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Faculty wide curriculum reform: the integrated engineering programme

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ABSTRACT
Many traditional engineering schools are struggling to balance the calls to provide an innovative engineering education that meet the demands of graduates and their employers with the constraints and momentum of their existing curriculum. In this paper we present the conceptual design behind a framework that integrates existing discipline-specific content with threads of professional skills and design through a backbone of problem-based learning experiences. This framework creates a student-centred pedagogy that has been implemented across eight departments of a large engineering school in a research-intensive university.

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Curriculum reform; problem-based-learning; multidisciplinary education; engineering education

Introduction

Engineering, as with all the creative arts, requires professionals with a range of skills, knowledge and attributes. It is widely being acknowledged that although necessary, a strong foundation in science, mathematics and the underpinning technical knowledge commonly associated with engineering, is not sufficient. Over the past two decades, this requirement for a broadening of the curriculum has been highlighted by a number of quarters, including industry (McMasters 2004; CBI 2009), the professional institutions (National Academy of Engineering 2004; Spinks, Silburn, and Birchall 2006; Rauhut 2007; Morgan and Ion 2014), and government (Perkins 2013). All have emphasised the need for a curriculum encompassing areas such as engineering's role within society and a whole set of transversal skills[1] from critical thinking to team working, socio-economic considerations, sustainability, ethics and entrepreneurship. In the US, a significant voice for change in engineering education has been held by Boeing (McMasters 2004). While, in the UK, the recent IET (2016) skills survey gave a stark assessment:

> There is deeper concern than in previous years around the skills, knowledge and experience of the future workforce – postgraduates, graduates, school leavers and apprentices.

A procession of reports have called for change, levelling criticism at the current engineering education process. Examples of the well-rehearsed arguments include investigations of the 'pipeline' of school leavers into engineering study (Perkins 2013) and particularly the difficulties faced by underrepresented groups to enter engineering (MacDonald 2014), through to the skills developed during university level education (Morgan and Ion 2014). In addition, the Royal Academy of Engineering produced a pair of reports which looked at the process of 'Educating Engineers for the twenty-first Century' from both the industry perspective (Spinks, Silburn, and Birchall 2006) and the academic

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viewpoint (Rauhut 2007), highlighting both skills shortages and skills gaps in the graduates being produced.

The mantra is simple – university engineering departments must produce graduates with not only the technical skills of the disciplines, but also with a wider range of transferable professional skills, an understanding of the societal context of engineering and in particular, an understanding of how to transfer such skills when in industry. The call for change seems clear, but what change is required? The Royal Academy of Engineering (Rauhut 2007) summed the end goal up as:

> University engineering courses must provide students with the range of knowledge and innovative problem-solving skills to work effectively in industry as well as motivating students to become engineers on graduation.

The stakeholder needs are clear, however many questions remain. This paper will look to address the following two questions; What does this change look like in the context of 'traditional' engineering programmes? How do we implement the changes we need to accomplish this new curriculum in an established university?

This paper will explore these two issues by giving the example of a faculty-wide curriculum development programme that aims to address the perceived skills gap identified above. It discusses how a spine of problem-based learning (PBL) was implemented in all programmes and used as a central thread of learning and a foundation to the study of engineering across a number of disciplines. It will start by briefly setting out the context of the developments and outlining the new engineering competences that staff within the faculty identified as critical to fulfilling skills gaps of graduates. It describes how these skills fed into the conceptual design of the programmes and the process by which they were introduced. It provides details of the model that was used and the theoretical and philosophical underpinning of the new curriculum. It concludes by discussing the change management process enacted to deliver this re-building of the curriculum across a number of disciplines.

Context

UCL is a multi-faculty, research intensive university, consistently rated within the top 20 universities world-wide. The UCL Faculty of Engineering Science is one of eleven faculties within UCL with a total student cohort of over 6000 students, of which around 3500 are at undergraduate level. The faculty has ten departments of which eight offered undergraduate degrees at the time of curriculum change. The faculty is supported by around 1000 staff, of which just over 310 are academic staff.

In 2011, the UCL Faculty of Engineering Science undertook a major review and revision of all its undergraduate educational programmes. This led, in 2014, to the introduction of the Integrated Engineering Programme (IEP) across eight departments and eight different programmes (each programme having a three-year Bachelors (BEng/BSc) and a four-year Integrated Masters (MEng/MSci) variant). The programmes are Biochemical Engineering, Biomedical Engineering,[2] Chemical Engineering, Civil Engineering, Computer Science, Electronic and Electrical Engineering, Management Science[3] and Mechanical Engineering. The first graduates from the three-year programmes graduated in September 2017, whilst the first four-year cohort graduated in September 2018.

What sets the IEP apart from other curriculum development initiatives is that it introduced and delivered a complete revision of engineering education across the majority of the Faculty. All students enter the IEP as part of one of their disciplinary specialisms but share a common framework of problem-based learning experiences and supported learning via a root-branch model that threads through the degree. The IEP framework and reasoning behind its different forms invoked is explained in the next section.

Specification of a cross-faculty model of an integrated curriculum

The development of the IEP started in 2011 with faculty-wide discussions on the possible philosophies, directions and pedagogies that are required to develop engineers for the latter half of the twenty-first century. As expected, the discussion covered both knowledge and skills in some depth, but also expanded into the attitudes and attributes expected of professional engineers that will be solving the global issues which are increasingly faced by humankind and may continue to be for future generations to come. A non-exclusive list was developed for consultation, drawing inspiration from many sources, for example, Olin (Kerns, Miller, and Kerns 2005), UniSA (Mills and Treagust 2003), CDIO (Crawley et al. 2007), and Aalborg (Krogh 2004). Topics such as practical application, communications and teamwork, critical thinking and analysis skills featured heavily as well as sustainability, ethics, entrepreneurship and leadership. The philosophy encapsulated in the IEP can be neatly summarised in the following definition of engineering:

> Engineering is … …
>
> The **art and practice** of changing the **physical world** for the **benefit of all**.

This updating of the famous Thomas Tredgold definition by Chris Wise of Expedition Engineering, further modified by Emanuela Tilley, encompasses three key elements of the curriculum.

Art and practice: Engineering is more than knowledge, certainly more than being able to solve equations. It has an art to it, and a creativity that requires development through experience. Following an idea developed by Lucas, Hanson, and Claxton (2014), we believe there is an engineering 'habit of mind', a way of thinking that needs to be nurtured and developed in the education we provide to engineers. This engineering approach can then underpin all life-long learning and experience to develop professional mastery.

