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A COMPARATIVE ANALYSIS OF DESIGN AND MANUFACTURE TEACHING IN MECHANICAL ENGINEERING

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ABSTRACT
This paper draws parallels and contrasts between the Design and Manufacture (D+M) focussed learning tracks of the Mechanical Engineering courses at Nottingham Trent University (NTU) and Imperial College London (ICL). These two institutions have historically had a different focus and vision. At NTU, various engineering courses undergo the same D+M module with the aim of delivering well-rounded engineers who have specialised within their own discipline and have acquired skills and knowledge in areas that are considered slightly outside their domain of study. D+M teaching is approached as a tool to encourage creativity across disciplines, within the themes of sustainability and robust product development. The objective is to remove inter-disciplinary barriers with the appreciation that problems of the present and future require pragmatic solutions from creative problem-solvers who are not limited by their disciplines of study. The Mechanical Engineering course at Imperial has a strong emphasis on theoretical and mathematical foundations, with D+M modules aiming to integrate knowledge obtained and to bring this theoretical knowledge into practice. Additionally, the students achieve competence in engineering drawing, standards, design methodologies, and workshop skills, as well as transferrable skills. The objective is to develop mechanical engineers who combine strong analytical foundations with innovative product development skills. Based on a comparative analysis of the two programmes, a two-axis digital/practical-breadth/depth map and a learning outcome map have been developed. These can enable D+M Module Leaders and Course Directors at different institutions to make more informed decisions about teaching, content, delivery, and the student journey.

Keywords: Design and manufacture, learning outcomes, pedagogies

1 INTRODUCTION
Mechanical Engineering is one of the traditional disciplines within the engineering sciences, and covers a wide variety of sub-branches, ranging from production to combustion and from nuclear applications to biomedical implementation. A typical mechanical engineering curriculum combines foundational topics, such as stress analysis and thermofluids, with modules that have a more practical and/or creative focus. These more practical and creative aspects are often taught as part of the Design and Manufacture (D+M) modules, which often take a more open-ended approach than the core, foundational modules. One of the objectives of the D+M modules is to provide students with the space to start understanding the roles of an engineer within society and help them overcome any thresholds in learning. These practical modules are not necessarily best assessed using traditional paper-based exams, and commonly followed approaches to these practical modules include problem-based learning, project-oriented learning and design-based learning. In this paper we describe and analyse two different approaches to D+M teaching, using the Mechanical Engineering courses at Nottingham Trent University (NTU) and at Imperial College London (ICL) as case studies. These two institutions have historically had a different focus and vision, and as a result differ significantly in their pedagogic approach as shown in Table 1.
The NTU Mechanical Engineering course is accredited by the Institution of Engineering and Technology (IET) and meets the academic requirements for registration as a Chartered Engineer. The course is also recognised by Conceive-Design-Implement-Operate (CDIO), a framework that encourages a project-based learning approach [1]. At the heart of the course are four core values: tools,

skills, creativity, and delivery. These are disseminated through a combination of engineering foundations and engineering applications entrenched throughout the curriculum. As opposed to traditional Mechanical Engineering courses, there are no explicit D+M modules in this course, instead these skills are embedded within a number of modules. The course dedicates a third of the year's academic credit to practical and project-based learning modules in each academic year, with half the year's academic credit dedicated to a project-based learning module in the final year of study. The project-based modules are shared amongst all NTU engineering courses (Electrical and Electronics Engineering, Sport Engineering, Biomedical Engineering and Mechanical Engineering). In addition to this, project-based learning is part of other core and specialist modules. This extensive focus on project-based learning is to inculcate team working, communication, project and time management skills in budding engineers while also enhancing technical and practical expertise via active learning.

