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SAME, SAME BUT DIFFERENT: CORE DESIGN TEACHING IN MECHANICAL ENGINEERING

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ABSTRACT
Mechanical Engineering students learn a lot in their first two years of study, building up core engineering knowledge. Courses and subjects range from Mathematics to Solid Mechanics, Thermodynamics to Materials Science. Design is also a fundamental aspect of any reputable Mechanical Engineering programme, as application in the real world is what separates the practice of Mechanical Engineering from Engineering Science. This paper studies the application of design in a number of Mechanical Engineering programmes, concentrating on the early first and second years of study as introductions and applied studies in design. It also looks at the common elements between institutions, as well as surprising differences-linking heavily with expectations from accreditation. The paper also compares the pedagogical approach of UK universities against their US counterparts, in particular those with a strong design philosophy. The learning outcomes of a sample of UK institutions were reviewed to identify key common objectives, and those objectives (as well as professional expectations) were analysed with 2nd year students. The paper concludes that whilst there is evidence of common subjects and principles taught in design within Mechanical Engineering programmes, there should be more focus on user needs and product development to align with established design process models and professional expectations.

Keywords: Mechanical Engineering, Design, Education, Programmes, Product design

1 INTRODUCTION AND DESIGN PROCESS/MODELS

The requirement for design teaching from a Mechanical Engineering point of view is that it can be run in parallel with other core engineering subjects, such as Thermodynamics and Maths, but moreover can be viewed as the ‘heart of the engineering curriculum’ as an approach to the teaching of design in higher education [1]. This view of integrated design principles was influenced by UK SPEC learning outcomes as shown in Table 1.

Table 1. Specific learning outcomes from UK-SPEC, as published by the Institution of Mechanical Engineers, with particular reference to design (2007) [1]

D1	Investigate and define a problem and identify constrains including environmental and sustainability limitations, health and safety and risk assessment issues
D1m	Wide knowledge and comprehensive understanding of design processes and methodologies and the ability to apply and adapt them in unfamiliar situations
D2	Understand customer and user needs and the importance of considerations such as aesthetics
D3	Identify and manage cost drivers
D4m	Ability to generate an innovative design for products, systems, components or processes to fulfil new needs
D5	Ensure fitness for purpose for all aspects of the problem including production, operation, maintenance and disposal
D6	Manage the design process and evaluate outcomes

However, these design competencies were generated for engineering industry requirements and needs from 2007. The UK SPEC documentation has undergone two editions in the last 10 years, and the interdisciplinary roles and requirements for engineers in 2018 have also changed. Looking at the third edition of UK SPEC published in 2014, the learning outcomes related to design for a Chartered Engineer (CEng) are shown in Table 2 [2].

Table 2. Specific learning outcomes from UK-SPEC: B- Apply appropriate theoretical and practical methods to the analysis and solution of engineering problems. (2014) [2]

B1	Identify potential projects and opportunities. This could include an ability to: • Establish and help develop solutions to meet users' requirements • Consider and implement new and emerging technologies • Enhance engineering practices, products, processes, systems and services • Use own knowledge of the employer's position to assess the viability of opportunities.
B2	Conduct appropriate research, and undertake design and development of engineering solutions. This could include an ability to: • Identify and agree appropriate research methodologies • Allocate and manage resources • Develop the necessary tests • Collect, analyse and evaluate the relevant data • Undertake engineering design • Prepare, present and agree design recommendations, with appropriate analysis of risk, and taking account of cost, quality, safety, reliability, appearance, fitness for purpose, security, intellectual property (IP) constraints and opportunities, and environmental impact.
B3	Manage implementation of design solutions, and evaluate their effectiveness. This could include an ability to: • Ensure that the application of the design results in the appropriate practical outcome • Implement design solutions, taking account of critical constraints, including due concern for safety and sustainability • Determine the criteria for evaluating the design solutions • Evaluate the outcome against the original specification • Actively learn from feedback on results to improve future design solutions and build best practice.

