



Practice-Based Engineering: Mathematical Competencies and Micro-Credentials

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Abstract

A practice-based engineering degree, in which students worked on real-world, team-based projects from day one and throughout their course, was designed to address the need for employability skills in a rapidly changing world. Teaching mathematics in this way required a very different approach to the lecture-exam based model prevalent in most engineering degrees. In order to ensure all students developed the fundamental skills and knowledge required of engineers, a micro-credential based curriculum was developed where micro-credentials were mapped to projects and delivered “just-in-time”. The curriculum contained forty-eight explicit mathematical micro-credentials in the areas of measurement and geometry, algebra, calculus, and statistics and probability as well as many more micro-credentials in other areas of curriculum that contain mathematical skills, from physics to project budgeting. Mathematical competencies were used as a framework in the design and analysis of the micro-credentials. This paper presents a description of, and reflection on the successes and challenges in implementing this model of teaching mathematics in engineering.

Keywords Micro-credentials · Engineering · Tertiary study · Practice-based · Mathematical competencies

Context

As universities are increasingly focusing on developing graduates’ professional skills in addition to academic knowledge, modes of teaching and learning are shifting. Students are increasingly encouraged and required to work in teams, to undertake authentic assessments and to present work orally and in written reports. The benefits of problem and project-based learning and design-based learning have been well explored and it is widely agreed that

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they are well suited to design-focused or project management related subjects. However, the suitability of these methods for teaching technical content such as mathematics and physics is less well agreed upon. This paper explores the question of how mathematics content can be taught in an entirely project-based engineering degree, what content is required, how and when it should be delivered, how students engage with the material, and the logistical challenges encountered in implementing such a model. A design-based research study is presented considering the mathematical aspects of the course grounded in the theories of practice-based learning and mathematical competencies.

The Bachelor of Engineering Practice was created at Swinburne University of Technology in Melbourne, Australia, in response to the need to produce employable and future-capable graduates (Beanland and Hadgraft 2014; King 2008). The course was co-designed with industry and community partners through a series of workshops with a diverse range of practicing engineers (Cook et al. 2017a) based on the processes recommended by Dowling and Hadgraft (2013). The outcome of this process was a course with a practice-based learning philosophy. Practice-based learning bridges the gap between traditional teaching and learning, in which theoretical knowledge is acquired first and applied in practice later, and work-integrated learning in which the work itself is the learning. In practice-based learning the work and the learning occur simultaneously (Mann et al. 2020) with students undertaking the type of tasks professionals in their field might tackle in an environment designed to model the workplace as closely as possible. The Bachelor of Engineering Practice was intended to be a four-year degree delivered entirely through real-world projects with no lectures or exams. This model presents a significant advantage in developing the professional and personal skills that are often lacking in recent graduates who have been trained to pass exams but not apply their knowledge in situ. However, it also poses significant challenges in ensuring all students develop a deep understanding of the fundamentals of engineering including mathematical knowledge and skills.

A micro-credential framework was adopted to underpin the projects, allow just-in-time learning and provide flexible pathways through the curriculum. The term micro-credential is used to describe a variety of alternative qualifications (Kato et al. 2020) and is here defined as a small module with a competency-based rather than graded assessment. Micro-credentials spanned the entire curriculum which included engineering discipline related content as well as professional (work) skills, thinking skills and an innovative “self” domain which explicitly covered reflective practice, learning strategies, cultural competence and social justice. The whole curriculum contained approximately 240 micro-credentials, all of which needed to be completed for a student to graduate. Micro-credentials, though mapped to projects, could be undertaken at any time allowing flexible pathways for students through the course. Each micro-credential was designed to represent approximately six hours work for a student. There was a synergistic relationship between the micro-credentials and the industry projects, with credentials providing the disciplinary knowledge required for the project, and the project providing an opportunity for students to gather evidence of their ability to apply the concepts in practice, which conversely was used to award the micro-credential.

The practice-based model allowed flexible pathways into the course in terms of prior mathematics study. Using the definitions of courses given by Barrington and Brown (2005) this course required elementary mathematics for entry as opposed to the more usual intermediate mathematics pre-requisite. This was intended to improve diversity in the student cohort as mathematics entry requirements limit the participation in

engineering of female students (Li and Koch 2017), students from low socioeconomic backgrounds (Peard 2002) and other demographics such as rural (Webster and Fisher 2003) and indigenous students (Atweh et al. 2004). The removal of higher level mathematics was considered possible due to the distributed nature of the mathematics curriculum throughout the course, rather than having mathematics units front loaded at the start of the degree.

The Bachelor of Engineering Practice ran for two years before being discontinued to allow project-based units to be integrated into all degrees in the faculty. This paper describes the micro-credential framework and pedagogy designed to deliver the mathematical content of the course. Given the premature termination of the course it is not possible to present outcomes from this mode of delivery, but the successes and challenges in setting up and running this model are analysed and described.

