CREATING CREATIVE ENGINEERS: EMBEDDING PROJECT BASED LEARNING THROUGHOUT AN ENGINEERING CURRIUCLUM

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ABSTRACT

The demands for students entering the workplace after their degree are ever-increasing. Employers are actively seeking individuals who haven't simply acquired technical skills and knowledge but are able to integrate problem solving, leadership, communication and time management skills with creativity and resilience. Often this requires dealing with unfamiliar situations within diverse, cross-disciplinary teams. Project based learning can help students bridge the gap between technical and management skills. By embedding project-based learning throughout the engineering curriculum, Nottingham Trent University (NTU) strives to produce well-rounded engineers who can apply traditional engineering skills and tools with creativity to deliver practical solutions. This paper details how project-based learning is embedded within the curriculum at NTU. Within this project centric curriculum, the student journey from foundation year to the final year of their studies is considered. Educator perspectives are used to highlight the benefits of this approach and illustrate its implementation.

KEYWORDS

Project based learning, Active learning, Faculty competence, Integrated Curriculum.
Standards: 1, 2, 3, 4, 5, 6, 7, 8, 9, 11

INTRODUCTION & LITERATURE

Traditional lecture-based approaches to higher education have been subject to increasing criticism in recent years (French and Kennedy, 2017). Critiques of didactic teaching have largely focused on the need for active learning with a student-centred focus (Biggs et al., 2022). Within STEM education, more active approaches toward teaching and learning are supported both by theories of learning (Piaget, 1926; Vygotsky, 1978) and empirical studies (Freeman et al., 2014; Handelsman et al., 2004).

Constructivism has come to be the major theoretical driving force behind much STEM education research (Matthews, 1993; Gil-Perez et al., 2002; Driver et al., 1994; Tobias and Duffy, 2009). The emphasis upon students' attempts to construct their own knowledge and understanding lends itself toward an active-learning approach and is opposed to practices centred on the passive intake of information. This may facilitate deep learning to allow the student to apply knowledge outside of the limited contexts explicitly introduced in teaching. This is particularly significant as demands on students move away from mastery of specific factual content and toward the capacity to gain new knowledge and apply this to unfamiliar problems, often while operating within an interdisciplinary environment.

Furthermore, employers' expectations for new engineering graduates extend beyond the mastery of technical skills and knowledge. Graduates must be able to communicate effectively, to work productively in a team, to manage their time when working to a deadline, and to demonstrate resilience, creativity, and originality (Hirudayaraj et al., 2021; Baukal et al., 2022). Development of the requisite behaviours, attitudes and dispositions is not readily achieved through traditional didactic lectures but requires exposure to situations in which they are actively exercised.

A key challenge facing engineering education is the reinforcement of disciplinary silos that may discourage engineering students in engaging with unfamiliar material (Hoople et al., 2018). The complex landscape of current social, economic, environmental, and medical challenges is multifaceted (Gómez Puente et al., 2013) and goes beyond the traditional realms of an engineer's responsibilities (Frodeman et al., 2017). This requires contemporary and future engineers to be socially connected, to be able to work within and across disciplines as well as understand, synthesize, and apply knowledge to fields outside their own domain (Barut et al., 2006; Fitzpatrick et al., 2021). Indeed, recent technological advancements such as artificial intelligence, Internet-of-things, and nanotechnology are not restricted to certain fields of expertise (Roy & Roy, 2021). Problems such as (but not limited to) climate change, access to clean water, cyber security and modern infrastructure cannot simply be solved by a single engineering discipline (Habbal, 2016).

Meeting this demand to produce professionals who can work in diverse environments across disciplines also requires instructors to not simply be mere transmitters of information (Mohedo & Bújez, 2014) instead they need competencies to become change agents (Qablan, 2018). To maximise learning outcomes from students, instructors must have competencies that are in-sync with the desired proficiencies of their students (Hattie, 2008). This can be partly achieved by ensuring a project-based learning curriculum that encourages instructors to keep up to date with advances in technology and pedagogies.