Physical world: The practice of engineering is inexplicably linked to the natural world. Here is the point where science and mathematics meet but must also join with practice. This expresses the concept that ultimately all that we do in engineering has some impact on the physical world. Regardless of whether we are some way removed from direct impact (for example, Software Engineering or Information Systems), we will have impact none the less because the practice of engineering creates change. Hence, it is important that we understand the constraints, be they physical laws or local context that will affect our designs and their function.

Benefit of all: Finally, we must extend the concept to include the impact of all changes of the physical world on our social worlds. This must be central to all design decisions. Our design processes must consider the potential impacts on people, wildlife, and the environment at all life stages of production and operation of engineering artefacts. Here we recognise that in some facets of engineering the impact is obvious. The UN Sustainable Development Goals (United Nations 2015) are commonly used to bring this impact to the fore, however, even the simplest app or the smallest electronic device will impact the user, their behaviour and the way they live. The scale of the impact will vary, but nevertheless it could be considerable and must be explicitly considered. The growing global movement, which calls for a consideration of impact at the early conceptual stages and throughout the design process of all technology development, clearly speaks to young people to a far greater extent than previous generations (Lawlor 2013) and is a major challenge to the engineering community (Stilgoe, Owen, and Macnaghten 2013).

Through a collaborative process with departments, this vision of engineering led to a framework for the IEP, which aims to produce a distinct and inclusive programme that produces highly self-aware, conscious, dynamic and employable engineering graduates through its five core pillars.

Demonstrate the interdisciplinary nature of engineering: From the start of the Programme students engage in research-based and problem-based activity, working in interdisciplinary teams. They are then encouraged to broaden their disciplinary knowledge in the second and third year through an interdisciplinary IEP Minors pathway that enables them to expand their technical knowledge. All students should have the opportunity to engage in a major interdisciplinary capstone project.

Practical engineering from the start: The first term sets large challenges to engage the students in sizable real-world problems, explicitly connected to societal impact. This is followed up with distinct problem-based elements throughout the first two years.

Emphasis on design, professional practice and skills: A comprehensive thread of design and professional practice workshops are aligned to the practical activities throughout the IEP in order to develop students' individual skill sets, both technical and non-technical, in the context of engineering problems. To address the skills and attributes identified above, particular emphasis was placed on integrating transversal skills into the core of the curriculum. Although often 'taught' within engineering programmes, they are often seen as add-ons by both staff and students rather than inherent in all activities of a professional engineer.

Personal support for students: The IEP integrates a strong sense of personal interaction between staff and students, with elements of the core teaching that allow students to personalise learning based on preferred style and need. Its aim is to explicitly promote self-learning and self-efficacy in developing autonomy and mastery within the student body.

Maintain disciplinary strengths and alignment to research: We still provide students with a strong disciplinary identity and a sense of belonging to their department, having had opportunities to learn from the work and leading research activities of their home department as well as across the faculty. The IEP Minors and earlier elements of the IEP provide coverage of the key interdisciplinary research areas within the faculty.

Design and development of IEP curriculum

It is helpful to start by defining what we mean by 'curricula' in our context. We take the framing of Goodlad (1979) in considering a curriculum as more than just a set of courses. Instead we view it as something that has many levels. The curriculum design process therefore started from the five key objectives, described above, which fit Goodlad's (1979) concept of 'ideal curricula'. With this starting point identified and agreed, the main task was to develop a framework in which they could be successfully integrated into the student experience to form the experiential curriculum acknowledging that this and the operational curriculum might be different in different departments (Goodlad 1979).

Active learning was adopted as a key strategy to address the curriculum objectives stated above (Freeman et al. 2014). In particular, problem-based learning and its variants have been identified as a common curriculum strategy when changing from what Kolmos (2017, 2) described as a 'mode 1' academic university where the emphasis is on theoretical learning to 'mode 3', a hybrid institution with a greater focus on social progress. As we shall describe later, this active learning philosophy (Christie and de Graaff 2017) was used as a central theme connecting the curriculum, rather than as an all-encompassing ideology.

Two important factors influenced the scope of the design. Firstly, it must be recognised that this was a 'revision' programme, which is now often referred to as an integrated teaching framework, rather than the chance for a fresh start with a blank sheet of paper and few constraints. Although in theory nothing was sacrosanct, a significant degree of pragmatism was needed. There were degree programmes already running, which meant that a deficit model of innovation (i.e. a strong message of 'new and improved') was inappropriate out of concern for alienating existing students and devaluing their own educational experience. In addition, with over 200 staff involved in the existing delivery, all potentially impacted by the changes, the scale of the challenge to engage all staff was not to be underestimated. The curriculum design processes, therefore required very careful consideration to highlight the areas that were really open to innovation and those areas which needed to remain in place – albeit potentially with modification, in their current form.

Secondly, it quickly became apparent that although they are great sources of inspiration, the highly innovative models pioneered by small, bespoke engineering colleges would neither be appropriate nor accepted by staff due to the scale of the local constraints. As identified by Kolmos, Hadgraft, and Holgaard (2016), change is necessarily highly individual and predicated on the local context. Although the staff were open to external ideas, the ability to draw on existing local experience and expertise was seen as vital to gain buy-in and acceptance. Therefore, models already operating within the university, often on a small scale or in a single class where used as exemplars for the changes being proposed (Mitchell, Canavan, and Smith 2010; Thomsen et al. 2010; Bell, Galilea, and Tolouei 2010). In addition, it allowed staff to engage with the ideas prior to their full implementation and gain insight from existing experience; this approach also gave confidence that the new curriculum could work in the context of UCL.

The resulting Integrated Engineering Programme is a faculty-wide curriculum that inserts both cross-cutting elements and threads of activity into the discipline-specific structures in each department. Although inserting elements that are inherently common in terms of syllabus, the IEP is deliberately flexible in terms of delivery so that it can be connected with activities undertaken within the disciplines. The term 'integrated' plays out in two distinct ways. Firstly, the IEP integrates the various strands and threads of activity undertaken by the students; the structure is designed to provide opportunities for students to bring together their theoretical learning with their practical skills in concert with transferable skills such as teamwork, communications and consideration of societal impact. Secondly, the structure aims to provide an 'integrated view of engineering' as a multi-disciplinary and creative activity that draws experts from key disciplinary areas and requires them to collaborate in identifying and designing innovative solutions to problems.