Mathematics and Project-Based Learning

Courses developed by the emerging world leaders in engineering education have an increased integration of work-based learning, more blended learning, explicit self-reflection and an emphasis on engineering design (Graham 2018), all facets of which address the future needs of the engineering workforce. To develop these skills, many institutions have shifted towards project-based learning (e.g. Kolmos and de Graaff 2014; Graham and Crawley 2010; Somerville et al. 2005). The benefits of problem-based and project-based learning have been well recognised in many areas of engineering education (Mills and Treagust 2003). Students are intrinsically motivated by the real-world applications of relevant projects and develop problem solving skills and professional ways of working. After undertaking project-based learning, students rated themselves as having improved across a range of professional skills, with particular emphasis on teamwork, communication, understanding of the design process and self-directed learning (Beagon et al. 2019). Capstone or final year projects are required in most engineering degrees, indeed they are explicitly stated in accreditation criteria from several accreditation bodies, and are an opportunity for students to apply the knowledge they have supposedly built from their previous study. However, mastery is not achieved in a single instance. Multiple projects are required in a degree to master the skills required for the workplace, with a variety of scenarios and the opportunity to learn through repetition and from failure. Increasingly project-based units are being introduced earlier in courses to motivate and inspire. For example, the Engineers Without Borders Challenge introduces first-year students to the socio-technical challenges inherent in real-world engineering through real humanitarian engineering projects. Problem-oriented and project-based education have been proposed as a means of providing students with the possibility of developing transferable skills, while at the same time exposing them to the complexities of global and cultural issues (Lehmann et al. 2008). Engineering design education is also often taught through projects or real-world challenges, with project-based learning (PBL) a preferred method of developing design thinking skills (Dym et al. 2005). Professional skills such as project management are also best experienced through the management of real or simulated projects.

The purpose of these projects is mostly focused on skill development such as teamwork, problem scoping and definition and communication. Indeed, one of the features of PBL is that there is no “correct” answer, and students learn to deal with

trade-offs and uncertainty as they will in the workplace. This contrasts with mathematics, where there may be multiple approaches to a problem but these approaches all lead towards a “correct” answer. While project-based learning can develop many skills, there have been concerns about teaching mathematics in such a manner due the hierarchical knowledge structure and complex problem solving required to develop a deep mathematical understanding (Perrenet et al. 2000). For example, a project requiring system modelling using differential equations requires students to have a core foundation of calculus knowledge and skills, which cannot be developed “on the fly”. There is also the issue of building fluency with repetition. While a conceptual understanding could be developed in a project-based context, the repetitive solving of similar problems traditional in mathematics teaching is required to build confidence and mathematical fluency. While mathematics teaching is often taught through applied examples and problems, entirely project-based units are few and far between. However, project-based mathematical units are possible, where the project is selected specially to demonstrate the application, for example when teaching differential equations (Carr and Ní Fhloinn 2017). Statistics lends itself well to being delivered through projects, with real data being more engaging than simulated data for explaining and practicing statistical techniques (Farrell and Carr 2019). To address the challenge of mathematics education in a project-based context Perrenet et al. (2000) suggest separate direct instruction in mathematics with supervised practice including demonstration of expert problem solving. This leads to the need for separate and explicit mathematics tuition within or alongside the project context.

Modularisation

The deceptively simple answer to the question of how to teach mathematics in a project-based engineering degree is to break up the content into small modules and deliver them “just-in-time” to support the content knowledge needed for each project. The smaller modules allow the content to be delivered when relevant, reducing the age-old complaint of students “when am I ever going to use this?” and are thus more motivational than block mathematics teaching in the first year of a course with the application of the knowledge not being required until later years, if ever. Smaller modules also provide more flexible pathways for students, as they can progress through them faster or slower depending on mathematical ability and background, rather than being constrained by term sized units. A need for smaller topic units is seen by many as the inevitable direction of education as students demand more personalised study and flexibility (Mischewski 2017). Recent Australian Qualifications Framework (AQF) reviews have focused heavily on shorter form credentials stating that “Future workers are increasingly likely to access formal, non-formal and informal learning through a process of lifelong learning” (AQF 2019 p.57). There are a confusing array of terms for such smaller units, for example micro-credentials, micro-units, digital badges, soft skills credentials, micro-credits, nano-degrees, MOOCs etc. (Lumina Foundation for Education 2015) and the proliferation of alternative credentials created and curated by a variety of academic, industry, academia and third-party providers is increasing. In Australia, at the time of writing, thirty-six out of forty-two universities are offering or developing micro-units in some form (AQF 2019 p.56). Micro-credentials were initially developed as a means of providing and recognising professional development and

have been implemented in higher education to broaden the range of skills that can be acknowledged beyond a standard university transcript (Bowen and Thomas 2014). Micro-credentials have been suggested for use in tertiary engineering courses to “provide students and employers with better information, support the mixing and matching of courses, give tertiary education organisations (TEOs) more flexibility and encourage innovation” (Mischewski 2017, p.5). While micro-credentials were initially used to demonstrate professional skills, the term is used here for the small mathematics modules developed in this context. These modules are consistent with the (broad) definition of a micro-credential given by Oliver (2019, p.i): “A micro-credential is a certification of assessed learning that is additional, alternative, complementary to or a component part of a formal qualification”.

Mathematical Competencies

Mathematical competence is defined as “someone’s insightful readiness to act appropriately in response to all kinds of mathematical challenges pertaining to given situations” (Niss and Højgaard 2019, p.4). Mathematics education in engineering traditionally has a strong focus on problem handling and developing formalisms. Other mathematical competencies such as “modelling”, “communicating mathematically” and “using tools and aids” are often not explicitly developed or assessed despite being skills frequently used by practicing engineers (Firouzi et al. 2014). It is also necessary to consider all the aspects of mathematical thinking (Cardella 2008), key aspects of which were identified by Schoenfeld (1992) as problem-solving strategies, resources and use of resources, and beliefs and affects.

The notion of mathematical competencies was further developed by the Danish KOM project (Niss 2003; Niss and Højgaard 2011; Niss and Højgaard 2019) which presented a broad and comprehensive view of mathematical competencies, describing eight competencies – mathematical thinking, problem handling, modelling, reasoning, representing mathematical entities, handling symbols and formalisms, communicating in, with and about mathematics and making use of aids and tools. van der Wal et al. (2017) also identified what they termed the ‘Techno-mathematical Literacies’ required by future engineers: data literacy, technical software skills, technical communication skills, sense of error, sense of number, technical creativity and technical drawing skills.

