A MASTER PROGRAMME IN SUSTAINABLE PRODUCT DESIGN: AN ENGINEERING APPROACH

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ABSTRACT
It is common to have post-graduate programmes that focus on sustainability. The most common lens to looking at sustainability is through a life cycle assessment (LCA) perspective and assessing the impact of the use of different materials and manufacturing processes in the overall footprint of products, or the broader ESG approach where environmental, social and governance are intertwined. Engineering programmes tend to focus on a rather more technical approach of life cycle assessment. Because of the details necessary for an LCA, the analyses are based on existing products, where all the information on materials and manufacturing are readily available. The Master of Science in Technology and Design in Sustainable Product Design (MTD-SPD) at the Singapore University of Technology and Design (SUTD) encompasses a course on Design for Sustainability where the usual aspects related to LCA are dealt with. However, two important aspects of product design with a significant impact on the environment are seldom considered: product architecture and product assembly. The MTD-SPD focuses on these aspects as well, to bring a fresh perspective into the discussion about sustainable development, deeply rooted in engineering.

Keywords: Sustainability, DFMA, product architecture

1 INTRODUCTION
The MTD-SPD programme is one of a series of Master programmes recently launched at SUTD with a common design thread [1] (a signature of SUTD) that connects the expertise at SUTD with the community in Singapore and abroad (with a high intake of foreign students from multiple countries and backgrounds). The programme includes a course in Design for Sustainability with the usual emphasis of integration between different disciplines in relation to the complex problem of sustainability, capturing its value from different perspectives.

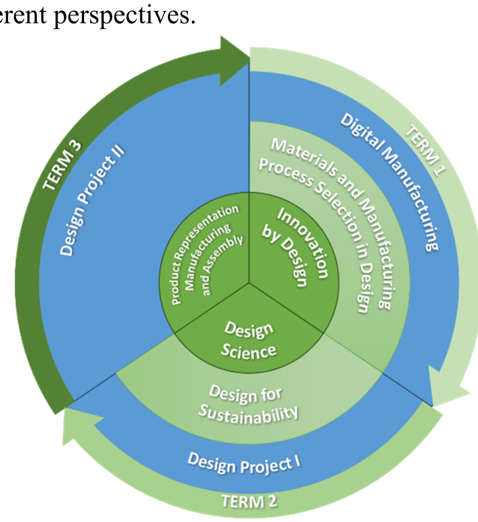

Figure 1. Curricular structure of the MTD in Sustainable Product Design

It uses proven general methods to investigate the impact of sustainability in the context of intra-company (by looking at the design, production, and organisation management processes), inter-company (by looking at supply chains and logistics) and at the end-of-life (by looking at the possible avenues to dispose, re-use or re-cycle products, and connecting this back to product design and organisation management). Two of the other courses in the programme are particularly interesting because of their emphases on materials, manufacturing, assembly and product architecture: Materials and Manufacturing Process Selection in Design (MMPSD) is a course that looks in detail at the impact of materials and manufacturing, and how different materials can have a significant impact in the overall product, both from a user perspective and from a sustainability perspective; and Product Representation Manufacturing and Assembly (PRMA), where Design for Manufacture and Assembly (DFMA) and product architecture are studied in terms of their impact in sustainability through analyses of assembly, disassembly, and servicing considerations. Figure 1 shows the overall structure of the programme. All the courses have a similar pedagogical approach and assessment strategy: students are graded based on an individual part, either done as an exam or quizzes during the term, and a team-based project where they explore the concepts hands-on with a real case study of their choice subject to approval from the instructors.