Within the revision process, departments were challenged to review and update their existing disciplinary content. This was a fundamental requirement as space was required in the timetable for the new activities and there was an opportunity to align existing theoretical content with the new practice elements being introduced. This process took on different forms in different departments, with those that engaged most coherently in this process finding the most success in their implementation of the other elements. However, it was also important to be realistic about the scale of redesign possible and the challenge inherent in engaging all staff in systematic re-building of the undergraduate taught curriculum. With this in mind the revision of the disciplinary elements ranged, even within the same department from the fairly minor to the quite radical.

Although considered as a potential starting point, early on in the design process it was decided that large classes with students from different engineering disciplines to teach fundamental technical subjects, such as thermodynamics, for example, would not be appropriate as, although the syllabi look similar on paper, the way they were addressed and the contextual nature of the subject within the discipline was considerably different. The only exception to this was when considering the mathematics syllabi. Here, it was felt that the ability to see the broad application of mathematics outside of a student's home discipline would in fact be of value. To this end, a faculty-wide mathematics syllabus was developed based on a common lecture series alongside discipline-specific tutorial and workshop sessions.

The result was a framework that, rather than dictating specific practices, gave latitude, for alternative implementations within the frame of a progression of supported PBL elements.

The integrated engineering programme teaching framework

The teaching framework of the elements developed to deliver the IEP can be seen in Figure 1. It shows a generic representation of how the new IEP cross-cutting elements implemented sit within the context of the whole set of discipline-specific degree programmes across the faculty.

Design projects

The centrepiece of the IEP is a set of problem-based learning elements which are shown as shaded activities shared across all departments. They include multi-disciplinary Engineering Challenges in term one of year one, one-week Scenarios when no other teaching takes place which are scheduled across the latter part of year one and throughout year two, and 'How to Change the World', a two-week interdisciplinary Scenario that runs after the end of the exam period at the end of year two. These form a central core, or 'spine' as it is often referred to, of problem-based learning activity that runs through all degree programmes and is interconnected with the other elements of both

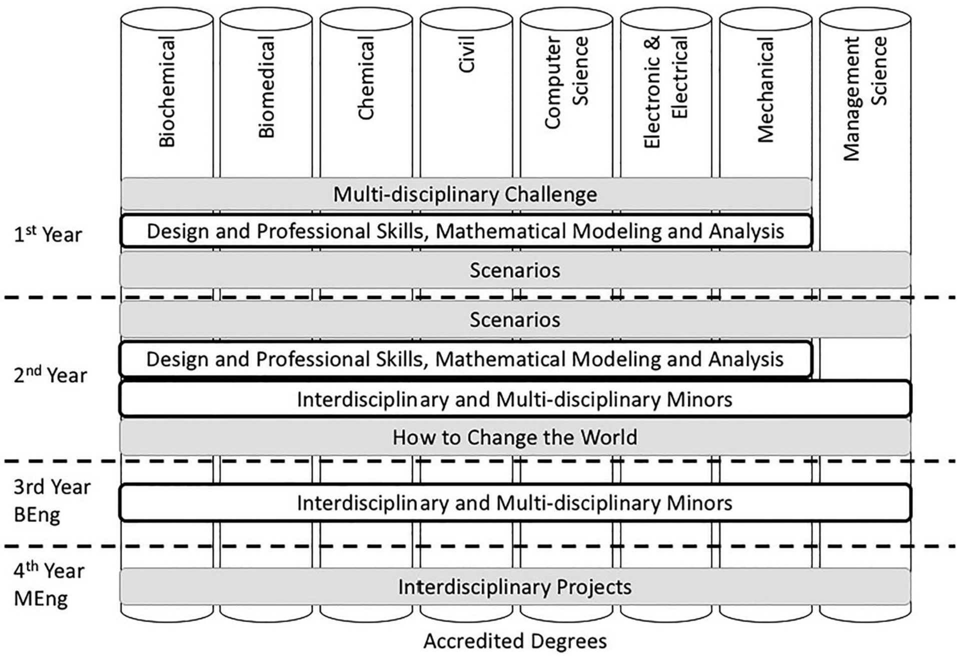

Figure 1. Overall structure of the integrated engineering programme.

the IEP and discipline-based core learning. The nature of these PBL elements is covered in more detail in the next section. The other IEP elements are designed to support or complement these activities.

Design and professional skills

In both years one and two of the IEP, a Design and Professional Skills module was introduced to support students in their learning of both technical and non-technical transversal skills. This was seen as key to developing skills for future employability, but also to support the learning journey of the student and to allow them to gain maximum benefit from the IEP project-based elements. We drew on a range of different styles for skills-based (Felder and Silverman 1988) and design-based learning (Dym et al. 2005) that allowed students to be introduced to and develop skills before having the opportunity to put them into practice via project work.

The Design and Professional Skills module brings together a range of topics required by all the major accreditation bodies but are too often found languishing in bespoke modules at the end of the degree programme unconnected to the core of the curriculum. The aim here was to create a robust and engaging multi-year syllabus of instruction in ethics, professional standards, sustainability, legal and management concepts, communication, risk and safety, creative and critical thinking, decision making, design and teamwork. It was recognised that although a common syllabus could be defined, implementation would need to be heavily tailored to each department. For example, the ethics concepts that are relevant to Biomedical Engineering, although sharing some common ground, are likely to be quite different to those concerning a Computer Scientist. Therefore, engagement with local practitioners and researchers in each department was necessary to develop specialist routes through this common syllabus structure.

Professional skills were very deliberately connected with design due to our insistence that it is through the process of design that these skills are put into practice. This leads to a thread that runs throughout the entirety of each degree, supporting students to develop the skills that they need to succeed in the problem-based elements and, by association, their future employment and employability. This integration was one of the most challenging elements to construct. The IEP aims to connect the development of a student's individual design and professional skill sets directly to their PBL experiences. Consider one incarnation of the design cycle, shown in Figure 2, which was specifically developed for the IEP and taught to all students in the Design and Professional Skills module. The cycle aims to demonstrate to students the various phases of design, from defining the need and developing a brief, through conceiving (ideation), testing those ideas and specifying a solution, to the making and use of a product or system. The arrows demonstrate that in the transition from each stage to the next, there is a need for analysis and judgement and often iteration for the success of that stage – for example, does the design solution meet the need and fulfil the brief?

We connected elements of the professional skills syllabus to the activities that students are required to complete in order to progress through all or part of the cycle. For example, in a Scenario, students might be expected to introduce ethical considerations into their development of the 'brief', use the tools of critical analysis (for example, a decision matrix) in their evaluation of designs they 'conceived' and follow the guidance on good presentation structure in their final presentation output at the end.

