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EMBEDDING SUSTAINABILITY IN THE ENGINEERING CURRICULUM: A COMPLIMENTARY APPROACH TO PERFORMANCE ENGINEERING AND SUSTAINABLE DESIGN

Ahmed Tamkin BUTT, Edward William Thomas CAUSTON and Matthew Alan WATKINS
Department of Engineering, Nottingham Trent University, United Kingdom

ABSTRACT
To address the UN Sustainable Development Goals, future engineers must effectively integrate sustainability into multiple areas of engineering throughout the lifecycle encompassing the design of products, development for manufacturing and end of life considerations. The impact of the quality of manufactured goods on product performance and sustainability is well documented. Furthermore, statistical methods commonly used to monitor and control product quality may be adapted to evaluate environmental performance. This paper details how sustainability is considered within the curriculum of two 3rd year modules of the Engineering courses at Nottingham Trent University, UK. The modules presented here are Performance Engineering and Sustainability in Engineering Design. Through a systematic analysis of the content, the authors have identified synergies in approaches to sustainability in the modules. It is anticipated that, through careful scaffolding and reinforcement of learning, budding engineers will be encouraged to adopt a holistic approach, in which sustainability is embedded throughout their practice.

Keywords: Performance engineering, quality management, sustainable design, inter-disciplinary engineering education

1 BACKGROUND
The exponential growth of the global economy and production has had an irreparable social and environmental impact [1, 2]. Indeed, sustainability is considered one of the greatest challenges for humanity in this century [3, 4]. In 2015, the UN General Assembly put forth "the agenda for sustainable development" which is constituted by 17 sustainable development goals (SDGs) [5, 6]. Engineering is expected to play a crucial role in achieving at least 12 of these 17 SDGs [7]. In light of this, future engineers need to be well equipped to understand, evaluate, and apply knowledge and skills from a range of inter-disciplinary fields [8] to ensure they consider a myriad of environmental and social factors when addressing current engineering problems [9].
Education for sustainable development (ESD) aims to equip individuals with necessary skills and knowledge to aid them in addressing sustainability [10]. It is essential that ESD is embedded in the engineering curriculum, providing students with opportunities to learn, practice and apply systemic thinking to real-world scenarios, enhancing their professional practice and responsible decision making [3]. ESD can be defined as an educational approach for creating awareness of issues related to sustainability [11], inculcating skills such as collaboration skills, critical and reflective thinking, entrepreneurship, and creativity. However, such skills cannot simply be taught by introducing new modules or adding content to a pre-existing curriculum, but they must be embedded throughout the degree programme [12].
A significant barrier to the adoption of a holistic approach toward sustainability is the use of modular curricula and the consequent tendency for students to compartmentalize knowledge and skills, failing to apply these outside of the context in which they were introduced [2, 13]. This raises an interesting question: to what extent can ESD be integrated into the curriculum *outside* of specific ESD modules. It is the contention of the authors that this is feasible for the educational practitioner even within the

confines of the curriculum in which they are operating and without the need for radical revisions to content. This paper considers two apparently divergent modules, one for which ESD is the explicit focus and one for which it is not. Through a systematic analysis, the authors propose means by which both may be adapted to support each other in pursuit of a more holistic approach toward ESD. In this way it is hoped that new engineers may be encouraged to embed sustainability throughout their practice.

2 MODULES – CONTENT, CONTEXT & ASSESSMENT

2.1 Performance Engineering

Performance Engineering is a 3rd year core undergraduate module taught across a single term to a mix of students from mechanical, electrical & electronic, biomedical and sport engineering. The aim of the module is to introduce students to a range of statistical and other techniques in the context of measuring, monitoring, and improving engineering performance to ensure quality and efficiency.

The module is taught across 10 weeks through a mixture of lectures, seminars, and online resources, comprising short video lectures, MCQs and problem sets to be completed asynchronously. Given the range of engineering disciplines and students represented, the focus is on laying a foundation from which students may subsequently build their knowledge within their own specialism as opposed to providing a comprehensive review of the topics considered.