2 LITERATURE REVIEW

Higher education plays a crucial role in promoting sustainability and fostering a mindset for the successful implementation of the United Nations Sustainable Development Goals [2]. Higher education can contribute to sustainability through innovation, planning, openness, and stakeholder training [3] and should also be embedded in teacher education programmes through a professional values framework, energising professional practice and promoting responsible climate change action [4]. In management education in particular, attention to sustainability has increased in recent years, but there is a lack of consistency in concepts and integration of teaching, programme design, and learning [5]. Sustainability in engineering education is increasingly recognised as essential for preparing future engineers to address the complex environmental, social, and economic challenges of the 21st century. This involves integrating sustainability concepts into engineering curricula and developing competencies that enable engineers to contribute effectively to sustainable development. Engineering education must focus on developing specific competencies related to sustainability. Key competencies include the ability to address conflicts related to sustainability, contextual awareness, and the integration of social responsibility into engineering practices. These competencies are crucial for engineers to provide adequate solutions to sustainability challenges [6, 7]. The integration of sustainability into engineering curricula is a growing trend, with various methods being employed to assess and enhance this integration. These methods include curriculum assessment, the use of competencies to evaluate implementations, and the incorporation of diverse teaching methods [8, 9] with a focus on ensuring that sustainability learning outcomes align with industry norms and accreditation criteria [10]. Design for manufacturing and assembly, and product architecture are frequently mentioned in these attempts at including sustainability in engineering but are seldom studied to the extent that their full potential is perceived and applied. Therefore, innovative teaching and learning strategies are essential for embedding sustainability in engineering education. These include real-world learning experiences, transdisciplinary approaches, and the use of educational tools and techniques that foster a holistic understanding of sustainability. However, examples of this kind of transdisciplinarity are seen more often in research than in education [11, 12]. In fact, Argento et al. [13] note the importance of establishing a trans-disciplinary dialogue within higher education institutions that both increases the competence of academics and generates consensus. Sustainability can be approached from very different angles, but these differences should be an asset rather than a (often communication) problem. To bridge this gap, management of higher education needs to be aware of the time and additional resources needed to enable academics to truly embrace sustainability with an inter- and trans-disciplinary approach. The current paper attempts to present one possible approach to sustainability education.

3 DESIGNS FOR SUSTAINABILITY (DFS)

3.1 Content and learning outcomes

This course focuses on applying systems thinking, eco-design and life cycle assessment (LCA) to the sustainable design of products, processes, and engineered systems. It introduces the concept of sustainability – both theory and applications – in various sectors such as energy, transport, manufacturing and industry. Students will get to apply tools to perform eco-design and life cycle environmental impact assessment, which provide decision guidance on the design, maintenance, and operations of products and systems.

3.2 Example of students' team project

For this project, students work in a group of 4 to 5 students to identify an old or second-hand product, which they will disassemble to investigate the components and materials used. Students will carry out a quantitative analysis using LCA to identify 'hotspots': materials and stage of life cycle that contributes most to environmental impact. They will then provide feasible suggestions to redesign the product to consider lower environmental impact, less energy use and/ or ease of disassembly, repair and recycling. An example of student project is the Life Cycle Assessment (LCA) of commonly used household products (see Figure 2)

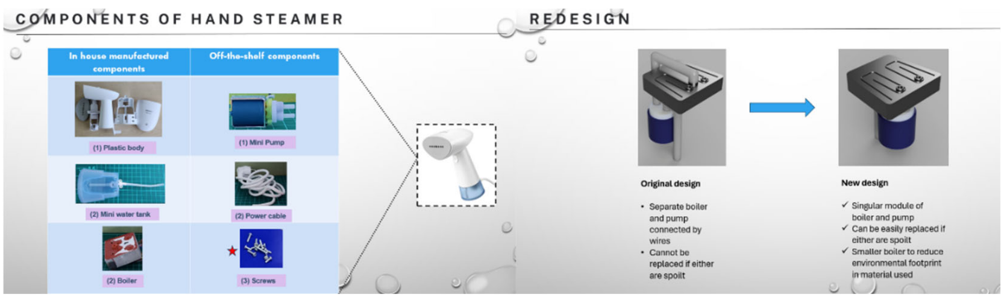

Figure 2. (left) Disassembly of hand steamer to investigate the components and design of the product. (right) One of the suggestions for the eco-design of the hand steamer after analysing the hotspots in the LCA study

4 MATERIALS AND MANUFATURING PROCESS SELECTION IN DESIGN (MMPSD)

4.1 Content and learning outcomes

This course intends to equip its students with a broad understanding of materials and manufacturing processes for application to engineering product design. The successful students will understand the nature and characteristics of broad categories of materials and will understand the range of their application, together with the manufacturing processes that can be used with each material category. Based on the requirements for a specific part or product, the students will be able to use software tools to select the most appropriate material or set of materials, together with the associated manufacturing processes. Students will also be able to assess the environmental impact of their decisions.
Given the very diverse background of the students taking this programme, the instructors decided to use a software (ANSYS Granta EduPack) and card game. ANSYS produced a deck of 40 cards with material properties that engages students in a fun way. The authors produced another deck of cards introducing manufacturing process characteristics, based on the software, to complement the material properties deck (Figure 3).