Project based learning is a process through which students are intended to experience integrative and formative teaching-learning experiences (Larmer, 2014). During university years, students are encouraged to take on real-life problems and expected to come up with an engineering solution to tackle them by incorporating their knowledge, skill, and expertise. During the first- and second year of their degree, students learn to design, test, and deliver a project in groups. When the student enters their final year, the expectation is to be capable of handling a project in a more individual manner (Graaf 2003). The CDIO approach encompasses a variety of active learning experiences (Crawley 2007). Project-based learning developed using CDIO standards aims to reinvent engineering education (Carmen 2021).

This paper discusses how project-based learning is embedded throughout the engineering curriculum at Nottingham Trent University (NTU) using the CDIO approach and its standards.

SELECTED EXAMPLES OF PROJECT BASED LEARNING AT NTU

Since its conception in 2017, NTU Engineering has allowed its students to choose between one of four disciplines: Electrical and Electronic, Sport, Biomedical and Mechanical Engineering. Each year students from all courses undertake 3 main types of modules:

1. **Core Modules:** These focus on fundamental engineering principles and are shared between all courses.

2. **Specialist Modules:** These provide skills and knowledge relevant to each specific course.
3. **Project-Based Modules**: These are shared between all courses to support the application of the skills and knowledge gained in the core and specialist modules.

Selected examples of project-based learning at NTU are provided in the following sections.

Green Home Design Project

Project Duration	Project Type	Year of study	CDIO Standards
3 Weeks	Group Project	Year 0	1, 2, 3, 4, 6, 7, 8, 11

Project description

In this project, Foundation Year students are assigned to small groups (4 to 5 students) and work together to design a green home incorporating a variety of technologies and demonstrating their understanding of heat transfer and methods to reduce energy use. Students are introduced to simple Computer Aided Design (CAD) with tinkerCAD. They then assign roles within the team, arrange communication methods and a schedule of team meetings. They are provided with a project guide detailing requirements and an expected timeline to produce project outputs. Over the course of the project, they must provide regular updates as to progress and are supported in managing teams and delivering outputs.

Project Outcome

The outcome of the project is a group poster and marketing brochure for a green home design, incorporating simple CAD models and evidence of relevant research. Students present their work during a poster presentation involving all Foundation Year students (~250 students). Successful completion of the project does not require extensive technical knowledge but does require students to perform effective research, to work effectively together, to manage their time, to communicate effectively both verbally and through their written outputs, and to demonstrate creativity and originality in their design concept balanced against practicality and an understanding of the context in which they are designing.

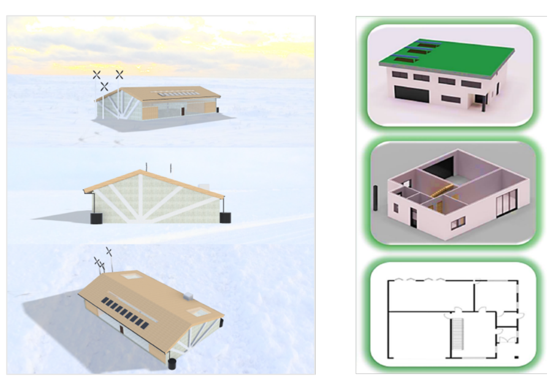

Figure 1: Examples of student CAD models of green home designs (Images courtesy of Groups 1 and 24).

Product Design Group Presentation

Project Duration	Project Type	Year of study	CDIO Standards
5 Weeks	Group Project	Year 0	1, 2, 3, 4, 6, 7, 8, 11

Project description

During this project, students are assigned to small teams in which to design a product, app or service and produce a business plan for a proposed start-up company producing and selling the product. A theme is chosen for each cohort; past themes include 'lockdown designs' (a product to assist people during lockdowns or who are otherwise unable to leave their home) and 'sustainable living'. Students self-assign roles within their team including CEO, Head of Design and Finance Director. Teams create a product design outline providing technical details of their design and a business plan detailing the objectives of their start-up company and the strategy to achieve these. During taught sessions, students are supported in conceiving and designing their product and in developing their business plan. Students are also expected to arrange team meetings outside of taught sessions and to appropriately document these.