The practice-based nature of this course, in which students are learning by practicing the ways of working they will later apply in the workplace, lends itself to the development of a broad range of mathematical competencies. The output from the industry consultation process emphasised the need for what Niss and Højgaard call the “use of aids and tools” and van de Wal et al. describe as “technical software skills”. There is also an increased opportunity to develop skills in communicating in, with and about mathematics, as the mathematics required in the projects is used as an argument for a design feature or recommendation, thus must be clearly communicated to the client. The team-based nature of the project work builds mathematical communication skills as team members develop solutions collaboratively thus have to practice using shared language and symbols. The assessment structure, described later in this paper, allows for a variety of competencies to be explicitly assessed.

For the design and analysis of mathematical content in this course, the mathematical competencies described by Niss and Højgaard (2019) and the techno-mathematical

literacies of van der Wal et al. (2017) were combined to give the following set of mathematical competencies relevant for future engineers:

- **Problem Handling**-Posing and solving mathematical problems by identifying and implementing a range of strategies.
- **Reasoning Mathematically**-Assessing chains of arguments, following and producing mathematical proof, reviewing and providing examples and counter-examples.
- **Modelling**-Applying mathematics to real-world problems, contexts and situations. Constructing, validating and critiquing mathematical models.
- **Sense of Number**-Handling and interpreting numbers sensibly, including suitable use of units.
- **Sense of Error**-Checking and verifying data and detecting errors, appreciation of uncertainty in numbers and measurements.
- **Data Literacy**-Analysing, interpreting and producing technical data and graphical representations.
- **Spatial Reasoning**-Thinking geometrically, interpreting and producing technical drawings.
- **Communication**-Communicating mathematical information in written, oral and visual forms with specialists and non-specialists.
- **Handling Formalisms**-Translating from natural language to mathematical symbols and vice versa. Manipulating expressions containing symbols and formulae and dealing with the rules and frameworks (formalisms) that govern them.
- **Using Tools**-Appropriately selecting and using tools such as graphical calculators, spreadsheets and other computing tools.

Mathematics Course Design

This section describes the design of the mathematical content in this course and an analysis of how the assessment tasks were constructed to develop mathematical competencies. Three contrasting examples of micro-credentials are presented to illustrate the different opportunities and challenges arising from this mode of teaching and learning mathematics.

Mathematical Content in Engineering

When designing a degree course from scratch there is potential to re-evaluate the required mathematical content. In the engineering education community there are conflicting calls for both more rigorous mathematical content on one hand, and less theoretical and more applied mathematical skills on the other. There are also concerns around the continually declining numbers of students studying higher-level mathematics in their secondary education (for example the current state in Australia is described by Li and Koch (2017)) requiring increasing support for early years students and the provision of bridging courses and alternate pathways.

The topics of the mathematical micro-credentials in this course were determined using the following approaches:

1. Industry consultation
2. Review of accreditation standards and literature
3. Content of existing engineering mathematics units

A series of industry consultation workshops were conducted with over a hundred individuals from more than eighty different engineering organisations being involved in the consultation (for details of the process see Cook et al. (2017a)). The industry co-design process, which was integral to designing the overall curriculum and the specifics of the non-technical domains, was unhelpful in providing insight into the required mathematics content (Cook et al. 2017b). In all co-design workshops there was a strong focus in the discussion on the importance of generic competencies such as communication and teamwork, making it challenging to elicit responses from industry participants focusing on more technical competencies. Where they did reference mathematical content, it was often to state that they didn't use much of what they had studied at university. This lack of recognition of the applications of mathematical knowledge and skills is consistent with published research. When practitioners are asked to identify the mathematical skills they use in practice, many underestimate the frequency and importance of the use of those skills (Pearson 1991; Cardella 2007). The difficulty in extracting information from self-reports has led to ethnographic and interview-based studies of the mathematical skills used by engineering students (Alpers 2011; Cardella 2007) and practitioners (Gainsburg 2006; Kent and Noss 2002). Given the mis-representation in self-reporting mathematics use, the industry workshops did not ultimately contribute to the mathematical content selection.

The industry consultation process did however consistently highlight the importance of using technology. The need to build models and perform calculations using common software such as Excel rather than using more specialist tools such as MATLAB was also stated by multiple participants though the need for graduates to have programming skills was also emphasised, which a program such as MATLAB can be used to develop. This led to micro-credentials on spreadsheets and MATLAB being included in the curriculum, and to the guiding principle of including the use of these tools in micro-credentials in all curriculum areas wherever possible. Thus, the industry workshops informed approaches to developing micro-credential content in terms of learning tasks and assessment, but did not contribute to the specific mathematics curriculum design.

This course was delivered in Australia, where the guidelines provided by the relevant professional body which accredits engineering degrees, Engineers Australia (EA), specifies a 'conceptual understanding of the mathematics, numerical analysis, statistics, and computer and information sciences which underpin the engineering discipline.' (EA 2011). Other accreditation bodies worldwide provide equivalent guidance. For example the Accreditation Board for Engineering and Technology in the United States of America require 'one year of a combination of college level mathematics and basic sciences (some with experimental experience) appropriate to the discipline' (ABET 2016) and the European Network for Accreditation of Engineering Education 'knowledge and understanding of the mathematics and other basic sciences underlying their engineering specialisation, at a level necessary to achieve the other programme outcomes' (ENAE 2008). The ENAE definition is particularly

interesting as different engineering majors require vastly different mathematical approaches and techniques, thus what is required will vary significantly between programmes.