Table 1. Comparison of design and manufacturing teaching at NTU and ICL

Features	NTU	ICL
Courses	BEng (Hons), MEng (Hons); with optional provisions of foundation and placement years	BEng (Hons), MEng (Hons); with an optional placement year
Disciplines	Sport, Biomedical, Electrical & Electronics and Mechanical Engineering	Mechanical Engineering only
Focus	Strong focus on design processes and methods. Workshop skills are acquired primarily via project-based learning	Engineering drawings, standards, design processes and methodologies, and workshop skills
Project Type	Recurrent themes of interdisciplinarity and collaborative learning through group work and some individual coursework	Evolution from individual work in year 1 to group work in year 2 and multi-level supergroups in year 3
Teaching Style	Primarily project-based learning with very little didactic teaching	Project-enhanced learning to apply and broaden didactic teaching

The Mechanical Engineering course at ICL is a four-year Integrated Master's course, with minimum entry criteria of A-levels awarded at A*A*A or 40 points in the baccalaureate. The curriculum has a strong emphasis on theoretical and mathematical foundations and takes a scientific approach to engineering. The course is accredited by the Institution of Mechanical Engineers and meets the academic requirements for registration as a Chartered Engineer. The programme has a core D+M module in each of the first two year's worth a sixth of the year's academic credit with the third year D+M module being worth a third of the year. The main objective of these three D+M modules is to integrate the theoretical knowledge obtained and to bring this theoretical knowledge into practice. In the first-year module, the students work individually to achieve basic competence in practical topics such as sketching, engineering drawing, standards, design processes and methodologies and workshop skills. In the second year the D+M module comprises two team-based projects, exposing the students to teamwork, project and time management and budgeting next to deepening their Engineering Design and Manufacture competencies. In the third-year module an additional layer of teams and required accountability is added as the students deliver a large engineering 'superproject' comprising three collaborating teams of four students. The objective of the three years is to provide a framework enabling a naturally evolving skillset that develops young mechanical engineers who combine a strong theoretical foundation, analytical skills, and the ability to utilise their knowledge to develop innovative products.

Both courses adhere to the UK Engineering Council Accreditation of Higher Education Programmes, fourth edition (AHEP4) [6]. The AHEP4 guideline defines 18 learning outcomes for a four-year Integrated Master's course and is widely used by UK Higher Education Institutions to define and assess their programme. Most of the learning outcomes have a direct or indirect link to D+M related modules. However, the methods used to achieve these learning outcomes are not specified in AHEP4 and the approach is decided by the educators. The aim of the present study is to analyse the D+M focused teaching within these two Mechanical Engineering programmes, which have traditionally had a different focus and approach. The study is aimed at creating an engineering design education framework that can be used to select a student-focused pedagogy.

2 METHODOLOGIES

The study was conducted in two phases. In the first phase both institutions provided documentation describing how design is taught within their department. This documentation detailed each design module on the course, the year in which it is taught, which engineering courses it is compulsory for and whether it is available as an elective for any others, its syllabus, the module learning outcomes and primary teaching methodologies. A comparative analysis of this information was carried out, allowing for commonalities to be identified as well as areas of significant difference. As both departments hold accreditation, the AHEP learning outcomes were also used as a framework to provide a common set of terms in this comparative analysis process. This enabled differences in phrasing and terminology to have a minimal effect on the analytical process. Once the first phase had identified the areas of most significant difference, as well as common themes, this enabled questions to be constructed to facilitate an interpretative phenomenological analysis via focus groups led by an independent researcher, who has been at ICL for less than a year and does not lead a design module and was therefore considered sufficiently independent to lead the focus group style discussion. The other two researchers are the educational leads for the design efforts within their departments and were therefore the participants of the focus group. As the process of teaching affects our perspective on its purpose and efficacy, as well as our understanding of the syllabus content, the phenomenon under analysis was design teaching, and the context was the respective institutions. Thus, the focus group discussed the key differences identified and the outcomes of this discussion analysed to gain a deeper understanding of the relevance and significance of the differences and commonalities of the courses.

3 RESULTS

The two institutions vary in terms of the breadth of design skills taught relative to the depth or detail this teaching goes into. In addition, the focus of the specific learning outcomes is different. When mapped onto a Venn diagram dividing the learning outcomes into three themes "Engineering Analysis", "Engineering Practice" and "Engineering & Society" these NTU-specific learning outcomes have their gravity at the intersecting central area of the diagram, see Figure 1(a). This correlates with the holistic nature of project-based learning instilling integrated skills. ICL covers fewer topics with an emphasis on Engineering-Practice based content, see Figure 1(b). This content is a continual focus year on year, resulting in a greater depth of understanding being attained in these areas and correlates with the institutional focus on scientific expertise.