Project Outcome

Upon completion of the project, teams present their designs in a 'Dragon'-Den' style bid in which each team makes their case for funding to a potential investor (the examiner). Students will have taken their design through from an initial concept to a detailed design outline and will have considered the context and market in which their start-up company will operate. They will have considered the objectives of their company and how these may be achieved, including analysis of potential competition, details of operations and the costs involved. To be successful requires that students work effectively with their team to integrate presentation, design and technical skills as well as business considerations.

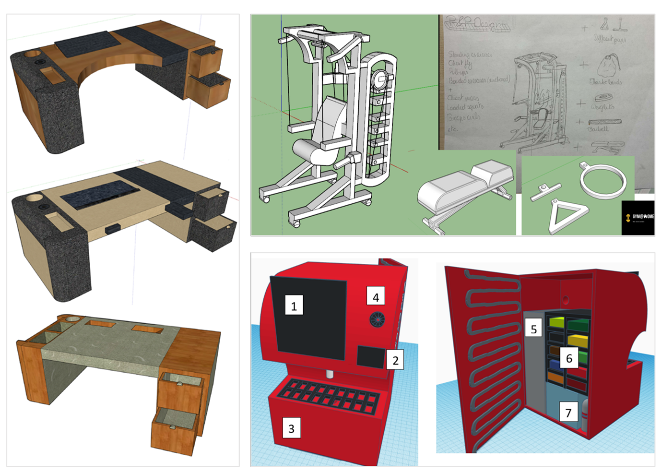

Figure 2: Examples of student CAD models of product designs. Left: Sofa desk. Right top: Home gym. Right bottom: Sustainable soda dispenser. (Images courtesy of Groups 6B, 2A and 3 respectively).

Reverse Engineering Project and Introduction to CAD modelling

Project Duration	Project Type	Year of study	CDIO Standards
10 Weeks	Group Project	Year 1	1, 2, 3, 4, 6, 7, 8, 9, 11

Project description

In this project all year 1 engineering students systematically deconstruct, analyse, document, and improve a single cylinder, 4 stroke engine. In tandem with the reverse engineering workshops, students undertake an introductory course on CAD modelling with Autodesk Fusion 360 using in-house tutorials. The project has 5 milestones: preliminary analysis, deconstruction & measurements, bill of materials, functional analysis & improvements, and reconstruction. Students work as a group and are expected to 3D model the components while going through the milestones of the project. Students are also expected to arrange team meetings outside of taught sessions.

Project Outcome

The outcome of this project is an extensive 3D model of the deconstructed components and their assembly and a formal technical report detailing the deconstruction, bill of materials, functional analysis, and improvements of the provided engine. The focus of the improvements proposed by the student groups consider the social, economic, and environmental impact of the product. There are avenues of implicit learning throughout this project such as project and time management, efficient communication, working in teams and use of hand tools.

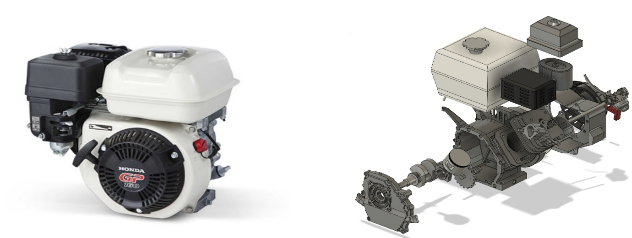

Figure 3: The Honda GP 160 engine deconstructed by the student groups (left) and an example of the 3D model produced by one of the student groups (right). (Images courtesy of Honda and Group 20)

Design for Manufacture project

Project Duration	Project Type	Year of study	CDIO Standards
5 Weeks	Individual Project	Year 1	1, 2, 3, 4, 6, 7, 8, 9, 11

Project Description

In this project, students apply their design and manufacturing knowledge (gained from the Reverse Engineering project) to two small projects; designing a laser cut wooden bridge and optimizing a 3D printed support pier. The projects include the characteristics of a traditional engineering project: research, restriction on available resources, dimensional specifications, creativity, virtual prototyping to optimize design and professional reporting.

