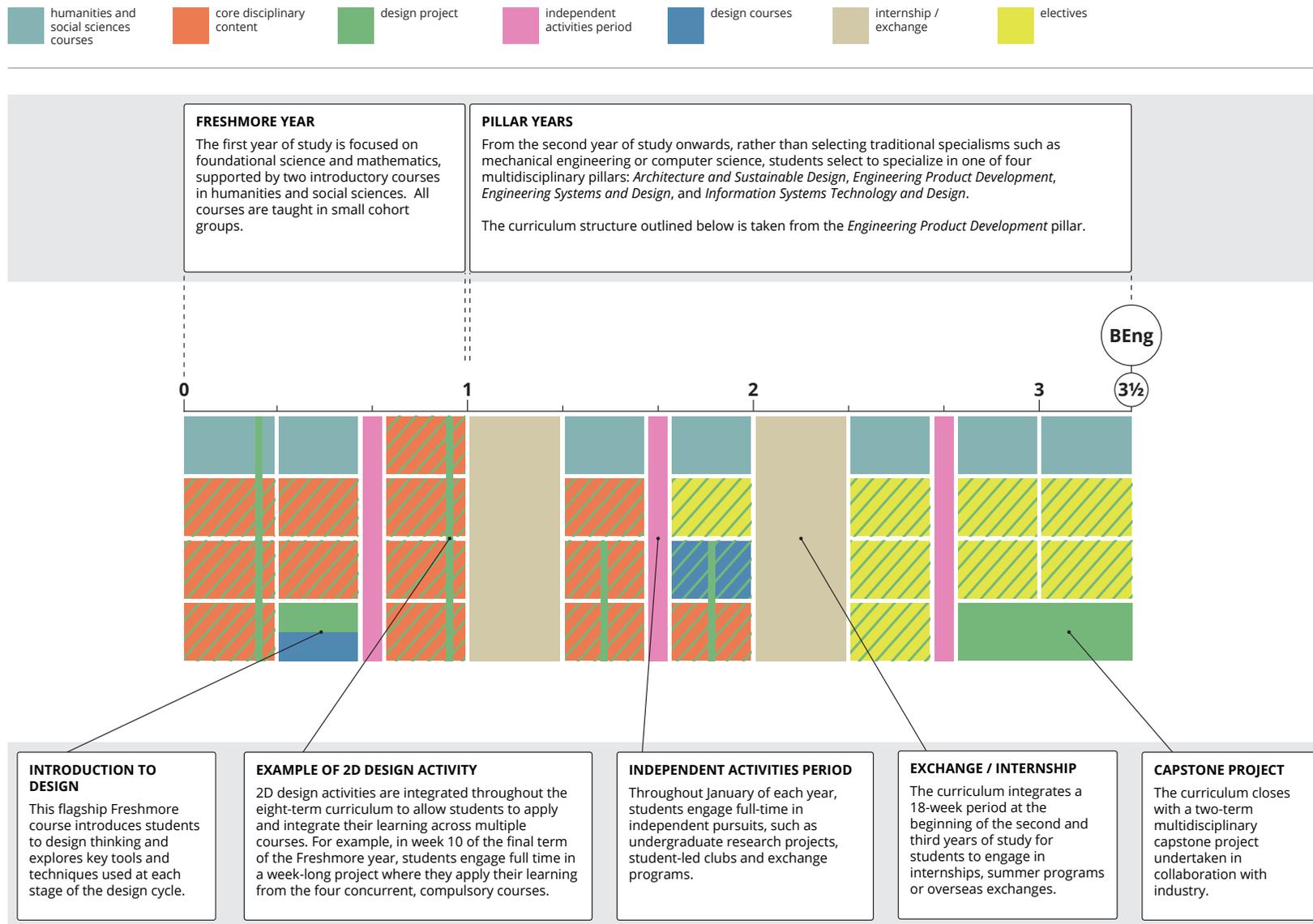


Figure 10. Outline structure of the SUTD curriculum, with the 'pillar years' taken from EPD

B.4.1. Freshmore year

SUTD’s first year of study is termed the ‘Freshmore’ year, so called because its extended three 14-week terms cover material traditionally associated with both a Freshman curriculum and the first half of a Sophomore curriculum. Offered as a common year for all incoming students, it brings together 12 equally-weighted required courses across the three terms of study, as outlined in Figure 11.

The Freshmore year looks and feels very different to the first year of a conventional engineering program in a number of respects. One is the extent to which active, hands-on, design-based learning is integrated into the curriculum, with almost every class structured around activities such as group discussions, problem-solving, prototyping and team competitions. Another striking feature – and despite an intake of around 450 students per year – is the small class sizes. The Freshmore year adopts a cohort-based approach; students spend the year working exclusively in a cohort group of 50 within a dedicated classroom. This small-group approach places considerable demands on campus space and faculty teaching teams; each course and project activity must be delivered and supported for each of nine separate cohort groups. However, interview feedback from students, graduates and faculty alike underlined the transformative role it plays in nurturing a community of support across the cohort and building students’ engagement and ambition. Many noted that working as part of these cohort communities on immersive team-based projects – both inside and outside of the curriculum – had been instrumental in nurturing students’ intrinsic motivation and *“shaking them out of chasing the paper grade.”* In the words of one final-year student:

“these 50 people you interact with every day for three terms. You stop being academically competitive, it is more collaborative ... People are willing to help each other. Willing to stay up all night to help another group. This is very unique to SUTD.”

As explored further in Box 12, the Freshmore year brings together four components: (i) foundational mathematics and science courses; (ii) introductory HASS courses; (iii) major, immersive 2D projects in each term of study; and (iv) the *Introduction to Design* course in Term 2.

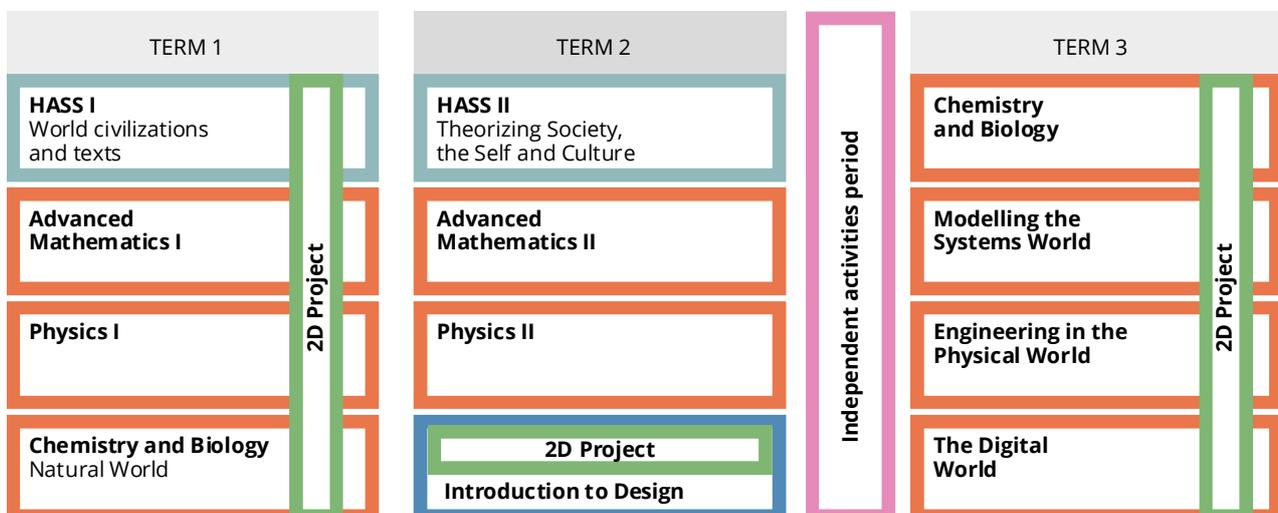


Figure 11. Curriculum structure of SUTD’s Freshmore year

Box 12: The four core components of SUTD's Freshmore year

Foundational mathematics, science and engineering courses are a key focus of the Freshmore year. Academic standards are high; much of the content covered, particularly during the first two terms of study, was directly translated over from the MIT curriculum. In the final term, three newly-developed foundational courses provide an introduction to SUTD's engineering pillars: the systems world (including operations research and system dynamics), the physical world (covering topics such as thermodynamics and statics) and the digital world (introducing modularity and abstraction as well as programming). Despite their focus on content delivery, all Freshmore foundational courses are immersed in active learning with extensive use of 1D and 2D activities. One example is from the 2017 iteration of the Physics II course. Student teams were each assigned one of the 20 core concepts covered in the courses – such as Gauss' law or electromagnetic waves – and were asked to *"design a 15 minute teaching module to explain this concept to high-school children."* At the close of term, the high-school children and their teachers are invited to SUTD to review and evaluate the modules.

Two **foundational HASS courses** are provided in the Freshmore year: the first provides *"an introduction to the philosophies upon which our civilization was built"* through an exploration of *"the world's great books,"* while the second offers *"an introduction to the dominant disciplines in social science."* Many interviewees noted *"the importance of HASS in broadening students' experiences beyond the purely technical."* As one explained: *"at Junior College, students can channel themselves into the science stream. They have very little exposure to social science. We need to build that exposure and make a connection between technology and the humanities...if SUTD wants to make the world 'better by design', then students need to understand the world and appreciate society."*

One major 2D project is embedded into each Freshmore term and calls upon students to integrate their learning from all four courses studied that term. For example, in 2017, the major 2D project in Term 1 asked student teams to assemble and launch a sugar-powered rocket. The project drew upon content from each of the Term 1 courses: from chemistry (focused on the power generated from the chemical reaction of sugar and potassium nitrate); physics (focused on the friction generated by the wire rope used to tether the rocket); mathematics (focused on predicting the distance travelled by the rocket); and HASS (focused on the social impact of rockets). At the close of this week-long project, each rocket was tested and the teams presented a poster of the research underpinning their design.

Introduction to Design, in Term 2 of study, was described by students, faculty and academic leaders alike as a *"flagship course"* that *"sets the tone for everything the students do here at SUTD."* A major goal of the course is *"to help students to deal with uncertainty and open-ended problems, which are not experiences many will have had before coming to SUTD."* It also offers a structured introduction to design thinking; in each week, students explore key tools and ideas that underpin progressive steps in the design cycle. These tools are applied in the Term 2 major 2D project that runs throughout the term. In 2017, for example, student teams were asked to identify, design and prototype a product that responds to the theme of *'the technological body'* and also draws upon what had been learned in at least two of the courses studied in Term 2. So, for example, teams could utilize global positioning (drawing upon the linear algebra learned in mathematics) or consider the influence of social interactions on their design (drawing on their social science HASS course). The final project is graded by faculty from these chosen courses. All cohorts are facilitated by one architect and one engineer.

B.4.2. Pillar years

After the Freshmore year, students specialize in one of four multidisciplinary ‘pillars’: ASD, EPD, ESD and ISTD. Although the curriculum structure varies between pillars, all incorporate the following three components:

- **pillar ‘core’:** during the first two to three terms of each pillar, students take a number of required courses that are fundamental to the subject. For example, in ISTD, these ‘core’ pillar courses include *Computational Structures* and *Introduction to Algorithms*.
- **electives:** on completion of the ‘core’ pillar courses, much of the curriculum is devoted to pillar-specific electives.⁵⁴ When choosing electives, most students opt to follow a ‘focus track’ within an identified field of interest, which typically comprises both required courses as well as open electives. For example, the *Cyber Security* focus track in ISTD offers ‘core’ classes in networks and security, as well as electives in fields such as machine learning.
- **HASS electives:** students select five HASS elective courses from around 40 options. Two broad types of HASS elective are offered. Some are designed “to speak to the intersection between social sciences and technology” – for example, *Technology and the Self* considers how technology can influence identity. Others offer a pure immersion in humanities and social sciences; for example, *Sages Through the Ages* considers Asian philosophies and *Film Studies* allows students to explore and produce their own short films.

The content covered during the pillar years draws heavily on MIT courses, particularly in the ‘core’ courses. The pedagogical approach is design-focused and active, with extensive use made of the university’s prototyping facilities. Indeed, one of the most striking features of the pillar curricula is the extent to which 1D, 2D and 3D activities are intertwined across and between courses and years. For example, Box 13 outlines some of the 2D and 3D projects integrated into the EPD curriculum; a pillar selected by around 120 students each year. The EPD curriculum is outlined in Figure 12.

TERM 4	TERM 5	TERM 6	TERM 7	TERM 8
HASS ELECTIVE	HASS ELECTIVE	HASS ELECTIVE	HASS ELECTIVE	HASS ELECTIVE
Probability and statistics	Core electives	Core electives	Advanced / technical electives	Advanced / technical electives
Circuits and electronics	System and control	Core electives	Advanced / technical electives	Advanced / technical electives
Structures and materials	Engineering design and project eng.	Core electives	Capstone project	

Figure 12. Outline structure of the EPD pillar curriculum

⁵⁴ In the ASD pillar, only a limited number of electives are offered; most of the curriculum is devoted to ‘core’ courses.

Box 13: Examples of the use of 2D and 3D activities in the EPD pillar

In addition to multiple 1D activities embedded within each course, 2D and 3D activities are interwoven across the EPD curriculum. Two examples are given below, illustrating 2D and 3D projects that connect with two EPD courses: *Circuits & Electronics* and *Engineering Design & Product Engineering*.

EXAMPLE 1: the core *Circuits & Electronics* course, taken in Term 4 of the EPD curriculum, connects with a range of 2D and 3D projects, including:

- a series of mini-2D activities linked with the Term 4 *Structures & Materials* course: every 3–4 weeks, students engage in a ‘mini 2D’ project that integrates key concepts covered that week in each of the two courses. These projects include building an energy-harvesting windmill or creating a device to detect the vibration of an aircraft bridge;
- a term-long 2D project linked with the Term 4 *Structures & Materials* course. It asks student teams “to come up with their own project idea” that draws on concepts from both courses; the only stipulation is that it must be aligned with one of EPD’s nine specialist ‘focus tracks’, such as *Robotics* and *Materials Science*. Past projects have included a mono-wheel that converts a manual wheelchair into an electric-drive wheelchair. As well as exploring the content of the two feeder courses (*Circuits & Electronics* and *Structures & Materials*), this 2D project is designed to “give students a feeling of what track they might want to follow” from Term 5 onwards;
- a 3D activity where *Circuits & Electronics* offers the first iteration of a four-term project focused on radar guns. As students progress through the curriculum, the focus of this ongoing project moves from the hardware, to the system and then to the software of the radar: in each participating course, students are asked to apply their learning to improve and refine the radar’s design. So, the *Circuits & Electronics* course asks students to build a simple low frequency radar and use it to measure the speed of cars on the highway. The control of the radar is then improved during the Term 5 *System & Control* course. The project is revisited in a number of EPD electives during Terms 7 and 8, including *Electromagnetism & Application* (to refine the antennae design), in *Signal Processing* (to process and analyze the signal from the radar) and *Fluid Mechanics* (to develop a positioning radar for use on a boat).

EXAMPLE 2: the core Term 5 *Engineering Design & Product Engineering* course connects with a number of projects, including two 2D activities, both of which are linked with the Term 5 core *System & Control* course:

- a week-long full-time 2D project to develop a feedback control system for a cart robot. Student teams are provided with a basic kit of components, including the robot chassis. Held in the middle of the term, the project is designed to introduce students to concepts such as block diagrams and PID controllers. As the close of the week, each cart must navigate an obstacle course in an elimination competition – the *2D Rally Championship* – that is open to the public.
- a term-long 2D project to advance the design of a spherical robot: student teams are first asked to evaluate and disassemble a spherical robot produced as part of SUTD faculty research. They then must propose, design, model and prototype three new unique features to their robot, which could be used in any application of their choosing.

B.4.3. Capstone project

Like many engineering programs around the world, the SUTD curriculum closes with a capstone project to consolidate, apply and reflect upon what has been learned during the degree. The SUTD capstone, however, is distinctive in two important respects.

Firstly, the capstone is **multidisciplinary**. It brings together final-year students from across the university, with each project team of six drawing its membership from at least two of SUTD's pillars. Mirroring the cohort model adopted in the Freshmore year, the multidisciplinary teams work within one of seven dedicated 'capstone' classrooms throughout the two-term project, with around 50 students in each room. Two faculty 'instructors', taken from two different pillars, are assigned to guide and facilitate the teams in each classroom. Additional guidance is also provided by communications instructors, who offer one-to-one support to teams as they develop their written and oral presentations. Student must also take short modules throughout the project in areas such as ethics, technical writing, safety, project management and data mining.

Secondly, the projects address **real-world challenges** that are "*industry supported and inspired.*" Each team tackles a unique brief set by an industry partner that addresses an authentic, multidisciplinary problem faced by the company. Drawing on their education in engineering, science, HASS and design, as well as each student's pillar specialism, the projects call upon teams to consider the technical and nontechnical aspects of their solution, as well as to produce a working prototype. The industry partner retains the IP of any ideas emerging from the project and will offer weekly mentorship to their team. Projects vary considerably in their size, scope and focus. Some are highly open-ended, such as a project posed by the company 3M⁵⁵ to identify potential applications for a flexible LED light. Others call upon teams to develop large-scale solutions. For example, a recent capstone project – which drew together students from all four pillars – was focused on a 'digital health studio'. The team developed a full-scale prototype of the interior of a 'smart' meeting room, which integrated new biomedical technology and data visualization to support medical examinations and briefings.

The vast majority of SUTD capstone projects are focused, as outlined above, on an industry-informed problem. However, up to five teams a year may opt to take what is termed an 'Entrepreneurial Capstone', which draws on students' own technology-based start-up idea. Students wishing to follow this route must first participate in a project validation process, comprising a three-day entrepreneurship boot camp, a three-week project review process and presentation of the project business case to the *Capstone Committee* for approval. Teams accepted onto the entrepreneurial track must raise SIN\$3k to support the project development. They are provided with a further SIN\$7k in funding from a government seed-funding agency and mentorship from a regional venture capitalist. Entrepreneurial capstone teams own the IP for their project and a number have already established start-up companies on graduation.

⁵⁵ 3M (<https://www.3m.com>)

B.5. Review and concluding comments

Thought leaders from Phase 1 of the study identified SUTD as the world's foremost 'emerging leader' in engineering education. This case study evaluation suggests that SUTD's premier position is well-founded: the university's undergraduate education stands apart from peers. The SUTD curriculum integrates many of the features predicted by thought leaders consulted in Phase 1 to distinguish the best engineering programs in the decades to come: it offers a design-centric, multidisciplinary education that is infused with hands-on problem-solving and emphasizes self-directed learning and student choice. Despite being co-designed by a team working across two continents, each of these features is embedded into a thoughtfully-designed curriculum that allows students to contextualize and assimilate their learning across courses and between years of study. Indeed, what is most striking about the SUTD education is its connectivity: connectivity between cross-disciplinary faculty teaching teams, connectivity between courses in the curriculum and connectivity between students, within and outside the curriculum. A major vehicle for this integrative learning is SUTD's innovative 4D projects.

Feedback from SUTD's students, faculty, graduates and graduate employers was overwhelmingly positive. In particular, many pointed to two attributes of SUTD students and graduates that set them apart from their peers – their intrinsic motivation and their adaptability – as discussed in turn below.

Interviewees repeatedly pointed to the **intrinsic motivation** of SUTD students and graduates. This was understood to be nurtured by the university's strong emphasis on non-curricular student-directed activities, the 'cohort-based' small group learning and the extensive use of design-based projects and hands-on learning. In the words of one SUTD student:

"making a prototype rather than just doing a paper exercise... makes you think differently. It is no longer about homework that you only need to spend two hours on. You get invested in it."

Indeed, SUTD student interviewees were notable for the degree to which they had reflected upon the university's distinctive educational approach and its impact on their learning. For example, one student commented on the role of the HASS courses within the SUTD curriculum:

"at other universities, HASS is not compulsory, but it makes you a more responsible engineer. It creates an 'understanding each other' culture... before I came to SUTD, I was more thinking about the technology, now, after HASS, I think about the human first. It changed how I am thinking"

Interviewees also consistently pointed to the **adaptability** of SUTD students and graduates: the adaptability to tackle ill-defined problems that "*spill over the boundaries of different disciplines*" as well as the adaptability to respond to the changing needs of projects and/or professional roles. Interview feedback from graduate employers suggested that this adaptability was one of the key attributes that set SUTD graduates apart. In the words of one:

"SUTD students can integrate into teams far more easily than other students. You can give them anything and they can stand back and see the problem... they are not just looking from the little box of their own discipline."

Similarly, SUTD faculty and academic leaders stressed the importance they placed on nurturing students' adaptability:

"...technologies are advancing so quickly that 30% or 40% of what students learn...will be redundant when they get into industry. So what is critical is that the students have confidence as a designer and are able to find the means to solve any particular problem... Our students get to understand that there is no project that a single discipline can solve all by itself... they wear different hats aligning to the needs of the project."

Taken together, stakeholder interview feedback suggests that the educational approach pioneered by SUTD offers significant potential to influence practice in engineering schools and institutions around the world. There are three features of SUTD's design-centered, multidisciplinary approach, in particular, that are likely to attract the interest of the wider engineering education community:

- **it is integrated throughout the curriculum:** design-centered multidisciplinary activities are embedded across the entire program – these experiences are not confined to a small number of flagship courses or projects that are isolated from the rest of the curriculum;
- **it is delivered at scale:** all 450 students joining SUTD each year participate in this innovative curriculum – the experience is not confined to small, selected student groups;
- **it is underpinned by rigor in the 'engineering fundamentals' and HASS:** almost all SUTD courses take their content directly from MIT, with the majority retaining equivalent expectations for student achievement – few compromises have been made to the programs' academic rigor.

It is the last of these features – the academic rigor of SUTD's approach – that may be of most interest to the engineering education community. A criticism often leveled at student-centered and project-based curricula is that the development of personal and professional competencies – such as systems-thinking, problem-solving and team-working – comes at the cost of 'dumbing down' academic standards in mathematics and the engineering sciences. A crucial feature of the SUTD curriculum is that much of its course content mirrors that delivered at MIT, a curriculum known worldwide for its academic rigor, with compromises to the depth of study made only in a handful of courses. As a result, the academic rigor of the SUTD curriculum is unquestionably high, despite its design-centered and project-based approach to the content delivery.

Evidence from the case study also makes clear the SUTD curriculum is not static: courses, projects and pillars are continuously being updated and redesigned. This evolutionary approach to curriculum development reflects the university's design-centered ethos, which emphasizes the needs and experience of the user. It also reflects the collaborative, student-centered culture of the university, where teaching is unapologetically held in the same esteem as research.

B.5.1. Success factors

Interview feedback suggested that three factors have underpinned the successful design and delivery of SUTD's distinctive undergraduate education.

The **first success factor** is the Singapore government's investment in and commitment to the university. Interviewees from across and beyond SUTD consistently noted that:

"Singapore is a country whose political leadership values education and values research and is prepared to invest in them. It is always searching for ways to be innovative and is prepared to listen to how we should do it."

These political and cultural values were understood to underpin the government's substantial investment in SUTD. This funding environment, in turn, has been vital in realizing many of SUTD's most distinctive features, such as its small group learning and its extensive use of hands-on, maker-based learning. As one external interviewee noted, *"typically, that kind of investment only happens with the capstone [project], but at SUTD, it is everywhere, in every course."* The Singapore government was also understood to *"trust in SUTD's leadership"* and offer the university the autonomy and flexibility needed to establish an educational culture and approach that was both unique and world-class. The government's *"hands-off"* approach has come with *"the mandate to create a university that is completely different, where design is center-stage."* This clearly articulated educational vision was seen to offer *"a single focus that is always towards design, we are not pulled in multiple directions... faculty clearly understand the objectives of the university and with that acceptance, all of the policies, courses, research efforts are aligned to this objective."*

The **second success factor** has been the added value of the university's collaboration with MIT. This high-profile partnership provided the credibility, expertise and practical support necessary to build a globally recognized and academically exacting undergraduate program from a blank slate. In particular, faculty and academic leaders from both MIT and SUTD consistently pointed to the influence of *"the intangibles of the relationship"* on SUTD's educational culture and curriculum. For example, many highlighted how the early exchange programs at MIT *"instilled that very special [innovative] culture in our students"* that is now understood to be self-sustaining across the SUTD student population. Others pointed to the collaborative approach established between MIT and SUTD faculty to the co-designing of courses: *"in the plans, there were so many unknowns, but [MIT] have had the capacity and interest to try interesting things with us... to push the boundaries."*

The **third, and perhaps most important, success factor** is the quality of SUTD's leadership. Supported by its partnership with MIT, the university has appointed a world-class, hand-picked leadership team and a cadre of outstanding young faculty that together will undoubtedly enable SUTD to continue to push the boundaries of design-focused research and innovation in science and technology. Alongside its stellar research credentials, the university also offers a deep commitment to its educational mission. Indeed, one of the most striking features of the interview feedback from SUTD's academic leaders was their shared educational vision and their clear personal commitment to establishing a new paradigm for engineering and architecture education. Building upon their own

experiences of educational change before joining SUTD, its academic leaders are deeply committed to the university's educational philosophy.

These institutional priorities are recognized and understood by SUTD faculty. In the words of one, *"the management is giving [us] flexibility to try new ideas... they just want to know how the students benefit, but the openness is there."* This empowerment of faculty to collaborate and innovate in teaching is supported by the university's distinctive culture, which, again, is shaped by its academic leadership. As one SUTD faculty member noted, *"it is a culture of no boundaries."*

B.5.2. Challenges faced

Interview feedback suggested that the SUTD education faces two major challenges over the coming years. Each is discussed in turn below.

The **first major challenge** is building the size of the university's undergraduate population. Current intakes stand at around 450 per year. However, SUTD is committed to increasing its intake numbers to 1000. With its overseas student intake capped at 30%, the university must look primarily to the national Singaporean market to enable this growth. Interview feedback pointed to a number of factors that may constrain national recruitment, including:

- the increasingly competitive higher education landscape in Singapore, with the number of publicly-funded universities in the city state doubling in number, from three to six, in the past decade, and both NUS and NTU benefitting from rapid rises in the global university rankings;
- the declining population of Singaporean prospective students resulting from the country's continuing low birthrate: *"we have an increasing number of universities [in Singapore] competing for a shrinking pool of candidates. It creates a problem of scale and quality."* As one interviewee commented: *"they will need to keep the integrity of recruitment, not in terms of academic rigor but in terms of the quirkiness of the students, their purity of ideal";*
- the reluctance of many prospective Singaporean students and their parents *"to take the risk of choosing a university that is still so young and is unranked"* in global university rankings, particularly since the educational collaboration with MIT has now ended.