Mathematical modelling and analysis

As mentioned above, a new, faculty-wide mathematics syllabus was developed and delivered via a common lecture series and discipline-specific tutorials and workshop sessions. Mathematics, which had previously been delivered in most degree programmes by the mathematics department, is now delivered by engineering staff with specific expertise in the application of mathematics to modelling and simulation of engineering problems. This change of emphasis can be seen in the integration of MATLAB as a core tool for applying mathematics to engineering design within the IEP (Nyamapfene and Lynch 2016). Mathematics is taught as a 15 credit[4] unit in each of the first two years of the degree programmes.

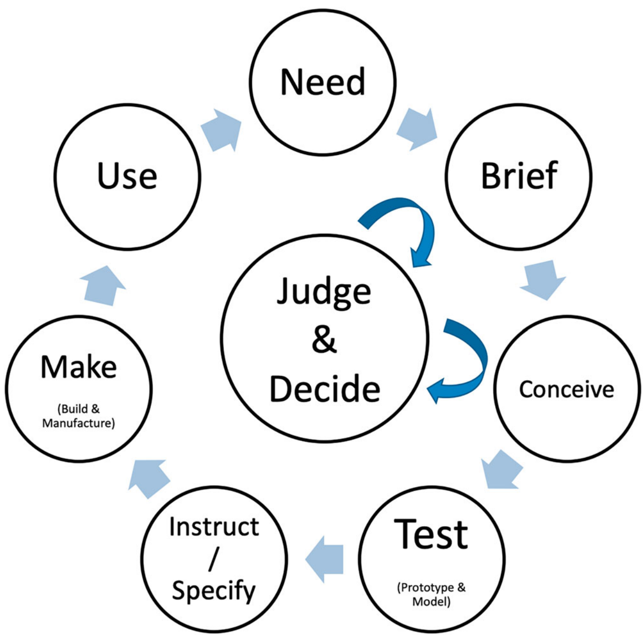

Figure 2. The design cycle.

Interdisciplinary and multi-disciplinary IEP minors

As Crawley (2015) points out, the undergraduate engineering curriculum is simultaneously faced with an ever-increasing body of technical knowledge, and increased demands for well-rounded, work-ready, engineering graduates. Whilst our PBL strategy can adequately address the skills agenda, we felt that in order to address Crawley's first requirement, the IEP also needed to provide students with opportunities to undertake in-depth studies in additional topics, either from disciplines complementary to engineering, or from interdisciplinary subjects that draw on the research strengths or industrial partnerships of academics within the faculty. To achieve this, all students study an IEP Minor pathway as part of their degree.

We define an IEP Minor pathway as a coherent set of learning activities that are available to students coming from a number of specialisms/departments that provides coverage of a topic to an advanced level. Specifically, each IEP Minor pathway consists of three 15 credit modules spread out across three terms in years two and three that are linked to each other to form a coherent, clear study pathway. Each IEP Minor has been designed to ensure that it is accessible to all students across the various engineering departments making up the faculty. This, therefore, requires that any pre-requisites and co-requisites be kept to an absolute minimum.

Problem-based learning in the IEP

The aim for our students across the faculty is that they graduate from their degree programmes with an advanced set of professional skills, similar understandings about engineering design, context and impact, and some shared identity, while also having expertise in very different technical fields, and an identification with their own discipline. We identified from the framework described above a set of central pedagogic themes that could be employed to achieve these aspirations. The key pedagogic device was the inclusion of problem- and project-based learning into the curriculum. This formed a central strand to all activities.

Problem-based learning (PBL), which was pioneered in medicine (Barrows 1992) is now commonly used across a number of disciplines (see Savin-Baden and Major 2004) including engineering (Perrenet, Bouhuijs, and Smits 2010). It is widely credited with a number of learning benefits including enhanced problem-solving skills, increased creativity and criticality, independent learning, and development of the team and communications skills (Kolmos 2002). These are all aligned with vocational/professional demands (de Graaff and Kolmos 2006) and prescribe it as an ideal vehicle to deliver a number of the objectives of the IEP.

PBL is generally characterised as an active learning technique built on the use of ill-structured problems (Barrows 1992) which form the core stimulus for the learning process (Savin-Baden and Major 2004). It is typically undertaken within groups or teams. We define PBL in the IEP as a broad category that can be encapsulated after Hanney and Savin-Baden (2013, 8) as:

> A time-bounded activity which is directed by the project participants or team, who determine the course of the project and the final output in response to a brief of some description.

This is the underpinning philosophy of our IEP PBL curriculum, which allows for a wide variety of interpretations of each PBL element to be delivered. For example, IEP PBL elements can differ in the scope of the brief, some are very ill-defined, open problems, while others are narrower and may require a solution to a specific engineering problem. However, in agreement with many practitioner-researchers in engineering education, we demand that the activities must be project-based, team-based, encourage a level of learner autonomy and have some element of authenticity (Savery and Duffy 1995). The element of 'authenticity' is key but must be suitable for and defined within the context of an early stage engineering student experience (Roach, Tilley, and Mitchell 2018). Within the broad interpretation there are many examples that we can draw upon, for example, enquiry-based learning (Kahn and O'Rourke 2004), design-based learning (Doppelt 2009), scenario-based learning (Thomsen et al. 2010), and project-based learning (Felder and Brent 2004). Therefore, in this context, we consider PBL as a global descriptor of our key active learning activities, the majority of which would also be classified as project-based learning very much in line with the project-led problem-based learning concept of (Hanney and Savin-Baden 2013).

As demonstrated in Figure 3, there is a 'spine' of PBL activities that are threaded throughout all degree programmes included within the IEP. The centre line includes all the PBL elements across the first two years of each programme. These PBL elements are consciously designed so that each thread, including mathematics and design and professional skills, feeds into this project work. This spine of PBL has been developed to provide students opportunities to put their theoretical knowledge and their design and professional skills into practice in the context of authentic practical experiences. We note that this is not to scale and that the discipline-specific technical content still dominates the curriculum (approximately 75%) but that it is now linked explicitly into the project work as shown. Figure 3 demonstrates how, in the course of their first two years, a student will have undertaken nine PBL elements (two five-week challenges, six one-week scenarios and the two-week How to Change the World Scenario). This then leads into the major project that all students undertake in their third year.

The majority of the IEP PBL elements very explicitly focused on design, providing students the opportunity to experience and develop transversal skills at the various stages of the design process, which is shown by the design cycle in Figure 2. Figure 4 demonstrates how the PBL elements of the IEP might be mapped onto this design cycle over the first three years of the programme. In the diagram, shaded areas show aspects of the design cycle covered by PBL. Those marked with an X are not considered and those marked 'given' are provided to the student by the instructor. The box at the bottom identifies the transferable skills that are explicit learning outcomes within each element.