A comprehensive guide on what constitutes the core mathematical knowledge required by engineers was produced by the SEFI mathematics working group (Alpers et al. 2013). Content is divided into four levels with increasing specialism. Core level 0 comprises the foundational knowledge that some students may have before entering higher education but others may need to develop in their first year. Core level 1 comprises the knowledge and skills necessary to underpin the general engineering science assumed to be essential for most engineering graduates. Levels 2 and 3 contain advanced knowledge required only for certain specialised engineering disciplines. The SEFI core curriculum has evolved over time (Barry and Steele 1993; Mustoe and Lawson 2002) with the most recent version incorporating mathematical competence, defined as “the ability to understand, judge, do and use mathematical concepts in relevant contexts and situations, which certainly is the predominant goal of the mathematical education for engineers.” (Alpers et al. 2013, p.5).

The Bachelor of Engineering Practice also had a commitment to encouraging diversity by having elementary level mathematics as the entry requirement to the course rather than intermediate level mathematics, which is the more common prerequisite for tertiary engineering degrees. The breakdown of the mathematical backgrounds of students who entered the course are presented in fig. 1.

Given the lowered entry requirements leading to 32% of the cohort having not studied intermediate or advanced mathematics at high-school, the entirety of the core level 0 content as described by Alpers et al. (2013) was included in the curriculum, along with the sections of cores 1 and 2 that overlapped with existing content of the non-project based degrees offered at the same university and those topics which were required to support the technical content of this particular degree (e.g. Boolean Algebra required for electronics micro-credentials).

The curriculum had forty-eight mathematics specific micro-credentials in the areas of algebra, calculus, statistics and probability, and measurement and geometry (Table 1). There are also additional mathematical competencies embedded in

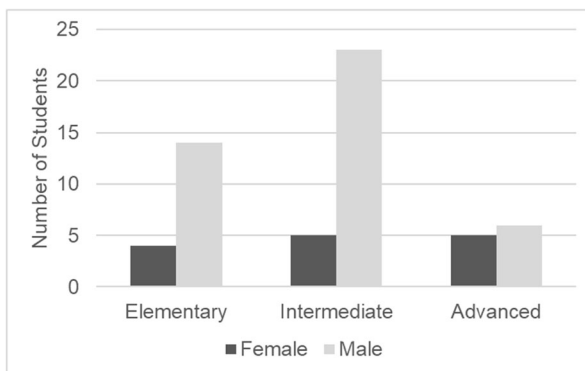


Fig. 1 Distribution of students commencing the Bachelor of Engineering Practice by the highest level of mathematics they studied previously using the classifications of Barrington and Brown (2005)

Table 1 The Mathematics curriculum micro-credentials. Italics represent micro-credentials that were created as required for the projects during the two-year operation of the Bachelor of Engineering Practice

Algebra	Calculus	Measurement & Geometry	Statistics & Probability
<i>Boolean Algebra</i>	<i>Introduction to Differentiation</i>	<i>Estimation & Fermi Calculations</i>	<i>Descriptive Statistics & Data Presentation</i>
<i>Transposition of formulae</i>	<i>Techniques of Differentiation</i>	<i>Units & Dimensional Analysis</i>	<i>Correlation and Regression</i>
<i>Polynomials</i>	<i>Simple Optimisation</i>	<i>Uncertainty Concepts</i>	<i>Concepts of Probability</i>
<i>Exponentials & Logarithms</i>	<i>Introduction to Integration</i>	Uncertainty Methods	<i>Probability Distributions (Binomial & Normal)</i>
Fractions & Partial Fractions	<i>Techniques of Integration</i>	Shape, Area & Volume	Probability Distributions (Poisson & Exponential)
<i>Financial Mathematics</i>	Motion and Calculus	Conic Sections	<i>Data Analysis</i>
Complex Numbers	<i>Ordinary Differential Equations</i>	<i>Introduction to Trigonometry</i>	Statistical Software
<i>Introduction to Vectors</i>	Ordinary Differential Equations 2	<i>Trigonometric Graphs & Modelling</i>	
Dot & Cross products	Taylor & Maclaurin Series	Trigonometric Identities	
Lines and Planes	Partial Differentiation	Hyperbolic Functions	
Introduction to Matrices	Multiple Integrals	<i>Polar Coordinates & Curves</i>	
Applications of Matrices	Fourier Series		
Eigenvectors & Eigenvalues	Fourier Transforms		
	Vector Calculus		
	Numerical Methods		
	Laplace Transforms		
	Z transforms		

much of the other disciplinary content as well as in the professional skills, which included representing data and project finance. Though this was the list of modules identified for this particular course, one of the benefits of a system that is modularised to such an extent is that it is relatively simple to add, remove or adapt modules. This makes it a model that can easily be adapted to specific engineering majors or other courses.

There is also a complicated web of pre-requisites underpinning this list. Pre-requisites exist not only between mathematics micro-credentials but also across subjects, with mathematics topics being required for physics, programming, electronics and design micro-credentials. However, while these pre-requisites were comprehensively mapped according to the hierarchy of content, there were pragmatic challenges in implementing them. This related to the ability of students to access micro-credentials when they had not completed a pre-requisite, even if they required content from a particular micro-credential to support a project. As such, the pre-requisites were “soft”,

meaning they were treated more as recommended pathways than as a “hard” rule requiring completion of one before another.

Micro-Credential Structure

Mathematics micro-credentials were developed by four academics with backgrounds in mathematics, physics and engineering. Templates and guides were provided to ensure consistency in structure and style to reduce cognitive load for students (Lambert et al. 2009). Each micro-credential consisted of three learning tasks and an application task. Learning tasks were a mixture of face-to-face classes, videos, workbooks, problem-sets and activities. The application task was used for assessment and could either be a problem arising from their project work (option A), or an artificially created applied task (option B).