Interview feedback suggested that the last of these factors is perhaps the most pressing:

"Singapore it is such a risk-adverse society and values education so much that taking a risk on education is particularly difficult... the concern parents have is not about the pedagogy, it's not about the education, it is 'will my child get a job at this new university?'"

Despite this considerable challenge, early proof of the success and impact of the SUTD education came in March 2017 with the publication of the Singapore graduate employment survey:⁵⁶ over 90% of SUTD's most recent graduates secured employment within six months of completion and had the highest average earnings of all Singapore graduates. One observer described this evidence as *"the final*

⁵⁶ Ministry of Education Singapore, Graduate employment survey, 2017 (<https://www.moe.gov.sg/docs/default-source/document/education/post-secondary/files/sutd.pdf>)

piece of validity SUTD needed” that will undoubtedly help to strengthen its brand across the wider community.

The **second major challenge** facing SUTD concerns the scalability of its educational approach and culture. Interviewees consistently noted that the university’s small faculty and student populations have helped to nurture a culture of collegiality and shared ideals across the institution. The university’s size has allowed it to react rapidly to problems and opportunities arising during its early development. It has also enabled *“conversations, interactions on a daily basis”* across the SUTD faculty, which have, for example, advanced new cross-disciplinary research collaborations and helped to ensure a consistency of approach in courses taught across multiple small cohorts of students. Many SUTD-based interviewees, however, asked the question:

“how can this ‘can do’ culture be maintained when we are no longer a small university, so it does not get diluted over time?”

In the words of one SUTD faculty: *“at the moment, we are a small group of like-minded people, it is very personalized. What must we do to keep the torch burning bright when our numbers grow?”* Some interviewees pointed to the challenge of increasing the university’s size without imposing new bureaucratic systems and divisions on the institutions: *“as they bring more people in, will it lapse into a siloed environment?”* The most significant concern raised by interviewees, however, was that institutional growth – and in particular the recruitment of new faculty – might compromise SUTD’s commitment to innovative and student-led education. Many of SUTD’s faculty appointed to date were described as *“fresh from post-docs...they have not been colored by decades in a more traditional university.”* As a result, they were described as *“more open to non-traditional [educational] approaches”* and willing to devote a greater proportion of their time to supporting the university’s 12-month teaching calendar. New appointees at mid-career level were seen to carry a risk of *“not [being] committed to the [educational] vision we have, the design ethos, they might start pulling the university towards the norm in higher education,”* through, for example, adopting a teacher-centered, lecture-based pedagogy for their courses or ceasing the practice of constantly renewing project themes.

It is clear that the strength of SUTD’s leadership in embracing and championing design-centered, multidisciplinary active learning will play a critical role in ensuring that the university’s education culture and approach are sustained as it expands. The current university President – who has been a critical force in establishing this culture – stepped down in late 2017. SUTD can look forward to the transition to a new President with confidence. Only five years after matriculating its first student, it has achieved a premier position within engineering education. It has promised, and has delivered, a model of engineering education that combines academic rigor with features recognized to distinguish the future global leaders.

Acronyms used in SUTD case study

ASD	Architecture and Sustainable Design
EPD	Engineering Product Development
ESD	Engineering Systems and Design
ISTD	Information Systems Technology and Design
NTU	Nanyang Technological University
NUS	National University of Singapore
SIT	Singapore Institute of Technology
SMA	Singapore–MIT Alliance
SMART	Singapore–MIT Alliance for Research and Technology
SMU	Singapore Management University
SUSS	Singapore University of Social Sciences
SUTD	Singapore University of Technology and Design
TIMSS	Trends in International Mathematics and Science Study

APPENDIX C CASE STUDY – UCL ENGINEERING, UNIVERSITY COLLEGE LONDON, UK

Reasons for selection of UCL Engineering as a case study

In 2014, UCL's Faculty of Engineering Science – UCL Engineering – implemented the Integrated Engineering Programme (IEP), a root-and-branch reform of the undergraduate curriculum across all engineering departments. The new educational approach has two major components:

- a common curriculum structure, adopted by all undergraduate programs across UCL Engineering, that is built around a series of authentic engineering projects;
- shared multidisciplinary team projects and Minors, bringing students together from across UCL Engineering.

Intake numbers to UCL Engineering are relatively high – over 950 students joined the Faculty in 2016/17 – and almost all study under the IEP curriculum. The first cohort of BEng students graduated from the IEP in July 2017, with their MEng counterparts due to graduate in July 2018.

UCL Engineering was identified by experts in Phase 1 of the study as both a 'current leader' and an 'emerging leader' in global engineering undergraduate education. Many commented on the significance of "*a university like UCL*" implementing such an ambitious and forward-looking educational reform. As one interviewee put it, "*...they are a massively research-intensive university, one of the top 10 in the world, that could have really laughed this off. But they didn't. They are taking the undergraduate education seriously.*"

C.1. Context

C.1.1. The university context

Established in 1826, University College London (UCL) is based in the Bloomsbury area of central London. The university supports a wide range of disciplines, from fine art to medicine and from astrophysics to anthropology. Recent years have been ones of significant growth in the university's size and reputation. In the last decade alone, the university's undergraduate population has increased from 12,000 to 18,000, and its graduate population has increased from 7,000 to 21,000. At the same time, UCL has advanced rapidly up the international university rankings; in the first year of publication of the *QS World Rankings*⁵⁷ in 2004, UCL was ranked 34th in the world; today it is ranked 7th. Indeed, UCL boasts a formidable global research reputation. In the UK's most recent national evaluation of university research,⁵⁸ published in 2014, UCL was identified as the country's leading research university.

UCL Engineering is one of the university's 11 Faculties. It comprises 11 departments, of which nine offer degree programs at the undergraduate level.⁵⁹ As illustrated in Figure 13, the undergraduate student population in UCL Engineering has grown almost threefold in the past decade, to over 3,000. This increase in student numbers has been built both from the recent introduction of new degree

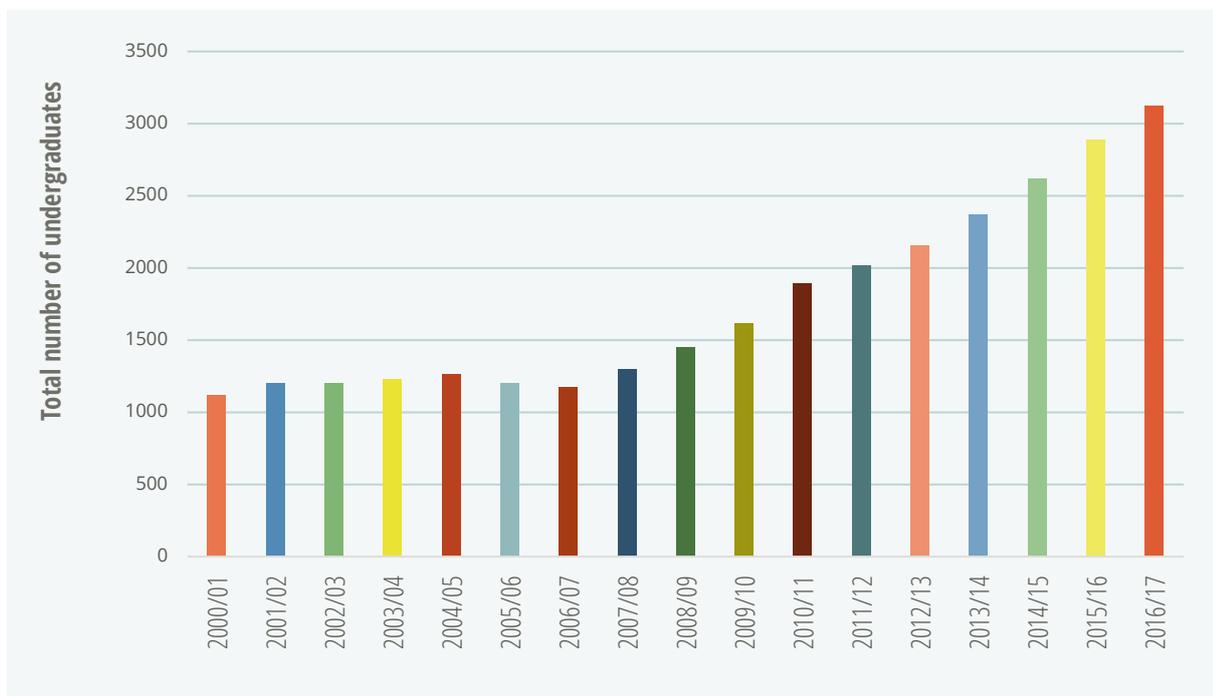


Figure 13. Total number of undergraduate students in UCL Engineering, 2000 to 2016

⁵⁷ QS World University Rankings (<https://www.topuniversities.com/university-rankings>)

⁵⁸ Research Excellence Framework 2014 (<http://www.ref.ac.uk/>)

⁵⁹ The nine departments in UCL Engineering offering undergraduate programs are: Biochemical Engineering, Chemical Engineering, Civil, Environmental & Geomatic Engineering, Computer Science, Electronic & Electrical Engineering, UCL School of Management, Mechanical Engineering, Medical Physics & Biomedical Engineering and Security & Crime Science.

programs into the Faculty⁶⁰ and a progressive growth in the cohort sizes among existing programs. For example, the UCL Engineering program with typically the largest student population is Mechanical Engineering, which has seen its undergraduate intake rise from 45 in the early 2000s to 150 today. The smallest intake cohort, of 25 students, is to the Biomedical Engineering Programme within the department of Medical Physics and Biomedical Engineering. The staff and student populations in UCL Engineering are also highly international: 53% of the Faculty's 309 FTE academic staff are non-UK nationals, as are 45% of its undergraduates.

C.1.2. The national context

A number of factors distinguish the UK higher education landscape from its international peers. Student participation rates are high: following progressive increases in enrolments in recent decades, over half of young people in the UK now enter higher education. The UK also attracts a significant number of overseas students – totaling 19% of the undergraduate student population – making the country the second most popular destination for overseas study worldwide. National spending on higher education in the UK is also high, one of the highest in the OECD.⁶¹ In England, these investment levels are partially supported by tuition fees paid via students loans. Tuition fees were introduced for undergraduate study in England 20 years ago, and have progressively increased in the years since. The government sets a maximum 'cap' on fees, which currently stands at £9.25k (approximately US\$12k) per annum, and is charged by most English universities for all degree subjects. As a result, average student debt for English graduates has increased significantly, doubling over the past four years to £50.8k (approximately US\$60k).

The increase in fees has brought the quality of UK undergraduate education into sharper focus, and has precipitated the introduction of a number of national systems to monitor and improve performance. For example, in 2005, the *National Student Survey (NSS)*⁶² was introduced, an annual survey of final-year students from UK universities, capturing students' perspectives on the quality of their education. More recently, the UK government introduced the *Teaching Excellence Framework (TEF)*,⁶³ a voluntary ranking system for grading the quality of a university's undergraduate learning environment and student outcomes. The current pilot version of the framework uses nationally-available quantitative indicators – such as NSS scores, student retention levels and graduate employment rates – along with a university's written statement, to grade institutions as bronze, silver or gold standard for teaching quality. The outcomes from this pilot were announced in June 2017: UCL was awarded silver status. From 2020, the TEF results will be used to determine the maximum level of tuition fees that can be charged by each university in England.

⁶⁰ Computer Science transferred into UCL Engineering from the Faculty of Mathematical & Physical Sciences in the mid-2000s and new Biomedical Engineering and Management Science programs were established in 2014.

⁶¹ OECD (2016). *Education at a Glance 2016: OECD Indicators, Country Note: United Kingdom*. OECD Publishing

⁶² National Student Survey (<http://www.thestudentsurvey.com>) is an annual survey of final-year students from UK universities, capturing their perspectives on the quality of their education.

⁶³ Teaching Excellence Framework (<http://www.hefce.ac.uk/lt/tef/>)

C.2. The development of the UCL engineering education

This section outlines the key milestones that have shaped the development of the *Integrated Engineering Programme* (IEP) at UCL. It is structured across three time periods:

- foundations for curricular reform (2011–2012);
- designing the new Faculty-wide educational approach (2012–2014);
- rolling out the IEP in UCL Engineering (2014–date).

Each is discussed in turn in the subsections below.

C.2.1. Foundations for curricular reform (2011–2012)

Interviewees characterized the undergraduate education in UCL Engineering⁶⁴ prior to 2011 as “*very engineering science-focused, very traditional, with very little group work or practical work.*” In addition, while “*we have been incredibly good at working in an interdisciplinary way in our research portfolio,*” departments were reported to have operated “*in independence, in very traditional silos*” in the educational domain. Indeed, in the words of one interviewee: “*there was not much to pick out our education from a standard engineering program.*” Against the background of an educational approach “*that had not changed much in 40 years,*” interviewees pointed to a number of “*islands of local innovation [in the Faculty], most substantially in Civil Engineering.*” In 2006, the Civil, Environmental and Geomatics Engineering (CEGE) department had implemented a root-and-branch reform of its undergraduate curriculum, creating a program that connected engineering disciplinary theory with a spine of authentic, immersive projects.

The seeds of reform were sown in early 2011, when the then Dean of UCL Engineering became increasingly convinced of the need for the Faculty to adopt a radically different approach to undergraduate education. His motivations stemmed from both internal and external drivers. The internal drivers for reform built upon a perception that the Faculty “*did not have a distinctive [educational] offering,*” was not “*exploiting our collective strength*” and “*lacked collective ownership of the programs*” by academic staff. The external drivers for reform focused on concerns that engineering graduates were leaving UCL without the breadth of professional skills to navigate diverse 21st century engineering careers and without “*a practiced familiarity with the core engineering skills.*” As the former Dean commented:

“our programs looked pretty much like the engineering education I had experienced and I wasn’t satisfied with that. I wanted something that looks like UCL, like our spirit, our values and our vision of engineering.”

Following a number of months of attempting to stimulate a wider discussion about the rationale for educational reform, in mid-2011 the former Dean crafted and circulated a document detailing “a

⁶⁴ Until 2014, UCL Engineering was known as the Faculty of Engineering Sciences.

complete redesign of all of the [engineering] programs" to academics across the Faculty. The response was immediate. As the former Dean recalled:

"... people were completely horrified. There was quite a strong reaction and it was the best possible thing that could have happened, because then suddenly people actually engaged. All of the educational rationale [had] just washed over people's heads, but actually when you came up with a curriculum plan – when they saw lectures and time-slots – then they engaged ... and from that point onwards we had amazingly constructive feedback from the Faculty."

Entitled the *Common Engineering Programme*, the proposed Faculty-wide educational approach brought together a number of components, including practice-led engineering problem-solving, shared cross-Faculty teaching of core engineering topics and the introduction of a specialist Minor. While much of the curriculum ownership continued to reside in the departments, the proposed program introduced both a common cross-Faculty curricular framework and significant components that would be delivered centrally, by a cross-Faculty teaching team. The proposal triggered considerable debate across the Faculty on both the merits of curriculum change and on the form and focus that this change might take. Although skepticism was initially expressed by many, a number of contextual factors proved instrumental in starting to engage departments with the need for educational reform. One driver was the rapid and ongoing growth to the student population: *"class sizes had increased significantly... and there was not a similar increase in staff numbers. We were really struggling... we knew something had to change."* At the same time, a number of departments were coming under increasing pressure to reshape their educational approach in light of *"disappointing scores"* in the NSS.⁶²

In early 2012, while debate continued across the Faculty, the Dean advertised a 0.5 FTE seconded position for a UCL engineering academic to lead the scoping and delivery of a Faculty-wide educational reform. The successful candidate, appointed in April 2012, was himself a former UCL student and had long been *"frustrated by the lack of practical application"* in the curriculum. Ten years of experimenting with problem-based learning at the module level in the Electronic and Electrical Engineering department had also led him to conclude that:

"... when you try to drop little bits in the curriculum, there are always fundamental limitations – like expecting students to develop teamwork by throwing them in teams. There was a group of us that wanted to do something more, but knew it had to be holistic to really work."

Interviewee responses, from across and beyond the Faculty, were striking in their positive assessment of the new appointee and the strengths he brought to the embryonic program of reform. He was consistently characterized as *"somebody that was known and respected by a lot of people"* and who understood the university's educational processes and the distinctive cultures within each department.

C.2.2. Designing the Faculty-wide educational reform (2012–2014)

The design of the new *Common Engineering Programme* – as it was known at the time – called for significant cross-Faculty engagement and effort involving around 120 academic staff and 80 teaching fellows. It evolved through three main waves of activity, as outlined below.

Wave 1: agreeing a common cross-Faculty educational approach. The initial task facing the newly-appointed Program Director was to canvass views from across and beyond the Faculty and establish broad agreement about the focus and structure of a shared education framework. Following six months of *“talking to people, listening to their views,”* he assembled *“an enthusiastic board of people from each department”* to explore questions such as, *“What skills did the departments want for their graduates?”* and, *“What examples of good practice already exist?”* The group also *“dissected the first two years of the curriculum in every department, covering the walls with post-it notes.”* By mid-2013, after *“a few rounds of talks and going back to the drawing board,”* a new cross-Faculty educational framework was agreed, as outlined in Box 14. Although retaining many elements of the Dean’s original proposal, it did not carry forward a cross-Faculty approach to the teaching of the fundamental engineering sciences, following significant concerns raised by departments. Reflecting this shift in focus, the educational framework was renamed as the *Integrated Engineering Programme (IEP)*, emphasizing *“integration across departments and integration of each component of the students’ education in a cohesive curriculum.”*

Box 14: The two core components of the IEP, as agreed by the cross-Faculty committee:

- **a common curricular structure across the Faculty:** although all engineering students would continue to be based within discipline-specific departments from entry to the university, a common Faculty-wide curricular structure would be adopted during the first two years of study. A centerpiece of this curriculum would be a series of *Scenarios*, operating in five-week cycles, where students spend four weeks acquiring a range of knowledge and skills that are applied in a one-week intensive design project;
- **shared multidisciplinary components:** all engineering students from across the Faculty would come together to engage in a series of multidisciplinary projects and modules, including the common teaching of mathematics.

Wave 2: departmental curricular reform. The second wave of activity focused on redesigning departmental curricula around the IEP framework. With little over a year until the launch of the IEP in September 2014, this process of curricular change was rapid and called for intensive and dedicated effort. In order to reduce the load on academic staff, most departments appointed a cadre of teaching fellows to drive forward change, who often brought considerable expertise in teaching and learning and/or industry experience. Many interviewees noted that this phase of work generated considerable debate within departments about the focus and goals of their undergraduate programs: *“the IEP brought a lot of issues to the fore, like what type of graduates are we trying to produce... what modules do we actually need?”* Reflecting differences in their profile, culture and priorities, approaches to curriculum reform varied enormously between departments. Some, such as Chemical Engineering, took the opportunity to overhaul the entire curriculum and pedagogical approach. Others were noted to have *“reconfigured their [existing] curriculum to fit around the IEP framework”* without adopting deeper changes. Others, such as Biomedical Engineering, were developing undergraduate programs for the first time and used the IEP framework as *“a scaffold to build the new curriculum around.”*

Wave 3: developing the IEP's cross-Faculty modules. The third wave of activity – focused on the IEP's multidisciplinary components – was driven by a newly-appointed cohort of teaching fellows. Following a series of small-scale pilots, a major test of the IEP model came in June 2014 with a pilot involving 700 students from across the Faculty. It focused on perhaps the most complex component of the new curriculum: *How to Change the World* (HTCTW), an open-ended, two-week humanitarian challenge that would bring together all engineering students at the end of Year 2. Taking its participants from the Faculty's existing second-year cohort, the HTCTW pilot shone a light on several critical challenges facing the IEP. In particular, the pilot was marred by low student engagement, driven primarily by the participants' lack of prior exposure to open-ended problem solving, and the activity timing, after the end-of-year exams when students were "*completely exhausted*." Nonetheless, the pilot offered considerable insights that would go on to shape the design of and preparation for many components of the IEP. For example, it underlined the need for dedicated support to help students appreciate the relevance and importance of their own discipline to complex multidisciplinary problems. It also highlighted the challenge of securing flexible teaching space for large-scale group project work on the UCL campus.

In parallel with the emerging plans for educational reform in UCL Engineering, the wider university environment for teaching and learning also entered a period of radical and far-reaching change. Despite significant growth in the university's student population over the previous decade, interviewee feedback suggested that "*research was our overriding priority*." In 2013, a new university Provost took post, who "*made it clear that he had inherited a world-class university that had taken its eye off the ball in teaching. He was very candid about that*." A number of key senior management appointments soon followed – including the *Vice-Provost for Student Affairs* and the Director of the *Centre for Advancing Learning and Teaching*⁶⁵ – each of whom were deeply committed to educational culture change and to supporting and rewarding the contribution of staff to improving the quality of student education.

In the months and years that followed, a series of far-reaching reforms were implemented across the university. For example, in 2014, UCL launched the *Connected Curriculum*,⁶⁶ a vision for the university's undergraduate education that was built around "*connecting students with research, connecting students across disciplines and connecting students to real world problems*." During this period, UCL also initiated root-and-branch reforms of its appointments and promotion systems, focused on transforming how teaching achievement was recognized and rewarded.

The vocal institutional commitment to educational culture change, along with new tools to drive forward reform, was noted by many interviewees as propelling the development of the IEP. In the words of one interviewee:

⁶⁵ The Centre for Advancing Learning and Teaching has since become UCL Arena (<https://www.ucl.ac.uk/teaching-learning/professional-development>).

⁶⁶ Connected Curriculum (https://www.ucl.ac.uk/teaching-learning/sites/teaching-learning/files/connected_curriculum_brochure_21_june_2017.pdf)

"...the stars aligned...we had a Provost that was talking about teaching, a Vice-Provost that was supportive, a Dean that was driving this and wanted to see it happen and a number of new Heads of Department and lecturers that came from outside of UCL that were willing to do new things."

C.2.3. Rolling out the IEP across the Faculty (2014–date)

The IEP was launched in September 2014. Innovative features of this new curriculum – described in detail in Section C.4 – are noted in Box 15. Within their first week of joining UCL, all new engineering students were participating in the IEP's core multidisciplinary experiences: a cross-Faculty five-week *Challenge* and shared *Design & Professional Skills* (D&PS) modules. Interviewees, however, consistently pointed to *"quite a few teething problems"* during these early months of delivery with *"a lot of negative feedback"* from the student participants that exacerbated residual concerns among some academic staff about the underlying merits of the systemic curriculum reform. As one interviewee noted, *"there was still a huge reluctance. Some [academics] felt the IEP was imposed and still needed convincing."*

Box 15: Innovative features of the IEP

- **Challenges:** two intensive five-week design projects tackled by incoming first-year students. In the IEP's first iteration, both *Challenges* were multidisciplinary and brought together students from across UCL Engineering;
- **Scenarios cycles:** five-week curricular clusters, which underpin the curriculum in Years 1 and 2 of study, where students spend four weeks learning engineering theory and skills that are then applied in a full-time one-week design project;
- **Design and Professional Skills (D&PS):** modules throughout the first three years of study, designed to build students' personal and professional skills;
- **Minors:** specialist options for second and third year students across UCL Engineering;
- **HTCTW:** a two-week, full-time multidisciplinary project focused on key societal challenges.

Interviewee feedback points to a number of factors that contributed to the problems faced during the early implementation of the IEP. Three issues stand out. The first issue related to a lack of expectation-setting among the incoming students. The first cohort of students studying under the IEP were reported to be unprepared for the levels of open-ended problem solving and self-directed learning they experienced: *"there was definitely a culture-shock of 'why can't they just give us the answers?'"* The second issue centered around the integration and cross-fertilization of core IEP components, particularly with respect to the D&PS module. Although delivered as a stand-alone module, D&PS was designed to closely integrate with the students' learning throughout the *Scenarios* and *Challenges*, such that they were able to learn, reflect upon and apply their professional skills in authentic contexts. During early iterations of the IEP, however, this integration proved challenging, and the experiences of some students and departments were that *"the professional skills [module] bore little relation to the rest of the courses."* The third issue related to *Challenge 1*: a project held in the first five weeks of the degree program that, at the time, brought together all first-year students from across the Faculty. The *Challenge* called upon students to work in multidisciplinary teams to tackle an authentic problem

framed around the sustainable energy needs of different countries across the world. Many students, however, struggled to connect with the problem posed, which was characterized as *“too vague and seemingly unrelated to what they understood to be their chosen discipline.”* In addition, as this *Challenge* was the students' first experience in their undergraduate studies, academics also voiced concerns that it appeared to come at the expense of alternative activities that would allow students to explore their specialist engineering discipline and connect as a departmental cohort.

In response to these concerns, a number of major adjustments were made to the IEP in 2016/17. Most significantly, *Challenge 1* was *“taken into the departments”*; in September 2016, each department delivered a new five-week experience to introduce their incoming cohort to the engineering discipline and to engage students with project-based learning. One example of the new approach taken to *Challenge 1* is provided in Box 16, taken from Mechanical Engineering.

Box 16: Challenge 1: UCL Mechanical Engineering

The 2016/17 Mechanical Engineering *Challenge 1* aimed to engage students and *“get them involved in something practical from day 1.”* It was framed around a single-cylinder internal combustion engine. The incoming cohort of 150 students was divided into six groups and each was given an engine stripped into component form. Each group of 25 was then split into five teams, and each *“assigned a unique sub-assembly of the engine,”* such as the fuel system or the cylinder head.