The first two elements form the year 1 Engineering Challenges module and take students through the majority of the design cycle. They act as an introduction to the process and a first opportunity to explicitly link concepts taught in Design and Professional Skills module, as well as the technical knowledge being developed elsewhere in the curriculum, to design-based projects. The next section shows the Scenarios. These are team-based projects undertaken within each discipline. Each Scenario covers very different content in terms of technical and transferable skills depending on the discipline and the links designed to that discipline's curriculum. Therefore, each discipline

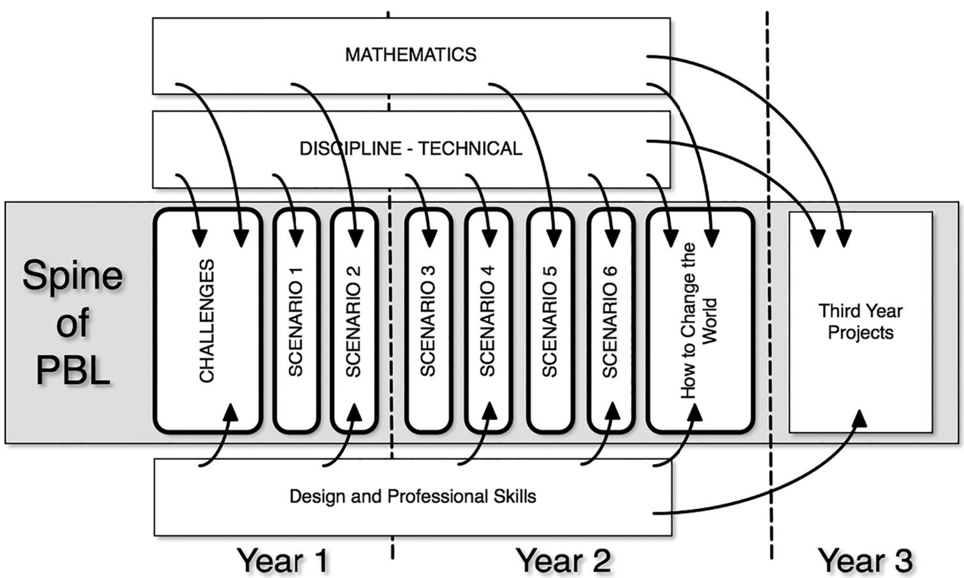

Figure 3. Relationship between integrated engineering programme elements.

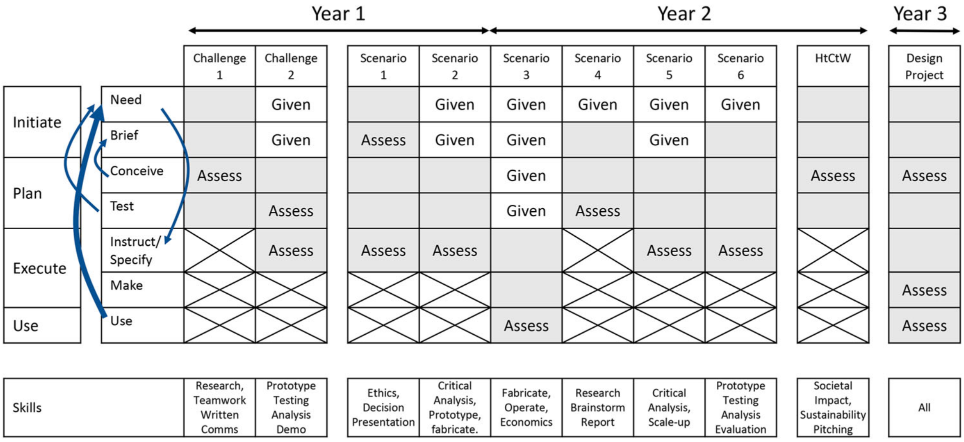

Figure 4. An example of mapping the problem-based learning elements to the design cycle across the first two years of the programme.

will produce their own mapping. Despite this, there is a common progression in terms of exposure to ever more complex problem-solving and design activities and increasing expectations in terms of the enacting of transferable skills.

In the Scenarios and Challenges, processes become more important than outputs. As Kolmos, de Graaff, and Du (2009) point out 'Student-centred curricula based on projects are *process-oriented* rather than product-oriented'. Students are directed to focus on the process, for example, the process of specifying or the process of testing. In each instance, the sections noted as 'given' enable the students to enter the design cycle with enough information so as to provide them with sufficient time to concentrate on the particular areas identified as linking to the key learning objects for that activity. Assessment may still be linked to output points, for example, in one Scenario the CAD drawings produced are the output but the key learning focus is on the processes undertaken to develop them. The final PBL element of the first two years, How to Change the World, adds significant societal context resulting in additional complexity, degrees of freedom and challenge to the navigation of the design cycle.

Our IEP PBL thread was conceived as preparation for the substantial design and research projects that students undertake in years three and four of their degree programmes. Traditionally, these were the first major project experience that most UK students had within their degree. It was commonly overwhelming, with some students spending much of their time getting to grips with the requirements of undertaking a major project as well as working in a team-based environment rather than using it as an opportunity to showcase and further develop the skills and learning acquired in their studies so far. The strand of projects also delivers two important elements of the IEP curriculum. Firstly, as described above it acts as the vehicle for students to make connections between their technical learning, providing a context for the theoretical and skills-based learning that takes place in other parts of the IEP. Secondly, the projects are connected to one another to provide a hierarchical structure allowing students to iteratively develop non-technical skills such as project management, communications, collaboration, teamwork and problem-solving. Further detail of the structure of each of these elements is provided below.

