SUSTAINABLE DESIGN AND PRODUCT DEATH

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ABSTRACT

This paper details the methods of teaching and assessment in a third-year engineering module, Sustainable Design and Product Death, which was developed in alignment with CDIO standards. The module elaborates on engineering design and design approach with a special focus on sustainability. Design for Total Control is at the helm of the module to ensure engineering students are equipped with the knowledge, tools, and skills to consider sustainability throughout the product lifecycle and have complete control of product development, from cradle to grave. The module also aims to equip students with the knowledge and practice of the Triple Bottom Line framework to account for the environment, as well as the socio-economic impact of their product development practice. The students enrolled in the module come from Mechanical, Biomedical, Electronics and Sport Engineering backgrounds, hence catering to a diverse audience was given particular attention throughout the delivery of the module. The module delivery included a blend of conventional lectures with student-driven seminars to encourage collaborative learning in a hybrid, on-site and online learning environment. The excellent student outputs and their use of various engineering tools to improve product sustainability presented here are a testament to the success of the module structure and delivery. The positive student feedback ratings and high student attainment presented, further reinforce the effectiveness of the teaching methods adopted and the content covered in the module.

KEYWORDS

Sustainable Product Design, Sustainable Development, Triple Bottom Line, Engineering Education, Standards 1, 2, 3, 5, 6, 7, 8

INTRODUCTION AND BACKGROUND

The drastic shift in societal focus to environmental longevity has triggered businesses globally to measure their impact on the world around them. There is a pressing need to evaluate the harm caused to global resources by the activities of these businesses (Jackson et al., 2011). Indeed, the current consumption and development patterns are proving exceedingly hard to sustain in a world with an ever-increasing population and growing consumer demand (Tischner & Charter, 2017) and are causing irreparable social and environmental damage (Watkins et al., 2021). Businesses not only need conscious awareness of their impact but also need to modify policies and procedures to mitigate this impact – this process broadly comes under the umbrella of Sustainable Development (WCED, 1987).

Triple Bottom Line accounting provides a framework to measure sustainability (Elkington, 1997) and demonstrates the success of an organisation steered towards sustainable development using three separate aspects, economic, social, and environmental (Goel, 2010). These have also been alternatively defined as the 3Ps: planet, profit, and people. Businesses benefit tremendously by focusing on all three of these aspects while developing products and services (Tischner & Charter, 2017). Product design plays a crucial role in reducing the negative social and environmental impact (Watkins et al., 2021) and promotes positive economic impact of the business. This is especially true since product design and development influences 80% of the economic cost as well as 80% of the social and environmental impact of a product (Tischner & Charter, 2017; Johnson & Gibson, 2014; McAloone & Bey, 2009).

Traditionally, designers were only responsible for design, while production came under the domain of manufacturers. The current increased demand in design function means that this separation in design and manufacturing tasks is no longer possible and the designer needs to take complete control of the entire lifecycle of the product, from concept generation to the end of its life (Johnson & Gibson, 2014). Considering the Triple Bottom Line, sustainable product design must not only consider conventional design aspects (functionality, aesthetics, etc.) and eco-design, whereby the environmental impact is given considerable importance, but also the social and ethical issues around the development of the product (Tischner & Charter, 2017; Watkins et al., 2021) as shown in Figure 1.

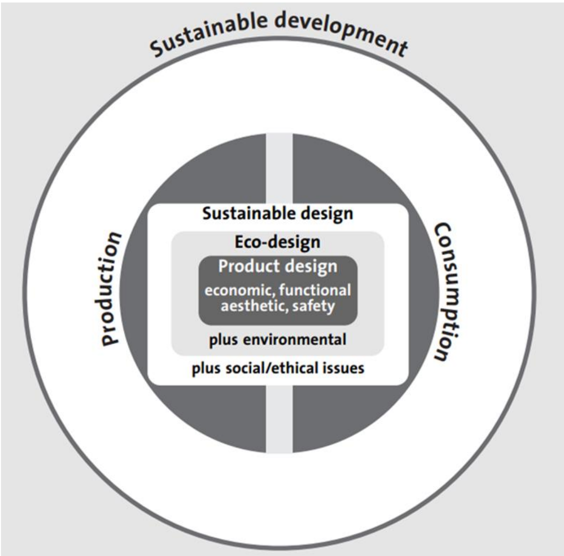


Figure 1:The relationship between eco-design, sustainable product design and sustainable development (Charter & Tischner, 2017)