Variations of these learning outcomes exist for Engineering Technicians (EngTech) and Incorporated Engineers (IEng). Although these competences focus more on problem solving and practical methodology, aspects of design remain an important part of the Engineering curriculum for accreditation and "can be used to integrate all engineering understanding" [3]. For Integrated MEng programmes, graduates are expected to use their design knowledge and skills to:

- *Understand and evaluate business, customer and user needs, including considerations such as the wider engineering context, public perception and aesthetics*
- *Investigate and define the problem, identifying any constraints including environmental and sustainability limitations; ethical, health, safety, security and risk issues; intellectual property; codes of practice and standards*
- *Work with information that may be incomplete or uncertain, quantify the effect of this on the design and, where appropriate, use theory or experimental research to mitigate deficiencies*
- *Apply advanced problem-solving skills, technical knowledge and understanding to establish rigorous and creative solutions that are fit for purpose for all aspects of the problem including production, operation, maintenance and disposal*
- *Plan and manage the design process, including cost drivers, and evaluate outcomes*
- *Communicate their work to technical and non-technical audiences Demonstrate wide knowledge and comprehensive understanding of design processes and methodologies and the ability to apply and adapt them in unfamiliar situations*
- *Demonstrate the ability to generate an innovative design for products, systems, components or processes to fulfil new needs*. [3]

To teach a course in design within Mechanical Engineering, it's necessary to implement a process or model that students should follow, driven by a design need. Well established models are referenced in course textbooks (e.g. Childs' Mechanical Design) as well as institutional handbooks and guidance.

One conceptual model for teaching design within higher education is defined by Armstrong in 2002 [4] as three key stages of realisation:

- Need – all design begins with a clearly defined need
- Vision – all designs arise from a creative response to that need
- Delivery – all designs result in a system or product that meets that need

In comparison, the 1999 Pahl & Beitz model is more pragmatic, and summarises the stages of the design process as four activities; clarification of task (market need), conceptual design, embodiment design and finally detail design. A comparison of the models is provided in Fig 1. [5].

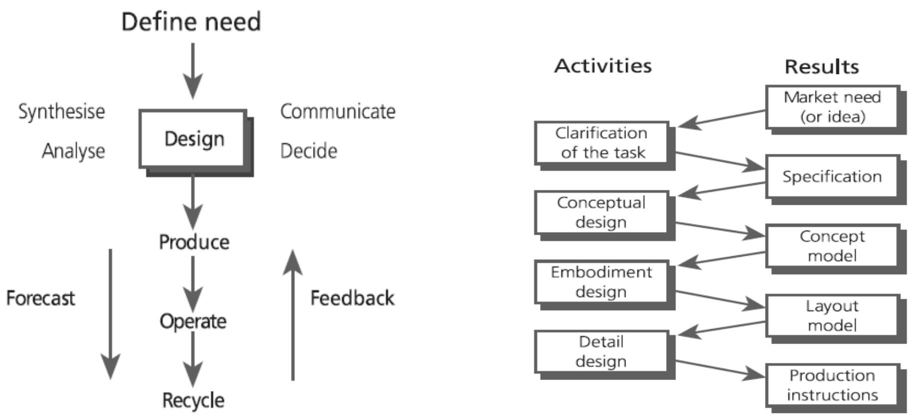

Figure 1. A comparison of needs based engineering design education frameworks, Armstrong and Pahl & Beitz, summarised by the Royal Academy of Engineering [5]

Pugh's total design process (1990) [6] provides similar core tasks as described in the Pahl & Beitz model, but with a more market driven approach tied to the design of viable products and four main stages; specification, conceptual design, detailed design and manufacture. Another generalised model is the Design Council's 'double diamond' (2005) [7] which provides a more problem focussed approach, with decision gates determined by four convergent and divergent stages of design; discover, define, develop and deliver.

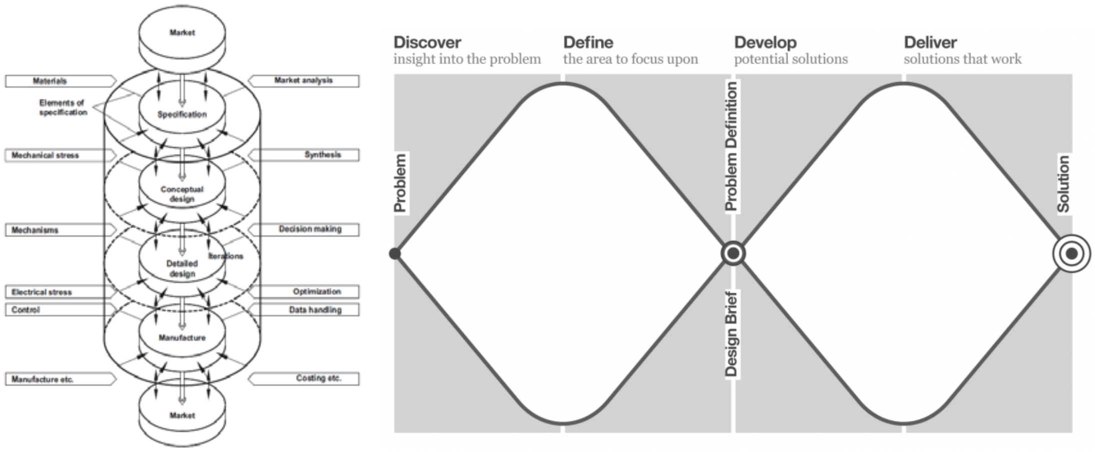

Figure 2. Pugh's total design process [6] and the Design Council's 'double diamond' [7]