With *“a real-life jigsaw in front of them,”* teams were asked to research each of the components of their sub-assembly and identify how they fit together. Although teams were not required to construct the components, by the end of the five-week *Challenge*, *“all five groups had a fully working engine.”* The D&PS modules delivered in parallel to *Challenge 1* were designed to integrate directly into these projects. So, for example, these modules introduced students to the CAD packages they needed to use when creating engineering drawings of their engine components. At the close of the project, each student was asked to prepare a short video and report about their sub-assembly, and each team was asked to create a video about *“how their engine works.”*

Despite the early issues faced, interview responses from the first IEP student cohort pointed to a progressive improvement in their experiences with the new curriculum as they advanced through their studies. In particular, many identified the department-based *Scenarios* as *“the highlight of my degree,”* allowing them to draw together and apply their learning from the preceding modules within *“an intensive, stressful but really fun week.”* One experience, in particular, however, appears to have been transformative in improving students' attitudes towards the IEP. In the final term of Year 2, UCL Engineering students often apply for industry internships or engineering-based experiences for the summer vacation. When the IEP cohort embarked on this application process, many were surprised to find that their experiences in the IEP *Challenges* and *Scenarios* *“was all the interviewer wanted to talk to me about...he was asking about how I dealt with conflict and how I managed my time and [I found that] I had a*

lot to say!" Similarly, many faculty interviewees suggested that students' internship application experience appeared to:

"flip their opinions [about the IEP] ... the positive feedback they got from interviews made them rethink their misconceptions of what we were doing. They became the best salespeople for the IEP... then they started to talk to the years below."

With these external experiences emphasizing the benefits of the IEP to their learning and employability, student engagement progressively grew. By the time the first IEP cohort participated in HTCTW at the end of Year 2, observers consistently pointed to *"a real energy in the room... [with] some fantastic ideas coming out."* Interview feedback from students in the first and second IEP cohorts was similarly positive, with many describing the skills they had gained from working with *"my peers from different engineering backgrounds"* as well as with external experts from across a range of sectors.

By early 2017, with the initial IEP roll-out complete and the first student cohort midway through their third year of study, attention turned to building upon this educational platform. In the months and years to come, the IEP team will dedicate particular effort in three areas:

- **ensuring that the Faculty's continuing educational development is informed by the latest evidence base and world-class expertise.** This will be advanced through the Centre for Engineering Education (CEE),⁶⁷ which was established in April 2015 as a major institutional and national hub for research in engineering education;
- **offering more authentic industry experiences.** For example, plans are underway to establish an optional industry-based project in the final year of BEng or MEng study which will be tackled by multidisciplinary teams of students from across UCL Engineering;
- **supporting the expansion of UCL Engineering within a new university campus.** In 2022, UCL will launch a new campus, UCL East,⁶⁸ in the former London 2012 Olympic Village. UCL East will bring 2500m² of new teaching space for UCL Engineering as well as some new undergraduate programs, such as Engineering Design and Mechatronics.

⁶⁷ Centre for Engineering Education (<http://www.engineering.ucl.ac.uk/centre-for-engineering-education/>)

⁶⁸ UCL East (<http://www.ucl.ac.uk/ucl-east>)

C.3. UCL Engineering's educational approach

Interviewees pointed to a number of defining features of the IEP's educational approach:

- **multidisciplinary learning through cross-Faculty projects and experiences:** allowing students to *"break out from their disciplinary silos,"* offering them critical insight into the role and place of their own engineering discipline as well as the tools *"to work effectively with people from a range of backgrounds and perspectives";*
- **the application of knowledge to practice:** allowing students to contextualize and reinforce their learning throughout the curriculum by applying their knowledge to authentic engineering problems, many of which have been developed with partners from industry, charities, development agencies and across the regional community;
- **focus on engineering as a vehicle for positive world change:** providing, as interviewees noted, *"students, from day one, with a sense of the power of engineers as people who can change the world for the good,"* and nurturing their *"capacity and confidence to use their engineering skills to make a positive impact on society";*
- **development of professional capabilities:** offering an education that blends both rigor in the engineering fundamentals with *"a real breadth of learning in many different professional skills like relating, working in teams and technical writing."*

UCL Engineering is not alone in driving forward an educational agenda that is underpinned by the features outlined above; some or all appear in the mission statements of many engineering schools worldwide. Where UCL Engineering stands apart, however, is in the scale of their application and in their integration across the full curriculum. In many engineering schools across the world, student-centered, project-based curricula cater only to small student numbers or a selected subgroup of the overall cohort. In addition, where authentic, multidisciplinary challenges are offered, they are often isolated from the rest of the curriculum, with students struggling to connect these experiences to their learning in the 'core' engineering modules. In contrast, the IEP education is integrated across the core curriculum for all engineering students. UCL Engineering engages a thousand incoming engineering students, from across eight departments, in immersive and authentic engineering projects that are integrated with their disciplinary modules into a coherent curriculum structure. In addition, the IEP curriculum provides students with a range of very different project experiences, varying in scope, length, format, intensity and assessment protocols. This diversity of experience helps students to develop an agile and adaptable approach to problem-solving across and beyond their undergraduate studies.

The capacity of UCL Engineering to deliver such large-scale educational innovations has been significantly enhanced by a number of important communities, tools and support systems. Three examples of such facilitators for reform are given below.

Firstly, the new cadre of teaching fellows, employed both centrally in the IEP team and embedded within departments, has brought dedicated expertise and educational rigor to the IEP transformation. In many cases, these teaching fellows do not simply fulfill administrative or teaching delivery roles; many have been charged with leading key curricular themes and experiences that run across the curriculum, enabling them to promote coherence and connectivity across the students' learning. The central IEP team has also provided staff training in areas such as 'facilitation' to advance the introduction of student-centered learning across the Faculty.

Secondly, the introduction of the IEP has catalyzed important advances in student assessment. A major challenge for project-centered curricula, particularly when delivered at large scale, is ensuring that individual student contributions to group projects are appropriately recognized and the marking system moderated accordingly. Inadequate recognition of contributions made by individual team members risks provoking widespread student disengagement. With project-based learning at the heart of the IEP curriculum, UCL Engineering has dedicated significant effort to creating new peer assessment tools that have proved to be innovative and effective. Examples of the new tools and projects developed by UCL Engineering include:

- the development and introduction of a student-generated peer-assessment rubric within the first-year *Challenges*, in which each student team identifies and agrees upon the criteria by which the contributions of team members will be assessed at the close of the project;⁶⁹
- the concept of '360-degree peer assessment', developed by the Biomedical Engineering department, which allows students to respond to and review the peer assessments made by their teammates, moderating the marks allocated accordingly;
- spearheading a UCL-wide initiative to develop a bespoke online peer assessment tool.⁷⁰

Thirdly, UCL Engineering has established the Centre for Engineering Education (CEE).⁶⁷ It brings together two functions: one internally-facing – *"to help us to change the Faculty's educational culture"* through evaluating student learning and offering academic support – and one externally-facing – *"to advance knowledge in engineering education"* and influence practice elsewhere. Co-hosted by UCL Engineering and the UCL Institute of Education,⁷¹ the CEE brings together UCL educational researchers with leading academics from institutions worldwide. From late-2017, the CEE will appoint its first post-doc to begin formal evaluation of the IEP. From September 2018, it will launch an MSc program in engineering education, targeting engineering academics.

A summary of UCL Engineering's educational approach, distilled from UCL documents and interview feedback, is provided in Table 3.

⁶⁹ Roach K., Smith, M.S., Tilley, E., Marie, J., Mitchell J.E. (2017) *How student-generated peer-assessment rubrics use affective criteria to evaluate teamwork*. Paper presented at SEFI Annual Conference.

⁷⁰ IPAC Consortium (<https://www.ucl.ac.uk/teaching-learning/news/2017/mar/how-assess-fairly-student-contributions-group-work>)

⁷¹ Institute of Education (<http://www.ucl.ac.uk/ioe>)

Educational feature	Details
Criteria for selection of student intake	In 2012, UCL ceased interviewing prospective students; candidates are now selected solely on the basis of high-school ('A' Level) grades and written submissions. In UCL Engineering, student selection is conducted on a departmental basis. UCL Engineering departments traditionally required prospective students to have studied mathematics and physics at 'A' Level. However, with girls accounting for only 20% of Physics 'A' Level entrants in the UK, most departments dropped this requirement following the introduction of the IEP in order to "address the Faculty's gender balance." CECE is alone, however, in not stipulating any prerequisite subjects for entry; successful candidates to this department are only required to have attained top 'A' Level grades in their chosen disciplines.
Flexibility and student choice	Students remain within their chosen engineering discipline from entry to UCL and throughout their degree. Choice is offered through the Minor (in Years 2 and 3) and electives (in Year 4).
Opportunities to work across disciplines	Shared IEP modules provide opportunities for students to work with peers from other engineering departments. Beyond electives, limited opportunities are available for them to work with students from outside engineering. However, many of the departmental <i>Scenarios</i> and projects connect students with industry, charities, schools and the wider community.
Pedagogical approach	Interviewees estimated that around 40% of the curriculum in most departments is delivered through project-based experiences. The remaining curriculum is largely devoted to 'core' engineering or Design and Professional Skills modules where pedagogical practice varies by department. Team teaching is largely confined to multidisciplinary IEP modules and departmental <i>Scenario</i> projects.
Assessment and feedback	Although the IEP has brought a slight reduction in the quantity of exams at the end of Years 1 and 2, it has also introduced new assessed deliverables during the rest of the academic year, typically linked to project work. Almost all such assessments are summative and therefore require second marking. As a result, many department-based interviewees suggested that "the net assessment [load] increased after the IEP came in." In addition, the introduction of the IEP has also heralded the development of a number of novel tools for the evaluation of individual contribution to team project work.
Teaching and learning support	At a Faculty level, teaching and learning support and training is provided both through the central IEP and through the CEE. At a university level, <i>UCL Arena</i> provides a number of pathways for professional development support in teaching and learning as well as access to the <i>UCL ChangeMaker</i> ⁷² grants, which funds collaborative staff/student educational reform projects.
Reward and recognition of teaching	UCL supports three career pathways: an academic track, an education-focused track and a research track. During the preparation of this case study, the university was rolling out a major reform to these pathways, much of which focused on improving and formalizing the recognition and reward of teaching achievement. For example, the new education-focused track supports advancement to a 'Professorial Teaching Fellow' position and the academic track provides much greater scope for advancement on the basis of educational impact.
Educational research activities	Interviewees reported a significant growth in engineering education research capacity since the introduction of the IEP, supported at the Faculty level by the CEE and at departmental level by emerging discipline-specific educational research groups. Areas of particular research focus include (i) problem-based and skills-based learning; and (ii) participation and inclusivity in engineering throughout schooling, higher education and professional careers.
Extra-curricular opportunities	In addition to those linked to each engineering department, a number of student-led clubs are organized at a Faculty level, ⁷³ many of which focus on engineering outreach. Students from UCL Engineering are also heavily involved with the <i>UCL Global Citizenship Programme</i> . ⁷⁴

Table 3. Key features of the approach to undergraduate education at UCL Engineering

⁷² *UCL ChangeMakers* (<http://www.ucl.ac.uk/changemakers>)

⁷³ *UCL Engineering clubs and societies* (<http://www.engineering.ucl.ac.uk/groups-and-societies/>)

⁷⁴ *UCL Global Citizenship Programme* (<http://www.ucl.ac.uk/global-citizenship-programme>)

C.4. Curriculum design

An outline of the IEP curriculum is provided in Figure 14. It comprises two broad components:

- 1. A common curriculum structure shared by all engineering departments** during Years 1 and 2 of study. Although these modules are designed and delivered at a departmental level, their goals, format and assessment protocols are shared across the Faculty. This common curriculum framework integrates a number of key elements:
 - **Challenges:** two immersive five-week projects at the start of Year 1 introducing students to the role and scope of engineering and setting a context for their studies;
 - **Scenarios:** a series of five-week curricular cycles where students spend four weeks building critical engineering skills and knowledge that they subsequently apply to tackle a one-week intensive design project;
 - **Design and Professional Skills:** a structured program of skill development that students can apply and build upon in their *Scenarios* and *Challenges*;
 - **Minors:** specialisms, often at the interface between engineering disciplines, such as sustainable building design, ocean engineering and regenerative medicines;
 - **Core engineering modules:** largely discipline-specific engineering modules.
- 2. Multidisciplinary experiences that bring together most or all students** from each year-group across UCL Engineering. These experiences are coordinated centrally by the Faculty and taught by cross-Faculty teams. They include:
 - **Challenge 2:** the second of two five-week *Challenges* held during Year 1, where students from across the Faculty tackle a multidisciplinary problem;
 - **common professional skills:** a shared set of professional skills modules – around a quarter of those taught in total – that are common to all departments;
 - **mathematics:** the only ‘core’ engineering module that is taught Faculty-wide;
 - **How to Change the World (HTCTW):** a two-week multidisciplinary project at the close of Year 2 where students tackle open-ended humanitarian problems.

The IEP focuses predominantly on the first two years of the BEng and MEng curriculum at UCL Engineering.⁷⁵ Years 3 and 4 of study are largely determined by each department, but most bring together individual or group projects with electives and core disciplinary content.

Each key element of the IEP – *Challenges*, Design and Professional Skills, ‘core’ engineering modules, *Scenarios*, HTCTW and Minors – is described in turn in the subsections that follow.

⁷⁵ Around 60% of UCL Engineering undergraduates take an MEng degree, which is four years in duration. The remaining BEng students follow a similar pathway, but complete their studies at the close of Year 3. The UCL Engineering academic year is divided into three 10-week terms; the final term is largely dedicated to exams.

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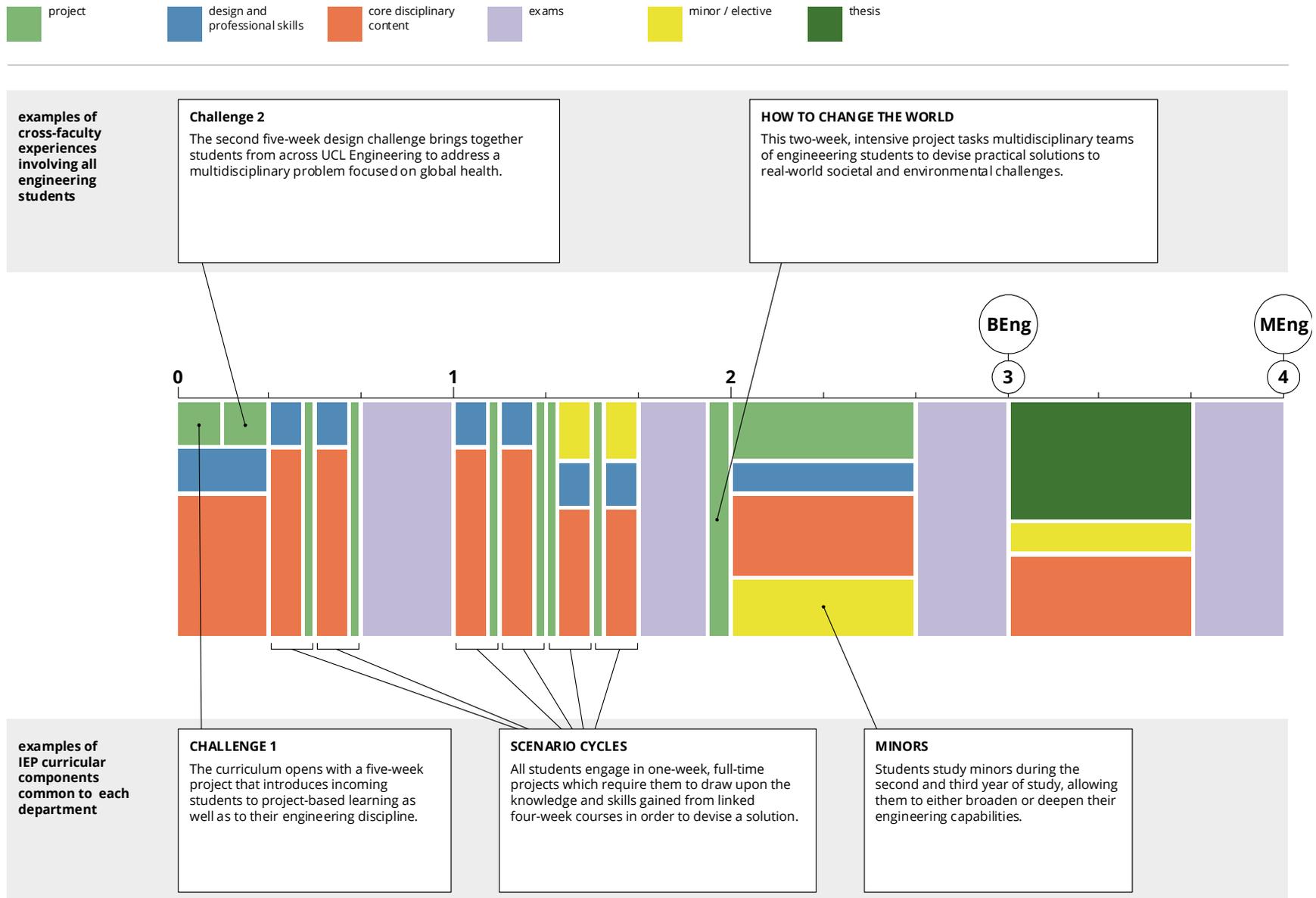


Figure 14 . Outline curriculum structure of the IEP at UCL

C.4.1. Challenges

On entry to their undergraduate studies, 700 students⁷⁶ from across UCL Engineering participate in the *Challenges*: two five-week projects that aim to: “introduce them to team-working and experiential learning, introduce them to engineering design and give them a very practical introduction to the impact engineers can have at a global scale.” The projects focus in turn on the two broad stages of the design cycle:

- **Challenge 1** is designed and delivered by departments. It asks students to take an open-ended problem and “explore and refine it, conduct research and coming up with ideas”;
- **Challenge 2** is a cross-Faculty experience involving all engineering students. It takes a “more tightly defined brief through to a working prototype.”

Box 17 and Box 18 provide further details of *Challenge 1* and *Challenge 2* respectively.

Box 17: Challenge 1

Challenge 1 is departmentally-based and designed to introduce students to their discipline and offer “a transition from the guided thinking they experience at [high] school to an independent, self-driven way of learning.” All departments adopt the same timetable, learning outcomes and assessment protocols for *Challenge 1*. For example, assessments involve both individual elements (such as a short video presentation and a self-reflective review) and team elements (such as a technical report and peer assessment).

While all departments follow a common framework for *Challenge 1*, each devises its own context and brief for the project. Some have taken a research-focused approach, such as Computer Science, which tasks student teams to each create a website to outline the activities of one of the department’s research groups. Other departments have focused on engineering design, such as CEGE, as outlined below.

The CEGE department framed its 2016/17 *Challenge 1* around the 2010 Chilean earthquake. Membership of each student team was drawn both from CEGE in the UK and *Adolfo Ibáñez University* (AIU) in Chile. Over the course of the five-week project, the UK and Chilean students were asked to collaborate remotely on a series of complementary projects that focused in turn on four key civil engineering themes: structures, geotechnical engineering, transportation and geomatics. For example, in the structures theme, CEGE students were asked to build and test a scale model of an office tower from the Chilean city of Concepción that collapsed during the 2010 earthquake; in turn, the AIU students were asked to create a numerical model of the tower to identify the mode of failure. Alongside the two two-hour weekly workshop sessions that supported and informed the teams’ progression through the projects, CEGE students were also expected to manage the online collaborations with their Chilean teammates.

⁷⁶ Management Science BSc students do not participate in the *Challenges*.

Box 18: Challenge 2

Challenge 2 brings together students from across UCL Engineering. It is coordinated by the central IEP team and delivered by a cross-Faculty teaching team. The project brief is tightly-defined and asks students *"to make a manufacturing plant for a TB vaccine in sub-saharan Africa, that makes vaccines on-site for the people that need it."* Seven hundred engineering students, from across seven departments, are divided into multidisciplinary teams of 35. Each team is built from three specialist groups, comprising:

- civil and mechanical engineers who focus on the power and structure of the plant;
- electrical engineering and computer scientists who focus on the control systems for the bioreactor;
- chemical, biochemical and biomedical engineers who focus on the bioreactor.

Each specialist group is provided with a technical brief and asked to produce a working prototype. Similar to *Challenge 1*, students are required to attend two two-hour sessions each week, which are designed to inform the teams' thinking and enable them to monitor their progress. Each multidisciplinary team also meets on a weekly basis to *"discuss progress and exchange information between groups."*

C.4.2. Design and Professional Skills (D&PS)

D&PS provides a structured approach to the progressive development of the students' professional engineering skills. Although taught departmentally, the modules adhere to a common set of learning outcomes and assessment protocols. Around one in four of D&PS modules is delivered to departments by the core IEP team, covering *"cross-cutting topics"* such as teamwork, leadership, communications and project management. Modules requiring *"a departmental-specific point-of-view,"* such as technical drawing, design, risk, ethics, law and professional standards, are developed and delivered by departments, typically by a team of teaching fellows.

D&PS modules are designed to coordinate with the *Challenges* and *Scenarios* such that the critical skills needed to tackle these projects are developed 'just-in-time'. For example, while engaged in *Challenge 1*, the concurrent D&PS modules bring students together in their *Challenge* teams to reflect upon and build their teamworking and planning skills. Then, during *Challenge 2*, when *"students are stepping up to work with others from outside their department,"* the concurrent D&PS module uses the *Challenge* schedule as a framework to explore and develop communications and project management skills. This learning is further advanced as students move into their departmental *Scenarios*. For example, Computer Science offers a five-week project during Year 1 where students work with local schools to develop interactive coding lessons for children aged 10–15. This experience calls upon students to put their D&PS learning into practice, for example, by *"communicating with people who are not Computer Scientists and managing the project carefully to meet their deadlines."*

C.4.3. Scenarios

The first and second years of the IEP curriculum are punctuated by six *Scenario* cycles. Although each *Scenario* is designed and delivered on a department-by-department basis, they all share a common structure. *Scenario* cycles are five weeks in duration and comprise four weeks of 'core' disciplinary and D&PS modules followed by a one-week full-time team project, designed to "*consolidate and contextualize what students have learned in the modules.*" The final two *Scenario* cycles (in Year 2, Term 2) reverse this format, and ask students to first tackle a one-week intensive project, and then explore the theories and principles that underpin it.

Often drawing on external partnerships with industry, charities and the regional community, the *Scenario* projects ask students to "*solve real engineering problems.*" As students progress through their studies, the *Scenario* projects are designed to become increasingly complex and open-ended. Most are managed by a departmental teaching fellow, with support from the academic leads of the linked modules. Each department has taken a distinctive approach to the design and delivery of their *Scenario* projects. Examples of the approaches taken are provided in the boxes overleaf: Box 19 outlines the six *Scenario* project briefs offered in Biomedical Engineering and Box 20 looks in more detail at one *Scenario* project from Chemical Engineering.

C.4.4. Core disciplinary modules

While the IEP introduced a new stream of project-based experiences into the UCL Engineering education, much of the curriculum continues to be dedicated to 'core' engineering disciplinary content. During the first two years of study, however, these 'core' modules are re-configured into four-week blocks such that they offer a theoretical context for each one-week *Scenario* project.

Most 'core' modules are taught traditionally, based around lectures, tutorials, workshops and 'labs'. However, an increasing number are adopting active, student-centered approaches. For example, the first-year fluid mechanics module in Biochemical Engineering has adopted a 'flipped classroom' approach; with videos and quizzes before class, application to real engineering problems during class and online problem-solving after class. Students draw heavily on their learning in this module as they tackle the linked *Scenario – Scenario 2* in Term 2 – where they are asked to "*evaluate the rheology of an unknown fluid sample, and design and characterize a mixing operation that will ensure the fluid is well mixed.*"

The only 'core' module taught Faculty-wide⁷⁷ – Year 1 and 2 Mathematics – is designed to "*embed engineering practice into mathematics.*" A cross-Faculty team of five academics delivers the mathematical theory to students in two groups of 300. Departmentally-based workshops then challenge students to apply these mathematical tools to solve discipline-specific engineering problems. These disciplinary workshops share a common structure and assessment protocol.

⁷⁷ Computer Science, Biochemical Engineering and Management Science students are offered separate, discipline-specific, mathematics education and do not participate in this Faculty-wide module.

Box 19: Briefs from the six Scenario projects offered in Biomedical Engineering

- **Scenario 1:** design a smartphone app for measuring pulse rates;
- **Scenario 2:** test the suitability of materials for a leg brace;
- **Scenario 3:** design and build an article of smart clothing for an athlete;
- **Scenario 4:** use electrical activity from an arm to control a computer game;
- **Scenario 5:** pitch a startup idea based on a real medical device developed by a researcher in the Biomedical Engineering department;
- **Scenario 6:** develop a prototype device to support independence and quality of life for a disabled population, as identified by a partner charity.

Box 20: Scenario 6 in Chemical Engineering

Each of the six Chemical Engineering *Scenarios* is led by a teaching fellow, who ensures that the week-long experiences align with the students' learning from linked D&PS modules and two of the four 'core' modules delivered during that term. *Scenarios* are delivered to a year-group cohort of between 140 and 160 students. To "keep the program fresh," new *Scenarios* are created every year, each focused on a different application of Chemical Engineering.

The 2016/17 *Scenario 6* (Year 2, Term 2) focused on the pharmaceutical industry. Students self-divided into groups of six and were presented with a deliberately open-ended brief, placing them as a senior engineering team in a pharmaceutical firm facing a looming competitive threat to their 'wonder-drug' to combat Alzheimer's disease. Teams were asked to produce a strategic report on how the firm should respond to the crisis faced. They were asked to include a number of elements in this report: (i) the development options for the reformulation of the drug and manufacturing process; (ii) research on the tablets used, calling for laboratory experimentation on their hardness and flowability; (iii) proposals on the optimal particle morphology of the crystals for drug formulation, calling for mathematical modeling; and (iv) a business strategy for the firm going forward. Midway through the week, teams were "*dropped a bombshell*": the firm's competitor would be entering the market much sooner than expected and, in addition to their strategic report, teams would be required to produce a market strategy and direct-to-consumer YouTube advert.