Delivery

The micro-credentials were hosted on the learning-management system in a separate unit shell that students were intended to be able to access throughout their entire degree. Unit shells, which housed the projects, linked to the micro-credentials that were required for each project. The initial design of the mathematical micro-credentials was that they would be wholly online, with face-to-face support provided through timetabled but unstructured “drop-in” sessions. However, drop-in sessions were poorly attended, and the first cohort of students requested more structured classes. This led to several micro-credentials having an introductory class as the first learning task. The majority of workload in this model was therefore connected to project facilitation, resource creation in designing the micro-credentials, and marking the submissions and re-submissions, rather than in face-to-face delivery.

Assessment of a Micro-Credential - Application Tasks

Application tasks contained the description of how students could evidence their ability to apply the content in practice in adherence to the practice-based philosophy of the course. The key point of difference in the assessment of an application task compared to a traditional unit is that the evidence provided must be of the content being applied, thus tasks are never simply question sheets or quizzes as these do not replicate engineering practice. This was intended to address the mismatch between modes of teaching and assessment described by Niss as a matter of “designing and adopting assessment instruments that are capable of telling us what we really want to know about students’ knowledge, insights, and skills in, with and about mathematics” (Niss 2003, p.4). With this aim, application tasks focussed not on what students knew, but what they could do.

Options A and B

There were two types of application tasks used to demonstrate learning. The first (Option A) was a detailed list of criteria, linked to the learning outcomes of the micro-credential, that could be demonstrated by the student in the context of a project or related

task. The second (Option B) was a more structured project or investigation. This option could be selected if the student did not have the opportunity in a project to collect the required evidence. Option B tasks still needed to be applied in a practical context and not merely a series of questions. Examples are provided in the examples below. Both option A and B tasks were assessed against the same criteria, so if a student could demonstrate their ability through a project they were working on, they could, and should, submit that evidence rather than undertaking an additional option B task.

Rubrics and Grading

The application task contained a description of the type and format of the evidence required along with a detailed rubric outlining each criterion to be demonstrated. Micro-credentials were not graded but were marked as either “complete” or “incomplete”. Students evidence had to be rated as proficient or advanced in all of the assessment criteria to complete the credential. Students could re-submit their evidence multiple times but had to explicitly respond to feedback comments in order to resubmit, an adaptation to the initial micro-credential grading process to counteract the student tendency to not address all feedback before resubmission leading to multiple rounds of marking, which was time consuming for both students and staff. This allowance of multiple submissions and the requirement to demonstrate competency in all assessment criteria allows students to progress at their own pace, provides significant formative feedback for those who require multiple submissions and ensures all students meet the proficient level in all mathematical competencies. However, it is labour intensive for staff, with the teaching load being shifted from content delivery to providing feedback to students on their work.

Mathematical Competency Analysis

Niss and Højgaard (2019) suggest mathematical competencies as a basis for designing curricula and as an analytic tool for describing the characteristics of educational materials. Thus the adapted set of competencies used in this work, combining the purely mathematical competencies of Niss and Højgaard (2019) with the Techno-mathematical Literacies described by van der Wal et al. (2017), were used to analyse the actual competencies assessed in the micro-credentials by coding each rubric criterion against one of the competencies.

It can be seen from Table 2 that problem handling is the most assessed competency, as is expected in mathematics education. Handling formalisms is also prevalent as this includes using correct terminology and symbols in mathematical workings. The intention of this mathematics curriculum, as required for a practice-based engineering degree, was to focus on application on mathematical techniques in projects, thus the modelling competency is also frequently assessed. Using Tools was another explicit goal of this curriculum design with its importance emphasised by the industry consultation process. Here, using tools appears in only nine rubric criteria, though this is likely an underestimate of the actual use of mathematical tools and aids by the students. This analysis only identifies the use of tools if explicitly mentioned in the criteria. Many other micro-credentials would allow or encourage the use of tools without formally assessing their use. It can also be seen that “reasoning mathematically” is assessed only infrequently as

Table 2 An analysis of the mathematical competencies in each rubric assessment criterion of the created micro-credentials

	Problem Handling	Reasoning Mathematically	Modelling	Sense of Number	Sense of Error	Sense of Data Literacy	Spatial Reasoning	Communication	Handling Formalisms	Using Tools
Boolean Algebra	4		1					1	3	
Transposition of Formulae	6							5	1	
Polynomials	2		3	1		1		2	1	1
Exponentials & Logarithms	3		3			3		1	1	1
Financial Mathematics	5		1			3		1		
Introduction to Vectors	6						1		3	
Introduction to Differentiation	9				1				1	
Techniques of Differentiation	7		1					1	1	
Simple Optimisation	4		2	1					2	
Introduction to Integration	2	2							1	
Techniques of Integration	5		1							2
Ordinary Differential Eqs. 1	5		1						1	1
Estimation and Fermi Calculations	1		3	2	2			2	1	
Units and Dimensional Analysis	4							2	2	
Uncertainty Concepts	3			1	2					
Uncertainty Methods	8		1	1	1					
Shape, Area and Volume	6			1			2		1	
Introduction to Trigonometry	4		1	2			1			
Trigonometric Graphs & Modelling	3		2	1			1		1	1
Polar Coordinates and Curves	2					3	2			
Descriptive Statistics & Data Presentation	5		1			2		1	1	1
Correlation & Regression	2	3								1
Concepts of Probability	2					1		3	2	
Probability Distributions: Normal & Binomial	5		1					1		1
TOTAL	103	5	23	10	6	13	7	20	24	9

the definition of reasoning in this case relates to mathematical proof as well as providing examples and counter-examples. Given the practice-based nature of this course proofs are not focussed on with the emphasis being more on methods and applications.