The engineering challenges

The first PBL activity that the students experience, from day one of their classes, occurs within the Engineering Challenges module. The module was specifically structured as two five-week projects to provide enough time for students to engage in the supporting skill-based and theoretical activities

The Challenges – Term 1	
Challenge 1 - Weeks 1-5	**Challenge 2 - Weeks 6-10**
Single discipline Team-based Research-based project Self-directed learning Open-ended (research and ideate)	Inter-disciplinary Global Health Project Team-based Practical project Self-directed learning Specific and goal directed (model, build and test)
Activity Flow Across The Challenges The projects are based on an engineering design process, where Challenge 1 represents the early, ideational and research phases of design and Challenge 2 represents the later prototyping phases of design.	
NEED – BRIEF - CONCEIVE	SPECIFY-BUILD-TEST

Figure 5. Flow and nature of activities in the challenges.

alongside their projects. This first variant of PBL is the most expanded in terms of the time spent, with the classes allocated in the timetable as two 2-h workshop sessions per week. The module was designed to provide an introduction, or perhaps more correctly an induction, to the style of learning that is needed to successfully engage in other IEP PBL elements. In this context there is considerable scaffolding and support provided to assist students to make a successful transition from what we assume to be a much more prescribed style of learning in school (Tilley and Mitchell 2015). These two projects also introduce the students to a broad range of aspects within the design cycle as a prelude to more focused activities that follow. We see this induction as a key method of setting expectations for the rest of their learning experience within the IEP as this is the point where students are conceptualising what it is to be an engineer. A perception that we aim to strengthen by introducing learning activities that align with the desirable outcomes such as problem-solving skills and independent learning (Tilley, Peters, and Mitchell 2014).

Although they are designed as a single learning journey, the two Challenges differ in focus (see Figure 5 for details). The first, delivered in the first five weeks of undergraduate year one studies, is a single discipline project which orientates students to their department and introduces them to their chosen discipline as well as the richness and innovative nature of the department's research. The project task of the first Challenge takes students through the early stages of design, from 'need' to 'conceive' with very little testing but a lot of decision making embedded and is unique to each department. The second Challenge locates itself in the 'conceive', 'test' and 'model/prototype' stages of design and is an interdisciplinary Challenge which consists of a single overarching contextual problem that takes in seven disciplines. The project is based around the manufacture of a vaccine in sub-Saharan Africa and disciplines are paired to work on specific 'technical briefs' required to manufacture vaccines for distribution in this context, from generating energy to the design of a bioreactor. We find that it is important in this, the first student experience of working across disciplines, to provide a structured experience, because it assists students with later projects, which require them to work in interdisciplinary teams comprising several engineering disciplines at once (see How to Change the World below). Having said that, in the second Challenge students from all disciplines do come together to discuss and share views on the ways in which their particular project task is impacted by considerations of cultural, economic and environmental context.

Scenarios

After the first term, students engage in tightly focused one-week activities within their departments based on a five-week pattern consisting of four weeks of traditional instruction followed by a one-week intense project activity. The primary aim of this element of the course is to connect discipline-specific theoretical learning with real projects in a demanding and concentrated burst. They continue to be centred on the design cycle but now often include the production of authentic artefacts as a mechanism to provide a realistic means of assessment. Scenarios at UCL were first developed in the Department of Civil, Environmental and Geomatic Engineering (Bell, Galilea, and Tolouei 2010) which allowed us to draw on considerable existing knowledge in the implementation of them. They had also been adopted by the Department of Electronic and Electrical Engineering which provided the development team with a strong basis on which to build (Thomsen et al. 2010). The Scenarios span a range of different approaches. In the context of the model of problem-based learning put forward by Kolmos, de Graaff, and Du (2009) derived from the work of Savin-Baden (2000, 2007) most fit within 'models III', 'IV' and 'VI', in that they all require an element of critical analysis beyond just the use of propositional knowledge within the scope of an open-ended (to a great or lesser extent) problem.

In term of the curriculum connections, some have identified specific technical topics (i.e. transmission lines), technical skill (i.e. CAD design) or professional skill (i.e. working with clients) as their foundations and use an authentic problem to enable students to expand their knowledge in that area. Others seek to connect a number of threads from the set of taught modules occurring in parallel within the academic term, promoting the connection between theoretical learning and practical experience. In both of these modes, a central tenet is that the content is drawn from key topics in the modules students will have studied over preceding weeks, either extending it or enabling connections. In one example, from the Department of Electrical and Electronic Engineering, the students are tasked with developing a system to non-destructively detect the telephone number that is being transmitted on a cable that runs through the teaching lab. In the weeks prior to this activity the class will have covered the electromagnetic theory required to understand the field created by a signal in a wire, the circuits required to amplify the sort of signals detected from such a wire, the process and requirements to transform signals from the analogue to the digital domain, and the Fourier techniques to determine the frequency components. Within the week they are expected to implement these four elements, taught in four separate modules within the degree programme and combine them to form a complete system.

Scenarios are generally kicked off with a short introductory lecture on Monday morning, followed by a series of milestones throughout the week. These are usually checkpoints that each of the student teams have to progress through to get to the next stage of the project. For example, outline designs might have to be signed off by Scenario academic and technical leaders before access to the lab or components are granted. Scenarios typically culminate in a competition or final showcase on the final Friday.

The one-week format does present some limitations on the type of problems that can be set and, in particular, presents challenges if fabrication or purchasing of specific components is required. One solution to this is to link the technical content and learning experience of two Scenarios. For example, in the Department of Mechanical Engineering, a pair of Scenarios requires students to design a solution to the IMechE Design Challenge.[5] This is an international team-based design challenge for first and second year engineering students, which usually requires the design, fabrication and testing of a motorised device to achieve a particular task (e.g. climb a metal tube pulling a chain). In the first of the pair, students undertake the design work, producing a CAD model of the system. This then allows five weeks for fabrication and purchasing of parts for the design before the assembly, testing and evaluation of the solution in the second week-long Scenario.

It is often asserted that assessment drives the student engagement (Biggs 1996), and this is even more evident within the confines of a one-week intensive mode of study. Over the course of a few years, assessment has been rationalised and streamlined, with an increasing focus on authentic outputs where immediate feedback can be provided. This has resulted in a shift from reports to demonstrations, pitches, interviews and other sorts of assessment mechanisms more in keeping with the authentic nature of the task at hand.

Table 1. Analysis of PBL elements in the three elements using the seven element model of problem- and project-based alignment (Kolmos, de Graaff, and Du 2009).