Due to the limited statistical knowledge of many students, early lectures are used to introduce and review standard statistical techniques including measures of average and of spread, probability distributions, sampling and estimators, the central limit theorem, correlation, regression, and hypothesis testing. Emphasis is placed on a conceptual understanding and engineering applications from across disciplines are used as examples. Simultaneously, students are encouraged to analyse engineering processes in relation to ensuring product quality.

Attention then shifts to common methods used within engineering to analyse processes. These include capability indices used to determine the ability of a process to operate within specified limits, the analysis of variance to determine the statistical significance of differences between populations, and statistical process control, especially Shewhart control charts, used to monitor and control processes. Factorial experiments, including factor and interaction effects, are considered in the context of improving process performance.

Finally, students are introduced to reliability engineering methods. These include lifetime distributions, failure rates, exponential, and Weibull distributions, the 'bathtub curve,' accelerated testing and reliability block diagrams.

Students are assessed through a 2-hour online examination and coursework assignment. The exam consists of short answer and calculation questions requiring students to select and apply methods from the module to analyse data provided. Students must also demonstrate an understanding of the practical implications and the limitations of their analysis. The coursework takes the form of a case study where students are presented with data related to a hypothetical manufacturing context for which they must apply techniques from the module to produce a management report detailing and justifying their recommendations.

2.2 Sustainability in Engineering Design

Sustainability in Engineering Design is an optional 3rd year module open to all four engineering disciplines at NTU. The module runs in term 2 and is informed by CDIO standards [14, 15]. The module aims to bring together and consolidate sustainable development within the domain of engineering design and product development. The module builds upon year 1 and year 2 core modules, Innovation and Engineering Solutions [16, 17] & Industrial Design and Product Case Studies [18] yet is still an introductory course and does not require any prerequisites. Due to the disciplinary diversity of the students enrolled in the module, the content is fairly broad. Students are equipped with the necessary tools and knowledge to tackle engineering design problems from a sustainable perspective, addressing the Triple Bottom Line [19] and Design for Total Control [20] philosophy. The objective is to move away from focusing solely on the end-of-life disposal to integrating sustainability considerations throughout the product lifecycle, being mindful of the resources consumed during the process but also considering disposal, maintenance, and various other socio-economic factors.

The module is taught across 11 weeks, through lectures, seminars, and drop-in sessions. Lectures cover the theory and principles of engineering design and sustainable engineering. Including product concept generation and development tools such as TILMAG, morphological analysis and detail the processes of product development such as phases of the product lifecycle (concept, detailed and final design specification). Students are given industrial examples of the progression of a product's life cycle detailing each of the stages, material sourcing, design, manufacturing, maintenance, usage, and disposal. At each stage of the product's life, environmental impact is discussed in terms of energy expenditure and resource consumption.

Following the product development lifecycle, sustainable engineering lectures lay the groundwork for the application of the Triple Bottom Line and Design for Total control by defining the environmental impact at each stage of the product's life calculating the embodied energy. This is performed using the Eco-audit facility in Ansys Granta EduPack software [21], which is introduced in the module with instruction on how to define these values and strategies are discussed on how to reduce the environmental impact at each stage. The drivers for sustainability in design such as legislation, social factors and financial incentives are also discussed within lectures before students are introduced to strategic sustainable design whereby consumer perspectives and sustainability certifications are considered.

The students are assessed via a 50% group coursework and a 50% individual product design project. The group coursework asks students to identify a key issue facing sustainability in engineering and propose a solution. In their groups, students are also expected to disassemble and document an engineered device to conduct a comprehensive eco-audit and propose methods of reducing the environmental impact of the device at different stages of its lifecycle. The individual design project requires students to and document the entire product lifecycle, whilst adhering to a set specification for a product given to them. The final submission is a technical report that details the development of the product from a technical and strategic standpoint, to maximize profit as well as reduce environmental impact.