Examples

An analysis of the design of learning and assessment tasks of three micro-credentials are presented as contrasting examples. They are “Estimation and Fermi Calculations”, selected as it encapsulated the practice-based philosophy, “Exponentials and Logarithms” to present more standard mathematical content and the chain of prerequisites, and “Probability Distributions” to provide an example of how micro-credentials could successfully integrate with projects. All the micro-credentials were delivered in both years of the course and the adaptations in between iterations are also presented.

Estimation and Fermi Calculations

Estimation and Fermi Calculations was the first mathematical micro-credential in the course. This micro-credential was delivered first for a range of reasons. Firstly, it had no pre-requisites and required little technical mathematics so students with an elementary mathematics background would not be immediately at a disadvantage. It also exemplified the practice-based philosophy of the course by focusing on modelling competencies and real-world applications rather than more procedural mathematics, moving students away from the idea that the only important goal in mathematics is a “correct” answer. Thirdly, it could easily be undertaken in a range projects. For both cohorts the first project was the Engineers Without Borders Challenge, in which students develop humanitarian engineering solutions to issues faced by a community. In this, students were faced with real-engineering challenges requiring them to make assumptions and estimates which this micro-credential provided a framework for doing.

The learning tasks of the micro-credential included videos describing Fermi calculations, online order of magnitude estimate questions, a structured group task estimating the number of dentists in Australia, and the application task requiring a reasoned estimate with workings and a second method to validate and assess the accuracy and limitations of the estimates of inputs and the final estimate. Option A was to complete this within a project context. The Engineers Without Borders Challenge provided multiple opportunities to undertake such reasoned estimates for many aspects of the designs. The Option B task required the same elements but with a scenario provided, which related to the size of a water tank required for a suburban house in Melbourne. Both versions of the task were assessed with the same rubric.

Several changes were made to the micro-credential between cohorts. Some were general to all micro-credentials after a year of course delivery. These included limiting the number of submissions students were allowed for the micro-credential to count towards a unit grade to three, and setting specific windows for submission and feedback. These changes were useful both to provide structure to students and to make the marking workload more manageable for staff.

The main improvement to this specific micro-credential was the additional requirement to submit the group activity, which was intended as a practice activity and to

encourage peer-peer interaction in a module delivered online. From discussions with students and analysis of page views on the learning management system, it was clear that students skipped over the learning tasks and went straight to the application task. By including elements from multiple learning tasks in the submission, students needed to engage with all aspects of the micro-credential. The second alteration was the addition of the assessment criterion “answers stated to an appropriate number of significant figures”. This was necessary as several students in the first cohort submitted well-reasoned order of magnitude estimates, but then stated answers with far too many significant figures, indicating a lack of understanding of precision and accuracy.

The criteria contained in the rubric for this micro-credential are shown in Table 3. It should be noted that the mathematical competencies are distinct but overlapping (Niss and Højgaard 2019), thus multiple competencies may be assessed by each criterion, but here only one has been identified as the main competency in each case.

Student feedback on this micro-credential was mixed. Students enjoyed the applied nature of it, contrasting the tasks with the highly process driven work they focussed on in high school. However, as it was students’ first experience of learning and assessment in this format, many struggled with the idea of competency-based assessment and re-submission. Where as in a grade-based system, achieving 9 out of 10 criteria would equate to a high-grade, in this competency-based system that counted as incomplete and required further work. As with all new modes of assessment, students required time to adjust to this system and initially pushed back against it.

Exponential and Logarithms

This micro-credential presented different challenges as those students who had passed intermediate or advanced mathematics should be familiar with this content, but those with elementary mathematics would need more support. As such, explanation and repetition was required for those students that needed to develop fluency, but could be optional for those already familiar with the material. Tasks included an introductory class, online videos and links to the HELM workbooks (Helping Engineers Learn

Table 3 Assessment criteria for the micro-credential “Estimation and Fermi Calculations”. *indicates criteria added for the second cohort

Rubric Assessment Criteria	Competency Assessed
Identifies parameters and variables	Modelling
Estimates values of parameters	Sense of Number
Clearly states assumptions	Modelling
Explains reasoning for assumptions (*referencing where appropriate)	Communication
Explains validity of assumptions and estimates (i.e. what is the range of values)	Sense of Error
Correct numerical processes and answers	Problem Handling
*Answers stated to an appropriate number of significant figures	Sense of Error
Workings clearly and correctly laid out and annotated	Communication
Correct use of mathematical notation	Handling Formalisms
Evaluates answer by sense check/order of magnitude estimate	Sense of Number
Validates answer using second method/source	Modelling

Mathematics), which were specifically designed to be student-centred (Harrison 2008). Additional material on indices was provided for those without intermediate or advanced mathematics in high school. The work from these tasks was formative only and the workbooks were not submitted, so it is unknown how many students actually engaged with this material. Had the course continued, submission of such work would likely have become mandatory.

This micro-credential did not connect directly to the content of any projects, but was required as a pre-requisite for the calculus stream (see Fig. 2 for a map of pre-requisites). As such, while an option A task existed, no students attempted it in a project context and all undertook the option B task. Creating option B tasks for content such as functions and calculus micro-credentials presented a challenge as these subjects are usually assessed through problem sets or exams. Here the practice-based philosophy required an applied task, which took more creativity and time to prepare, and, as with all authentic assessment task, more time to mark. For this micro-credential the option B task contained a choice of investigations. The first was on RC circuits, with students having the option of constructing a physical circuit and making measurements or using an online circuit simulator. They plotted graphs of the voltage across a capacitor when charging and discharging and both measured and used logarithms to calculate the time constant of the circuit for different values of resistance and capacitance. The second option related to Newton's law of cooling and required students to undertake a practical investigation using a thermometer and a hot drink. Both tasks involved collecting data, plotting graphs of measured and modelled data, using logarithms to find constants and writing laboratory reports containing all elements of the outcomes (Table 4).