Scenario 6 was designed for integration with two 'core' modules delivered during Term 2 of Year 2 in Chemical Engineering – *Separation Processes 2* and *Crystallization* – and established close partnerships with the academics involved in each. The academic lead from *Separation Processes 2* also "*came in as a 'subject matter expert', working for the company, during the launch lecture [for the Scenario], to discuss the active therapeutic and crystallization aspects*" of the brief. The project also integrated key topics covered by the linked D&PS modules. For example, the law components of the D&PS module helped to support students' work in "*navigating the legal frameworks for pharmaceuticals, including the discovery and approval processes for drugs*," while the ethics components supported students as they developed an advert for their drug which was "*made in good faith and demonstrated ethical judgment that was sensitive to the wider audience.*"

C.4.5. Minors

During the second and third year of study, all students select to study one Minor from around 20 options. Minors fall within two broad categories: some are designed to broaden students' skills in disciplines complementary to engineering (such as foreign languages and management) while others are designed to immerse students in a cutting-edge engineering research field that stands on the interface between disciplines (such as crime & security engineering, intelligent systems and engineering & public policy). A typical format for a Minor is outlined in Box 21.

Box 21: Typical format for UCL Engineering Minors

Each Minor comprises three modules. Early modules typically provide an introduction to the field, often drawing on expert guest lecturers from across and beyond UCL. The final module is often framed around an authentic project, where students can explore the topic further as part of a multidisciplinary team. For example, the department of Electronic and Electrical Engineering currently coordinates three Minors: *nanotechnology*, *connected systems* and *sustainable energy*. In 2016/17, the final project in the *sustainable energy* Minor asked student teams to undertake a needs brief and develop new energy solutions for a rural Kenyan community where only 5% of the community has access to national grid electricity. In the 2017/18 iteration of the *connected systems* Minor, which is focused on the Internet of Things, the closing project will ask students to develop 'smart campus' solutions for the new UCL East⁶⁸ campus; future years may focus on 'wearable technology' in collaboration with the London College of Fashion.

C.4.6. How to Change the World

During the last two weeks of Year 2, 750 UCL Engineering students come together to participate in HTCTW, a full-time, intensive multidisciplinary activity. Its goals are twofold: (i) to engage students with the role engineers can play in addressing some of the world's major social and environmental challenges; and (ii) to build students' capabilities to tackle challenging and open-ended multidisciplinary problems. The problems posed are intentionally ill-defined, with students offered "*a lot less scaffolding than they would have had in the Challenges.*"

Students are divided into five cohorts, each addressing a different humanitarian challenge, such as the use of smart technologies to encourage energy-saving, or the supply of safe, clean water and sanitation. Students are then allocated into multidisciplinary teams of four or five to develop practical and novel solutions to their chosen challenge. HTCTW is delivered by a cross-Faculty teaching team, with two academics and one post-graduate teaching assistant managing each challenge cohort of 150 students. Challenge-specific mentorship and guidance is also provided to the student teams by external partners, from organizations such as the World Bank, Red Cross and Arup; 65 external partners engaged in HTCTW 2017, spread across the five cohorts.

Following development of their solutions during the second week of the activity, teams deliver a '*pitch and poster*' presentation to a judging panel of external experts at a final showcase event.

C.5. Review and concluding comments

The IEP provides a robust curricula blueprint – from one of the world’s premier research-led universities – for student-centered, project-based learning that is immersed in authentic engineering practice. It offers an exemplar of educational best practice in three domains.

The **first domain** is the integration of ambitious multidisciplinary experiences into the engineering curriculum. Through Faculty-wide activities like HTCTW, students address multidimensional, open-ended problems that require them to work with those from different perspectives, backgrounds and areas of specialism. These experiences also offer students an invaluable insight into the role and application of their disciplinary specialism in real engineering problems.

The **second domain** is the coherent curricular framework offered by the IEP, that allows students to reinforce and advance their understanding of engineering theory through its direct application to real-world problems. Large elements of the curriculum are divided into discrete clusters, where the ‘core engineering content’ is delivered alongside immersive and engaging projects in which this learning must be applied. This approach is most visible in the *Scenario* cycles delivered during the first two years of study. Interview outcomes highlighted the diversity of *Scenarios* offered by departments and the creativity and insight with which they had been designed.

The **third domain** of best practice is the scale over which the IEP has been delivered. The reach and scope of the IEP are impressive; this is not a ‘bolt-on’ experience or an option offered to a small subsection of the student cohort. Almost all of the 1000 undergraduates commencing study at UCL Engineering participate in the IEP.

While noting the problems experienced during the IEP’s early implementation, students, staff and senior managers alike pointed to a vast improvement to the educational approach, and thereby the student experience, in the months and years since. Many appeared to use the HTCTW experience as a barometer of the improved quality and impact of the IEP curriculum over time – they pointed, in particular, to vast improvements in student engagement and learning during the last three iterations of this activity. At the same time, almost half of the UCL academics and senior managers interviewed noted “*unexpected effects*” of the introduction of the IEP on the Faculty culture and attitudes towards teaching. Many suggested that it had “*broken down barriers between departments*” and offered a platform for “*a new spirit for educational research.*” Others reported that “*we now seem to be a Faculty where there is a buzz about teaching. It seems to have changed the conversation entirely.*”

Despite these strong foundations, the full impact of the IEP has yet to be realized: “*the true test of the IEP won’t come for a few years, until we get feedback from employers and we can see the quality of PhD candidates.*” To capture such impact evidence in a systematic manner, the CEE⁶⁷ is developing a longitudinal study to determine the influence of the IEP on the capabilities, attitudes and career trajectories of its graduates.

C.5.1. Success factors

Interviewee feedback pointed to a number of success factors that have underpinned the development and delivery of the IEP. Three factors stand out, as outlined below:

- **quality of Faculty leadership:** when describing the successes of the IEP, many interviewees referred to the strength of Faculty leadership in driving the change. It was seen as a flexible and responsive leadership approach that offered *“a balance between vision and ambition with a pragmatism about how we can make this work.”* In particular, many pointed to the founding director of the IEP, who has since become the associate dean for teaching and learning. With a long history at UCL, this individual was characterized as a well-known and respected figure across campus who brought *“a real understanding of the ground, the culture, the people.”* Interviewees also described the associate dean as offering *“a soft leadership style, where he listens to everyone and people respond to that. It means that they can tolerate change more easily.”*
- **supportive institutional environment:** in parallel to the development of the IEP, the culture and support systems in teaching and learning at UCL were being transformed, and the university leadership was vocal and explicit in its support for educational reform. In the words of one interviewee, *“this undoubtedly played a role in helping to make the change happen.”* In particular, changes to UCL’s promotion systems were identified as an explicit signal that *“the university was prepared to put its money where its mouth is”* to improve educational quality. In doing so, the university has instilled a new confidence in academics about investing time and developing expertise in teaching and learning. At the same time, interviewees from UCL Engineering senior management noted that *“the university did not get in the way of what we were trying to do,”* providing the Faculty with considerable freedom regarding the direction and focus of the change process.
- **empowering departments to drive change from the ‘bottom-up’:** the IEP transformation was described as providing *“a philosophy that came from the top down but with the implementation coming from bottom up.”* Ensuring that departments were provided with *“freedom in the direction of change”* – one that reflects their priorities, interests and culture – was understood to be critical to the success of the reform. In many departments, the new cohort of teaching fellows, and the talent, energy and ideas they provided, proved critical in establishing a community of *“committed individuals that made the change happen.”* UCL Engineering now employs around 80 teaching fellows in full- or part-time roles. Many of these new appointees quickly assumed pivotal roles within their departments, often with responsibility for designing and delivering project *Scenarios* or for ensuring the coherence of student learning in *“main-line subject areas, as these thread through the curriculum.”*

C.5.2. Challenges faced

UCL Engineering has faced a range of challenges in delivering the IEP. Some mirror the **practical constraints** experienced by universities across the world in the transition to experiential, student-centered learning, including:

- **inflexibility of university learning spaces:** many interviewees noted that UCL offered insufficient flat-floored flexible learning spaces to support the large-scale project-based learning experiences that are integral to the IEP: *“that is an area where the rubber hits the road and that’s where we faced most problems.”* Instead, some reported that they had to *“configure the projects to fit the spaces we have, rather than the other way around.”* However, many of these issues are likely to be resolved as the extensive and state of the art new teaching spaces from UCL East⁶⁸ come online from 2022.
- **increases in curricular ‘load’:** interviewees suggested that, following the introduction of the IEP, *“the curriculum is more demanding than it used to be.”* Despite the introduction of new curricular components – such as *Scenarios* and *Challenges* – some departments were reported to be reluctant to *“cut down the existing core content,”* leading to higher contact hours overall. Other interviewees pointed to a net increase in the assessment load, with assessments associated with the new curricular components being included in addition to – rather than instead of – existing exams, assignments and coursework.
- **integration of curricular components:** the IEP is built from key curricular components (*Scenarios*, *Challenges*, ‘core’ fundamentals, etc.) that are designed to allow students to contextualize, integrate and apply their learning across their studies. Interview outcomes suggested that this integration – and the cross-fertilization of themes, knowledge and skills between each component – required further development in some departments.

In addition to these practical constraints, the IEP implementation has faced challenges that have posed a more fundamental barrier to the implementation and sustainability of the curricular reform. Three stand out in particular.

The **first challenge** relates to *“poor communication of the purposes of the IEP to students.”* Indeed, Faculty senior managers consistently identified this issue as *“the one thing I would do differently, better, if I had to do it again.”* As one explained:

“We were doing something quite different and disruptive and we didn’t spend enough time explaining to the students why. So they suddenly found themselves in a situation where they were being asked to do things very differently to what they saw engineering students doing elsewhere and they didn’t understand why.”

With limited information offered to incoming students about the drivers and goals of the IEP, many voiced frustration with the approach taken; frustration that was understood by some to be further compounded by *“dissenters”* among academic staff who *“shared their views with students in a way that was not helpful.”*

The **second challenge** facing the IEP is achieving an effective balance between, on the one hand, establishing a cross-Faculty educational model that is coherent, ambitious and evidence-informed, and, on the other hand, ensuring that each department retains ownership of their disciplinary curriculum and is able to shape its development according to their own priorities and culture. The IEP has called upon departments to invest considerable time and expertise in fundamental educational reform. Some of the ideas and approaches developed, however, lie beyond the IEP structure and do not conform to all elements of its timetabling requirements. As a result, a number of departments have asked for discretion in their curricula approach. For example, while both Management Science and Computer Science have integrated authentic project-based experiences throughout their curricula that *“are in the spirit of the IEP,”* the format of these activities does not strictly adhere to the five-week *Scenario* cycle. CEGE also faced particular challenges. Coming on the back of a well-regarded and radical overhaul to its own departmental curriculum, the IEP called on CEGE to engage in a second round of far-reaching educational reforms. The model subsequently adopted by CEGE was described as *“a compromise between the IEP approach and the department’s [existing] approach.”* A major challenge facing the IEP in the months and years to come will be to maintain an effective balance between *“giving departments more control without losing the program philosophy and going back to where we were, before the IEP.”*

The **third challenge** faced by the IEP relates to the roles and focus of teaching staff. While the extent differed between departments, interviewee feedback suggested that the introduction of the IEP has led to a bifurcation of academic staff roles: that the transition away from teacher-centered delivery of ‘engineering content’ and towards project-centered learning had left *“research-focused staff, who would have taught the traditional lectures, doing less teaching”* and *“staff that are more interested in teaching taking on a much greater load.”* Interviewees among this latter group consistently reported that *“setting up the program took a lot of work, and my research suffered.”* Where this reshaping of academic activities reflects the interests and priorities of staff members, this separation of roles may not necessarily present a problem. However, its success rests on the capacity of the new UCL promotion system to appropriately recognize and reward the contribution of academics in the education domain. Notes of concern were expressed by some interviewees in this regard: *“a lot of people who were heavily involved in the IEP have been promoted to full professor, but for the less high-profile people, their work has not been recognized.”*

Despite the challenges faced, however, the IEP offers a world-class educational model and both the Faculty and university have been explicit about their commitment to sustain and strengthen these educational reforms. At the same time, the growing educational expertise embedded in departments, the IEP team and the CEE ensure that UCL has a solid platform on which to continue to advance their innovative and evidence-informed curriculum.

Acronyms used in UCL Engineering case study

AIU	Adolfo Ibáñez University
CEE	Centre for Engineering Education
CEGE	Civil, Environmental and Geomatics Engineering
D&PS	Design and Professional Skills
HTCTW	How to Change the World
IEP	Integrated Engineering Programme
NSS	National Student Survey
TEF	Teaching Excellence Framework
UCL	University College London

APPENDIX D CASE STUDY – CSU ENGINEERING, CHARLES STURT UNIVERSITY, AUSTRALIA

Reasons for selection of CSU Engineering as a case study

Charles Sturt University (CSU) is based in south-eastern Australia, in a regional area set apart from the country's large metropolitan hubs. Since 2016, its engineering school – CSU Engineering – has offered a five-and-a-half-year joint bachelor/master program in Civil Systems Engineering. The program combines an 18-month on-campus education, that is framed around a series of project-based challenges, with four years of off-campus, work-based learning. The most distinctive feature of the CSU Engineering program, however, is its approach to self-directed online learning. Almost all 'technical engineering content' – including both knowledge and skills – is delivered online and accessed by students as and when they need it.

CSU Engineering is among the top 10 'emerging leaders' in engineering education identified by experts during Phase 1 of the study. When selecting CSU Engineering, experts pointed in particular to its innovative blend of online, project-based and work-based pedagogical approaches. The newly-developed program was described as "*completely rethinking what engineering education ought to look like*" with the potential to be "*very influential, if they can pull it off.*"

D.1. Context

D.1.1. The university context

Charles Sturt University (CSU) is located in regional south-eastern Australia, in an area marked by low population density, away from the country's major metropolitan hubs. Named after a British explorer, the university was established in 1989, following the merger of three Colleges of Advanced Education. It is based across seven campuses⁷⁸ in regional New South Wales. CSU attracts an annual research income of AUS\$14m and ranks 25th nationally for publication output. However, as outlined below, what sets CSU apart from its national peers is its pedagogical focus on online and work-based learning and its commitment to the regional community.

CSU has long been Australia's largest provider of distance and online education. It is home to around 40,000 students, spread in roughly equal numbers between three populations: on-campus undergraduates, off-campus undergraduates studying online, and off-campus post-graduates studying online. Its undergraduate intake is distinctive in a number of respects. For example, 71% are over the age of 21 (compared to a national average of 54%) and, among on-campus students, 77% are from remote or regional Australia. CSU's intake is also predominantly first generation students: in 2016, only 14% of its incoming undergraduates indicated that their parents held a undergraduate degree. As a result, many interviewees noted that, *"CSU's number one competitor is not going to university...so in the markets in which we sell ourselves, it is all about aspiration-building to choose higher education."* One of the university's major selling points to this community is its strong employment rates: 84% of CSU students gain employment within their field of study within six months of graduation, the highest proportion of any Australian university. Many interviewees, from both within and outside CSU, credited its employability rates to the university's integration of work placements:

"just about every course at CSU has a work-based learning component, to make sure that when you graduate, you are ready to go. The bottom line is that you don't come to CSU for the brand, the reputation, you come to CSU for a job and a profession."

Another feature that distinguishes CSU from many national peers is its driving mission *"to build skills and knowledge in our regions."* This proudly-held commitment to the economic and social development of its host region was underlined by almost every CSU-based interviewee. Indeed, CSU was described as *"a university with dirt under its fingernails"* and *"a place without pretension that wants to improve the lives of the people we serve."* This regional focus has shaped many of the university's strategic decisions and was attributed to its *"willingness to take risks"* when investing in new ideas, such as the recent AUS\$40m investment in the establishment of a new campus in the previously underserved town of Port Macquarie.

⁷⁸ The university's seven campuses are in Albury-Wodonga, Bathurst, Canberra Dubbo, Goulburn, Orange, Port Macquarie and Wagga Wagga. CSU also has study centers in Brisbane, Melbourne and Sydney.

CSU Engineering is based on the university's Bathurst campus, 200km inland of Sydney and separated from the city by the Blue Mountain National Park. It is one of only two engineering schools in regional New South Wales: *"once you get beyond the Blue Mountains, there is [almost] no one else...if you take a map of New South Wales, our turf is everything but Sydney."* Sydney, however, is a major hub for higher education, with around one third of the country's 100,000 engineering students currently studying within the city basin. In contrast, the staffing and student numbers at CSU Engineering are small. Two student cohorts have enrolled to date: 29 students entered in February 2016 and 28 students entered in February 2017. These groups were described as *"half-cohorts,"* with annual intake intended to reach a steady state of 50 students from 2018. CSU Engineering's 10 staff members include two Professors of Engineering Education, two Engineers in Residence (EIR), one laboratory manager and five faculty, many of whom bring a strong background in engineering education research. The EIR aim to infuse professional practices, experiences and expectations into the program's culture. In addition to their teaching and student mentorship responsibilities, the EIR are expected *"to maintain their engineering credentials"* by working with regional industry in a consultancy capacity. The income generated by CSU Engineering's consulting activities is being used to fund student scholarships as well as the program's engineering education research activities, including a new PhD program.

D.1.2. The national context

At the national level, Australia is the sixth largest country in the world and home to around 24 million people. Its population is predominantly located in the coastal and urban regions, with around 85% of inhabitants living within 50km of the country's coastline. Participation in Australian tertiary education has grown considerably over the past 25 years. Today, 43% of the country's adults hold at least a bachelor degree, one of the highest levels in the OECD.⁷⁹ International student numbers have also increased significantly in recent years: between 2001 and 2016, the country's share of the global international student market increased from 4% to 11%. Today, even at undergraduate level, international students account for around 30% of engineering enrolments. Engineering degree programs are offered at 35 universities across Australia, with national undergraduate intakes totalling around 12,000 per year.

Australia is also notable for the vitality of its engineering education community. Operating for almost 30 years, the *Australasian Association for Engineering Education*⁸⁰ supports a national journal, an annual conference and a strengthening profile of engineering education research. Indeed, a recent analysis suggested that Australian authors accounted for 21% of publications in engineering education, placing the country second only to the US by publication volume.⁸¹

⁷⁹ OECD (2016) Australia: Education at a Glance 2016: Highlights. OCED Publishing

⁸⁰ Australasian Association for Engineering Education (<http://www.aeee.net.au>)

⁸¹ Jesiek, B.K., Borrego, M., Beddoes, K., Hurtado, M., Rajendran, P., & Sangam, D. (2011). Mapping Global Trends in Engineering Education Research, 2005–2008. *International Journal of Engineering Education*, 27(1), 77–90.

D.2. The development of the CSU Engineering program

This section summarizes the milestones, events and activities that have marked the genesis, establishment and growth of CSU Engineering. It is structured around three time periods:

- the foundations for a new engineering program at CSU (2011–2014);
- the development of the CSU Engineering curriculum and approach (2014–2016);
- the launch of the new engineering program (from 2016).

D.2.1. The foundations for a new engineering program at CSU

Rooted in a mission to *“support our regions and the professions that sustain our regions,”* CSU built its disciplinary base around the economic and social needs of regional New South Wales. Building on these established strengths in professions *“that are the lifeblood of the regional economy”* – such as nursing, teaching and accountancy – the past 20 years has seen the university diversify further to include disciplines such as dentistry and veterinary science.

One discipline that had proved difficult to *“get off the ground,”* however, was engineering. The rationale for establishing an engineering program at CSU was widely acknowledged, with growing calls from industry and local councils to increase the regional talent pool of skilled engineering professionals. In particular, it had long been recognized that *“if you train them in the region, you keep them in the region,”* and existing local high-school graduates seeking an engineering education would typically *“disappear over the Blue Mountains to go to university in Sydney or on the coast and never come back.”* With a number of CSU’s senior managers being trained engineers, many within the university were also noted to *“understand and appreciate the power of engineering to transform communities.”* However, concerns remained about the viability of a new engineering program within the CSU regional setting:

“...we would be the 37th engineering school in Australia. We had no reputation in engineering. We don’t have a brand. The big question is why would people want to come to us? What would stop them going to the University of New South Wales?”

The conclusion reached was that if CSU was to establish an engineering program, it must offer prospective students *“something completely unique, something they could not get anywhere else.”* In 2011, a small team was assembled to develop a feasibility study for the formation of a *“very different type”* of engineering program at CSU. An external consultant was engaged to drive forward its development. She brought expertise, experience and connectivity in engineering education, including a longstanding role as Chair of the *Engineers Australia* accreditation board and a role as Deputy Chair of the *Washington Accord Committee*, the international body that oversees a global accreditation agreement for professional engineering degrees.

Drawing on a wealth of data and consultations with employers and prospective students, the team developed a business case for a distinctive new engineering program that offered the potential to *“keep [local] students in our region and attract other people from over the Blue Mountains to CSU.”* These requirements are outlined in Box 22. At the heart of the proposed program was an extended series of work placements that *“that offered students the industry experience they needed to walk into a job and walk*

into Chartered [Professional Engineer, CEng] status." The national engineering accreditation body, *Engineers Australia*, requires engineering programs to incorporate a minimum of 480 hours' exposure to professional practice, equivalent to around 12 weeks. The proposed new CSU Engineering program took this experience much further, embedding four years of paid work placements.

Box 22: Proposed features for the new CSU Engineering program

- it should be five-and-a-half years in duration, with the first 18 months based on campus and the last four years dedicated to off-campus paid work placements;
- it should offer a distinctive approach that *"situates the program in a niche market"* and positions it *"at the forefront of engineering education"* nationally and globally;
- it should provide students with *"future-proof"* professional capabilities – self-motivation, entrepreneurial attitudes, systems thinking – that will allow them to adapt to the changing needs and demands of engineering careers within and beyond the regions;
- it should be focused on civil engineering, as *"the most relevant discipline for the needs and demands of the region,"* as a combined bachelor/master program;
- it should be based within the CSU Business School, to allow the program to draw on existing institutional strengths in management and entrepreneurship.

With this blueprint for the new engineering program in place, and provisional approval from the university to proceed, the next step was *"to find someone who was able to lead it."* Interviewees involved with the search for potential candidates made clear that *"there were very few people out there that had all the qualities we were looking for... they needed to be ambitious, they needed to be a strong leader and understand the constraints of the academic systems and they needed to have proven flair and creativity in engineering education. The list was very short!"*

One such candidate, however, was identified and *"by pure good fortune"* had recently left the role as dean of engineering at Central Queensland University. The candidate offered a global profile and proven track record in evidence-based curricular reform in a number of universities across Australia. As he explained, the mandate to shape a pioneering new engineering program, from the ground up – unconstrained by the culture, practices or protocols of an existing program – played a major role in his decision to accept the role:

"I knew I would forever regret not doing this... this time, I would not be working against the inertia of an existing program, I would be at a university willing to give us a tail wind... with a blank page, you don't have the legacy of what you are replacing."

The Foundation Professor of Engineering took up post in April 2014. Many interviewees noted that his appointment brought *"a step-change in the vision and momentum of the project... [the new Foundation Professor] was a dynamo of energy and took the thing to a whole new level that we weren't even thinking about. His passion was contagious."*

His first priority was to address what were understood to be the two critical risks for the new program that: (i) it would attract insufficient student numbers to break even; and (ii) it would not establish a

sufficiently large pipeline of work placements to support the student cohorts in steady state. From his appointment, therefore, much of the Foundation Professor's time was devoted to mitigating these risks through relationship building with the regional engineering and educational communities.

D.2.2. The development of the CSU Engineering curriculum and approach

Timelines for the development of the CSU Engineering program were short. Formal approval to launch the new program was granted by the university Senior Executive in October 2014 and the date for entry of the first student cohort set for February 2016. This left just 501 days to establish the program's curriculum, staffing and learning spaces. While development time was severely constrained, the university worked hard to ensure that very few structural and operational constraints were imposed on the embryonic program. Indeed, senior university managers continued to support and encourage the development of a distinctive and innovative approach. As one interviewee noted, the Dean of the CSU Business School at the time was:

"...not just giving us permission to do things differently, but giving us a mandate to do it differently. She understood that you can't just come up with the same old product and expect it to be successful, you need to be orthogonal to the rest of the market...She made us differentiate ourselves."

So, for example, the university permitted CSU Engineering to step aside from the standard CSU practice of structuring the curriculum around four eight-point subjects each year. This exemption provided the emerging program with the flexibility to offer students major immersive projects, both on- and off-campus. CSU Engineering was also offered considerable flexibility in the creation of its learning spaces. With a budget of around AUS\$14m, the Foundation Professor worked closely with the architects to develop an engineering building that *"embodied the ethos and professionalism that we were trying to create in the program."* In place of lecture theaters, were open and informal learning spaces which students could access 24 hours a day. Many interviewees went on to note the critical role that these spaces have played since in building aspirations, attitudes and community among the student cohort: *"they are there from morning to evening – meeting, working on prototypes, working together – it's a beautiful space."*

By early 2015, key elements of CSU Engineering were well underway: the program structure had been defined, the new building was under construction and discussion with targeted employers to host work placements had begun in earnest. However, with only 12 months until the arrival of its first students and no additional program staff yet in post, a key challenge facing the Foundation Professor was developing the curriculum in a time-limited period that *"remained true to the innovative vision we had set out."* As one observer noted, *"it would have been so much easier for them to compromise. They had so little time, a lot of people would have just taken part of [an engineering curriculum] from elsewhere and just translated it over."* Instead, the Foundation Professor chose to drive forward the curriculum design through harnessing the combined experience and expertise of a hand-picked group of engineering education innovators, practitioners and researchers from across Australia.