Project Outcome

The outcome of this project is a portfolio style presentation in which students present their initial ideas for the bridge and support pier design, the simulations conducted for optimum material usage while ensuring the product is safe and can sustain a predefined weight. Finally, the students present their manufactured bridges and support piers, reflecting upon the entire design to manufacture process, all the way from concept generation to final product and identifying the skills gained along the way.

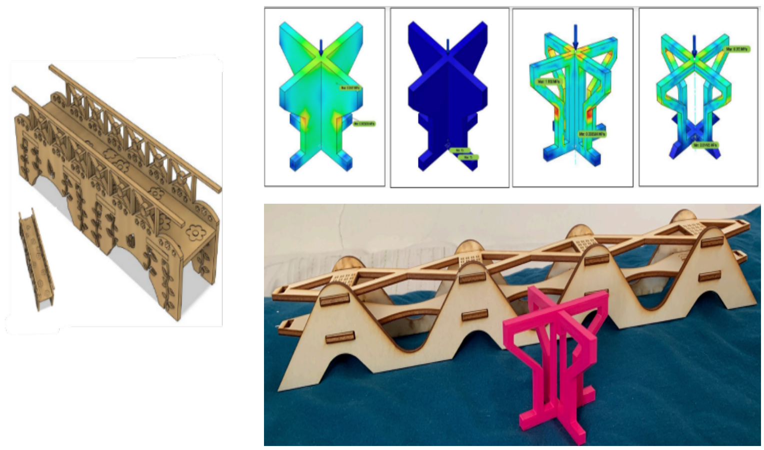

Figure 4: Examples of the 3D models produced, simulations conducted and the manufactured products (Images courtesy of J. Jesenko and J. Birks.)

Mars Rover Project

Project Duration	Project Type	Year of study	CDIO Standards
6 Weeks	Group Project	Year 1	1, 2, 3, 4, 6, 7, 8, 11

Project Description

In this group project, students are tasked to design a vehicle that can carry two astronauts safely from the orbit of Mars to the surface. The lander's journey begins in low orbit at a given altitude, at a certain initial velocity and is influenced by Mars' gravity. The students must take into consideration a number a design constraint such as Mars' atmosphere and its impact on the astronaut's safety, use of rockets to slow down the descent is not allowed and finally Mars' terrain must be considered. The project is broken down into 5 main milestones: conceptual design, material selection, calculations of the forces acting on the lander, heat shield design and compilation of a final report.

Project Outcome

The outcome of this project is a group report that details the design parameters defined by the groups during concept generation, the material selection with appropriate justifications, the forces acting on the lander (drag, lift and gravity) and finally the design of the heat shield that incorporates a thermal protection system. All the outcomes mentioned are consolidated to produce an extensive CAD model of a Mars Lander.

Figure 5: Examples of Mars Rover design concepts.
(Images courtesy of Group 2 and Group 23)

Industrial Design and Product Case Studies

Project Duration	Project Type	Year of study	CDIO Standards
10 Weeks	Group Project	Year 2	1, 2, 3, 4, 6, 7, 8, 11

Project Description

Within this module, all year 2 students undertake a design analysis and optimization project. The project focuses on design, design parameters, and Computational Fluid Dynamics (CFD) simulations to measure the drag acting on a cyclist in different positions and on an aero foil at different angles of attack, with the aim to minimise the drag forces and find the optimum cycling position and angle of attack, respectively. Sports and Biomedical Engineering students focus on the cycling positions while Electronics and Mechanical Engineering students work with the aero foil. Experimental results are collected to compare with the numerical results. For the cycling positions a member of the team undergoes a wind tunnel test in an in-house sports laboratory while for the aero foil, 3D printed models of the designed aero foil are tested in a wind tunnel.

Project Outcome

The outcome of this project is a technical report that covers the analysis and optimizations undertaken. The report focuses on the CAD models created as well as the design and simulation parameters used. Students learn how to conduct mesh independence tests before finally comparing numerical and experimental results to conclude optimum cycling positions or angle of attacks in the case of an aero foil.