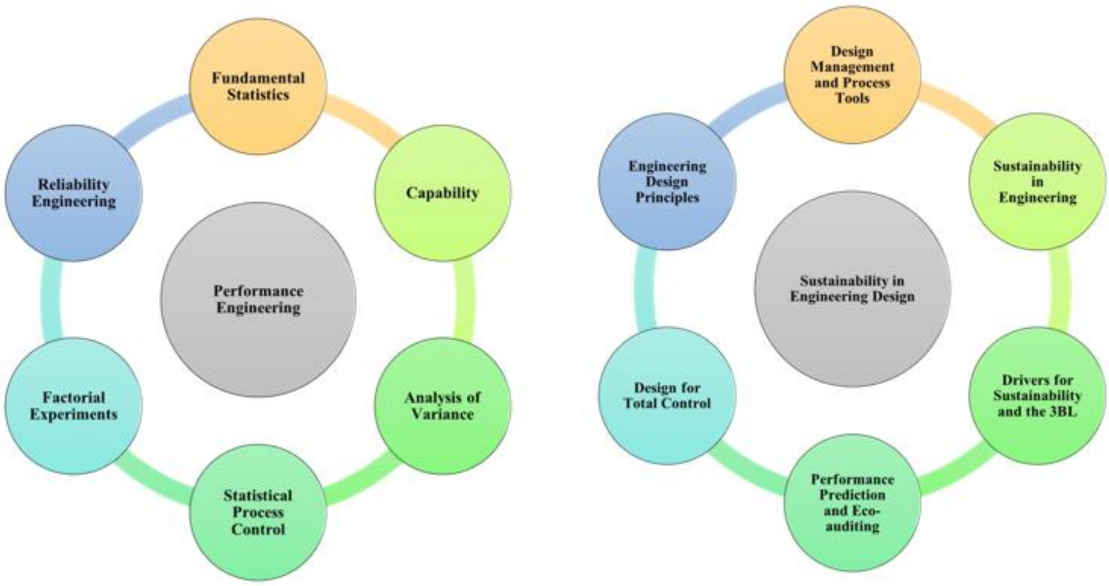

Figure 1. Comparison of the content covered in the modules in focus

3 DISCUSSIONS

It is evident that the content of these two modules *(Figure 1)* has significant differences in terms of learning and skills gained. At first glance, using these as a starting point for embedding sustainability in the engineering curriculum might seem counterintuitive. However, it is argued that the challenge of identifying synergies in these modules and finding opportunities for inter-disciplinary education despite these differences make this an excellent exercise, illustrating how educational practitioners may achieve this even while operating within the confines of an existing curriculum.

Potential synergies may relate to content, pedagogy, placement within the course curriculum or a mixture of these. While there is little explicit overlap in the content of the two modules as currently delivered, the broad learning outcomes do afford the possibility of reinterpretation. In doing so, it is critical that core content is not neglected. Perhaps the simplest way to achieve this is during student application of knowledge and skills from each module both through summative assessments and formative standalone tasks. These may require students to explore for themselves the possibilities for applying techniques drawn from Performance Engineering to Sustainability in Engineering Design. Both modules emphasize the importance of effective and efficient manufacturing processes and many of the methods used to enhance product quality and reliability may equally be applied in the pursuit of sustainability goals. Such tasks may also expand the range of learning methodologies applied within the modules, introducing more discursive opportunities into Performance Engineering while emphasizing the applicability of mathematical methods within Sustainability in Engineering Design.

Opportunities may also be present in the sequential ordering of the two modules, in that Performance Engineering is delivered to students immediately before Sustainability in Engineering Design. By embedding sustainability within the former and drawing upon methods from Performance Engineering in the latter, a sense of continuity may be achieved. The focus thus shifts toward a student-centred curriculum emphasizing the student's journey and how they are equipped with the necessary skills that encourage a pragmatic engineering practice.