It is essential that sustainable development is integrated in the development of future engineering education (Gumaelius & Kolmos, 2020) as higher education can help students recognise, understand, critically analyse, and resolve complex issues around sustainability (Seatter & Ceulemans, 2017). Kioupi & Voulvoulis (2019) consider sustainable development as an ideal end goal and highlight educational programs can equip the current and future generations with the tools to achieve this goal. The integration of sustainable development in education does however, come with its own challenges. Once such challenge is that sustainable education is prescriptive in establishing certain environmental targets (Alvarez & Rogers, 2006) due to which student input is neglected and they are simply assigned a supposedly correct stance on sustainability issues (Cheah, 2021). Instead, the aim should be to use sustainability issues as a probe to encourage student thinking (Seatter & Ceulemans, 2017). Students should hence be provided with necessary challenges, knowledge, and tools to resolve the complex issues around sustainability and a learning environment that is conducive to critical thinking.

CDIO standards offer guidelines for educational reform (Rosén et al., 2021) and integration of sustainable development is evident in the updated twelve core CDIO standards (Malmqvist et al., 2020). The department of engineering at Nottingham Trent University (NTU) is still in its infancy but is making great progress in aligning its courses with CDIO standards and developing them further. Two of the courses that have been previously reported are Innovation and Engineering Solutions (Siegkas, 2019; Butt & Siegkas, 2021) as well as Product Design and Case Studies (Siegkas, 2021). This paper presents teaching methods and assessments that are part of the latest module developed within the engineering curriculum at NTU, that adopts several CDIO standards to inform and enhance the student learning experience. The module entitled 'Sustainable Design and Product Death' integrates sustainable development with engineering education as a means to provide engineering students at NTU the tools and knowledge to holistically tackle sustainability issues in line with the Triple Bottom Line. As opposed to being prescriptive, the module presents students with an opportunity to critically analyse and solve sustainability related issues in engineering design.

MODULE DESCRIPTION AND DELIVERY

The module in question here is a third-year optional module for all engineering disciplines at NTU (Electronic, Mechanical, Sport and Biomedical Engineering). Due to the diversity of the students' engineering backgrounds, the content of the module was kept fairly broad. Although, not a prerequisite, Innovation and Engineering Solutions (Butt & Siegkas, 2021; Siegkas, 2020) and Industrial Design and Product Case Studies (Siegkas, 2021) reported previously, have some similar content to this module however, Sustainable Design and Product Death is still an introductory course and can be treated as a stand-alone module. The main aim of the module was to introduce sustainable engineering within the domain of engineering design to encourage product development in any engineering discipline that is not only mindful of the resources used but also the product's use and eventual disposal all the while considering socio-economic factors. The overlap between these two domains allowed students at NTU to take direct and complete control of the entire design cycle while considering sustainability at each stage of product development (Figure 2).

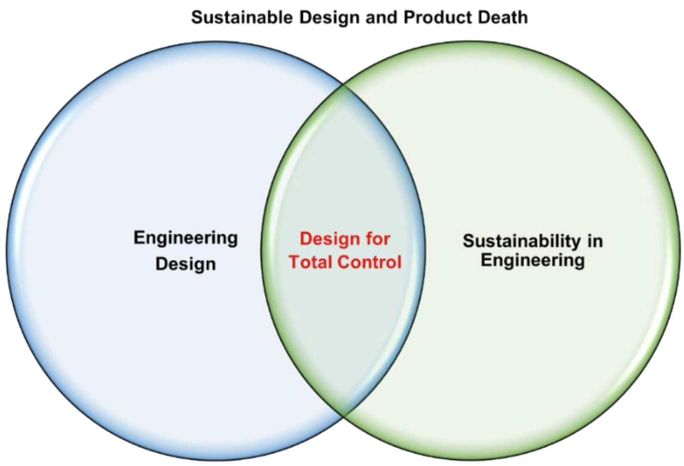


Figure 2: Overlap between conventional engineering design and sustainable engineering to provide complete control over sustainability considerations throughout product development