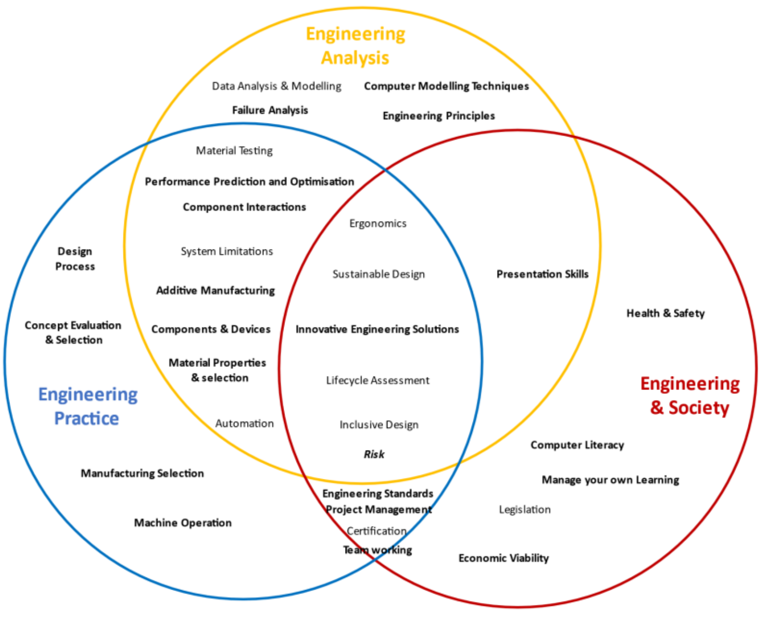

Figure 1. (a) NTU

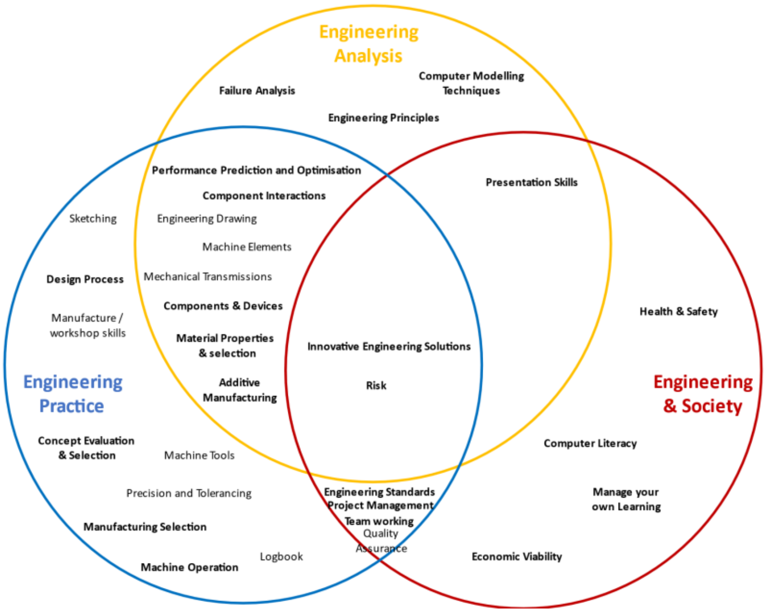

Figure 1. (b) ICL

Figure 1. Division of learning outcomes over the themes "Engineering Analysis", "Engineering Practice" and "Engineering & Society". Bold font indicates learning outcomes shared by both institutions

A related divergence was identified in the nature of the application and deliverables, with NTU focusing on digital skills including virtual prototyping, digital optimisation and CAD for additive manufacture. ICL on the other hand requires that students pass a module covering practical workshop skills, and subsequently use these skills in their second, third, and optionally in their fourth year, to manufacture functional physical prototypes. The two axes of skill development can be visualised in Figure 2 below:

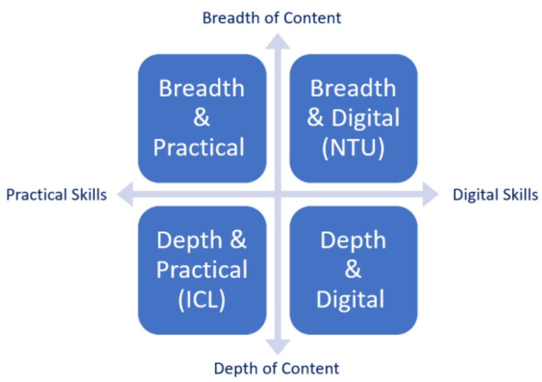

Figure 2. Two axis Digital/Practical-Depth/Breadth Chart

Due to constraints on teaching time and resources within a degree course educators must make choices between topics and methodologies. The chart maps out the resulting divergences in skill areas identified though our analysis, and the emerging foci of D+M teaching. As an example, NTU covers a much wider range of design topics, including sustainable design, inclusive design, automation, and anthropometrics and assesses students on virtual/digital artefacts such as 3D models and online showcases, hence is located in the top right "breadth and digital" sector. ICL covers fewer topics but goes to greater depth, such as selection of bearings and implementation of drawing standards. Students are assessed using physical prototypes and test events, hence ICL is located in the diametrically opposed "depth and practical" sector.

4 DISCUSSIONS

The rapid evolution of knowledge in the 18th and 19th century resulted in specialisation within the field of engineering [2]. Over time, the establishment of 'mainstream' engineering disciplines such as Mechanical, Chemical, Electrical and Electronics Engineering as well as policy, and cultural differences have resulted in the development of silos within engineering and engineering education [3]. However, the emergence of the fourth industrial revolution has resulted in the renewed spread of interdisciplinary approaches within engineering [4] and indeed, the acquisition of interdisciplinary skills is regarded an important objective of contemporary scientific and engineering education [5]. Compared to previous iterations, the learning outcomes of the fourth edition of AHEP have a greater emphasis on inclusive design, innovation, sustainability, and ethics. Within a societal context, AHEP4 places a stronger focus on equality, diversity, and puts forth explicit learning outcomes for security and the mitigation of security risks [6]. This requirement for increased awareness of ethics and the society at large has brought a focus on interdisciplinarity to engineering education. The broad and integrative nature of D+M focused modules means they often become a compendium for the wide range of practical and transferrable skills that do not have an obvious home within the theoretical and more engineering science-focused modules. Whilst this may have certain benefits, such as allowing the students to experience engineering to its broadest extent and without many of the constraints of classroom teaching, this approach may also result in a lack of focus for these modules, and in some cases students perceive these modules as having insufficient engineering content. This affects the student journey and diminishes the efficacy of teaching.

In addition to offering core Mechanical Engineering modules such as Thermodynamics and Solid Mechanics, a significant proportion of the curriculum at NTU focuses on project-based modules that are shared amongst all engineering courses. Without being explicitly D+M focussed, these modules cover a myriad of D+M topics. As an example, the project-based learning modules culminate in a three-week long 'Grand Challenge'. In this project, students are put in cross-disciplinary and cross-year teams to devise an innovative solution to an existing challenge. Some themes covered in the past include energy harvesting, sustainable development, and wireless networks. Within the general theme, the student groups focus on a sub-theme such as medical devices or space and exploration. The deliverables are a group presentation in a tradeshow, a promotional video, a business model canvas, and a demonstrator that acts as a prototype of the solution devised. The themes are deliberately kept broad and not restricted to a specific discipline, enabling students from various engineering backgrounds to come out of their disciplinary silos and integrate their knowledge to produce innovative solutions. For instance, a Mechanical Engineering student would bring specific skills and knowledge to the project but also gets an opportunity to learn and apply skills and knowledge from the other disciplines. Consequently, the presented solutions are the result of an integrated engineering approach. In devising their solutions, the students must also consider factors such as ethics, budgeting, marketing and promotion, communication, presentation, and user experience. The integrated curriculum encourages interdisciplinarity and has agility to adapt to and include new learning outcomes, such as equality, diversity and inclusion. However, catering to a range of engineering courses within the same project means that the depth of the content can be compromised. As an example, these modules may focus more on inclusive, sustainable and user-friendly design but might not explore the specifics of machine elements.