Curriculum element	Challenges	Scenarios	How to change the world
Objectives and knowledge	Understanding design cycle, societal impact, research skills, transferable skills	Disciplinary knowledge, Transferable skills development	Problem definition and solving. Societal impact
Type of problems and project	Knowledge and skills across disciplinary boundaries. Multiple but constrained outcomes	Heavily design project focused. Relatively open-ended, centred around application of knowledge and practice of skills	Multi-dimensional, open-ended and wicked problems
Progression, size and duration	Introductory and design to set expectation, acclimatise and prepare students. Two projects, each 5 weeks with 4 h of contact per week. Runs in parallel to taught curriculum ~25% of Term 1. Interdisciplinary elements	Very clear progression become increasingly unstructured and supported. Six occasions each are 1-week intensive as distinct learning object. 1/5 of activity. Disciplinary focus	Capstone with expectation of high level of critical analysis. 2-week intensive. Highly interdisciplinary. Socially relevant and focused on impact
Students' learning	Supported by modules run in parallel with the aim of constructing knowledge. Predominantly team-based, small proportion of learning individual	Supported by multiple courses, drawing from a range of existing learning. Combination of collaboration, individual and for collective knowledge and innovation	Drawing on a wide range of elements across the first two years. Collaboration for innovation
Academic staff and facilitation	Specifically trained facilitators. Emphasis on development of teamwork skills. High level of support	Progressively reduced scaffolding	Range of trained staff, academic, PGTA and UGTA. Support available but highly student led
Space and organisation	Range of classroom environments. High degree of structure	Both classroom and lab-based exercises. Decreasing structure, increased us of check-points as key engagement	Fairly open structure, with milestones, open team working environment
Assessment and evaluation	Predominantly team, summative assessment	Predominantly team, summative assessment. Emphasis on authentic outputs aligned with design task	Team and summative, authentic and integrates with design deliverables

Over the course of the three terms (in years one and two) the students are progressively provided with less structure and scaffolding, with the problems becoming increasingly broader, complex and more open-ended.

How to change the world

The final IEP PBL activity, at the end of the second year, is an intense and immersive two-week project called 'How to Change the World'. This expands the scope of a Scenario to present students with 'wicked' problems (Buchanan 1992) derived from the UN Sustainable Development Goals (SDGs) (United Nations 2015). Such project-based programmes are increasingly becoming of interest, however, unlike many, for example the National Academy for Engineering Grand Challenges Scholars Programme,[6] ours is not extra-curricular and a selective add-on but an integrated part of the curriculum that is the capstone of the project-based learning experience in the first two years.

Within this exercise, students are required to undertake a project which begins with a problem that is highly undefined, very broad and rich in societal context, and contains within it the scope for multiple engineering solutions that will have varying impacts. In addition, students work for the first time in fully interdisciplinary teams consisting of up to six engineering disciplines in each team. The aim of How to Change the World is to encourage students to engage creatively with a design process that has a concept of 'impact on humanity' in mind from the start. The activity provides an experience of how engineering must be part of tackling enormous global challenges of the kind described by the SDGs. It emphasises the necessity for interdisciplinary work to address such urgent, high-level problems. This adds another layer of complexity to the PBL activity, through the social element of the project. It requires students to consider a wider range of design criteria that demand analysis not just of the engineering feasibility but also of socio-cultural desirability and viability such that it (Brown and Katz 2009) harmonises with the broader context.

Students begin by identifying and ring-fencing their own problem within the larger scope of the SDG that they wish to address. Through a series of steps involving a reflection on their individual disciplinary knowledge plus an identification and sharing of what their individual expertise brings to the problem, the students formulate their own problem brief. The value of this is that students rarely get an opportunity to work within a very broad canvas and to define their own area of focus within it based on how their own skills and understandings can work together in the team. Following their formulation of a brief, the teams move on to defining a solution, which they defend at the end of the activity to a panel of external experts, from industry, third or public sectors. As they progress from brief to the solution, the teams are given opportunities to discuss their ideas and get feedback from external experts, to join facilitated sessions to move their thinking forward and to get support on completing deliverables successfully.

Integration of threads

In the framing of Savin-Baden and Major's (2004, 37) model of eight modes of PBL implementation in the curriculum, we argue that the IEP is closest to 'Mode 7: the integrated approach'. At first sight, the framework looks similar to both 'Mode 5: two-strand approach' and 'Mode 6: Patchwork problem-based learning'. However, both of these modules assume that PBL runs insolation (in parallel in the case of Mode 5 and sequentially for Mode 6) to the rest of the curriculum. Although, both parallel (Challenges) and sequential (Scenarios) modes occur in the IEP, this is deliberate and designed to be connected in a way not described in these modes. That being said, the model suggests a dominance of PBL, whereas, in practice, an IEP student would experience only around 25% of their curriculum as PBL. However, it is certainly true, in keeping with the definition of this mode, that PBL is 'not merely a strategy but a curriculum philosophy', with a considerable proportion of the surrounding curriculum specifically designed to support these activities. It is also true that all problems are sequential and linked, as demonstrated in Figure 4, and, most importantly, that the students are specifically equipped for the IEP.

To consider the three main PBL elements we adopt the seven element model of problem- and project-based alignment (Kolmos, de Graaff, and Du 2009), to analyse the learning journey that students take through the curriculum. This analysis is shown in Table 1. For each of the three PBL curriculum elements we describe how they operate against the seven element model of problem- and project-based alignment. This analysis demonstrates how the three different activities implement different forms of PBL depending on their objectives and their place within the curriculum. It shows an evolution of complexity and openness as students' progress through the curriculum.

Development of teamworking skills

As discussed earlier, the Design and Professional Skills modules in years one and two aim to support the individual skills associated with project work, however, it has also been acknowledged that team-based skills are also vital to enable students to engage and draw maximum benefit from the problem-based learning environment (Pieterse and Thompson 2010). One of the ways we support student teams is by providing team-building activities and a workshop that aims to increase self-awareness by engaging students in a discussion around the roles of team members, team strategies, team rules, and the features of effective teamwork. In addition, we also offer a profiling tool. A number of different tools are available to support the development of self-awareness typically through the analysis of traits and/or identification of predisposition towards certain behaviours (Belbin 2010; Felder, Felder, and Dietz 2002). Our preference was for StrengthsFinder2.0 (Louis 2012) which, by focusing on personal strengths (i.e. positive traits) enables students to exercise their strengths rather than to improve their weaknesses. Our aim in doing this was to enable students to gain confidence by focusing on strengths, acknowledging weaknesses, and to learn the impact they may have on others and on the project as a whole by working from their strengths. This forms a basis of an introduction-practice-reflection process that gives students the vocabulary to have a meaningful conversation around team roles and team performance (Tilley, Peters, and Mitchell 2014).

Implementing change

The implementation of a faculty-wide curriculum development project within a research-intensive environment has many complexities and there is much that can be learned from how a large-scale interdisciplinary teaching framework was adopted, continues to evolve, and how it is still changing the organisational culture five years on from its inception. Placed in the context of the three modes of innovation identified by Kolmos, Hadgraft, and Holgaard (2016), it is clear that this development is in the *re-building* strategy category, which, as they identify, represents an unusually high-level of systematic change for a traditional university. It required a change at the individual (micro) level, representing individual staff and the organisation (meso) level in addition to an understanding of the interaction and integration between these two levels. The implementation of the IEP was characterised by both top-down and bottom-up processes with strong leadership at faculty level that initially drove the initiation of the educational change programme and the definition of the high-level vision, coupled with space for those in departments to shape the overall direction and take ownership of innovation within the boundaries prescribed (de Graaff and Kolmos 2006).