The module was delivered via 11 lectures (2 hours each), 10 seminars/tutorial sessions (2 hours each) and a further 10 drop-in sessions (1 hour each). The lectures covered the theory of engineering design, sustainable engineering in practice and deployed a range of industrial examples to contextualize the product lifecycle. The lectures were adapted from the book by Johnson & Gibson (2014) and the content was divided into two main sections:

Design: The lectures covered the entire design process such as the phases of design, evolution of design, design information, design output and tools used for the design processes. The conventional design cycles including (but not limited to) Concept, Detailed and Final Design Specifications were demonstrated but themes of environmental impact and sustainability at each stage were discussed. The discussion also involved the energy and financial expenditures at each stage (sourcing, manufacture, design, etc.). In essence, the classic design and manufacture model was illustrated and compared with the Sustainable Engineering Design Whole Life Model (Figure 3) and the aim of this comparison was to ensure that sustainability is embedded through the product lifecycle. Various design tools were also taught which included TILMAG, morphological analysis, heuristic redefinition, etc. for the generation of ideas. The lectures were kept interactive with discussions around product development and industrial examples that allowed students an opportunity to provide their input in the product development lifecycle.

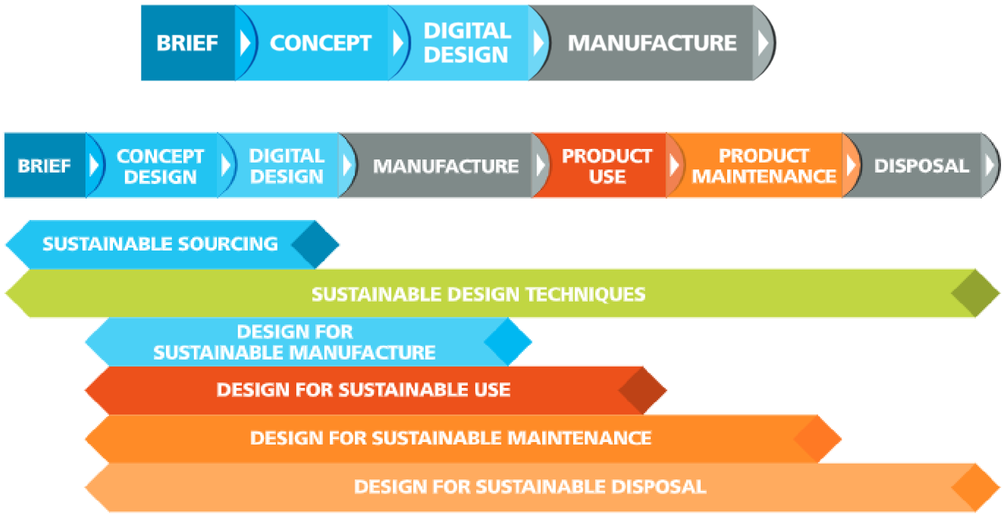


Figure 3: Classic design model (above) VS Sustainable Engineering Design Whole-Life Model (Below) (Johnson & Gibson, 2014)

Sustainability in Engineering: The second section of the lectures provided context for sustainability by defining sustainable development through the Triple Bottom Line. Again, sustainability throughout the product lifecycle was emphasized, however this time, metrics for sustainability at each stage were defined in addition to providing suggestions on how to reduce energy and cost expenditure at each stage of product development. The metrics were based on the value of the embodied energy at a particular stage, called a sustainable value (Johnson & Gibson, 2014). The metrics defined at each stage are illustrated in Figure 4. Ansys Granta was introduced within the lectures for eco-audits and robust materials/manufacturing process selection as well as to provide values for the metrics defined at each stage. The sustainability section of the lectures also covered drivers of sustainability in design such as regulations and legislation around the world, tools outside legislation for sustainable development and the financial and social drivers of sustainability. Strategic sustainable design was also brought into focus whereby the merits and application of the Triple Bottom Line (using case studies) was discussed along with the consumer's perspective of sustainable design.