4.2 Example of students' team project

One example of the type of projects proposed by students is the disposable lunch box, done by Jonathan Her Wei Quan, Welela Meka Kedir, Abyudhaya Padmanegara, and Ping Jing. In this project, the students tried to come up with a selection of materials and manufacturing processes that minimise the environmental impact of the product without penalising the cost. A survey was done with the target audience for this product to understand their preferences and other aspects of using such a product. The team found out that many users of disposable lunch boxes like the fact that they are disposable, but also want them to be durable, which creates some conflict in the design requirements. The way to incorporate both disposability and durability was to look at different combinations of paper and plastic, for which the EduPack software was used to extract material properties. EduPack also performs an eco-audit of the various options, allowing some birds-eye view comparison to be done (Figure 4). The final proposed product was a Spruce paper substrate coated with Polypropylene plastic film, with the specific sequence of manufacturing processes.

Figure 3. The deck of cards with material properties from ANSYS Granta (top left); The deck of cards with manufacturing process characteristics (bottom left); Zoom in to some of the cards from the manufacturing process cards (right)

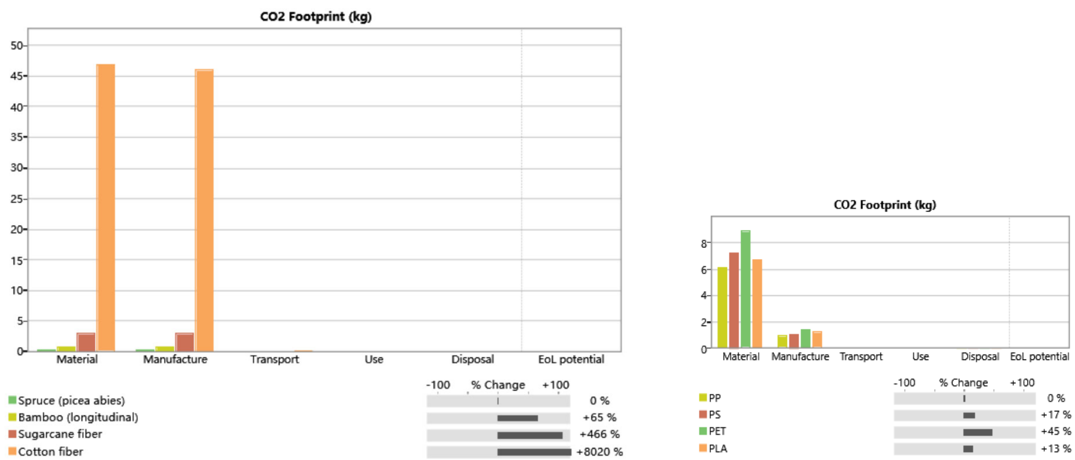

Figure 4. CO2 footprint of substrate(left) and coating (right) for various alternative materials

5 PRODUCT REPRESENTATION, MANUFACTURING, AND ASSEMBLY (PRMA)

5.1 Content and learning outcomes

The course is divided into two parts. The first part explores how the modes of representation of a product concept throughout the design process have an impact on the product itself, and how best to communicate the product concept to different stakeholders. The second part looks at strategies for manufacturing and assembly of physical mass-produced products, and the implications of product architecture on these decisions. Prior basic knowledge of CAD systems is recommended, together with a basic understanding of materials, manufacturing, and structured processes to select them.

At the end of the course, students will be able to understand assembly requirements, product management and product platforms, be able to redesign a product to improve manufacturability and assemblability, consider product assembly and product architecture when selecting materials and processes, and have a basic understanding of cost, and how it is influenced by architecture, assemblability, and manufacturability.

5.2 Example of students' team project

Another example of a student project is the electric kettle, done by students Yan Chang, Shen Zichong, Wu Zouyi, Wang Boyuan, Yang Xupeng, and Su Wensheng. In this project, the objective was to find ways of assembling and disassembling the product in a way that minimises labour, therefore contributing to reducing the environmental impact and lifecycle cost, with potential redesign of some components. The first step was to disassemble an existing electric kettle to understand all the components and how they work together, figure out some form of product architecture (Figure 5), and then redesign the product in a way that minimises environmental impact. After doing this, the team stroke a balance between an increase of 0.75% in CO2eq in production and a decrease in 13.2% in CO2eq during use.