In February 2015, CSU Engineering hosted the *Tangible Curriculum Week* in an airport hotel in Sydney. The five-day intensive meeting had 16 participants, drawn predominantly from Australia's engineering

education community and supported by representatives from regional industry and educational designers from CSU. Through distilling the ideas and experience in the room, the goal was to build a cutting-edge, evidence-based engineering curriculum that both drew on global best practice and was unconstrained by the legacy of traditional educational approaches: *“the deal was, we don't leave this hotel until we have a curriculum!”* Attendees described a highly creative, collegial and open atmosphere, where they were able to explore educational ideas that would have been *“almost impossible for us to try in our own [institutions].”* In the words of one participant, *“we came together as a group of individuals to do something formative for the engineering education sector.”*

Box 23: Three key proposals taken forward from the Tangible Curriculum Week

- **a professional engineering culture:** to establish the program as a professional workplace that educates *“student engineers rather than engineering students, with all of the professionalism and autonomy that this implies.”* This *“culture of treating the students as professionals-in-training”* went on to form a defining feature of CSU Engineering;
- **underpinned by self-directed learning:** to allow students to identify, explore and acquire their learning independently. The curriculum was thus divided into two discrete components: one devoted to intensive project-based challenges, that call on students to tackle authentic engineering problems, and the other devoted to the ‘content’ knowledge and skills necessary to tackle these problems, that students access as and when needed;
- **embedding flexible, state of the art online learning:** to develop an online platform to deliver all engineering knowledge and skills, with each topic offered in *“small bite-sized chunks rather than semester-long courses, giving people freedom in how they learn.”*

The week played a major role in the evolution of CSU Engineering. The three key proposals that emerged – summarized in Box 23 – would together become defining features of the program: a professional engineering culture; an expectation for self-directed student learning; and the transfer of all learning in the engineering ‘fundamentals’ and professional skills into the online domain. The online ‘content’ component was to become the *topic tree*, arguably the most distinctive feature of the CSU Engineering curriculum, where the core engineering concepts and skills are disaggregated into discrete three-hour topics and accessed independently online by students.

A few weeks after the *Tangible Curriculum Week*, the program's new Professor of Engineering Education took up post, bringing with him a distinguished US-based academic career in both civil engineering and engineering education research. In the months that followed, eight further appointments were made to the CSU Engineering team – including five faculty, two Engineers in Residence and a Laboratory Manager – many of whom brought an academic background and experience from outside Australia. A number of interviewees noted the quality and blend of skills introduced by this new group:

“the team is diverse – some with an engineering education research background, some with an industry background and some are civil engineering academics with a background in each of the different specialist areas – but all of them have a passion for engineering education and a student centricity.”

In the months following these appointments, significant effort was focused on detailed curricular development: designing the project-based *challenges* and creating each of the component topics for the online *topic tree*. This work called for benchmarking of leading national civil engineering programs and a survey of engineering graduate employers. In parallel to these curricular developments, the Foundation Professor continued to build the program's industry partnerships, paving the way for student work placement opportunities, and founded the program's external advisory committee. The advisory committee brought together key champions from local government, industry and social development organizations. In the words of one committee member, its Terms of Reference called for the CSU Engineering program to *"offer transformative practice that sets the agenda for engineering education internationally... everything we do should be positively disruptive."* It is interesting to note that the individual appointed to lead this advisory committee was the former CEO of *Engineers Without Borders Australia*, reflected the program's growing emphasis on *"human-centered and societally relevant engineering."*

With each of the major curricular components in place, CSU started to actively market the program to prospective students in July 2016. As many interviewees noted, time-scales were short: *"we started advertising six months before the first intake, which was two months before [prospective students] put their preferences to the university allocation system."*

D.2.3. The launch of CSU Engineering (from 2016)

The first cohort of 28 students enrolled in CSU Engineering in February 2016. Many interviewees noted that the group quickly *"adopted the [CSU Engineering building] as their own"* and formed a strong, cohesive identity as they engaged with their first project: to work together to build a *Rube Goldberg* machine.⁸² At the same time, much of the curriculum was still under development. In the words of one CSU Engineering faculty member, *"we were only just a few months ahead of the students, the [online] topic tree was still under construction and we were still nailing down the details of the challenges."* With *"a completely novel curriculum in play,"* staff were also aware that they would need to be responsive to ongoing student feedback and adapt the program in real time to any unforeseen difficulties faced.

One issue that quickly became apparent was that many students were struggling to adjust to a self-directed mode of learning. The program called upon students to work in teams to tackle 'real world' *challenges*, while at the same time working independently to build their engineering knowledge and skills from the online *topic tree*. Both elements turn upon students' motivation and time management skills. Two distinct learning styles emerged among the student cohort: some were highly motivated and dedicated excessive time to their team-based *challenges*, while others *"saw the schedule, decided that they didn't need to do much work and took extra shifts in their day job."* Neither group, however, were committing sufficient time to the online *topic tree*. As a result, many students were in danger of not completing the minimum number of online topics necessary to take their work placements the following year. In response, the CSU Engineering team introduced a number of mechanisms to

⁸² A Rube Goldberg machine is a device that uses a sequence of linked steps in a 'domino effect' to complete a simple task in a deliberately convoluted manner.

encourage students to establish a weekly routine that would allow them to maintain steady progress through the *topic tree*. For example, a conceptual ‘MetroGnome’ was introduced, as “*a hypothetical student that completes the topics at a steady rate throughout the year and emails students each week to let them know how many he has done.*” Although a number of student interviewees noted that “*the MetroGnome is not a popular character!*” progress on the online *topic tree* soon increased. As one faculty member observed, “*it took them a while to get there, but students started to realise how much work they needed to put into the topic tree, week after week, if they were going to be able to graduate.*”

In June 2016, CSU Engineering hosted its first *EngFest*, an annual event to showcase the students’ work to regional employers and the wider community. This event was the first opportunity for the external community to review and benchmark the early impact of the new program. Interviewee feedback about the students’ progress was universally positive. One external interviewee who attended *EngFest* described being “*blown away by the students’ work, the way they were able to communicate their ideas was amazing, and they had only been [at CSU] for a few months.*” Although it is difficult to directly compare the learning outcomes at CSU Engineering with those at peer engineering schools, one interesting point of comparison came a few weeks after the 2016 *EngFest*. As outlined in Box 24, one of the CSU student teams from *Challenge 1* (the first major project in the CSU Engineering curriculum) entered and subsequently won the *EWB Challenge*,⁸³ a design competition that brings together 9000 engineering students from across Australia and New Zealand.

The second cohort of 28 students joined CSU Engineering in February 2017. While this new cohort was tackling their initial on-campus *challenges*, the first student cohort was preparing to embark on their off-campus work placements. The allocation of students’ work placements followed conventional engineering employment protocols: students responded to written ‘adverts’ and shortlisted candidates were interviewed (by both the employer and CSU Engineering staff) before selection. In addition to showcasing student work from both enrolled year-groups, therefore, the second annual *EngFest* marked a major milestone for this first cohort, as they ‘graduated’ to become ‘cadet engineers’ and entered their work placements. Again, interview feedback from external attendees to the program’s second *EngFest* was consistently positive, with many pointing to “*the systems thinking capabilities of the students [which] is quite different to anything I have seen anywhere else.*”

The MIT Benchmarking Study site visit took place during *EngFest 2017*, as the inaugural student cohort were embarking on their first work placements in July 2017. Many interviewees pointed to these experiences as “*the first real test*” of the quality and impact of CSU Engineering’s educational approach. The students’ placement performance turns on their professional capabilities, academic preparation and – perhaps most importantly – capacity for self-motivation and independent study. As one CSU Engineering staff member commented

“the reputation of CSU Engineering walks out of the door [when the placements start]...The students feel more strongly than we do that they are carrying this reputation. They know that if they fail on the placement, we will have a hard time finding placements in the future.”

⁸³ *EWB Challenge* (<http://www.ewbchallenge.org>)

Many also noted that *“in the regions, word of mouth is very, very important. Reputations are quick to build and quick to die.”* It is therefore with some trepidation – among both staff and students – that CSU Engineering will remotely support and monitor these work placements.

Box 24: EWB Challenge 2016

First established in 2007, the *Engineers Without Borders (EWB) Challenge*⁸³ is a design competition for first-year engineering students to develop technology-centered ideas to advance authentic social development projects. Working in teams, students are asked to develop a design solution to one or more of the social development needs highlighted by EWB and the challenge partner. The *EWB Challenge* is embedded into the curriculum at 30 universities in Australia and New Zealand, with around 9000 first-year engineering students participating each year. Teams are judged on a number of criteria, including demonstration of their technical understanding, communication of their idea and consideration of the economic, social and environmental aspects of the design.

In February 2016, two weeks after starting their undergraduate studies, the first cohort of CSU student engineers started work on the *EWB Challenge*. The 2016 challenge design brief centered on a refugee settlement in Western Zambia. One of the CSU teams – calling themselves *Team Two Good to Waste* – focused on organic waste management. As one of the team members explained, *“we all came from a farming background, so the consensus was that we should look at composting.”* Their research into the refugee camp had revealed the dual problems of a lack of fresh fruit and vegetables, leading to stunted growth among many of the camp’s children, and the difficulties of disposing of organic waste, leading to unsanitary landfill sites around the camp. The team developed and prototyped a rotating composting system made from a recycled grain storage drum. Using only locally-sourced materials for its construction, the system was designed to provide families living within the camp with organic fertilization for small vegetable gardens while at the same time reducing environmental waste.

Team Two Good to Waste was selected as one of the four teams to represent CSU at the New South Wales semi-finals: they then went on to win both the semi-finals and the finals of the competition. Coming from an engineering program that had only been operational for a matter of months, the success of the CSU Engineering team in this well-established national competition came as a surprise to many. As one observer commented, *“for Charles Sturt – a completely new engineering school that a lot of us knew nothing about – to come from nowhere and win the competition was incredible.”* Interviewees involved in the organization of the *EWB Challenge* final consistently pointed to two factors that marked out the CSU Engineering team: the quality of their communication and the integration of their technical engineering ideas into deep appreciation of the regional context. One local *EWB Challenge* organizer noted in particular that the CSU team:

“really understood and appreciated the [regional] context and were very integrated in their consideration of the technology. They considered the local skills and capacity and how it related to the technology... They also presented themselves with maturity and confidence, as a professional team, as people working for a client, not as a student project.”

CSU Engineering staff credited the team’s success to a number of factors, including the levels of mentorship and support offered to the teams, the self-directed learning approach taken by the students – *“they really did their research, not just in the topic tree, they took the time to understand the region, the problem”* – and the repeated opportunities for teams to practice and improve the quality of their presentations, through events such as *EngFest*.

D.3. CSU Engineering's educational approach

All interviewees were invited to identify the most distinctive features of the engineering program at CSU. CSU students, in particular, noted the lack of “*exams and lectures*” as well as the extended work placements that allowed them “*to be paid while you study.*” Many CSU Engineering staff pointed to “*the ethical values and the people-centered approach*” taken to the curriculum design and delivery. However, two factors were consistently identified across all interviewee groups – both internal and external to the program – that set CSU Engineering apart from peer programs, nationally and globally.

The first factor is a **professional, work-ready environment**. The close industry partnerships that lie at the heart of the CSU Engineering program were noted to be “*engrained in the culture and the expectations on students*” enrolled in the program. This culture is reflected in the curricular “*focus on practical engineering and preparing people for the workplace,*” where students are able “*to work on real engineering problems and are treated like professionals*” from the point of entry to the program. The professional culture and approach is also apparent in the design of the new engineering building, that, in the words of one interviewee, “*feels more like a tech start-up workplace than a university.*” Even the language used by CSU Engineering staff – who refer to incoming engineering students as ‘student engineers’ – emphasizes their role as “*professionals in training*” with only 18 months to prepare for their work placements.

The second factor is **experiential and self-directed learning**. The program takes a student-centered, experiential approach that emphasizes self-directed learning. Students are confronted with a series of on-campus *challenges* and work-based problems and are expected to identify, master and apply the knowledge and skills necessary to tackle them as well as reflect upon their learning. The *challenges* posed are authentic and build progressively in complexity throughout the curriculum. What really sets the CSU Engineering program apart, however, is its approach to self-directed online learning. Almost all ‘technical engineering content’ – including both knowledge acquisition and skills development – is delivered online and is accessed by students as and when they need it. Students are encouraged to direct and manage their own learning goals. The majority of staff time is therefore devoted to face-to-face mentorship and support of students and student teams. As one interviewee from outside CSU explained:

“the ethos of ownership that they are trying to drive is so important. We can’t afford docile bodies in industry. The world is so agile now, the people driving the projects in an organization need to be proactive, not passive. They need to be self-aware and self-starting in terms of the questions that they ask. What CSU has created is a different way of thinking.”

Key features of CSU Engineering's educational approach are outlined in Table 4.

Educational feature	Details
Criteria for selection of student intake	CSU Engineering is the only engineering school in Australia that does not stipulate a formal threshold attainment level in mathematics for selection to the program. Indeed, the program has no academic 'prerequisites' for its intake. One interviewee from the CSU Engineering staff noted that <i>"on the basis of high-school scores, only a small fraction of our students – around 10% – would have got into the University of New South Wales,"</i> the state's largest engineering school. The student selection process for CSU Engineering involves two stages. Firstly, prospective students are asked to respond to five questions, such as <i>'how do engineers contribute to society', 'how will you contribute to the diversity of our school'</i> and <i>'how are you academically prepared to study at CSU Engineering?'</i> Secondly, shortlisted candidates are invited for a 30-minute on-campus interview for final selection.
Flexibility and student choice	Beyond the 'core' required subjects, students are free to complete any topics they choose from the <i>topic tree</i> , guided by both their interests and the focus of their projects/placements. Students also select which work placements they wish to apply for. During the final two years of study, students must select one of three areas of civil engineering in which to specialize – structural, water or geotechnical – and are required to complete a mandatory branch of the <i>topic tree</i> corresponding to that field.
Opportunities to work across disciplines	No curricular opportunities exist for CSU Engineering students to work alongside students from other disciplines. However, during both the on-campus challenges and off-campus work placements, students will spend a considerable portion of their time interacting with communities and professionals from across and beyond engineering.
Pedagogical approach	CSU Engineering offers a highly student-centered and experiential education. It blends project- and problem-based learning (through on-campus <i>challenges</i> and off-campus work-placements) with self-directed study (through a network of online learning 'topics' which students must demonstrate mastery of in order to complete). The education also emphasizes self-reflection, with students setting their own goals and reflecting on their progress, achievements and failures.
Assessment and feedback	Assessment loads are high. In addition to any project or work deliverables, students would typically be required to submit the following assessed components on a weekly basis: <ul style="list-style-type: none"> • tests/assignments associated with around three topics from the online <i>topic tree</i>; • written review of the contributions made by teammates to projects; • self-reflection on their progress towards their learning goals and upcoming targets; • documentation of evidence of achievement in their portfolios. Each week they would also receive an automatically-generated report on their <i>topic tree</i> progress and feedback from both their personal mentor and their <i>challenge/industry</i> mentor.
Teaching and learning support	All CSU Engineering staff without existing educational qualifications have completed a post-graduate certificate in teaching and learning since starting through the university. Support for the development and use of the <i>topic tree</i> is offered by a commercial provider.
Reward and recognition of teaching	CSU-based interviewees noted that <i>"the promotion criteria at the university are fairly traditional"</i> with research output as the major criterion. It was suggested that, beyond a minimum threshold of 'acceptable teaching', the current university promotion pathways <i>"might struggle"</i> to recognize additional contributions made in teaching and learning.
Educational research activities	The CSU Engineering team includes four individuals with a global profile and record in engineering education research. As one interviewee pointed out, <i>"expertise in engineering education [in Australia] tends to be scattered – one person here, two people there – so we are now [one of] the largest engineering education research groups in the country."</i> Research interests include automated assessment and feedback and self-directed, problem-based learning. Plans are also underway to establish a new PhD program in engineering education and appoint an additional researcher to the group, at Associate Professor level.
Extra-curricular opportunities	Beyond the typical range of extra-curricular activities offered by the university, CSU Engineering students have recently established a student-led engineering society.

Table 4. Key features of the CSU Engineering education approach and support systems

D.4. Curriculum design

As outlined overleaf in Figure 15, the five-and-a-half-year CSU Engineering curriculum is structured in two distinct phases.

The **first phase** of the curriculum (from Year 0 to Year 1.5) is based on campus and structured around a series of team-based design *challenges*. Drawing on face-to-face support from CSU Engineering faculty, it focuses on immersing students in the broader societal context of engineering, building their technical engineering knowledge and strengthening their professional capabilities in preparation for their work placement. It is also designed to build their capacity for independent self-directed learning, such that they are equipped to source and assimilate the knowledge and skills they need to tackle the projects and problems they face when off-campus, during and beyond their work placements. With each *challenge*, the scaffolding provided to students is progressively reduced to support their development as independent learners.

The **second phase** of the curriculum (from Year 1.5 to Year 5.5) is based off-campus and structured around a sequence of four paid 12-month work placements. Amongst the first cohort of CSU Engineering students, around one third have taken work placements in local government, with the remaining two thirds working in private industry. Students sign 12-month employment contracts and learning contracts with their employer on the understanding that one day per week will be dedicated to their studies. Students submit weekly reflections to their CSU mentor, who will visit them in person at their place of work at least once during each placement year. An industry mentor also provides dedicated mentorship and training opportunities to the students and provides them with weekly feedback on their progress. Industry mentors are provided with online and on-campus training for their role prior to the placement and are also appointed as CSU Engineering adjunct lecturers for the duration of the placement. The second and final years of work placements are focused on students' bachelor and master thesis projects respectively. The focus of the thesis topics is agreed between the students, CSU mentor and industry mentor, but is likely to draw upon particular challenges and opportunities identified through their work placements.

Running across these two phases, and throughout the program, are three pillars of activity:

- **project/portfolio-based pillar** (comprising 42% of the curriculum) offering project and work-based experiences for students to contextualize, apply and explore their learning;
- **online 'topic tree' pillar** (comprising 50% of the curriculum) providing 'bite-sized' learning in engineering theory and skills which students access online as and when needed;
- **performance planning and review pillar** (comprising 8% of the curriculum) allowing students to identify and reflect upon their learning goals and achievements.

Each of these three curricular pillars is described in turn in the subsections that follow.

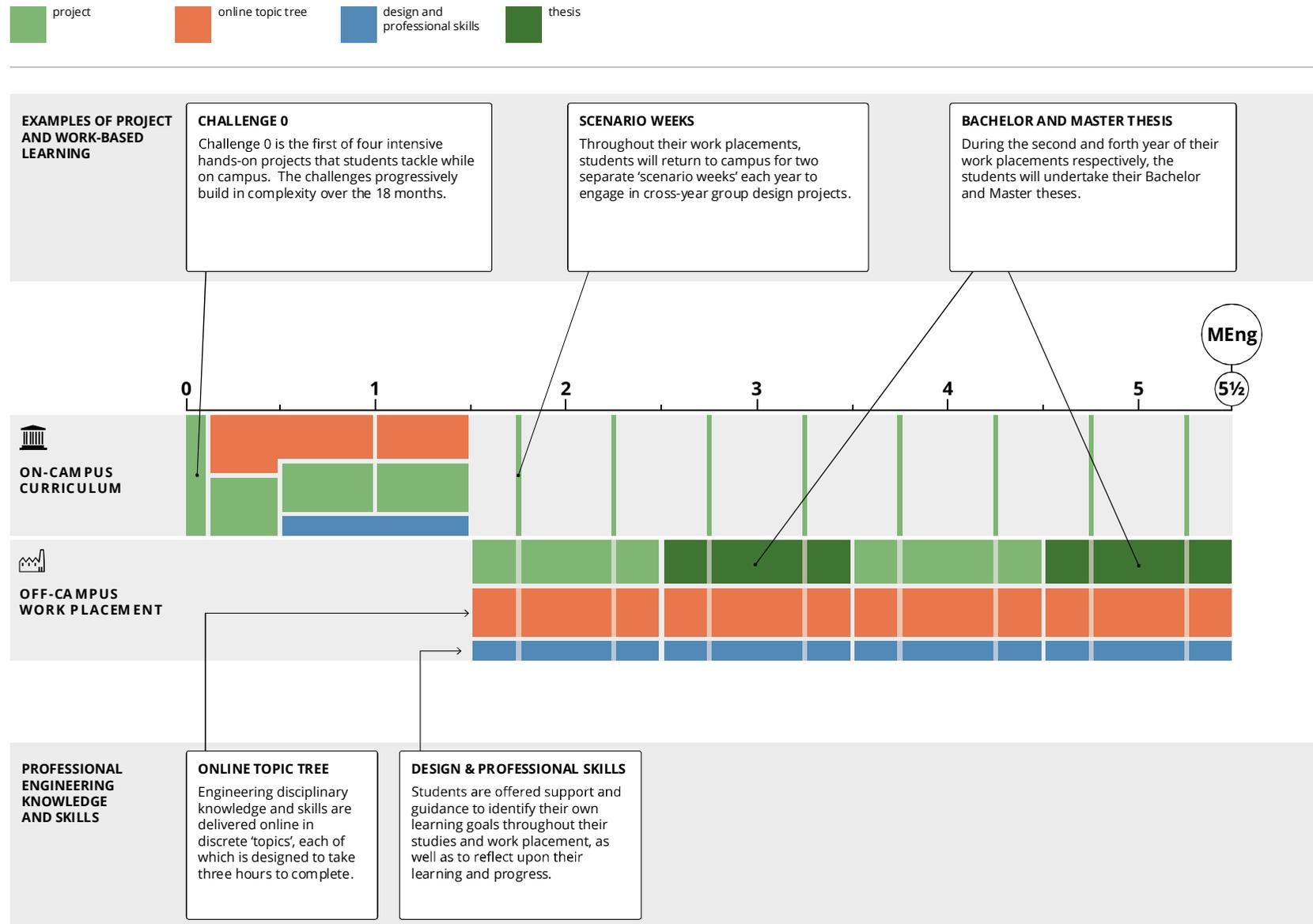


Figure 15. Outline structure of the CSU Engineering curriculum

D.4.1. Project and portfolio-based pillar

Accounting for around 42% of the curriculum, the 'project and portfolio-based pillar' is devoted to project-based learning. The nature of these project experiences changes as the students move through the on-campus and off-campus portions of their studies.

During the **first 18 months of study**, students are confronted with a series of team-based *challenges* that build progressively in complexity throughout the on-campus portion of the curriculum. An outline of each of these *challenges* is provided overleaf in Table 5. Students are expected to access the online *topic tree* to identify and master any new knowledge and skills that they need to tackle their *challenge*. Weekly support is typically provided to the students through: (i) a meeting with their team mentor to discuss progress and challenges faced; and (ii) a three-hour workshop with the *challenge* coordinator to provide guidance and information on the project. Students document their achievements and learning for each *challenge* through online portfolios, which capture both contributions of the team (through, for example, project plans, cost analyses and presentations) and contributions of the individual (through, for example, failure reports and peer reviews of other teams in the cohort). This experience is designed to *"get students used to the idea of how to prepare a portfolio – to outline how they are using their professional skills, how they are applying engineering methods and engineering tools – so that they are able to do it independently during their placements."*

During the **four years working off-campus**, the real-life problems and projects encountered by students during their placements are used as the context for the 'project and portfolio-based pillar'. During the first and third work placements, the pillar is devoted to the preparation of online portfolios of students' achievements and learning during their in-work experience. Each portfolio addresses a different topic – such as how they have tackled an ethical problem or how they have been accountable for the work of others – and, together, is designed to build the resources needed for the student to apply for chartered professional engineer status on graduation. The second and fourth placements are devoted to the bachelor ('cornerstone') and master ('capstone') theses respectively and focus on specific problems and projects from the student's workplace. In addition to guidance and support from both their industry and CSU mentors, students will also be able to access additional resources – such as the CSU Engineering laboratories – as they work remotely on their theses. Specifically-designed *topic tree* subjects will also guide students through, for example, the design of a literature review and the preparation of a thesis report. In addition to the annual *EngFest*, all students working on placement will return to campus twice each year for week-long residential 'scenario weeks'. These project-based experiences will be designed to nurture *"inter-generational learning"* between year-groups and *"fill in any gaps in knowledge that the students are missing during their work placements."*

Challenge 0 – Rube Goldberg Engineering Challenge (two weeks, full-time)

The first two weeks of the curriculum are devoted, full-time, to the construction of a Rube Goldberg⁸² machine across the floor of the engineering building. This pass/fail challenge is designed to build the cohesion of the student cohort and familiarize students with team working. Each team of three is asked to create at least four working steps of the machine that connects with at least two other teams. The cohort is provided with the first and last step of the sequence, and asked to work together to create everything between.

Challenge 1: Humanitarian Challenge (12 weeks)

This semester-long project is designed to help students “*understand the human aspect of engineering projects.*” As described in Box 24, it is structured around the *EWB Challenge*, a national competition for first-year engineering students to tackle humanitarian design-based challenges. In addition to the basic requirements of the *EWB Challenge*, CSU students are required to develop a prototype and an extensive design portfolio. As the first major challenge of the curriculum, this project was described as offering students “*a lot of scaffolding and support to get to their solution. This reduces as they move through the challenges.*”

Challenge 2: Process-Focused Engineering Challenge (12 weeks)

Challenge 2 is designed to “*help students learn resilience to change and to failure.*” The full year-group work on a single multi-dimensional challenge for a virtual client, with each team focused on one aspect of the problem. For example, the 2016 challenge was to develop a proposal for a fictional *Bathurst Olympic Village*, with teams allocated to specific areas such as ‘*roads and overpass*’ or ‘*drainage and sewage*’. With the virtual client “*changing the scope throughout the exercise and flooding the teams with information so that it is difficult to prioritize,*” CSU Engineering staff suggested that the challenge offered a “*near death experience*” for the students. As one noted, “*it is supposed to be uncomfortable and frustrating and...helps [students] to reflect on what makes people good to work with and they come to the realization that you need to work with other teams for a collective positive outcome.*” In addition to the design portfolio, prototype and final report, the full student cohort must deliver a final project presentation as a group. As with all challenges, students submit online weekly reviews of team members’ contributions that are used to moderate the assessment for team-based components.

Challenge 3: Client Lead Engineering Challenge (15 weeks)

The final challenge is designed “*to give students resilience to pressure and prepare them for their work placement.*” It is the only challenge where students may select their own teammates and mentor, based on their experience in the previous projects. Teams are asked to identify a client from the regional community that they subsequently work together with, to “*design a solution to a real engineering problem*” faced by their chosen business. For example, in 2017, projects included the design of a water heating and recycling system for a local age-care facility and the development of new furniture materials from recycled coffee waste for a local café. At the challenge close, in addition to prototypes, team reports and individual portfolios, teams must pitch their ideas to the client at the final *EngFest* before commencing their work placements.