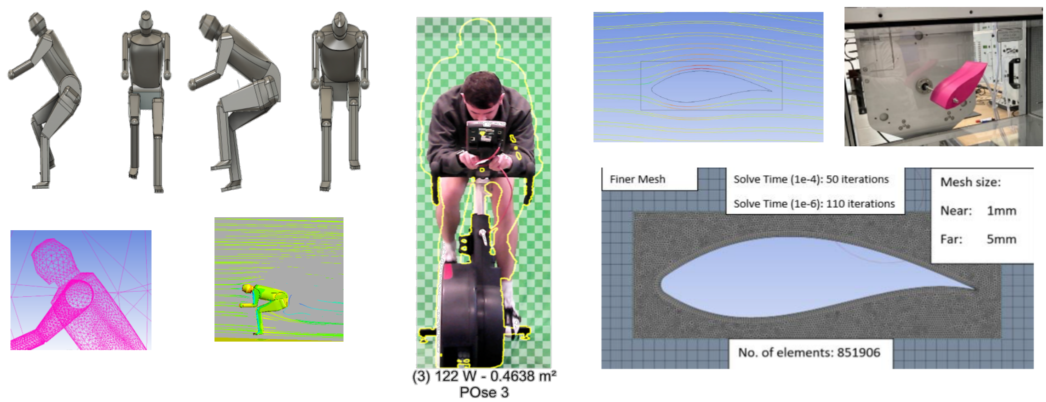

Figure 6: Examples of CAD models, generated meshes, CFD simualtions and experiments conducted as part of Industrial Design and Product Case studies
(Images courtesy of Bio Group 6 and Mech Group 6)

NTU Engineering Grand Challenge

Project Duration	Project Type	Year of study	CDIO Standards
6 Weeks	Individual Project	Year 1 & 2	1, 2, 3, 4, 6, 7, 8, 9, 11

Project Description

Grand Challenge is a major 3-week full-time project where teams of students conceive, design, implement and demonstrate a concept technical solution to an industry challenge. The project runs at the end of the academic year for all first and second-year engineering students. Students are put in cross-year and cross-disciplinary groups. The project is designed to integrate what year 1 and year 2 students have learned throughout their degrees till the point of the Grand Challenge. The Grand Challenge has a yearly theme such as (but not limited to) sustainable development, energy harvesting and future networks and further sub-themes where the main theme is applied, these include healthcare, transportation, consumer devices, portable devices and wearables. Each student group is supervised by a member of staff who acts as a non-executive director.

Project Outcome

The outcome of this project is a developed & evaluated concept, working demonstrator, business model canvas and a promotional video. Student groups present their findings in an annual tradeshow hosted by the department of engineering where industrial partners and the entire faculty are invited to assess the innovative ideas put forth by students. Students are assessed based on their concept design and its evaluation, creativity, effectiveness of demonstration and professionalism and project management demonstrated throughout the project.

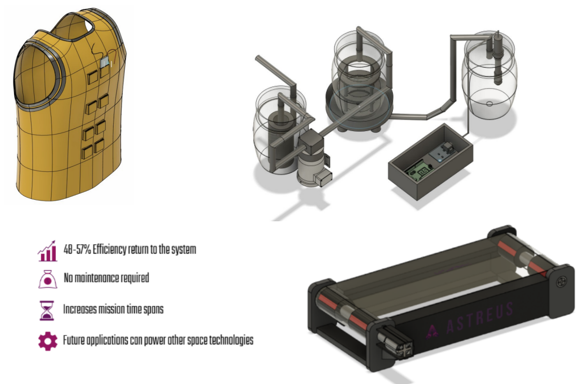

Figure 7: Selected student outputs from the Grand Challenge
(Images courtesy of Group 4, Group 6 and Group 13)

Sustainability in Engineering Design

Project Duration	Project Type	Year of study	CDIO Standards
10 Weeks	Group Project	Year 3	1, 2, 3, 4, 6, 7, 8,11

Project Description

This is the third-year optional module for all engineering disciplines at NTU. Within the module, students undertake a product design project whereby they are given design constraints based on a client's requirements. An important aspect of the project in addition to inclusion of the conventional design processes is the consideration of sustainability at each stage of the product lifecycle.