This micro-credential was completed well, with most student issues relating to the time taken to complete it rather than the content. Without project integration it was perceived as an additional task that distracted them from the project. Many students further struggled with the Newton's Law of Cooling task as their poor experimental design led to long data collection times. However, the practical element of the task was generally found to be enjoyable by students and the use of logarithms to find constants modelling system behaviour worked well as an applied task.

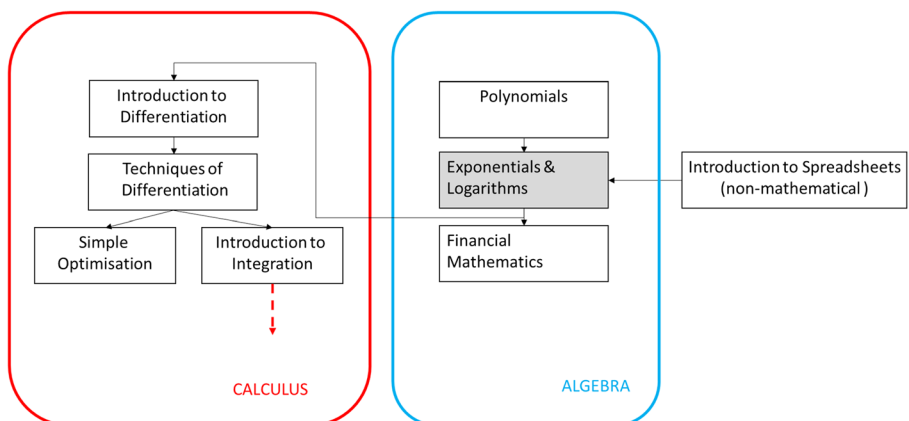


Fig. 2 A map of the pre-requisite web associated with the micro-credential "Exponentials & Logarithms"

Table 4 Assessment criteria for the micro-credential “Exponentials and Logarithms”

Rubric Assessment Criteria	Competency Assessed
Correctly manipulate expressions containing indices including: multiplying and dividing, converting between forms containing positive and negative indices, converting between forms containing fraction indices and root and dealing with exponents of exponents.	Problem Handling
Correct use of appropriate mathematical notation to represent indices.	Handling Formalisms
Plot appropriate graph displaying exponential/logarithmic features.	Data Literacy
Plot appropriate linear graph using either a log scale or by taking logarithms of one of the variables.	Data Literacy
Interprets graphical data to create a correct mathematical expression.	Modelling
Plots measured data and mathematical model on same graph.	Data Literacy
Uses software (excel or other) to plot appropriate graphs.	Using Tools
Graphs clear with labelled axes, titles etc.	Communication
Collects data from physical/ simulated system (takes accurate, repeated measurements in appropriate increments to model system)	Modelling
Produces a mathematical expression to model/predict system behaviour	Problem Handling
Compares exponential model to data/ considers limits of validity of the mathematical model.	Modelling
Correctly uses laws of logarithms to manipulate expressions.	Problem Handling

Probability Distributions: Binomial and Normal

This micro-credential was mapped in both years to projects relating to the entrepreneurship aspects of the engineering curriculum. Both projects focussed on designing products for people, one a biomedical device, the other an educational toy. For this, students needed to work with anthropometric data describing the distribution of sizes of features of the human body. This data is normally distributed, so this project required and understanding of the concept of normal distributions and provided an opportunity to deliver the content with an immediate application. The micro-credential had one pre-requisite, “concepts of probability”, which was delivered in the first week of the six-week project, when project work was focussed on problem scoping and ideation. The probability distributions micro-credential was delivered mid-project when the detailed designs were being developed requiring precise measurements and calculations.

Feedback from students on other micro-credentials had indicated that for mathematical content they preferred a blended rather than wholly online delivery, so introductory one-hour classes were introduced to several micro-credentials. For this micro-credential the class became the first learning task and introduced the key ideas, provided examples of expert problem solving (as recommended by Perrenet et al. (2000)) and allowed students to work on questions with support.

For the assessment, students were required to submit both a structured task on binomial distributions that was part of the learning task, and either an option A or B task on normal distributions (Table 5). The option A task was chosen by several students, likely those who had taken the responsibility for dealing with the anthropometric data in their project group.

Table 5 Assessment criteria for the micro-credential “Probability Distributions: Binomial and Normal”

Rubric Assessment Criteria	Competency Assessed
Appropriately model a real-world scenario using a binomial distribution	Modelling
Calculate binomial probabilities using the formula	Problem Handling
Calculate binomial probabilities using software	Using tools
Calculate the expected value of a binomial distribution	Problem Handling
Calculate the variance of a binomial distribution	Problem Handling
Relate the area under the frequency curve of the standard normal distribution to probabilities (include images)	Communication
Convert between a normal distribution and the standard normal distribution	Problem Handling
Calculate probabilities using the standard normal distribution	Problem Handling

However, most students selected option B. This suggests that, even when the mathematical content is directly connected to project work, when working in groups not all students will have the same learning experiences and other opportunities to explore and demonstrate understanding of the material should be provided.

Student feedback on the unit in the first year commented positively on the relevance of the micro-credentials to the project. Students were keen to plot their distributions and include them in their project reports as well as micro-credential assignment submissions, and at no point was the common cry of “when am I ever going to use this?” heard.

Discussion

Micro-Credentials and Projects

Students engaged most with micro-credentials when the mathematical content was explicitly connected to the project outcomes. This is described by van der Wal et al. (2017 p.S98) as reducing mathematics as an “island”. They found that almost all the engineers they interviewed complained that a serious obstacle to their learning was the mathematics content being completely separated from the rest of their courses.