Table 5. Outline of CSU Engineering’s on-campus challenges

D.4.2. Topic tree pillar

In a traditional engineering curriculum, ‘technical content’ – including engineering disciplinary ‘fundamentals’ and professional skills – is typically delivered via weekly lectures, tutorials and laboratories. In the CSU Engineering curriculum, this content has been disaggregated into a set of ‘topics’ that are delivered online for students to access independently, when and how they wish. Each topic forms one leaf of the *topic tree*, as illustrated in Figure 16. The *topic tree* provides a visual map of the relationships and dependencies between topics and specialist branches of engineering. Using an online platform, students are able to track their progress through the *topic tree* and identify the topics they wish to target based on their own interests and/or specific problems encountered in their *challenges* or work placements. To design, construct and manage the *topic tree*, CSU Engineering has worked closely with a commercial company, *Realizeit*.⁸⁴ The *Realizeit* software provides “*all the mapping of the links between topics, the prerequisite chains and [information on] who has completed what [topics].*” Many interviewees pointed to the mapping capabilities of the software as crucial to the *topic tree*’s success: “*that’s the key value – the ability to handle a 1000 topic map, and to display it visually, and to let students navigate through it on demand.*”

Each topic is designed to take the average student around three hours to complete. In addition to written content, videos and app-simulations (as appropriate), each topic offers the students opportunities to apply their learning to a real problem, and closes with a final assessment. A ‘mastery’ approach is taken, whereby students must score 75% or more in their assessment for the topic to be considered complete: as such, topics are a ‘pass/fail’. When operating in steady state, the assessment and student feedback for the majority of topics will be automated. At present, however, fully automated assessment and feedback is only offered for around a third of topics. Topics that cannot be offered exclusively online, such as engineering laboratories, are offered as ‘live topics’. In these cases, students must group together and approach the staff member concerned to arrange a suitable time for an in-person session.

The successful operation of the *topic tree* relies on students’ self-directed learning and continued engagement with the program. Although students are free to complete any elements of the *topic tree* that they wish, a number of minimum requirements are stipulated:

- before commencing their work placement, students must have completed 240 topics, including 80 mandatory topics that focus on a range of areas from fundamental engineering science/mathematics to CAD drawing;
- by graduation, students must have completed 600 topics, including at least 80 from their chosen civil engineering specialism (either water, structural or geotechnical engineering).

⁸⁴ Realizeit, based in Dublin and Chicago (<http://realizeitlearning.com>)

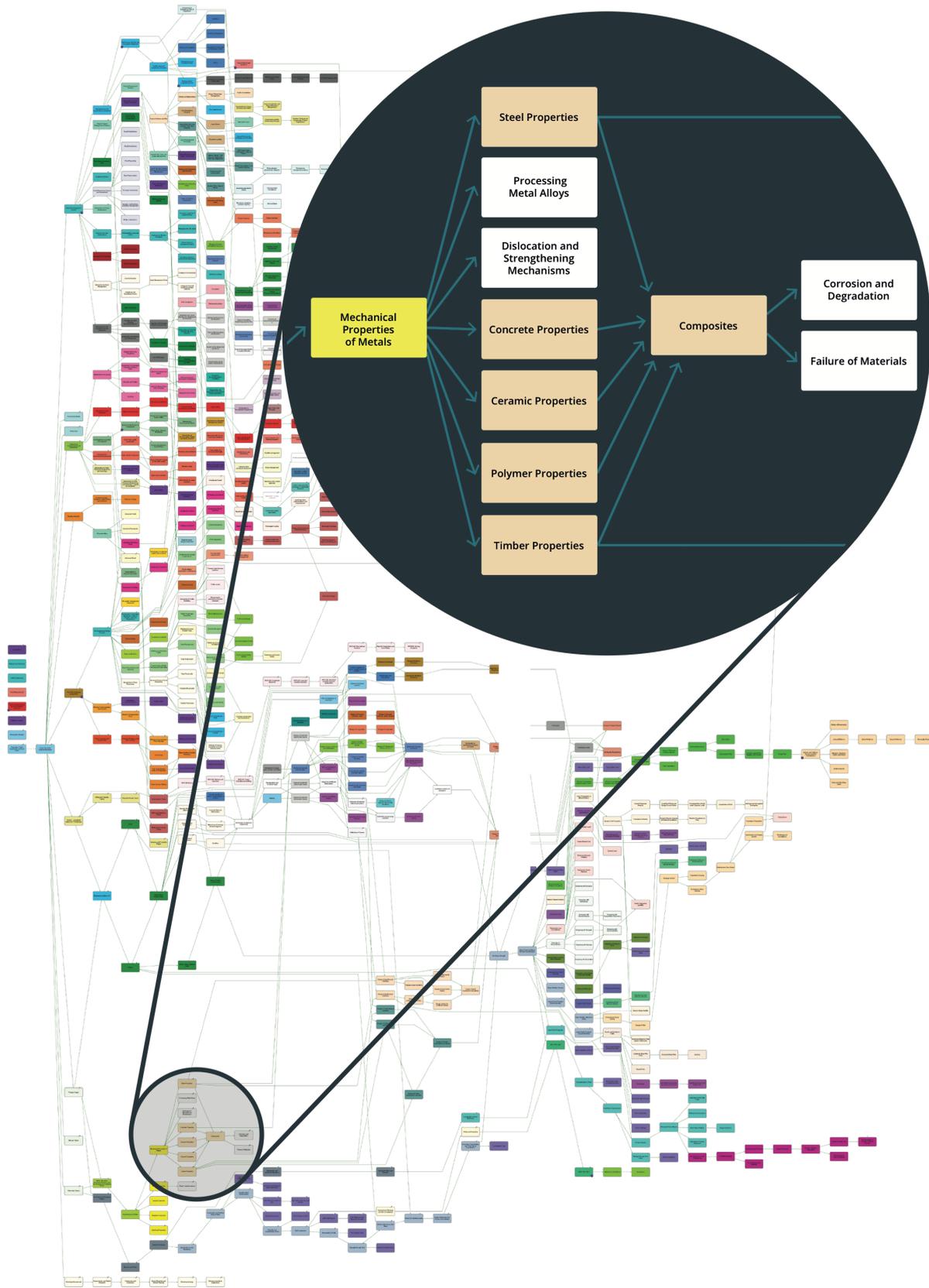


Figure 16. The CSU Engineering *topic tree*, with one section (covering the *mechanical properties of metals*) shown in more detail

Students work relatively independently to complete these requirements. However, their progress is monitored by CSU Engineering staff, with support provided where needed. For example, where *“a lot of people are spending time on a topic but not completing it,”* face-to-face or online tutorials are organized to support specific concerns or difficulties.

The *topic tree* is still under construction. To date, around 300 topics are available, with a further 700 under development. It is anticipated that one third of topics will be sourced externally from *“the best of the online material that is out there, that we cannot improve upon,”* with the remainder developed in-house.

D.4.3. Performance planning and review pillar

The ‘performance planning and review’ pillar is designed to *“empower students to set their own goals for their learning and track the progress they are making,”* helping them to manage their time and reflect upon their learning. Starting in the second term of the program, this pillar offers students a spine of study support and self-reflection throughout the rest of their studies.

Students first meet with their CSU Engineering mentor at the close of *Challenge 1* to *“decide on the goals they need to reach before going on work placement.”* Drawing on their experiences from the first six months of study, these goals include their planned curricular progress in fundamental and specialist topics, as well as target areas for personal and professional development. Students meet with their mentor each quarter and, on a weekly basis, are asked to submit reflections on progress and targets for the coming week. Their progress is further supported by fortnightly workshops, designed to advance students’ self-reflections in areas such as ‘goal-setting’ and ‘conflict management’.

At the end of each semester, students submit a reflective portfolio. Although some student interviewees spoke about the burden of *“having to write reflections every week,”* most pointed to the benefits that this pillar offers. As one noted:

“it has made me think more about what it will mean for me to be a professional engineer and how to structure my time. It really helped with my [placement] interview... there were all sorts of questions that I would not have been able to answer before.”

While on placement, students are asked to undertake a ‘personal and professional audit’ at the start of each year to identify their goals. This audit is used to draw up a ‘learning agreement’ which is signed by the student, CSU mentor and industry mentor, and reviewed three times each year to monitor the student’s progress and achievements. Continuing their weekly reflections, students submit a portfolio at the close of each placement. While off-campus, students continue to prepare and submit weekly reflections and complete a portfolio at the close of each work placement.

D.5. Review and concluding comments

CSU Engineering offers a radically different approach to undergraduate engineering education; none of the program's component parts or pedagogical approaches would be familiar elements of a traditional, teacher-centered, engineering curriculum. In particular, CSU Engineering brings together many of the features that the 50 thought leaders (see Section 9) identified as likely to distinguish the world's leading engineering programs in the decades to come. These include: a pedagogy that advances self-directed learning and student self-reflection; a focus on human-centered engineering; diverse opportunities for students to explore and apply engineering learning through authentic problems; the use of responsive, state of the art learning technology; and *"the benefits of workplace experience in developing transferable attributes in graduates."*

However, when asked to identify the characteristics that set CSU Engineering apart on a global stage, external observers consistently pointed to the blend of face-to-face project-based learning with student-directed online learning: *"the first 18 months is exceptional, it embodies all aspects of best practice that I have seen."* One characterized the *topic tree's* platform for flexible *"just in time"* learning as *"the most innovative thing I have ever seen in pedagogy."*

Despite these evident innovations, the ranking of CSU Engineering among the top 10 of 'emerging leaders' in the field might come as a surprise to many; that a newly-established program in regional Australia with only 57 registered students should be on the radar of so many global experts in the field. One factor that has propelled its global profile is undoubtedly *"the caliber of the people that it brought on board"* to design and deliver the program. Interview feedback from external observers, however, suggests that the top 10 ranking of CSU Engineering stems primarily from its potential to influence practice elsewhere. Two particular program characteristics were highlighted. Firstly, many pointed to the potential for CSU Engineering's on-campus educational approach – blending project-based and online learning – to *"scale up to much larger cohorts of students."* Although the program's annual student intake is currently capped at 50, the approach taken was considered by many external observers to hold considerable potential to be applied successfully to *"much, much larger cohort sizes."* Secondly, the CSU Engineering experience was understood to provide critical insight into the 'value add' of a world-class, student-centered education on the learning of *"ordinary, rather than exceptional, students."* Were the program to demonstrate significant improvements in the skills, motivations, mindsets and aspirations of its intake demographic of 'ordinary' students, it would undoubtedly endorse the transferability of the approach to any other engineering program across the world.

CSU Engineering, however, is a young program and evidence of its impact on student learning will not be available for a number of years to come. Nonetheless, interview feedback from external observers was universally positive. As one noted: *"... I've never seen anything like it before, but I am really excited by what I see. It is a new chapter in engineering education."*

D.5.1. Success factors

Interview feedback suggests that three factors have been instrumental in the successful design and delivery of the CSU Engineering program, as outlined in turn below.

The **first factor** underpinning CSU Engineering's success has been its ability – and, in particular, the ability of the Foundation Professor – to nurture and draw upon external expertise and good will from across both the university and the country. For example, when describing the role played by CSU in the program's development, one interviewee noted:

"[CSU Engineering] were given \$15m of university funds and no one is bitter about it because everyone feels that they had a part in something that is special and they are all important for its success. So, Facilities had an incredible success getting the building up and running in 12 months and Student Administration had a success in creating a little miracle with the timetabling. They all have a piece of the success."

At a national level, the design of CSU Engineering drew upon the expertise and experience of a well-established and collegial Australian engineering education community: *"there has been a real sense that they are all working for a common good and there is a genuine academic and intellectual honesty about how they all try to share that."* The community engaged in the program's development has included well-regarded national accreditation representatives, educational innovators and educational research experts.

The **second success factor** has been the strong and consistent support from the university's senior management. Many among the CSU Engineering team noted that senior CSU managers *"brought no expectations or preconditions about what [the program] should look like"* and, instead, *"allowed us to break the university's rules"* in order to accommodate the program's unconventional timetabling, staffing, budgeting and on-campus space requirements. As a result of this *"unwavering support,"* the vision and design of the program *"has not been watered down along the way"* and has remained largely uncompromised by institutional constraints or protocols. University senior management, in turn, noted that they were comfortable to *"stick to our guns, hold our nerve and not frustrate the Foundation Professor before this thing blossoms."*

The **third success factor** has been the expertise and leadership of the CSU Engineering team. External interviewees consistently commented on the *"caliber of the program's teaching staff"* who were characterized as *"a critical mass of people that are respected in the profession that had a passion to change practice."* The team brings together industry experience with extensive expertise in pedagogical scholarship, which one interviewee described as *"the strongest pedigree of engineering education research in Australia."* As a result, the educational approach is both evidence-based and draws upon international best practice. Interviewees also underlined the collegiality and common purpose of this team, as well as the critical role played by the leadership of the Foundation Professor and Professor of Engineering Education, who were reported to offer a crucial balance of skills: *"vision and passion"* and *"steady, trusted wisdom"* respectively.

D.5.2. Challenges faced

CSU Engineering was established under a constrained timeline, with much of the curriculum being developed just *"12 months ahead of time."* At this early stage in its development, many elements of the program remain unproven. In particular, when asked to identify the challenges facing the program's success and sustainability, interviewees consistently pointed to four issues:

- **maintaining student engagement:** one challenge faced early on was *"dealing with the caliber of students we get, where they are not as self-motivated coming in as we had hoped,"* leaving some students ill-prepared for self-directed learning. The program is likely to face similar issues as students move into their work placements. While on campus, students benefit from face-to-face support from both staff and peers, and the CSU Engineering team are able to quickly identify and deal with any problems that arise. However, off campus, students are likely to be isolated from peers and must manage their studies and work pressures concurrently. As a result, there is a risk that some will struggle to maintain their motivation for self-directed study and fall behind;
- **increasing student recruitment:** as a newly-established program in a regional university, a major challenge facing CSU Engineering will be meeting its annual student intake targets, particularly while it builds its profile and reputation among prospective students. As one external observer commented: *"the biggest challenge facing CSU is exposure. If future Australian engineers and their families were aware of and actually understood the CSU model during their decision-making process for choosing a university, the enrolments would sky-rocket. The difficulty is in creating the awareness and understanding in a broad cross-section of the population";*
- **securing ongoing work placements:** when CSU Engineering is operating in steady state, with an annual intake of 50 students, it must secure and support 200 12-month work placements each year. Each placement must expose students to varied and challenging professional engineering problems and offer a supportive and engaging learning environment. For a program with small staff numbers, providing this pipeline of work experiences on an ongoing basis will present a considerable challenge;
- **retaining key institutional leaders:** interview outcomes made clear that the success of the program over the coming years is likely to rest upon the continued tenure of two key leaders: the university vice-chancellor and the Foundation Professor of CSU Engineering. Both current and previous university vice-chancellors have offered the program a largely unconstrained space in which to evolve and have not imposed unrealistic expectations on its pace of growth or early impact. At the same time, the Foundation Professor was characterized as a linchpin of the program's internal and external collaborations, whose continued *"passion, drive and insight"* would be pivotal to the program's continued success *"at least until the graduation of our first students."*

Both the university senior management and the CSU Engineering team are well aware of these four challenges, and significant effort is devoted to mitigating the risks. Interview outcomes, however, suggest that CSU Engineering may face an additional challenge, one that is partially born of its ambition and early success, as outlined briefly below.

When asked to describe the vision and mission of the CSU Engineering program, interviewees would typically speak to one of the following two narratives:

- that it offers a cutting-edge engineering education – informed by global best practice in student-centered, experiential and online learning – that aims to nurture graduates who are highly-motivated and adaptable systems-thinkers;
- that it supports and advances engineering capabilities in regional Australia, using work-based learning to nurture graduates who are experienced in and attuned to the distinct challenges facing regional engineers.

While not incompatible, the priorities and goal associated with each of these two narratives are distinctly different, as are the measures for program success. Reconciling these two perspectives is likely to present a number of challenges to the CSU Engineering team in the months and years to come. Where this conflict is most evident is in the work placements during the final four years of study. In 2017, most of the work placements secured for the first cohort of students were geographically close to the CSU campus footprint and within small-to-medium regional companies or local councils. After 18 months of diverse and challenging problem-solving, some interviewees questioned whether these work-based experiences would inspire students and continue to *“extend their horizons”* and capabilities as they progressed through their studies. Concerns centered, in particular, on the potential impact of students taking all four years of their placements with companies that are both regionally-based and *“pretty traditional”* in their operation and focus. CSU Engineering is planning to offer *“big dream placements”* for students in later years of study and has recently sent 10 students to the EWB summit in Cambodia. However, this ambition may be constrained by the prevailing expectation among many students that they will receive an income during their four years of off-campus study: this will severely restrict the types of placements that CSU Engineering is able to secure, and is likely to rule out, for example, placements within startups or within the not-for-profit sector.

There is no doubt that the first 18 months of the CSU Engineering curriculum has been phenomenally successful: the student interviewees who had completed the first 18 months of study on the program were strikingly articulate, motivated and well-informed young engineers. The challenge facing the CSU Engineering team will be to ensure that these students’ future work placements allow them to continue this learning trajectory, such that extensive employment options are open to them on graduation, be that in regional Australia or elsewhere in the world.

Acronyms used in CSU Engineering case study

CSU	Charles Sturt University
EIR	Engineers in Residence
EWB	Engineers Without Borders

APPENDIX E CASE STUDY – TU DELFT, NETHERLANDS

Reasons for selection of TU Delft as a case study

Delft University of Technology (TU Delft) was one of four institutions to feature prominently on the lists of both 'current leaders' and 'emerging leaders' in engineering education compiled during Phase 1 of the study. A range of factors were seen to explain its position as "*a global thought leader in engineering education,*" including innovative engineering programs in Aerospace Engineering and Industrial Design, the early development of open and online education, ambitious and successful student-led activities, and its investment in the teaching skills of academic staff. Underpinning these initiatives was what interviewees identified as "*a Delft spirit and attitude, where they are forward-thinking, ambitious and entrepreneurial and committed to education.*" This spirit was seen to be in step with key aspects of wider Dutch culture, including the values of inclusivity and egalitarianism, a cultural 'fit' that has also enabled a high degree of collaboration and partnership between Dutch universities. Crucially, TU Delft's pre-eminent position within the engineering education community was attributed to the quality of its educational leadership. This, in turn, has facilitated 'bottom-up' educational innovation including influential discussion papers, and is now paving the way to a new educational vision for the university.

E.1. Context

E.1.1. The university context

Established in 1842, Delft University of Technology (TU Delft) is the oldest and largest of the three technology-specialist universities in the Netherlands. It is located in the historic city of Delft, 60km south-west of Amsterdam, the Dutch capital.

TU Delft is formed of eight Faculties that encompass engineering, applied science and design.⁸⁵ Many interviewees noted the autonomy accorded to Faculties, enabling each to pursue its own practices and to respond quickly to new opportunities. The university was also characterized as “*open and accessible, with a flat hierarchy in the organization and less bureaucracy than other universities.*” Interviewees consistently highlighted TU Delft’s “*open, transparent attitude, with a willingness to work together*” and “*its active, can-do engineering mentality.*” Indeed, this “*Delft spirit*” was seen to pervade all aspects of university life, as evidenced in the institution’s early decision to become a pioneer in open-access online learning and its highly ambitious extra-curricular student-led projects. Interviewees traced Delft’s “*spirit*” back to its early history and its deeply-embedded ethic of social responsibility. They pointed, for example, to the pivotal national role the university played in developing the country’s industries following World War II and in building the country’s coastal defenses in the face of rising sea levels. As one teacher⁸⁶ noted:

“There are all sorts of circumstances by which Delft became relevant from a social point of view. For a long time, we were the only technical university in the Netherlands.... So, the attitude is ‘we can do it’. If your land is threatened by flooding, you have to just solve the problem. You can’t move to higher land, because there is no higher land here. We constructed dykes and dams [that are designed to withstand] one-in-a-thousand-year flooding. You start engineering with the mentality that we are going to protect the country. We are going to work on this and by golly we are going to succeed!”

This “*problem-solving and socially-relevant*” approach to engineering is also reflected in the university’s longstanding research collaborations with industry. Indeed, over one third of TU Delft’s €385 million annual research income is sourced from industry. Its research outputs are also world-class, with the university ranked 63rd and 54th in the world in the *Times Higher Education World University Rankings*⁸⁷ and the *QS World University Rankings*¹⁰ respectively.

⁸⁵ TU Delft’s eight Faculties: Architecture & the Built Environment; Civil Engineering & Geosciences; Electrical Engineering, Mathematics & Computer Science; Industrial Design Engineering; Aerospace Engineering; Technology, Policy & Management; Applied Sciences; Mechanical Maritime & Materials Engineering.

⁸⁶ At TU Delft, the term ‘teacher’ is used to describe faculty or academic staff. This term is used throughout the case study to avoid confusion with the eight ‘Faculties’ that comprise the university.

⁸⁷ *Times Higher Education World University Rankings 2018* (<https://www.timeshighereducation.com/world-university-rankings>)

Following the introduction of the Bologna Process⁸⁸ across the Netherlands in 2002, TU Delft's five-year undergraduate curriculum underwent systemic reform to create two distinct cycles: a three-year bachelor program and a two-year master program. Most Dutch students complete both cycles: at TU Delft, 97% of undergraduate students progress to master programs at the university, typically remaining in the same Faculty. Most of the university's 17 bachelor programs are taught in Dutch and are home to a student population of around 11,400, of which 26% are female.

As outlined in Figure 17, the past decade has brought rapid growth to TU Delft's master program population, which now stands at over 10,000. The growth has been driven by increasing numbers of overseas students attracted to the university's 33 master programs, which are exclusively taught in English; by 2016, 34% of TU Delft master students were non-Dutch, compared to 25% in 2006.

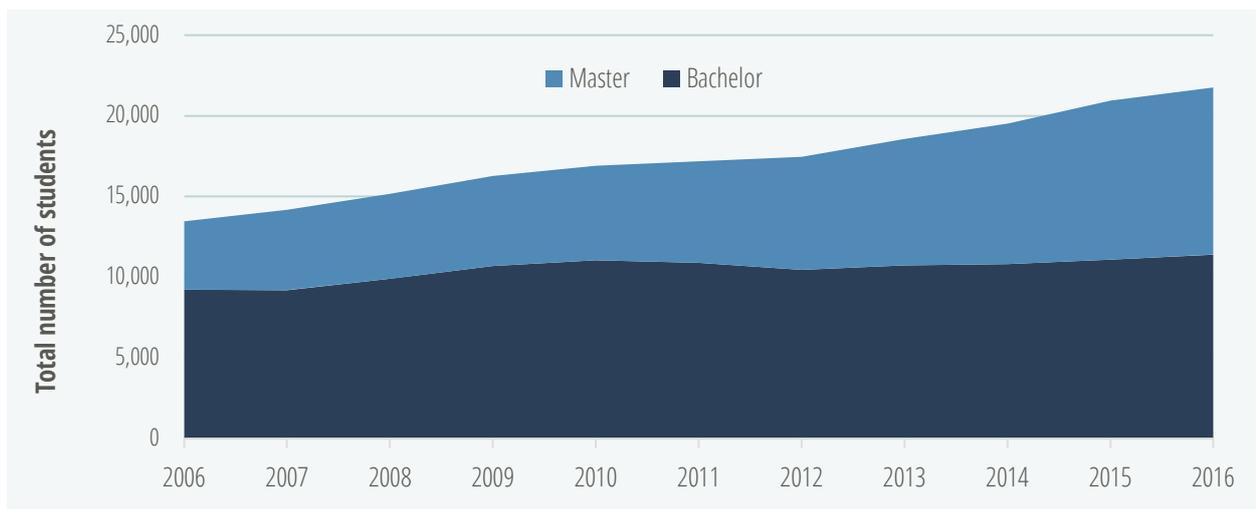


Figure 17. Total bachelor and master population at TU Delft, 2006-2016

E.1.2. The national context

The Netherlands is a small and densely-populated country; its population of 17 million is housed within an area around twice the size of New Jersey. The Dutch higher education system is among the most highly-regarded in the world; in the 2018 *Times Higher Education World University Rankings*, it is outperformed only by the US and UK. All 13 Dutch research universities appear within the world's top 200 ranked institutions,⁸⁷ with TU Delft ranked second in this national group.

A distinctive aspect of the higher education system in the Netherlands – and one which was repeatedly highlighted during the interviews – is the level of collaboration and partnership between its 13 research-oriented institutions. In the words of one interviewee, *“when a country is so small, if you don't open your doors and windows and cooperate, how can you compete?”* Many interviewees suggested a sector-wide culture of collaboration played a critical role in shaping the direction and progress of the country's university system. This has included an agreement to introduce a national *University Teaching*

⁸⁸ The Bologna Declaration was signed in 1999 by 29 European countries to (i) establish a three-cycle system of bachelor, master and doctorate, (ii) strengthen quality assurance, and (iii) support the inter-institutional recognition of qualifications and periods of study (http://ec.europa.eu/education/policy/higher-education/bologna-process_en).

Qualification (UTQ) for university teachers and a cross-institutional alliance that has secured agreement with the world's major publishers to make scientific papers free to access.⁸⁹

Recent decades have brought major changes to the Dutch higher education system, including an increase in the student population and a decline in government financial support. In the decade from 2006, intake numbers at bachelor and master level almost doubled across Dutch research universities. Over the same period, the Dutch higher education sector has also transitioned towards English-language delivery. Today, 60% of bachelor and master degree programs at the country's research-oriented universities are taught in English. These shifts have brought a growing overseas student population to the country: in the decade to 2016, the proportion of international bachelor and master students at research-oriented universities increased from 8% to 18%.