Project Outcome

The outcome of this project is a virtual product that has been designed based on specific design constraints and a report that details the student's design thinking and the decision making in terms of conceptual design, detailed design, materials and manufacturing methods adopted and sustainability considerations throughout the product development lifecycle. The students demonstrate the use of eco-audits at various stages of product development as well as the use of several design tools that ensure sustainability considerations cater to the triple bottom line (focus on the Social, Economic and Environmental impact of the product).

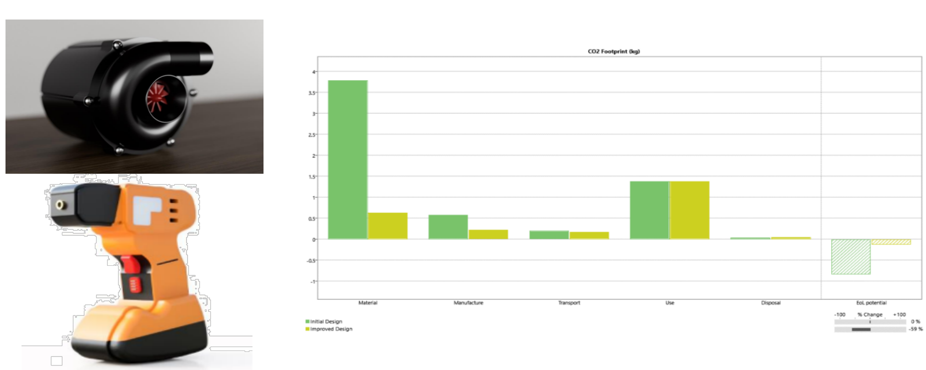

Figure 8: Examples of student outputs
(Images courtesy of Samuel Border, Chiagozie Ogwo Group 4)

Individual Engineering project for BEng and MEng students

Project Duration	Project Type	Year of study	CDIO Standards
20 Weeks	Individual Project	Year 3 & 4	1, 2, 3, 5, 7, 8, 10, 11, 12

Project Description

All students in the third and fourth year undertake the Individual Engineering projects. Students are from varied engineering backgrounds, i.e., Mechanical, Biomedical, Sport, Electrical and Electronics Engineering. Students are expected to conduct a literature review, develop conceptual designs and then with the help of subject-relevant techniques, tools and engineering methodologies implement and operate these as systems, products and (or) processes. Throughout the year, workshops and professional resources are introduced to help guide them towards their successful project completion.

Project categories

As part of their projects, students should be able to identify, design and perform critical analyses of results. Individual projects can range from computer modelling, laboratory experiments, design & manufacturing, research based, numerical simulations, and development of software programs. Regardless of their nature, all projects are assessed based upon gateways which act as milestones to track student progress and provide formative assessment before their final submission.

Project Outcome

For BEng students, the outcome of this project is a final report/paper, presentation/demonstration at the Degree Show, and portfolio submission through Pebble Pad. The report/paper assesses their ability to concisely articulate the technical knowledge gained over the course of the project. Students showcase their knowledge and demonstrate their learning in a final Degree show attended by both academics and industry representatives. The portfolio consolidates their learning journey throughout their degree and reflects upon the projects previously completed across all years. MEng students are also assessed through a report/paper and Degree Show demonstration towards the end of their academic year.

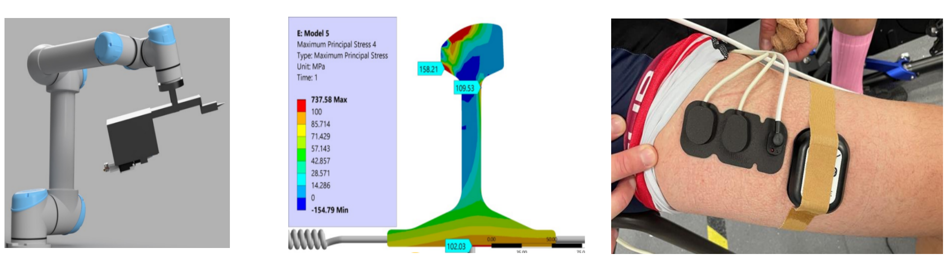

Figure 9: Example from the final year degree show
(Images courtesy of Shiv Jivan, Eleanor Martins & Gheed Maher)