From the processes discussed, the overall methodology of design education from an engineering perspective is to define market needs, and then through a series of core tasks (from specification to detail design/manufacture) to come to a viable solution to meet those needs. The next stage of investigation is to review the taught design content from a sample of Mechanical Engineering programmes on how well they address these needs. This entails first and second year core design subjects, among the foundation of engineering subjects. This paper considers what common attributes define design teaching with Mechanical Engineering-and if UK institutions are delivering on the expectations of professional engineers defined by the accreditation of higher education programmes.

2 DESIGN TEACHING IN MECHANICAL ENGINEERING-INSTITUTIONAL APPROACHES

At the time of writing, Cambridge is ranked 1st for Mechanical Engineering in The Complete University Guide 2018 [8]. The Guardian University Guide 2018 [9] places Leeds as the highest ranked institution for Mechanical Engineering. For general engineering, Imperial College London comes out on top. The Times Higher Education 2018 rankings [10] contain Cambridge, Oxford and Imperial College London within the top ten institutions in the world from Mechanical/Aerospace engineering subject areas and are the top 3 in the UK for the subject area. The UK study will concentrate on Oxford, Cambridge and Leeds with the centre of the study being Imperial College London, where students were asked to reflect on their design teaching. To begin, the Cambridge Engineering course provides common general engineering subjects in years 1 and 2, with specialisation into Mechanical Engineering in the third year. The first year design coursework comprises of technical drawings, a product design activity, as well as the design and build of an AM radio and electro-mechanical device. In the second year, students are tasked with a group exercise to design and build a mobile robot vehicle (Fig. 3).

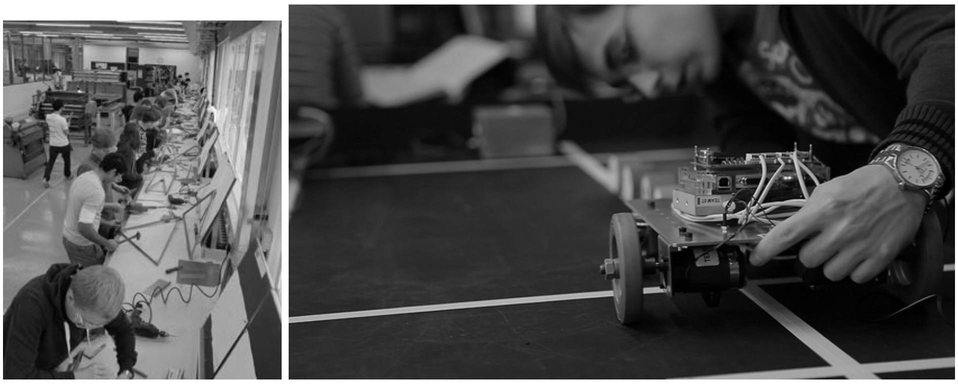

Figure 3. Cambridge engineering students working on a structural design project in year 1 and a robot competition as part of year 2 coursework

Oxford's MEng Engineering Science course also provides core engineering subjects in years 1 and 2, with optional modules in third year and research specialisation in Mechanical Engineering in fourth year. Design activities are taught as practical work, with design and build projects in the first year focusing on structural and mechanical engineering areas. The second year introduces a team based activity to design and build a solar race robot similar to Cambridge. In comparison, at Imperial College London, the dedicated Mechanical Engineering programme contains two first and second year Design & Manufacture modules. In the first year, students are introduced to CAD, engineering drawing, workshop skills, manufacturing and process knowledge and the design of shafts and transmission components. In the second year, groups of students are tasked to design and build an electric scooter [11] with mechanical transmission, and an individual product design exercise (Fig.4).