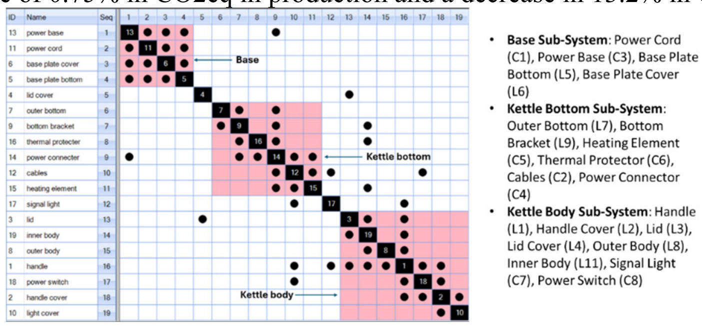

Figure 5. Design structure matrix [14] of the product, with identification of modules

6 STUDENT FEEDBACK

The Sustainable Product Design programme had one complete run with a student intake in September 2023 which already graduated, and a second intake in September 2024. At the time of this writing, two runs of MMPSD have completed, and one complete run of both DFS and PRMA. The student feedback will be from the first run of these courses. All students complete an end-of-term feedback form on a number of questions about the course using a 5-point Likert scale (where 1 is "strongly disagree/very poor" and 5 is "strongly agree/very good"). Table 1 shows the results for the three courses on their first run, plus the second run of MMPSD. At the end of the survey there is a section for open-ended feedback for "What did you like about the course", "What would you like to change about this course".

For DFS, some general comments from the students indicated "interesting" or "meaningful". One particular comment mentioned: "The course is interesting and takes a different direction from what is generally taught […], which I like, it feels like a refreshing breath of air to have this sort of format." Regarding areas to improve, the most commonly mentioned area was the "workload" of the course. This may be due to having two projects – mid-term and end-of-term – which require deliverables of both group presentations and group reports.

For the first run of MMPSD, one student commented that "Overall, the classes were pretty informative, but the theory study was boring", referring to the presentation of basic principles of materials properties. Another student mentioned that the course was "[…] very informative and you will be able to recognise many materials, and material compositions from the course. [I also] enjoyed the process of discussing and analysing issues together among group members. We can help each other and complement each other's strengths and weaknesses to enhance our teamwork". Another student was asking for "More mechanical content" to be included. This shows one of the dilemmas of the course, which is to deal with incoming students of varying degrees of awareness of the underlying principles pertaining to materials properties and characterisation, as well as knowledge of the characteristics of manufacturing processes. Some of the concerns of the students were taken into account before the start of the second run, and the overall performance as rated by the students, improved by comparison to the previous year, as seen in Table 1. The open-ended questions did not call attention to excessive detail or shallow content but rather praised the use of the software and the mini card games on materials and manufacturing.

For PRMA, one student commented that "Content was relevant though can be a bit heavy and dense. The additional reading references helps". Other students liked the "Comprehensive Coverage [and] Emphasis on Interdisciplinary Thinking", "Good classroom atmosphere", or "very interesting to disassemble and reassemble some small toys arranged in class". In contrast, some students expressed their concern about some other topics like "The lecture should be more detailed and introduce more practical cases", or "[…] a lot of things you don't understand when you study across disciplines. Go into a little more detail". Again, the contradictory responses reflect, to some extent, the differences in background of the incoming students.

Table 1. Students' response to the end-of-term survey

Course and year survey response	DFS	PRMA	MMPSD	MMPSD

	2024	2024	2023	2024
The course has stimulated my interest to learn more about the subject	4.0	4.1	4.7	4.7
The course has improved my knowledge on the subject.	4.2	4.2	4.7	4.9
The course is well organised and structured.	4.3	4.2	4.6	4.9
The course workload is manageable.	3.6	4.1	4.7	4.9
After going through all the classes and assessments, I will be able to do what is prescribed in the learning objectives	4.0	4.1	4.7	4.8
The course involved me in active learning experiences.	4.1	4.4	4.6	4.8
What is your overall rating of the course?	4.2	4.4	4.5	4.7

7 CONCLUSIONS AND FUTURE WORK

Overall, the authors feel that this programme has been a success in its first run, and improvements are being made in the second run, considering the feedback received from the students. The students in the second run are still in the programme and will graduate in August 2025. A clearer picture of the overall outcome of the improvements made will be available after that date, and more improvements may be implemented, which the authors hope to share in a later publication.

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