A challenge to be addressed in this mode of learning is that of curriculum coverage. While it was simple in the early years to map mathematical content to projects, it would have become trickier in later years when more niche topic areas needed to be covered. Potentially the curriculum would itself have evolved to match the mathematics required for common industry projects, rather than projects being artificially sought out to map to the curriculum. It is worth noting that the topics required for first year projects were heavily algebra, measurement and statistics focussed. Calculus was not required until more technically challenging projects were undertaken at the end of the second year. The issue of managing pre-requisites would also become more challenging with more projects, students having choice of projects, and larger numbers of students.

Student Engagement

A downside of flexible learning pathways and no exams was that the framework allowed for procrastination among the students. Over the two years of the course the weighting of the micro-credentials as part of the unit grade assessment was initially increased, and then a hurdle introduced requiring 40% of micro-credentials mapped to a unit to be achieved for the unit to be passed, regardless of project grades. These measures were improving micro-credential completion but still allowed students to avoid areas of the curriculum they struggled with. As all micro-credentials were required for completion in order to graduate, it would have been interesting to study patterns of attainment in later years, when procrastination could no longer be employed, though the discontinuation of the course has prevented this. In some ways, this method of assessment provides a better method of supporting students and tracking progress than an exam-based model. Students have more control over the pace of their progress, receive more feedback, and educators have greater visibility of the specific micro-credentials students are struggling with to better target face-to-face support. The need to demonstrate at least a proficient level of competency in all criteria can be compared to an exam-based course where a student can progress with a bare pass in all mathematics units and no record of which specific aspects of the curriculum have been mastered or, perhaps more importantly, not mastered.

In terms of micro-credential learning tasks, initially they were not assessed, with the application task being the only item aligned to the rubric. This led to students skipping to the end and only engaging with the assessed content. Increasingly problem sets from learning tasks were elements that were required to be submitted and included in the rubric. These problem sets used online question banks allowing multiple question attempts and reducing the marking burden on staff. Practically, marking is an issue that needs to be seriously considered by anyone thinking of adopting this or a similar model. Marking workload was controlled by limiting the number of resubmissions allowed within a unit, so for a micro-credential to count towards a unit grade it had to be achieved within three submissions. This also reduced the tendency to submit a half-attempt at a task and await feedback. A resubmission template was also introduced in which students had to indicate how they had responded to feedback and what they had changed between submissions. These challenges are consistent with those identified by Hung (2011), with human factors and workload and resource issues recognised as difficulties in implementing project-based learning.

Collaboration and Academic Integrity

Another feature of interest in this course is the collaborative aspect that stems from the team-based project work. Cardella (2008) advocates for the use of social resources in mathematics education, which is ubiquitous in this degree as students work in project teams from day one of their studies and use the same collegial approach to tackling mathematical problems. This has interesting implications for academic integrity as there is a grey area between working socially and collaboratively, which is encouraged, and plagiarism.

Key Design Considerations

From the successes and challenges faced in designing and implementing mathematical content of a practice-based engineering degree, the following points are noted for those considering adopting aspects of this model:

Modularisation-breaking down content into smaller units is required for just-in-time delivery relevant to project work. This has benefits in terms of motivation as the relevance of the content is provided by the project, however it leads to complexity in terms of pre-requisites, tracking student completion and increases workload for staff and students alike. Other benefits of a modularised curriculum include easy alterations to courses in terms of the addition, substitution or adaptation of micro-credentials.

Technical support-the number of units, amount of online content and complicated chain of pre-requisites required specialist technical support in terms of display and navigation through the learning management system and for tracking student progress. The technical challenges should be considered by anyone looking at adopting a modularised teaching and learning model.

Blended delivery-students preferred a mix of online and face-to-face support rather than the wholly online delivery initially intended. All the work presented here took place pre COVID-19, so it will be interesting to see how students and academics in the future approach balancing online and face-to-face interactions.

Mathematical competencies-This model has the potential to develop a range of mathematical competencies beyond the traditional focus on problem handling, mathematical reasoning and handling formalisms. The practice-based philosophy led to a greater application of modelling competencies and the application of the design principles arising from the industry consultation added an emphasis on using tools and aids.

Competency-based assessment-students initially struggled with a binary mark of “complete” or “incomplete”, being used to getting percentages or grades. The micro-credential and project model could easily be implemented with a grading system rather than a competency-based system in a different context.

Workload for staff-The workload in this model was shifted away from delivery, with most of the content online. The content was labour intensive to create but would have needed little input once it was finished. The ongoing workload was instead shifted to marking, which was an iterative process of providing feedback and marking re-submissions. This process would need significant adapting to be viable from a workload and financial perspective.

Conclusions

The modularisation of mathematics curriculum is a practical way not only of delivering mathematics content in a project focused degree, but also of providing flexible pathways for students with different mathematics backgrounds and requiring different mathematics for their specific majors. However, one of the drawbacks of modularisation is the increased frequency of assessment which impacts student workload and has practical implications for staff marking time. With increased online delivery, the teaching workload in the model described here is shifted from content

delivery to marking and providing feedback. Overall, this model is a new way of approaching mathematics education in engineering, which provides students with mathematical skills directly applicable to engineering as a profession and gives them increased flexibility in developing these skills. As the course has been discontinued, there will be no opportunity to track projects or students over time as initially intended so no conclusions can be drawn about the success of this model in producing mathematically competent engineering graduates. However, it is hoped that the reflections stated here can inform others design of modularised curricula as it is likely that this is a direction that higher education will increasingly move in to meet student demands for personalisation and flexibility in the future.

Compliance with Ethical Standards

Conflict of Interest The author states that there is no conflict of interest.

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