Given the focus in Performance Engineering is on improving product quality and reliability, it is appropriate to open a debate as to how these characteristics relate to the integration of sustainability into design and manufacturing processes. Reliable products do not require replacing as frequently, reducing demand on resources and the impact of manufacturing and transport; efficient manufacturing means less waste and lower energy demands; higher quality products may be more energy efficient in operation. Simultaneously, we must acknowledge that the need for sustainable processes and products imposes additional restrictions that may sometimes conflict with quality requirements and increase costs. In this context, it may be informative to introduce ISO 9000 and ISO 14000 [22] to highlight the overlap between quality and environmental management systems.

The possibility of adapting statistical process control and capability techniques to emissions data [23] provides an opportunity for students to apply mathematical methods in the pursuit of environmental goals, countering initial perceptions students may have that sustainability is a purely qualitative philosophy. Case studies introducing these techniques in the context of enhancing sustainability may encourage awareness of the possibilities for utilizing methods drawn from outside traditional sustainability education.

Finally, while the emphasis of Performance Engineering is on the application of statistical techniques to enhance quality and efficiency, there is scope to expand the concept of performance to encompass sustainability as an explicit objective while maintaining the specified learning outcomes. To avoid sacrificing existing content, this may be best achieved through the coursework assignment. Moving the assignment away from an exercise in data analysis and toward a research-based task on a given scenario could allow students to integrate sustainable development within the analysis of a manufacturing process, avoiding perceptions that this has been artificially added into the assessment.

As Performance Engineering is a core module, by the time students start Sustainability in Engineering Design, they are already well versed in the design of experiments and reliability engineering. Within their individual product design projects for Sustainability in Engineering Design, students need to integrate sustainability in manufacturing by assessing and selecting the most appropriate manufacturing techniques. Indeed, the quality of production processes has been defined in terms of reliability and sustainability [24] and it is understood that efficient manufacturing leads to better product quality and reduces production losses, in turn increasing the sustainability of the entire process. A task could then be added to the individual product design project, to ask students to use techniques learnt from Performance Engineering to design experiments to determine optimum manufacturing conditions. Additionally, proposing a quantitative method to assess whether their chosen manufacturing methods meet the desired specifications.

As noted, reliable products do not need to be replaced very often. Product longevity ensures we can move away from the "use and throw" mindset to encourage a more sustainable "use and maintain" mindset. Developing efficient reliability assessment techniques ensures the performance is not compromised under unprecedented or demanding conditions [25]. Reliability analysis learnt in Performance Engineering can be used by students during the individual product design project to propose a methodology for assessing product reliability. This will encourage students to embed reliability throughout the product development cycle.

Under the proposed modifications, students will have already been introduced to ISO 9000 and ISO 14000, and therefore will appreciate the rigorous processes and requirements of quality management certifications. Consequently, the introduction of strategic sustainable design via certifications and eco-labelling will be more easily understood and implemented in their individual projects.

4 CONCLUSIONS

This paper has illustrated how educational practitioners might work together to embed ESD more fully within the curriculum. Despite operating within curriculum constraints, synergies have been identified even in divergent engineering modules. Through this, interventions have been proposed to encourage future engineers to adopt a holistic approach toward embedding sustainability throughout their practice. The authors suggest that a crucial component of embedding ESD is for educators to consider the student journey and how sustainability themes run between modules. The focus should be upon how students are engaging with these themes and not merely upon introducing sustainability as an add-on component to be taught. To achieve this, educators working with the same cohort of students should be encouraged to enter a dynamic discourse, sharing both their interpretation of learning outcomes and their approach to achieving and assessing these. In this way they may be able to step beyond an analysis of specifications and reimagine their approach toward achieving learning outcomes concurrently with embedding sustainability. By pairing ESD practitioners with other educators, the latter may be supported in bringing sustainability themes into their modules while the former may better contextualize their teaching within the curriculum.

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