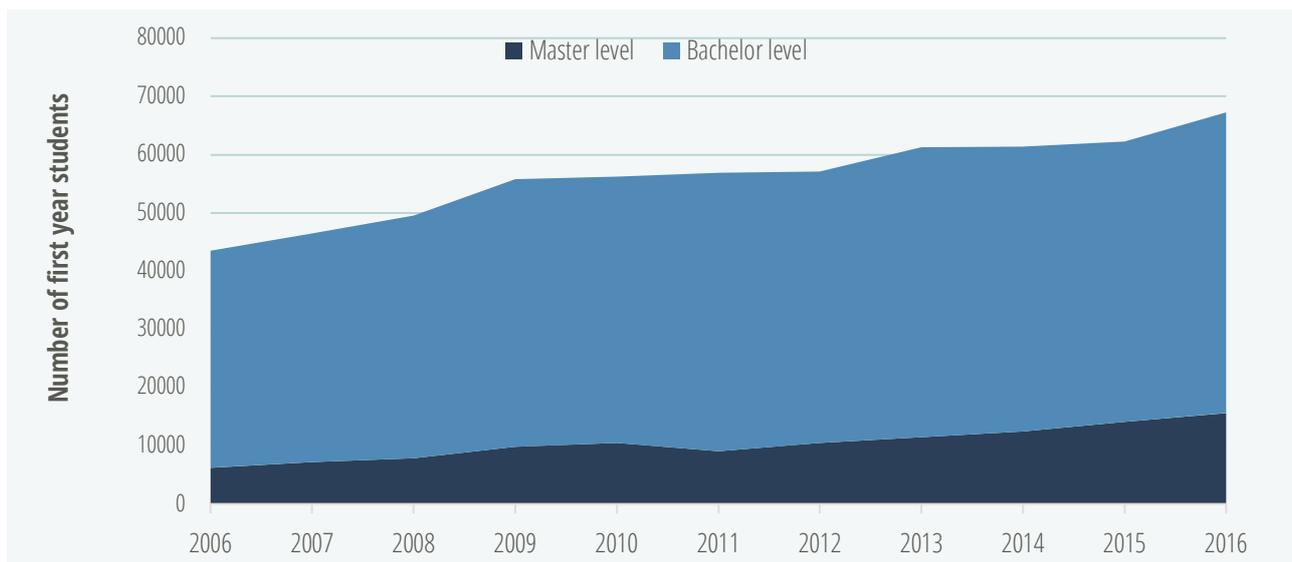


Figure 18. Total number of first year students at the 13 Dutch research universities at bachelor and master level, 2006-2016

Increasing student numbers have been accompanied by a decline in government funding per European student, which has fallen from around €20k in 2000 to around €15k in 2014. In 2015, the grants paid by the government to students (to cover their annual tuition fees and living costs) were replaced with loans, to be repaid after graduation. Revenue from loan repayments started to accrue from September 2017 and will be invested back into university teaching across the country, including the creation of new teaching positions and programs to support educational research.

Entry to university is managed on the principle of 'open access': students with the appropriate qualifications are entitled to a place to study at the program and university of their choice. Until recently, places on over-subscribed programs were allocated using a weighted lottery system that was controlled centrally by the Dutch government. Government changes introduced in 2016, however, provide universities with more freedom to select students for over-subscribed programs.

⁸⁹ The Netherlands: Paving the way for open access (<http://www.magazine-on-the-spot.nl/openaccess/eng/>)

E.2. The development of TU Delft's educational approach

Unlike the other case studies, TU Delft's position among the emerging leaders in engineering education is not the result of systematic reform or a blank-slate development. Instead, its strength lies in its capacity for incremental change, and, in particular, for maintaining its reputation for academic excellence while embracing educational innovations that subsequently become sector-wide. Vital to the process of incremental change has been cross-campus consultation and consensus-building, centrally supported by the provision of "*opportunities and space*" for teachers and Faculties to drive educational reform from the bottom up. One interviewee characterized this process of teacher-led educational reform to be:

"like the way oil spreads on water,... change happened slowly – by consensus, in small steps, letting people get used to the idea all the time."

This section outlines key milestones and activities that have shaped the evolution of TU Delft's education over the past two decades. The timeline is built from interviewee feedback and recollections of those involved. Starting in 2005, it is structured around five time periods:

- Section E.2.1:** enhancing the profile of education at TU Delft (2005–2010);
- Section E.2.2:** establishment of a drive to improve 'study success' (2010–2013);
- Section E.2.3:** growth in external connectivity and online learning (2013–2015);
- Section E.2.4:** development of a new educational vision and support system (from 2015);
- Section E.2.5:** emergence and growth of ambitious student-led activities (1999 to date).

Interwoven across the first four time periods are two important dimensions of TU Delft's educational success: (i) institutional leadership in education; and (ii) the growth of open and online learning. The final time period described – that of the student-led extra-curricular activities – has grown in parallel to, and largely independently from, the educational changes at the institutional level. Linking all streams, however, has been strategic institutional investment in areas with the potential to catalyze educational change across the institution: in the teaching skills of academic staff, in educational technologies and in extra-curricular student-led learning.

E.2.1. Enhancing the profile of education at TU Delft (2005–2010)

Interviewees from both outside and within TU Delft consistently noted its proudly-held reputation for academic rigor in engineering education and the teaching of the engineering fundamentals. Historically, these features were combined with an immersion in engineering practice, drawing on the rich and diverse industry experience of its teaching staff. Through the 1990s, however, the university's practice of hiring teachers from industry or offering split industry/academic posts was curtailed under growing national and global competitive pressure in research. Education-focused roles at the university were phased out at a time when TU Delft's research strengths were gaining global prominence. However, there was growing recognition within the university that "*education had been put too much in the back seat,*" overshadowed by the institution's research success.

To many, this imbalance in the university's mission was symbolized by the predominant focus on research by its Executive Board. In 2003, the university appointed its first Vice-President for Education, later becoming Vice-President for Education and Operations in 2005. Interviewees noted that this appointment:

"was a big boost to the institution... He was able to put education on the agenda and [offer] a counterbalance to the focus on research."

Soon after, a cross-campus consultation was initiated to assess the university's needs and ambitions in education. Institution-wide changes quickly followed, including the appointment of Directors of Education for each Faculty and a suite of new opportunities for networking and sharing educational ideas. Cross-institutional collaborations were also established, most notably an agreement across Dutch research universities to introduce a mandatory UTQ qualification for teaching staff. By 2010, TU Delft required all new academic staff and lecturers to gain this UTQ within five years of their appointment. Despite the challenges of driving change in such a decentralized university, many interviewees pointed to an increasing emphasis on *"the role of education on campus."*

The educational initiatives launched across the university were also seen to pave the way for more radical 'bottom-up' change driven by individual Faculties. Two notable educational reforms initiated at this time were in the Faculties of Industrial Design Engineering (in 2007) and Aerospace Engineering (in 2009). Both reforms were driven by a Faculty-wide effort and responded to a critical appraisal of the changing professional roles and responsibilities of their graduates. Both revised curricula also offered an integrated approach, structured around a series of authentic design-centered problems. For example, one of the second-year projects in the Industrial Design Engineering curriculum challenges students to design and build a wooden toy, with the prototypes road-tested and evaluated by groups of local schoolchildren.

During this period, the university also started to build its capabilities in open and online learning, starting with the launch of the TU Delft open courseware website in 2007. It was not until 2010, however, that a full-time team was dedicated to developing and managing this online content, which included slides, examinations and lectures captured by video from the back of the classroom. The team also started to look strategically at what content might add most value to the online audience and started to create dedicated materials for what was termed the 'stumble' courses – *"courses that a lot of students have particular problems with, like calculus"* – and dedicated online introductory courses to around half of the bachelor programs.

E.2.2. Establishment of a drive to improve ‘study success’ (2010–2013)

In the two decades leading up to 2010, participation in Dutch higher education had risen steadily from 400,000 to over 600,000 students. Anticipating equally significant increases in the decade to come, in 2010 the Dutch government commissioned a review of the national higher education system and its capacity to support such an expansion at a time of increasing economic constraint. The review outcomes⁹⁰ identified a number of critical challenges facing the national sector, including high drop-out rates, extended study completion times and insufficient curricular flexibility. Some challenges were particularly evident at TU Delft. Pass rates and retention rates at the university were the lowest in the country: only 22% of the students who had passed their first year went on to complete the three-year bachelor program within four years; average time to completion of the combined five-year master and bachelor programs was 7.5 years.

In response, TU Delft launched the *Study Success* program in 2011. It brought a suite of reforms to the bachelor education, including “*a measure that requires all first-year students to achieve 75% of their study credits in the first year of study*” in order to continue to the second year of study. The reforms achieved rapid improvements in student outcomes: between 2011 and 2015, the proportion of bachelor students who, having completed their first year of study, went on to complete their degree in four years, increased from 22% to 55%. A number of Faculties used the *Study Success* program as a platform for more radical reforms to their undergraduate programs. One example was the Faculty of Architecture and the Built Environment, as outlined in Box 25.

Box 25: Educational reforms in the Faculty of Architecture and the Built Environment

Prior to 2011, the bachelor program in Architecture, Urbanism and Building Sciences had one of the lowest student retention rates in the university. The curriculum was seen to be fragmented, with multiple small courses operating in parallel that offered limited coherence to the learning and “*a lot of repetition, redundancy and overlap in the material.*” Implemented in 2013, the new curriculum was designed “*from the bottom-up, with all teachers involved in the process.*” It comprised six core curricular threads⁹¹ woven across the three-year curriculum, offering students a transparent educational structure and allowing them to build and integrate competencies in each thread throughout their studies. One third of the new curriculum was dedicated to the design thread, delivered through two seven-week projects each year. Courses running in parallel to the design projects were designed to provide a theoretical context to these team-based challenges and/or support the development of the skills and attitudes necessary to tackle them. A dedicated team of professors was assigned to oversee each curricular thread as it ran throughout the three-year program, to ensure its coherence and integration of learning.

⁹⁰ Veerman, C., et al. (2010). Threefold differentiation – recommendations of the committee on the future sustainability of the Dutch higher education system. The Hague: Ministry of Education.

⁹¹ The curricular threads are: design; technology; fundamentals; society, practice and process; academic skills; representation, visualization and form.

E.2.3. Growth in external connectivity and online learning (2013–2015)

2013 marked the beginning of a more ambitious and outward-looking period of educational change at TU Delft. While the university-wide reforms implemented from 2005–2013 were characterized by some interviewees as *“removing the ‘tail’ of poor practice in teaching,”* the period from 2013 heralded new opportunities for innovation in education and for collaboration outside the university. For example, in 2013, TU Delft forged two strategic national alliances in teaching and learning: the 3TU Centre for Engineering Education⁹² (later becoming 4TU), as a collaboration between the country’s technical universities, and the Centre for Education and Learning,⁹³ as part of a wider partnership between the universities of Leiden, Delft and Erasmus (LDE). In addition to opportunities for educational research and network-building, these alliances paved the way for new cross-disciplinary, cross-institutional programs, such as the joint bachelor in *Clinical Technology*.⁹⁴

The key development that stands out at TU Delft during this period, however, is the rapid growth of its open and online learning capacity. The university’s activities in this domain had grown steadily since 2010, and production on its first set of Massive Open Online Courses (MOOCs) began in late 2012. However, TU Delft’s ambitions in this open and online learning advanced significantly from 2013. Many interviewees credited this shift in focus to the appointment of a new Vice-President for Education and Operations early in 2013. A past president of the *Open Education Consortium*,⁹⁵ she was seen to bring an energy and commitment to the university’s investment in open and online learning, as well as a global network of expertise and new ideas.

Together with a newly-appointed Director of Education, the new Vice-President launched a university-wide consultation on the potential for establishing TU Delft as the European leader in open and online learning. The plan gained traction with teaching staff and managers alike. The vision of creating open-access educational resources *“struck a chord with what people wanted for the country.”* It responded to the Dutch *“free and open”* culture that has seen the country play a key role in the global ‘open science’ and ‘open education’ movements.⁸⁹ As many interviewees noted, *“as a public university, we have a social responsibility to give back to the country. This is something important to people.”* The university’s engineering base provided further impetus: it was suggested that *“as engineers, people were more aware of the impact that disruptive technologies can have and were open to the idea that the same could happen with online learning.”* Many noted that *“this was the moment for us to decide, are we a front-runner or a follower [in online learning]... Could we take the risk of being left behind?”* Momentum was reinforced when the first set of MOOCs, launched in September 2013, were *“an instant success,”* receiving 80,000 enrolments in the first few months. Their success contributed to university-wide recognition of the potential for TU Delft to extend its global reputation through a pioneering approach to online learning.

⁹² 4TU Centre for Engineering Education (<https://www.4tu.nl/cee/en/>)

⁹³ Centre for Education and Learning (<http://www.educationandlearning.nl/home>)

⁹⁴ Clinical Technology, LDE consortium (<https://www.tudelft.nl/en/education/programmes/bachelors/kt/bachelor-of-clinical-technology/>)

⁹⁵ Open Education Consortium (<http://www.oecconsortium.org>)

Further institutional investment quickly followed. The TU Delft Extension School in open and online education was opened in spring 2014 and focused on four core areas: (i) open courseware; (ii) MOOCs; (iii) online academic courses with paid enrollment; and (iv) professional education courses with paid enrolment. The 25 FTE staff appointed to the *School* were noted to be *“a very international and young group,”* bringing expertise and experience from outside the country. The Extension School took a co-design approach to developing online materials; each participating teaching staff member worked as part of a dedicated team with business developers, technologists and educational specialists to design, build, deliver and review each new online product.

Following the establishment of the Extension School, online learning at TU Delft quickly became *“a jewel in the crown”* of the university’s educational provision, with its MOOCs achieving over a million enrolments by September 2016. In addition to *“the professionalism and creativity of the [Extension School] team,”* the success of the university’s online provision can be attributed to the engagement of a core group of the university’s teaching staff. Here, *“the huge success”* of the early MOOCs was identified as a catalyst for far-reaching changes in attitudes towards educational innovation across campus through two mechanisms.

Firstly, the early MOOCs stimulated interest in open-access provision. As one interviewee noted: *“for faculty, a big motivation was the visibility of individual teachers. These professors [involved in the early MOOCs] were being recognized not only through their research but for their education. They go to conferences and everyone recognizes them. They are stars! ... It is a new avenue for them to create networks around their research topic.”* Notable among these high-profile early successes was the *Solar Energy* MOOC, outlined in Box 26.

Secondly, growing interest in open access provision helped to break down *“an engrained culture”* of resistance to pedagogical training among its research leaders. The experience of developing online materials – *“which can be reviewed by anyone, anywhere in the world”* – was described to be *“a sobering experience”* for many. In the words of one, *“if you put things out there, to the world, you have to think twice about the quality. It needs to be topnotch.”* Many within and outside the Extension School suggested that, as a result, participating teachers:

“were much more open to taking pedagogical advice.... When they are in the Extension School, people step into a different mode and ask for help, take advice and start working on their education as part of a team.”

Since the launch of the Extension School, the use of blended learning in the university’s bachelor and master programs has increased significantly. One example is the campus-wide reform to mathematics teaching for first- and second-year bachelor students (see Box 27). At a broader level, TU Delft is also exploring the potential for on-campus students to gain formal credit for studying MOOCs from other institutions worldwide. The pilot initiative, launched late 2015, is designed to offer students a more flexible way to learn, as well as more choice in the course they can follow.

Box 26: Solar Energy MOOC

Launched in 2013, the *Solar Energy* MOOC⁹⁶ was among the first to be developed at TU Delft. Bringing together 6–10 minute videos with custom animations, exercises, assignments and exams, this eight-week course guides students through the design of a photovoltaic system.

In its first year alone, the MOOC attracted 57,000 enrollments; total enrollments to date have exceeded 160,000. The MOOC is particularly noted for the levels of active peer-to-peer interaction and learning that it has facilitated between students, as well as the student-generated content and information. Indeed, in the first year alone, feedback from the MOOC's registered learners was used to generate the world's largest database of images of regional solar energy systems.

Drawing on both the experience and the materials developed through this MOOC, the TU Delft on-campus master elective in *Solar Energy* was transformed to a flipped classroom model. Launched in September 2014, the course was designed to run concurrently with the MOOC. Students were asked to follow the MOOC's lectures online, with classroom time devoted to exercises and discussion. Using this approach, the instructor was able to cover 30% more material in the course than had previously been possible. The new pedagogy also yielded significant improvements in students' exam performance. In the four years between 2010–2013, the pass rate for the on-campus *Solar Energy* elective had fluctuated between 67% and 72%: following the introduction of the flipped classroom approach in 2014, pass rates increased to 89%.

Box 27: Blended learning approach to mathematics teaching in Years 1 and 2

Mathematics education is a mandatory element of the bachelor programs at TU Delft, delivered by the Applied Mathematics department to all first- and second-year students. Each mathematics course – such as calculus, linear algebra and statistics – is tailored to the particular needs and disciplinary focus of each bachelor program. Nonetheless, the model was recognized to have problems, including low student engagement and the difficulties of delivering effective mathematics education to large numbers of students through a traditional lectured-based approach.

In response, TU Delft launched a major initiative in 2014 to transition its mathematics teaching to a blended learning approach, starting with a pilot in Civil Engineering. The new courses were developed in partnership with learning developers at the TU Delft Extension School and involved the training of all 25 mathematics teachers in the Applied Mathematics department. Using a flipped classroom approach, students watch an introductory video and complete exercises online before class, work in groups on discipline-specific exercises during class, and then take online quizzes and homework after class. Course components are tailored to the students' discipline of study and regular feedback is provided, both online and in-class. Active learning and student engagement is further supported using interactive concept maps, designed to guide students through each mathematical concept and reinforce the relationships between them. To date, the new blended learning approach has been rolled out across four of the eight Faculties at TU Delft.

⁹⁶ TU Delft, Solar Energy MOOC (<https://online-learning.tudelft.nl/courses/solar-energy/>)

E.2.4. Development of a new educational vision and support system (from 2015)

The period from 2015 has brought two major educational developments to TU Delft, each of which is likely to have a profound effect on the institution's culture and curriculum in the future.

The **first wave of activity** has focused on how educational development and innovation are supported at TU Delft. Despite its growing successes in the open and online domain, there was an increasing institutional recognition that the pressure for research excellence *"does not leave teachers with space to collaborate, innovate or improve their teaching."* Seeking to create *"a more balanced picture between education and research,"* TU Delft launched the *Spotlight on Education* initiative in 2016. The initiative provided opportunities to support and celebrate innovation, risk-taking and exploration in teaching and learning, including two-year teaching fellowships to support new innovations in the classroom and prizes for the leading university teachers. To further consolidate and strengthen its capacity for educational innovation, in September 2017, TU Delft established the Teaching Academy⁹⁷ to provide a single access point for teaching and learning support across campus. The new Academy will integrate TU Delft's support in online, blended and face-to-face learning, previously *"scattered across campus,"* into a single facility. It is designed to act as *"an incubator and accelerator for educational development,"* providing professional development (courses and support in on-campus and online teaching and learning, including institutional teacher training), hands-on support (including one-to-one support for teachers involved in the development of on-campus courses and MOOCs) and innovative development (more intensive support for new ideas, innovations and research projects in education).

The **second wave of activity** focused on articulating TU Delft's educational vision and ambition for the years to come. The origins of this process date back to an influential report, first published in 2014, written by the Director of Education in TU Delft's department of Aerospace Engineering.⁹⁸ Taking a horizon-scanning approach, the report articulated *"vision statements for the attributes that our engineering students will have to acquire for a successful career in the world of work."* The report stirred considerable debate, across and beyond TU Delft. Shortly after its publication, in early 2015 a series of five workshops was organized by the TU Delft Directors of Education and the 4TU Centre for Engineering Education to explore how the university's education and target student intake should change in the coming decades. Termed the 'Free Spirits Think Tank', these workshops brought together students, teachers and university managers from across TU Delft.

The workshop outputs were used as stepping stones to build the university's first institution-wide educational vision statement. As many interviewees made clear, *"TU Delft is not a university that has a lot of written policies or unnecessary paperwork."* In consequence, there was an unwillingness to prepare a document *"full of bland and meaningless statements that could apply anywhere – this would just end up in a drawer and no one would read it."* Instead, during 2016–2017, the university embarked on a two-year iterative process – consulting with students, teachers and Faculty managers across campus – to identify

⁹⁷ TU Delft Teaching Academy (<https://www.tudelft.nl/teachingacademy/>)

⁹⁸ Kamp, A. (2014). Engineering Education in a Rapidly Changing World (<http://www.cdio.org/node/6183>)

and articulate the distinct qualities of the TU Delft education and chart a course for its future development.

Bringing together the outputs from each of the consultations, the (as yet unpublished) vision statement explores some of the educational challenges currently facing the university, such as how to adapt to the significant increases in the student population, both from home and overseas markets. The statement also highlights discussion points for future development in its educational portfolio. Many of these proposals – such as offering students the flexibility to select specialist pathways of study, and offering more cross-disciplinary experiences – aligned strongly with the major changes to global engineering education anticipated by the thought leaders in the first phase of this study.

E.2.5. Emergence and growth of ambitious student-led extra-curricular activities

TU Delft has long been known for its student-led extra-curricular activities. Even among Dutch universities, with their tradition of student-led activity, *“the vivid culture”* at TU Delft stands out. The university’s student-led activities vary widely, and include social clubs, student councils and one ‘study association’ for each of the university’s Faculties; for example, in Aerospace Engineering, 95% of its bachelor and master student cohort are members of the Faculty’s student-led ‘study association’. Viewed in a wider international context, TU Delft’s clubs and societies are distinguished by their independence from the university and for the level of time invested in them by students. Each year, the university officially acknowledges and financially supports a significant number of students that take time out of their studies to fulfill full-time administrative duties in a club or society; it is recognized, however, that many more students take such full-time roles without formal university acknowledgement. However, until 1999/2000, very few of these extra-curricular activities focused on the application of engineering and technology; instead, most did not extend beyond *“hobby clubs, like the motorbike and car repair clubs.”*

This changed in 1999, when a small group of master students set themselves the goal of winning the *World Solar Challenge*,⁹⁹ giving themselves two years to design and build a world-class solar car from a standing start. TU Delft interviewees noted that:

“in the beginning, no one believed these guys could do it. They had told us ‘we are going to join the race in Australia for solar cars and we are going to win’. At the time, there were big companies [participating] in the race, like General Motors and Honda. Everyone thought they were crazy. There was no provision, no place for them to build, they had no money, nothing.”

With support from a Delft professor who was a former astronaut, the students were soon connected with companies that went on to sponsor their fledgling team. They took up residence in *“an old basement of a building, without any kind of formal permission from the [university] Board”* and were soon joined by the *Formula Student* team, which had been established by a group of TU Delft master students the previous year.

⁹⁹ World Solar Challenge (<https://www.worldsolarchallenge.org>)

In 2001, much to the surprise of observers within and outside TU Delft, the nine members of the solar team – named the *Nuon Solar Team*¹⁰⁰ – won the *World Solar Challenge*. The team then went on to win the next two iterations of this biennial competition, in 2003 and 2005. Interviewees noted that these achievements, which were covered by the national press:

"gave the university a lot of exposure. The spin-off of the success was enormous ... it became a decision point for [prospective] students and a lot of students started to come to Delft."

Throughout this period, the three existing student-led teams based at TU Delft – *Nuon Solar Team*, *Formula Student* team¹⁰¹ and *Delft Water Bike Technology*¹⁰² – operated relatively independently from one another and struggled to find a space in which to work on their vehicles. In 2007, after a number of years of moving between empty spaces on campus, they took residence in a workshop space in the Faculty of Civil Engineering and Geosciences. Following strong lobbying from key academic staff, this space was to become the permanent home for the teams and in 2009 was renamed the DreamHall. Together, the teams became known as the 'DreamTeams', standing for *Dream Realisation of Extremely Advanced Machines*, or D:Dream for short, pronounced 'daydream' in Dutch. As such, the DreamHall was designed as "a place where students could realize crazy ideas" in a team-based environment. Although the hall was 'owned' by TU Delft, the student teams continued to work independently from the university.

The establishment of the DreamHall was understood to have a dramatic impact on the coherence and visibility of the teams across campus. Very soon, new student groups were pitching to join the space. Most were at a bachelor level of study. All brought highly ambitious goals, aimed considerably beyond what one might expect from undergraduate and master students. For example, the *Human Power Team* was established in 2010, with the aim of breaking the world speed record for a human-powered vehicle. This record was achieved in 2013, with the third iteration of the team's design, with a recumbent bicycle that reached a top speed of 134km/hr. Another team, DARE (the *Delft Aerospace Rocket Engineering* team), set itself the challenge of being the first student team to reach space and has already broken the European altitude record.

Although autonomy has remained a core feature of the teams, from 2013 the university started to provide more formal support to the DreamHall. This totals around €1.5m per year, and includes the premises, a full-time building manager, student assistants and the organization of workshops to support the teams. At the start of each year, a two-week 'top track' program of workshops provides teams with coaching and training in topics ranging from financial administration to fluid dynamics. The university support is complemented by company sponsorship, which is estimated to be around €5–10m across the teams. Today, the DreamHall houses around 400 students across nine teams. The majority of team members are bachelor-level students, and around a quarter of them are engaged full time on their project. Workloads among team members are high; full-time team members typically

¹⁰⁰ Nuon Solar Team (<http://www.nuonsolarteam.nl/?lang=en>)

¹⁰¹ Formula Student team Delft (<https://www.fsteamdelft.nl>)

¹⁰² *Delft Water Bike Technology* has since been disbanded.

devote around 80 hours per week on their project, while other 'part-time' students typically devote at least 10–15 hours per week.

The DreamTeams have been phenomenally successful. Interviewees from outside the university noted the reputation established by teams such as the *Nuon Solar Team* and *Delft Formula Student* team through *"consistently coming first in these international competitions – year after year, it always seem to be Delft coming in first place."* Many of the teams have focused on projects with a social development or environmental ambition, such as the development of an exoskeleton designed to increase the mobility of paraplegics or a system to clean the oceans of plastic. This societal orientation reflects TU Delft's strong value base and the deep-seated university culture of contributing to the wellbeing of the Netherlands and wider society.

There appear to be three factors that set the DreamTeams apart from their international peers. The **first** is their consistent focus on renewal, rather than evolutionary development; most teams work on a 12-month cycle, with 85% of the team newly appointed each year to start afresh with a new design. An advisory group of DreamTeams alumni provide advice where needed and select the 'core' full-time team member each year, *"to provide continuity and to make sure that they learn from previous experience."* A **second** factor in their success is the high levels of creativity and ambition that the teams generate. Interviewee feedback suggests that this has been fed by the significant successes achieved by the early teams, resulting in a desire among each cohort to *"outdo"* the teams that have gone before them. In the words of one interviewee, *"there is a tribal mentality – with the other countries but also between teams – you want to do better than last year's guys, you want to be the best."*

The **third** success factor is the teams' motivation and engagement. Many interviewees attributed these qualities to the autonomy with which the students have managed and directed these initiatives. In the words of one:

"it is by and for the students. You don't get credit points for participating. You don't have professors looking over your shoulders. It is the students, together, working for something that is bigger than themselves and so they are intrinsically motivated. That last couple of percent, that makes you win, comes from intrinsic motivation, and it makes all the difference."