ICL has a more traditional programme, with the curriculum comprising core Mechanical Engineering modules. The D+M journey of the students evolves from introductory in the first year to a project simulating a real engineering design studio in the third year: In the first year the D+M content has a similar structure as the foundational modules, with a focus on machine components, tolerances and fits, manufacture, as well as engineering drawing and CAD. In addition, the students complete a five-day introductory workshop skills training. The module is assessed by completing an individual design assignment. In second year, the integrative nature of design is introduced, with students first working on an introductory Design & Make group project that builds on first year experiences and adds teamwork and project management components. The module is subsequently concluded with a week-long full-time intensive group design project, with as deliverables five daily reports, an oral presentation, a poster presentation, and individual logbooks as well as a self and peer assessment. The third-year D+M module covers 33% of the year, and the students work throughout the year on delivering a large innovative project. This includes designing, making and testing a prototype product that is integrated in a larger so-called 'superproject', comprising three teams of four students. Project topics have a strong mechanical focus and range from a functional wind tunnel to a human-powered hydrofoil. The project builds on the strong theoretical knowledge that the students developed in their core subjects, and includes aspects such as customer-interaction, project management and budget and acquisition responsibilities. The module concludes with an exhibition and a customer presentation of the developed prototype.

Whilst the delivery of the Mechanical Engineering programmes at the two institutions is clearly different in terms of method, content, and student journey, there are also many similarities. Design modules are often used as the catch-all subject for teaching and assessing transferrable skills such as teamwork, project management, communication, and presentation, which the students do not perceive as core engineering skills. The D+M modules are not typically assessed using a traditional paper-based exam, but often comprise an engineering focused project that is assessed in terms of a client-oriented delivery. This enables students to experience engineering practice akin to industry. For many, this is how they learn what engineering truly means, thus crossing the threshold to becoming an engineer and gaining more value from their studies [7].

Limitations to this study: The study presented is the outcome of a series of focus group discussions on the structure and delivery of Design and Manufacture modules at two institutions in the UK, using the AHEP4 guidelines as the starting point. These two institutions have taken a distinctly different pedagogic approach and have a markedly different student body. The aim of the study was to explore differences and communalities in the programmes, without bias, criticism or judgment. Consequently, the size of the focus group was deliberately limited to only include three experienced D+M educators and thus it should be noted that the results presented are qualitative and do not hold any statistical value. It is envisioned that the presented overview may form the basis of a wider exploration that incorporates other institutions, both within the UK and internationally, and also includes opinions of current and past students as well as employees and marketeers.

5 CONCLUSIONS

The two Mechanical Engineering programmes compared in this study have significant differences in the delivery of their Design and Manufacture modules. At the same time, both institutions deliver a UK-based accredited Integrated Master's degree in Mechanical Engineering, meaning there are also significant communalities. Both institutions deliver open-ended collaborative design projects that require integrative skills and creativity and that enable the students to develop practical skills as well as experience the role of engineers in society. The skillset expected from a modern Mechanical Engineer is currently rapidly evolving, meaning educational programmes will need to evolve and develop, introducing new content and consequently also having to choose which topics to reduce or even abandon. The digital/practical and breadth/depth chart and the learning outcome mapping in the Venn diagram can provide Mechanical Engineering educators with an initial development tool, enabling them to make more deliberate and informed decisions about teaching, content, delivery, and the student journey. Such decisions may be dependent on institutional strengths and expertise as well as pedagogical requirements for the typical student body at that institution, and this variety can be seen as beneficial. The diagrams may also form the basis for a more extensive mapping operation of mechanical engineering design teaching across international institutions.

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