DISCUSSION

At NTU, project-based learning is integrated into the curriculum from an early stage. By asking students to apply technical knowledge and skills in pursuit of project goals, learning may be better contextualized, resilience enhanced, creativity and problem solving fostered and opportunities afforded for the development of interpersonal skills critical to future careers. It is the opinion of the authors that these benefits to students are maximized when project-based learning is used in parallel with the teaching of relevant technical subjects and across the curriculum from the beginning of their university studies. Curriculum models in which these educational goals are addressed only after the development of technical knowledge in the latter stages of university study may fail to yield students adequately prepared for the workplace. Cultivation of the requisite skills, attitudes and behaviors requires time and repeated opportunities to demonstrate and develop these characteristics. Simultaneously, the learning of relevant technical knowledge may be enhanced through application to the project's students engage in.

Student journey

Critical to an analysis of the educational approach taken at NTU is to consider the student journey and how the design of projects and expectations of students develop from foundation through to final year. As illustrated above, the technical expertise required in Foundation Year projects is low, with the focus being on effective teamwork, time management and communication skills. The low technical requirements allow a broad definition of required project outcomes and significant autonomy as to the choice of design. The inexperience of students requires significant support to manage team cohesion and strict scaffolding of timelines to ensure project outputs are delivered. In years 1 and 2, many projects focus upon the development and application of technical skills acquired both during completion of the project and from other modules. The higher technical proficiency required necessitates more strictly defined outcomes. Generally, students work in groups which help support project delivery. Projects generally build upon the technical knowledge gained from previous project work.

By contrast, the Grand Challenge at the end of Years 1 and 2 affords greater autonomy in choice of design and project outputs. While the development of technical expertise is still central to the project, more focus is placed upon the effective operation of the team and upon communicating and marketing the design. Academics acting as non-executive directors provide guidance but do not assist directly with concept generation or design delivery. In their final year, Individual Engineering projects require a far higher level of technical expertise, especially in industry funded projects. While guidance is given regarding project outputs and supervisors' support with both technical aspects and project management, responsibility for project delivery is placed fully upon the student. As projects are individual, support from peers is not readily available. This evolution from Foundation through to Final Year projects allows students to develop the confidence to exercise their creativity in the context of technical project objectives.

Disciplinary Silos

It has been argued that the current state of engineering education produces “siloized disciplinary experts” who, after graduation, go on to work with people from other disciplines (Fitzpatrick et al., 2021). At an undergraduate level, all engineering students at NTU undergo a significant amount of group work as part of the Green Home Design project, Reverse Engineering project, Mars Rover Project, Industrial Design and Product Case Studies project and the Grand Challenge. These projects allow engineering students to work with students within their own engineering disciplines but also with students outside their disciplines, helping them in adopting a transdisciplinary ethos. It is noteworthy that none of the projects are designed to cater to a specific discipline; as an example, Biomedical Engineering students work with simulations and experiments to optimize cycling positions – something that is traditionally associated with Sports Engineering. Similarly, in the reverse engineering project, Electrical and Electronics Engineering students work with a 4-stroke engine, which is traditionally associated with Mechanical Engineers. The objective here is to provide students with opportunities to engage with a range of knowledge and skills, with the hopes of breaking these engineering silos to nurture innovation (Roy & Roy, 2021).