In the early stages of the educational change programme, formal and directional leadership from senior management was important (Graham 2018). In the main, this was needed to arrest the momentum of the existent structures and start conversations around possible pedagogic innovations. It should be noted, that unlike the case studies highlighted by Graham (2012), at UCL there was no 'crisis'. The faculty was not under particular external pressure to change. There was, however, a growing cohort of staff, scattered across most departments, that were unhappy with the current approaches and looking for opportunities to deliver innovations in teaching. However, at the start of the process most were not in senior enough positions within their departments or did not have the support of their leadership to make changes at any sort of scale. In time, these would become agents for change who became part of the core team negotiating the disciplinary boundaries and developing the interdisciplinary threads of the IEP curriculum, as well as leading their own disciplinary response.

Although many directions for change where suggested, and a fairly long process of negotiation was needed to agree a direction of travel, there were a number of elements of common ground. Key points of agreement were in regard to the need for an emphasis on design and practical engineering, tempered by a desire that the rigorous roots in fundamental science and mathematics for which the departments are known must not be lost. There was also reasonable consensus on the need for embedding skills-based teaching and learning firmly within the curriculum. The driver for change was to create a new curriculum that was student-centred and aspirational but also pragmatic, recognising that a change management process was necessary to transform existing discipline-specific degree programmes and that a significant amount of the existing content had to remain, albeit with some modifications. We were also fortunate to have one department, Civil, Environmental and Geomatic Engineering, who had made major changes, proving, to some at least, that change was possible and could be successful.

In the conceptualisation of the IEP, it was these enthusiasts who were key to driving the process. Given new powers and emboldened by the support of senior management they were able to build communities in their departments to drive change. Again, in line with the description of systematic change by Kolmos, Hadgraft, and Holgaard (2016), it was recognised that both curriculum and culture needed to be addressed. In the development of cultural change, concepts such as the foundation of communities of practice (Wenger 2000) emerge as vital in supporting staff as well as access to faculty development programmes.

The implementation of this ambition has played out differently depending on the inherent culture and existing teaching practices within each of the departments involved. While some departments enthusiastically embraced the opportunity of the 're-building strategy', others, while excepting parts of the shared vision, felt less comfortable with the crossing of disciplines involved in this model and adopted more of a hybrid model of 're-building' and 'integrating'. This was pragmatically accepted as part of the journey required toward adoption, with a focus instead on the delivery of the core philosophies of the IEP as a minimum criterion.

Building on the shared vision of the direction of the programmes, the co-creation process enabled the front-line academics to engage and provide bottom-up input to the overall IEP curriculum design as well as develop bespoke innovations and implementations within their discipline. As the framework developed, each element was scrutinised to identify what the minimum levels of compliance would be to make the cross-faculty programme work. Although not always explicitly set, these were known as acceptable thresholds, with everything above each threshold open to negotiation.

As the IEP has become embedded in the degree programmes, informal processes became more important. It is important to note that the programmes are still, very much department-based, with the department themselves providing the majority of the IEP teaching and assessment, even in the cross-cutting elements. The cross-faculty integrated activities were led by a newly hired small team of teaching-focused staff based in the faculty, coordinating staff from all departments. Typical of many change initiatives, the new cross-department curriculum was received with differing levels of enthusiasm and implemented with different levels of success in each department. This reflects both the culture and context of each department and often manifested itself in the level of engagement of key staff.

We are aware that the change management processes needed to develop the different phases of change, evolved at different rates. Each phase required different strategies and processes from the period of rapid, step-change, to the period of embedding, maintaining and supporting fundamental elements of the change as each department took on increased ownership of the IEP and developed increased autonomy.

The challenge remaining is to ensure that there is a balance between strong top-down leadership and distributed leadership consisting of a less formal directive processes, so that the maintenance of harmonised IEP curriculum standards across eight departments is inclusive and effective. For change to be sustainable, it is seen as vital that the departments take ownership of the IEP for their students. This is now happening to different degrees in every department, with the balance being to maintain the inherent connections of the IEP, while allowing each of the departments to own and innovate within the model established. In many respects this is the power of the framework approach proposed by the IEP, in that it can be adaptively applied as a foundation, but then can also continue to grow and evolve within departments as their capability to extend it becomes apparent.

Conclusions

This paper outlines the concept of a multi-disciplinary cross-faculty teaching framework of delivering an innovative undergraduate engineering curriculum centred on a programme of problem-based learning experience. It explains the rationale for the elements within the framework and how its structure integrates with existing elements of the collective curriculum. In contrast to most whole-curriculum innovation models the Integrated Engineering Programme at UCL adopts a pragmatic approach, carefully selecting areas within the existing curricula that were in need of revision while forming a structure that allows other areas to co-exist or be modified via evolution rather than necessitating a revolution in teaching content and style. We have outlined that, in our experience, a combination of a top-down drive for innovation coupled with enthusiasm and bottom-up support for change within the context of a consistent framework is vital to achieve sustainable change. A key point of learning from this process is that flexible leadership is required that is both clear in the direction of travel but also cognisant of context, challenges and desires of each discipline. With this in mind, we believe that the framework model developed here, which outlines a clear set of objectives and curriculum elements, but that leaves scope for individual departments and disciplines to adapt and take ownership of the majority of elements is a good model for cross-department curriculum development. In addition, we argue that this type of model, that compliments an existing teaching structure, albeit with some new elements being required, is a more realistic approach to enable curriculum innovation within traditional engineering schools.

Notes

1. These are often also referred to as professional or transferable skills. In this work we use the language inclusively to also mean transversal or soft skills.
2. The Biomedical Engineering degree was a new programme not operating before the introduction of the IEP.
3. The Management Science degree was a new programme not operating before the introduction of the IEP which follows the general framework but does not share all the core modules.
4. 120 credits needed per year, this module is equivalent to 7.5 ECTS.
5. IMechE Design Challenge https://www.imeche.org/events/challenges/design-challenge accessed 27/3/18.
6. National Academy for Engineering Grand Challenges Scholars Programme – http://www.engineeringchallenges.org/GrandChallengeScholarsProgram.aspx.

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