Figure 4. A product based project and electric scooter challenge are examples of second year design teaching at Imperial College London [11]

Leeds also offers a dedicated Mechanical Engineering programme, with two compulsory modules in Design and Manufacture. First year students learn the basics of CAD, engineering sketching, manufacturing and process design. Projects entail a top-down conceptual design, the design and build of a buggy or glider in a team and the design and manufacture of a mechanical assembly. The second year module introduces more complexity in the team-based design and builds activity by introducing the use of sensors and actuators. Overall, there are similarities to Imperial College London's approach. To establish if design education from UK universities is suitably benchmarked with that of the expectations of Mechanical Engineering in a global context, the approach undertaken by US institutions such as Stanford and MIT was considered. Stanford's Mechanical Engineering programme is ranked 1st in the Times Higher Education league table and the programme distinguishes itself by having Design as a core engineering education theme, driven by an empathic understanding of human need. This is evident in the programme's design teaching philosophy, for example, in the team-based capstone course ME113 Mechanical Engineering Design, students need to complete prerequisite courses where there is a balance of needs finding, product definition and conceptual development with more analytical engineering subjects. Some student projects from ME113 include a wall-walking robot for bridge inspection, and a device for washing wheelchair tyres. Another good example is 'ME 171E aerial robot design' where students are tasked with the design and build of a consumer friendly delivery system; exploring market needs such as emergency supplies and delivery of cupcakes for special occasions [12]. A learning outcome of MIT's BSc in Mechanical Engineering programme is to "*lead the conception, design and implementation of new products, processes, services and systems*" and includes minors in Design and Manufacturing 1 and 2 as well as The Product Engineering Process. Both courses are accredited by ABET (Accreditation Board for Engineering and Technology).

3 METHODOLOGY AND RESULTS-COMPARING MODULES & ME2 STUDY

By compiling the design module aims, objectives and learning outcomes of UK institutions into a word cloud generator, and seeking out the most used terms (excluding 'design' and 'engineering') the term '*product*' is referred to 20 times. *'Process'* is referred to 12 times. A study was also conducted with twenty 2nd year Mechanical Engineering students who had completed their final individual design project for the Design and Manufacture 2 course at Imperial College London. (Fig. 5)

Figure 5. A word cloud generated from Mechanical Engineering design module aims of UK institutions

Despite differences in approach, it is indicated that a product focus forms a major objective in design teaching across UK institutions. 10 respondents of the ME2 study were asked questions regarding their professional learning outcomes and reflections from their recent exercise. 80% believed that gaining a "*Wide knowledge and comprehensive understanding of design processes and methodologies, and the ability to apply and adapt them in unfamiliar situations"* was an important design attribute to the project with 70% using a 'double-diamond' design process. Reassuringly many students identified the project aim to produce a viable product; however 80% suggested that the *"Ability both to apply appropriate engineering analysis methods for solving complex problems in engineering and to assess their limitations*" was an expected learning outcome of professional engineers in respect to Design. 60% of students suggested that Design stood equally with Science/Maths and Engineering Analysis as the heart of the engineering curriculum; no students selected Design outright.

4 DISCUSSION

Cambridge and Oxford have similar programmes with common first and second year teaching. Both have a group based robot based competition activity in the second year which allows the students to explore design, make and test principles. There is some evidence of market need (e.g. factory floor robot) but these are not explicit in the learning outcomes. Although the robot challenges are fun, engaging and use multi-disciplinary skills, they tend to be biased towards problem solving skills and application, as opposed to the challenges of designing a viable product. The Imperial College and Leeds programmes have similar, dedicated Design and Manufacturing modules in years 1 and 2. The Imperial College modules focus on mechanical assemblies and transmission components, whereas the Leeds programme offers less constrained challenges, applying core knowledge from other modules. Only the individual design activity (the design of a product) from Imperial College focuses on delivering a viable solution for a market need; although from the results of the study it seems some learning objectives can be confused. Looking at the changing learning outcomes of charted engineers and the basis of engineering design education framework, one can argue that these fun, engaging projects could get carried away in analytical problem solving approaches and should be grounded with a pragmatic user need, like Stanford, to face the challenges of manufacturing and delivering a product to market. Such needs based context in design is important for achieving the learning outcomes necessary for integrated MEng programmes, and delivering all levels of Pugh's total design methodology and the double diamond model. Mechanical Engineering graduates need to understand *what* they need to deliver in design project work, *how* they are going to achieve it and ultimately *why* it is important.

5 CONCLUSION

Four UK institutions have been reviewed in aspects of core design teaching within Mechanical Engineering, comparing common design modules and benchmarking them against two US institutions. Although students engage in challenging and fun design projects (involving robots, scooters and aircraft) there can be too much focus on analytical approaches and practical outcomes. Key learning objectives attributed to understanding design in professional engineering can be misinterpreted or lost. More focus is needed on product drivers & challenges of the task; in particular user and market needs.

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