Faculty competence & managing projects

Resource-intensive projects such as the Reverse Engineering project and the Grand Challenge have an added advantage of upskilling the staff involved in these projects. The entire technical team involved in the Reverse Engineering Project (including the author leading the project) had to deconstruct and reconstruct the engine at least once. This was to ensure familiarity with the constituents of the engine and awareness of the subject matter. Along with using conventional hand tools, the exercise encouraged learning specialist tools such as strap wrenches, telescopic and feeler gauges. Moreover, this deconstruction, reconstruction and measurement was translated into the creation of 3 separate manuals that were then used by students while working on the project. Similarly, being a non-executive director in the Grand Challenge, the entire faculty has to engage with unfamiliar material and are challenged intellectually, essentially creating an opportunity for lifelong learning. For clarification, all three authors come from different backgrounds (Mechanical Engineering, Physics and Electrical Engineering), yet all of them had to act as non-executive directors for student groups working with wireless networks in one year and energy harvesting in the next.

Moreover, the final year projects aren't only challenging for the students but also the supervisors; the background of the student and the supervisor might not be the same. Consequently, both must try to come out of their disciplinary silos and expand their research domains. There are over 200 students who complete the final year individual projects. This presents a range of challenges from a module management perspective. It is very important where possible that the students get a project of their own choice aligned to their interests. Irrespective of the nature of the project, learning outcomes must be aligned with the generalized gateways. These gateways mainly focus on timely delivery of the projects and help student to design, build and deliver the project in accordance with CDIO standards.

The context

Ensuring safety of the astronaut (Mars Rover project), conducting eco-audits during product development to measure environmental and economic impact (Sustainability in Engineering Design), developing business models (Grand Challenge) all demonstrate that the social, economic and environmental dimensions are embedded throughout the NTU engineering curriculum. Moving away from technical specialism and increasing exposure to these aspects are essential in maximizing an engineer's impact for the common good (Altringer & Habbal, 2015).

CONCLUSIONS & RECOMMENDATIONS

Throughout their time at NTU, students engage in a range of projects to contextualize their learning and develop the broad array of personal and professional characteristics sought by employers. Combining technical instruction with project-based learning from the beginning of their studies may yield a more active learning experience and help students to bridge the gap between technical and management skills. Through repeated exposure to challenging problem scenarios, students may develop resilience and creativity in their application of traditional engineering skills and tools.

In delivery of this curriculum, it is crucial that technical instruction does not become diluted, that is, that we do not focus upon the development of students' creative, personal and interpersonal skills at the *expense* of adequate development of technical skills and knowledge. Rather, an effective curriculum should make use of project-based learning in such a way that these technical skills and knowledge are enhanced not diminished. At NTU this is achieved through supporting project focused learning with parallel instruction in technical subjects and through construction of many project tasks to explicitly incorporate the knowledge gained from these and to build upon it.

While the engineering students at NTU are given ample opportunity to engage with knowledge and individuals outside their engineering discipline, the authors believe there is still a lot of room for engagement with disciplines such as the arts, humanities, and social sciences. This will help these future engineers create social awareness and adopt all-inclusive mindsets that will ensure they contribute to creating a sustainable society. Pairing NTU engineering students with students engaged with disciplines outside engineering, perhaps in the Grand Challenge would be an excellent starting point.

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BIOGRAPHICAL INFORMATION

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Arooj Mubashara Siddiqui received her Master and PhD degree in Mobile Broadband Communication systems from Lancaster University, UK (2013, 2017). She is currently working as Senior Lecturer at the Department of Engineering, School of Science and Technology, Nottingham Trent University, UK. Prior to that, she was a Research Associate at University of Surrey (2019-2020). She has worked as a Research Assistant during her PhD in Infolab 21, Lancaster university, UK (2014-2017). Her research interests lie in next-generation wireless communications 5G/B5G, Energy Harvesting, Green Communication and Satellite Communications. At NTU, she has been implementing CDIO initiative into new courses offered to post graduate students.

Edward William Causton received his MPhys from the University of Oxford in 2006 and his MSc and PhD in theoretical biophysics from the University of Leeds in 2011. After working for several years in secondary science education, he completed a masters degree in the philosophy of education at the Institute of Education (UCL) and subsequently taught at Nottingham Trent International College. In his current role as Senior Lecturer in Nottingham Trent University's Department of Engineering, he is leader of the Foundation Year in Engineering and Mathematics as well as module leader for the 3rd year module Performance Engineering.

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