Many also credited the university's 'hands-off' approach in supporting but not directing the teams: *"they have believed in them, they have trusted them and they have given them the space to fly."* In the coming years, the university is looking to develop a second space for the DreamTeams, to meet the growing demand from new student teams to join the DreamHall.

E.3. TU Delft's educational approach

Unlike the other three institutions considered for case study evaluation in this MIT-commissioned report, TU Delft does not offer a single overarching model for its engineering education. Instead, its programs are characterized by their diversity. The 17 bachelor programs and 33 master programs at TU Delft are designed and delivered relatively independently and considerable variation in curricular design and pedagogy exists between them. However, they share common characteristics.

All interviewees, from both within and outside the university, were asked to identify the distinguishing features of TU Delft's educational approach. Four features were consistently highlighted. The first two relate to qualities for which engineering education at the university has long been known; the third and fourth illustrate its capacity to embrace and harness change to ensure TU Delft remains at the forefront of educational innovation:

- **deep disciplinary knowledge:** all interviewees highlighted the technical rigor of the TU Delft education, with its students graduating with *"a solid background in maths, mechanics and the engineering fundamentals"*;
- **the integration of engineering, science and design:** each program was understood to bring together a blend of engineering, science and design, although the weighting placed on each within the curriculum varies considerably by discipline;
- **an ambitious student culture of initiative and hands-on learning:** the culture of TU Delft was seen to promote ambition and leadership among its student population, with significant opportunities to apply their knowledge to real engineering problems. Much of this activity is driven and supported by the student-led extra-curricular activities, which operate relatively independently of the university;
- **a pioneering approach to blended and online learning:** many interviewees noted the university's growing strength in online learning and the positive impact this has had in recent years on student learning, both on- and off-campus.

Table 6 provides an overview of the key features of the university's education and the structures and processes that support it. The data included in Table 6 is distilled from interviews with stakeholders to TU Delft's undergraduate programs.

Educational feature	Details
Criteria for selection of student intake	Historically, and in line with Dutch government policy, TU Delft has not selected its bachelor intake; it enrolled from across the 20% of the prospective student population that gained the requisite secondary-school diploma and had chosen to study at the university. Places on over-subscribed programs were allocated through a national weighted lottery system. Since 2016, however, over-subscribed programs may seek permission from the government to devise and introduce their own selection criteria. Aerospace Engineering will be one of the first TU Delft Faculties to introduce student selection for all incoming students. Through this new system, prospective students will be selected using a four-stage process: completion of the <i>Introduction to Aeronautical Engineering</i> mini MOOC; a test designed to evaluate motivation for academic study; tests in mathematics and physics; and an assignment in aeronautical engineering.
Flexibility and student choice	Interviewees consistently reported that, aside from the minor in Year 3 of study, limited choice is offered to students during their bachelor studies: <i>“students all follow a single track.”</i> At the master level, students are typically offered more choice through specialist sub-disciplines. The university is also discussing the feasibility of introducing distinct ‘profile tracks’ to allow routes for master students to specialize in particular fields of interest.
Opportunities to work across disciplines	At both bachelor and master level, few curricular opportunities are offered for students to work with individuals from outside their disciplinary cohort, apart from during the minor or master electives. Most of the multidisciplinary experiences available to students are offered outside the curriculum, through student-led clubs and societies.
Pedagogical approach	Interviewees reported that pedagogical practice varies significantly by Faculty; while some take a teacher-centered, theoretically-driven approach, others have adopted active, student-centered learning across the curriculum. For example, in Industrial Design Engineering, more than 50% of the curriculum is project-based.
Teaching and learning support	In September 2017, TU Delft launched the Teaching Academy. ⁹⁷ Described by one interviewee as a <i>“one-stop-shop for teaching and learning support,”</i> it brings together the support functions previously supplied by the Extension School and OC Focus (TU Delft’s teaching and learning support center, originally established in 2007). The new Teaching Academy will offer: <ul style="list-style-type: none"> • professional development courses, workshops and UTQ training; • ‘hands-on’ support for online or on-campus course development; • focused one-to-one support for teaching innovations, both online and on-campus.
Reward and recognition of teaching	Interviewees consistently reported that academic appointment, and promotion at TU Delft, <i>“is based almost completely on research achievement.”</i> The university offers a special promotion route to full professorship for <i>“young outstanding researchers”</i> ; one such recent promotion has been made on the basis of blended portfolio of excellence in both research and education. The university recently introduced an annual prize for innovation in teaching as well as a Teaching Fellowship scheme, which offers teachers €50k over two years to support innovative and evidence-based teaching.
Educational research activities	No formal engineering education research groups or centers operate at the university. At present, most educational research is undertaken by individual teachers in collaborations with the 4TU or the LDE. It was anticipated that the educational research base within the university will grow with the establishment of the Teaching Academy ⁹⁷ in September 2017.
Extra-curricular opportunities	Extra-curricular activities play a crucial role in student learning at TU Delft. Over half of students participate in one or more club or society. Although some focus on social activities, sports or other pursuits, a high proportion are focused on science and engineering and their application to society. One key feature of the clubs is their independence from the university; most operate without any supervision, tutoring or involvement by TU Delft staff.

Table 6. Key features of the TU Delft educational approach and support system

E.4. Curriculum design

The TU Delft education is structured according to the Bologna 3+2 model,⁸⁸ offering a three-year bachelor program followed by a two-year master program. There is no common first year; students specialize in their chosen engineering discipline on entry to their undergraduate studies.

Apart from a minor¹⁰³ during the bachelor program and an elective space in the master program, limited commonality exists between the university's programs, at both the bachelor and master level. As one academic leader noted, *"it is a policy not to have an underlying curriculum structure. We don't want to impose a structure on Faculties."* In order to showcase a sample curriculum for the purposes of this TU Delft case study, therefore, interviewees were asked to identify which program they considered to exemplify best practice at the university. Three programs were consistently identified by interviewees from within and outside TU Delft: Aerospace Engineering, Industrial Design Engineering and Architecture, Urbanism and Building Sciences. One of these three programs has been selected as an example of the university's approach to curriculum design. This section therefore focuses on the bachelor and master programs from Aerospace Engineering, the curriculum structure for which is outlined in Figure 19.

The **Faculty of Aerospace Engineering** is home to 1400 bachelor students, 1200 master students and 70 FTE academic staff. Both the bachelor and master programs are taught exclusively in English; at the master level, 44% of the enrolled students are non-Dutch. Student interviewees from across the university characterized the program as *"the hardest and most intensive course at Delft."* With an application-to-acceptance rate of 3:1, places on the bachelor program are also the most sought-after at the university.

Together, the bachelor and master programs are designed to educate the 'T-shaped engineer':

- the broad education at bachelor level – developing foundational knowledge with integrative problem-solving, design and teamworking skills – represents the horizontal bar of the 'T';
- the in-depth education at master level – developing specialist knowledge and research skills within a professional field – represents the vertical stem of the 'T'.

The bachelor program takes an active, project-based approach that emphasizes the application of deep disciplinary knowledge to authentic engineering problems. For example, 40% of class contact time at bachelor level is devoted to project or lab work. This active approach is reflected in the design of the Faculty's learning spaces: the new 'Fellowship Building' contains no tiered lecture theatres, but rather 45 project spaces, two studio classrooms and a several tutorial rooms. Curricular delivery is also supported by a significant number of teaching assistants; for the bachelor program alone, the Faculty employs 15 FTE teaching assistants.

¹⁰³ All bachelor students take a semester-long minor at the beginning of Year 3. Students can opt to select a minor from within their home department (to deepen their disciplinary knowledge and skills) but are encouraged to select a minor from elsewhere across TU Delft, from another Dutch institution or from abroad (to broaden their knowledge and skills).

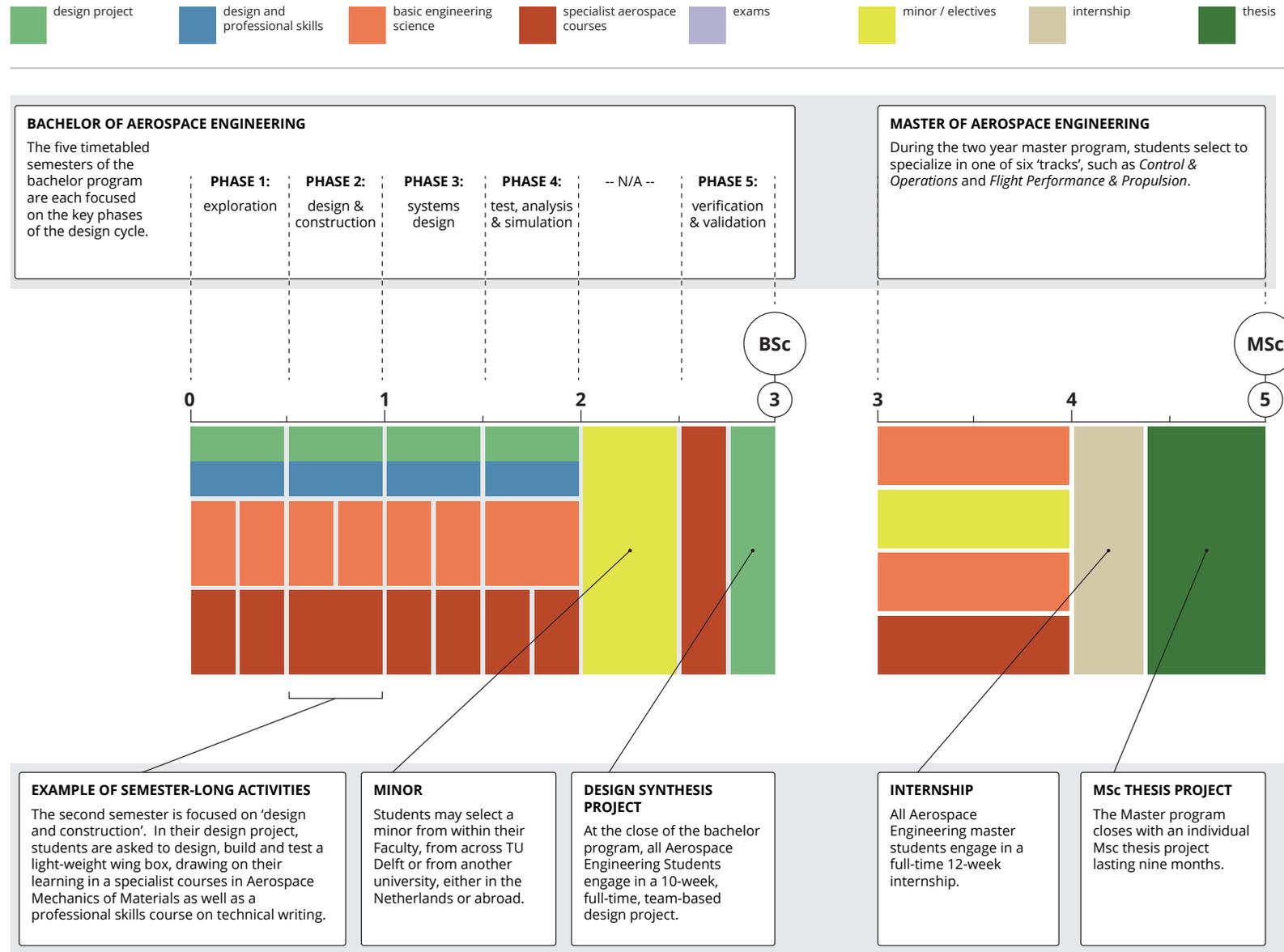


Figure 19. Outline structure of the Aerospace Engineering curriculum at TU Delft

E.4.1. Aerospace Engineering bachelor program

At the bachelor level, the Aerospace Engineering curriculum comprises three equally-weighted sets of courses that run concurrently throughout the three-year program (see Figure 19). These three required courses are:

- **aerospace design projects:** design projects – one per semester – and associated professional skills course (such as oral presentation and technical and scientific writing);
- **basic engineering sciences:** foundational courses in subjects such as mechanics, physics and calculus, which are increasingly delivered through active and/or blended learning;
- **specialist courses in aerospace engineering and technology:** theoretical aerospace courses in subjects such as aerodynamics, aero-structures and aero-materials.

The aerospace design projects form the spine around which the rest of the curriculum is built, with students tackling one major design project each semester. As shown in Figure 19, each successive project focuses, in turn, on the key steps that an engineer takes to design a new product or system: (i) exploration; (ii) conceptual design; (iii) system design; (iv) analysis & simulation; and (v) synthesis and validation. As they build through the bachelor program, the projects grow in complexity and call for increased self-directed learning by student teams. Each project is supported by courses in aerospace design and/or professional skills. The first three design projects are guided and tutored by a group of student teaching assistants. The group is composed of selected and trained students from the third year of the bachelor and the master programs. Around 25 student teaching assistants support the supervision and grading of each project.

Each project is designed to integrate, apply and explore some of the themes emerging from the specialist courses in aerospace engineering and technology. For example, semester 1 focuses on 'exploration'; the design project brief poses the question '*why does an aircraft have a tail?*', asking students to design and build an aircraft without a tail, which is subsequently tested in a wind tunnel. The project is supported by the students' learning in two aerospace engineering and technology courses: *Introduction to Aerospace Engineering* and *Aerospace Materials*. At the same time, students are also offered skills training workshops in study skills and technical drawing.

The bachelor program culminates in a 10-week full-time *Design Synthesis* project. As its name suggests, the project calls for students to work through each stage of the design cycle, as explored individually in previous projects, as well as integrate their learning from across the preceding years of bachelor study. Each student team of 10 takes on a different challenge: either a design problem or an original research-design question relating to system or mission design. All *Design Synthesis* projects are strongly related to practice, with recent themes focused on formation flying satellites, missions to Mars and innovative plane concepts. Student teams work within a dedicated project space for the semester and are provided with a suite of professional development workshops and courses in areas such as oral presentation, systems engineering and project management.

E.4.2. Aerospace Engineering master program

The Aerospace Engineering master program is two years in duration. While all bachelor students follow the same study pathway, the master program provides significant scope for student flexibility and choice. On entry, students select their specialist track from six options, which include *Space Flight*, *Aerospace Structures & Materials* and *Aerodynamics & Wind Energy*. All six tracks follow the same curricular structure. Each is managed and delivered by the corresponding Faculty research group.

The **first year** of study comprises four components:

- 'core' modules relating to students' chosen specialist track;
- thematic 'profiles' where students are able to further specialize in a sub-discipline, selecting, for example, the Wind Energy profile in the Aerodynamics & Wind Energy track;
- 'electives' which may be taken from within the Faculty, or from across or beyond TU Delft;
- a literature study, designed to prepare students for the MSc thesis project in Year 2.

One of the aerospace electives offered to students is *Forensic Engineering*. Taught by a Senior Air Safety Investigator for the Dutch Safety Board, the course is designed to nurture students' ability to critically review failures and performance problems. It comprises eight lectures which take students through each step of an air accident investigation, drawing on real examples, and two practical sessions, where students work in teams to apply their knowledge in the analysis of an accident scenario. In the final exam, groups of students are confronted with an 'accident scene' – "*simulated in the physical world by building a crash investigation site with scattered airplane parts... in a green area on the campus*" – and given an hour to conduct their investigation. Two weeks later, each student is asked to submit a field accident report. Another master elective under development is the *Building Aircraft* course, where students will build a VAN RV12 light aircraft in a simulated aircraft factory setting over the course of 20 weeks.

The **second year** of the master program comprises an internship and an MSc thesis project. The 12-week full-time internship is compulsory for all students and designed to immerse them in a real professional environment. In all, 300–400 Aerospace Engineering students take internships each year, of which around 80% will be taken abroad. Across the Faculty, considerable staff resources are invested in nurturing relationships with aerospace companies worldwide to support this large-scale internship program. Prior to starting the internship, students complete a self-evaluation, which is complemented by an assessment made by their company supervisors at the midpoint of their internship. On completion, students also submit a self-reflective review of what they learned during the internship, both technically and professionally. The master program ends with an individual MSc thesis project, either as an in-depth specialist research study or an expert design project within the students' disciplinary specialism.

E.5. Review and concluding comments

TU Delft featured among the top 10 ‘current leaders’ and ‘emerging leaders’ in engineering education. Its reputation derives from a blend of factors which have enabled it to remain at the forefront of educational practice. Key among these is what interviewees referred to as “*the Delft spirit*.” It is an ethos of openness and inclusivity that enables new ideas and innovative approaches to emerge from across the university community, from students and teachers as well as university leaders and managers. The egalitarian principles that inform this ethos are embedded in Dutch society and, consistent with these principles, interviewees described how TU Delft has nurtured an environment where creativity can flourish. The quality of its students bears testimony to the success of its approach. So too does the university’s growing reputation as “*a global thought leader in engineering education*,” a position which has undoubtedly been advanced by influential position papers such as *Engineering Education in a Rapidly Changing World*, first published in 2014⁹⁸ and later revised in 2016.⁹

In addition to its egalitarian culture, interviewee feedback suggested that three features of the TU Delft educational portfolio set it apart as an ‘emerging leader’. Each development was seen to stand out for its quality and impact:

- the design-centered educational approach established in a number of the university’s Faculties, including Architecture and the Built Environment, Industrial Design Engineering and Aerospace Engineering. Each combines a strong grounding in the fundamental disciplines with opportunities for students to apply and contextualize their learning;
- the ambitious and visionary student-led culture that has driven the creation of the DreamTeams. The quality and professionalism of this initiative is recognized to be world-leading. Feedback from within and beyond TU Delft suggests that it plays a crucial role in both building the professional capabilities of its participants and supporting the university’s global reputation in engineering education;
- the university’s growing strength in open and online learning. Interview feedback suggested that TU Delft’s dedicated and professional support in this domain has advanced engineering learning among student communities on-campus and worldwide.

E.5.1. Success factors

Three mechanisms in particular appear to have been critical to the university’s educational successes, as outlined in turn below.

Strong, open and responsive leadership: The majority of interviewees pointed to the accessibility and quality of TU Delft’s leadership in education. In the words of one:

“if anyone, anywhere has a problem or has an idea, you just email it to [the Vice-President for Education] and you’ll get a reply... it will be taken seriously and be listened to.”

The educational approaches for which TU Delft is internationally recognized – design-led curricula, student-led activities and online learning – have been given targeted support when and where needed.

In TU Delft's decentralized environment, the groups leading each of these initiatives have also been given the freedom to be creative without the structural and regulatory constraints found in many academic institutions. The university has been responsive to their changing needs and willing to champion, invest in and support them at each stage of their development.

For example, despite taking a 'hands-off' approach to supporting the DreamTeams, the university's interventions – such as providing the DreamHall as a space for project development and training workshops – have been critical. In particular, the DreamHall has enabled the community and network of teams to grow and has supported a continuous stream of new student-led ideas. Many interviewees also commented on the university's continued leadership in championing and building support for open and online learning. In the words of one:

"the whole organization always wholeheartedly supported this initiative. We always wanted to be leading in online education. [The Vice-President] has been very consistent in saying the same things repeatedly over 10 years – this has not changed with the wind, with new management – open and online learning is good for the university and good for the country."

The use of online learning as a tool for on-campus educational change: The rapid success of TU Delft's open and online education has not only enriched the lives of the off-campus students enrolled on its courses. It also appears to have inspired and supported a change in the university's educational culture, away from traditional teacher-led teaching and towards active, student-centered learning. The agents of change were the group of teachers engaged in the early development of TU Delft's MOOCs. Interview feedback suggested that this group of pioneering teachers were acutely aware that the online material they were developing would be *"out there for the world to see"* to a potentially large audience. Many were motivated to create flagship materials with a strong international profile. As a result, this group of teachers were understood to be particularly motivated to *"create the best possible product"* and, consequently, engaged with educational design principles *"in a way that they hadn't done before."* This engagement with evidence-based pedagogical practice was significantly advanced by the effective and professional support offered by the Extension School in the design and production of the MOOCs: *"I was flabbergasted by the support on offer... I have not heard of anyone that has not had a positive experience."* Following completion of these early MOOCs, this group of teachers started to experiment with evidence-based, active learning techniques in their own classrooms. These innovations quickly sent ripples across campus; many among this group of teachers were high-profile figures and up-and-coming research leaders in their field. Feedback suggests that these experiences raised the status of education on campus and shifted attitudes towards student-centered learning among teaching staff more widely. In the words of one:

"MOOCs have brought a change in how people see their teaching. Before, you could be a star in education, but it was only locally. But this is for the whole world ... You are making something that goes out of the classroom. It has blaming and shaming – you can make a fool of yourself very easily. So you want to have help... It helps you really think about what you are teaching."

A culture that supports horizon-scanning and consensus-building: The culture of open debate and collaboration is deeply engrained at TU Delft. It is an environment where decisions are made through shared agreements – *“we continue until we have compromise”* – an approach that was endorsed by the majority of those interviewed:

“I don’t believe in a university where the Board say how things are going to be. I value tremendously that the university is owned by the academic staff. So you have to come up with arguments. Change will happen by the people who believe in change coming up with the evidence and showing others that it works.”

Many noted that, although time-consuming, this deliberative approach results in decisions that are trusted and respected across the university population, *“even if you might not agree with the decision, you believe in the process.”* In more recent years, the consensus-building approach has been used to horizon-scan: to look strategically at how engineering education can best adapt to the changing role of professional engineers. It has exposed the entire university to many of the issues and challenges facing the global engineering education community, and has built a strong platform for an institution-wide shift in its educational priorities. It is clear that TU Delft now stands at a crossroads, from which more radical change can follow as the university takes its educational vision forward in the years to come.

E.5.2. Challenges faced

Many of the successes of TU Delft’s educational approach are associated with its decentralized institutional structure; so too are many of its challenges. The three examples of best institutional practice consistently identified by interviewees – the programs in Faculties such as Industrial Design Engineering, DreamTeams and the open and online learning capacity – have been driven from the ground up as separate, discrete threads of activity. Indeed, interviewees from both within and outside TU Delft referred to the university as *“a collection of islands and small kingdoms,”* where *“the bright spots are scattered”* and pedagogical practice varies considerably across the institution. Limited program connectivity appears to exist between Faculties and few structural changes have been imposed on teachers that were not mandated by the national government.

The university is now, however, at a turning point. Its draft vision statement presents a number of radical ideas for educational change, including the introduction of greater student flexibility and choice and the integration of new multidisciplinary, active learning experiences. For many Faculties, these proposals would require significant educational change, both pedagogical – away from a largely teacher-centered approach, as well as curricular – away from undergraduate programs focused almost exclusively on *“deep disciplinary knowledge [that] seem to forget about ...the societal or business context.”* The proposals would also require significant cross-Faculty cooperation and institution-wide changes. As this suggests, a bottom-up approach to reform is unlikely to be sufficient if these proposed ideas are to be successfully implemented.

The realization of the reforms proposed in the university’s ‘vision’ document is also likely to require a step change in TU Delft’s culture. For example, a number of interviewees characterized the university’s

educational culture as *“insular,”* with few lecturers actively engaged in external engineering education networks to learn from pedagogical research or best practice elsewhere:

“TU Delft staff seldom visit educational conferences, seminars or events outside TU Delft to either disseminate their best educational practice or harvest from what other persons are doing in the world.”

Another major challenge faced by the university – highlighted by more than half of interviewees consulted, both internal and external to TU Delft – was the perceived lack of recognition of teaching. In the words of one, *“we still don’t have a culture where education is seen to be anywhere near as important as research.”* Many interviewees noted that this constrains career opportunities for teachers, by *“hindering staff from taking the extra step on the education side,”* thus limiting the capacity of the university to deliver on its ambitious proposals for curricular reform.

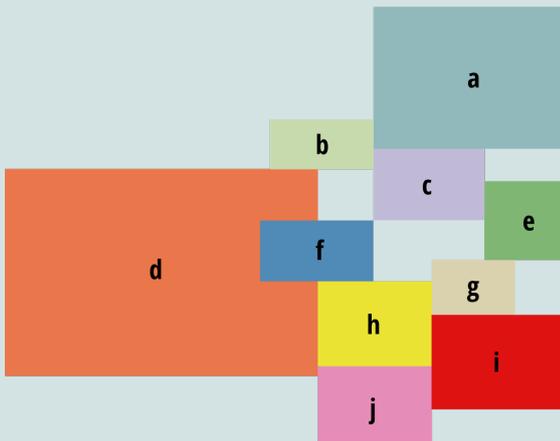
One individual was recently promoted to full professorship on a blended teaching and research profile through TU Delft’s specialist ‘high potential’ pathway. However, interview feedback suggested that this case was an outlier; the perception of the majority of those consulted was that the university *“only considers the research qualities”* of candidates for promotion. Similarly, with TU Delft’s lecturers organized by research centers, line management was described as conducted *“by the professors in charge of your research group... so annual appraisals will only talk about your research targets, teaching is hardly discussed.”* Perhaps for this reason, interview feedback pointed to a particular challenge faced by the university in establishing a culture of shared ownership for the curriculum: in most cases, one or two teachers take sole responsibility for the delivery of individual courses and have little oversight across the rest of the curriculum. As a result, curricula in some Faculties were described as being *“fragmented and overstuffed”* with limited coherence or integration between courses.

These and other challenges face the university as it establishes its new Teaching Academy⁹⁷ and seeks to pilot and develop its new vision in teaching and learning. However, its history of delivering high-quality engineering education suggests that TU Delft will be able to build upon its culture of engagement in educational change and retain its position among the global thought leaders in engineering education.

Acronyms used in TU Delft case study

DARE	Delft Aerospace Rocket Engineering
LDE	Leiden, Delft and Erasmus
MOOCS	Massive Open Online Courses
UTQ	University Teaching Qualification

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