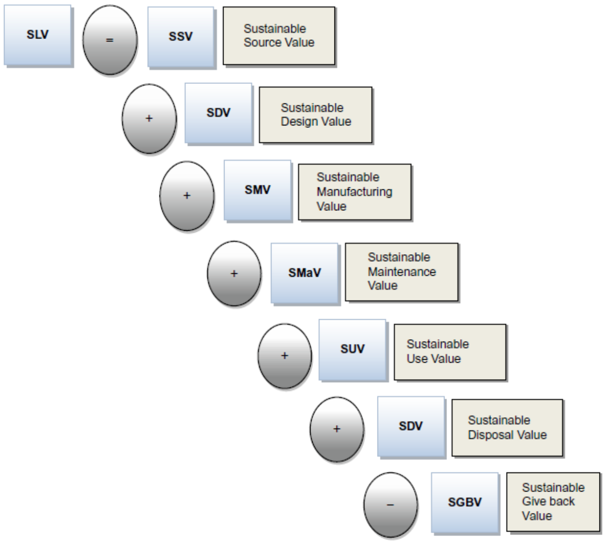


Figure 4: Sustainable Whole-Life Model (Johnson & Gibson, 2014)

The students were assessed via a product design project (50%) and an online examination (50%) at the end of the term. The product design project gave students a design brief to develop a motor driven product that can inflate tires, beachballs, air mattresses, etc and one of the constraints was that the client is interested in a low-cost product that will increase their product margin but not at the expense of the environment. The final submission for the project was a technical report that detailed all the phases of the product development from concept generation to a detailed design. An important aspect of the project in addition to inclusion of the conventional product development processes was the consideration for sustainability. Sustainability had to be considered throughout the product lifecycle but a separate section on sustainability considerations was also expected in the report to allow for the socio-economic impact of the product to be included. The marking criteria used for the product design project is given in Table 1.

Table 1: Marking criteria used for the product design project report

Product Design Project	
General Criteria	**Product Design Specific criteria**
General report structure	Introduction & Literature
Figures and tables	Concept design
Abstract	Detail Design
Conclusion	Materials and Manufacturing
References	Sustainability considerations

Interactive student-centred seminars were run in tandem with the lectures. The seminars focused on providing students with the means to communicate and apply the knowledge gained in lectures through instructor guidance, tutorials, and discussions. A flipped classroom was deployed in these seminars to allow the students to work on the product design project. Video tutorials on CAD design were provided along with tutorials on using Ansys Granta for the students to practice at home. A product design workbook was created and provided to students which covered a myriad of product development processes ranging from understanding the design brief to producing a final specification for the product. The students were provided the lectures and resources such as video tutorials in advance so that a discussion around the workbook could take place in the seminar. The activities in the seminar were further broken down into design phases namely Product Design Specification (PDS), Concept Design Specification (CDS), and Final Design Specification (PDS)/Product Specification (PS). The schedule for the seminar activities (Table 2) was also released to the students at the start of the term so they were aware of what to prepare for before attending the seminar discussions. The first 8 seminars took place online due to the governmental restrictions surrounding COVID 19. The discussions moved along via instructor probes, arguments from students and further aided by peer-to-peer discussions. A recurrent probe in all the seminars was the impact of a specific activity (design, sourcing, manufacture, etc.) on the environment, society, and profit to ensure the themes of the Triple Bottom Line were always considered at each step of the development of the product.

Table 2: Flipped classroom seminar schedule

Seminar	Activity	Gateway
1	CAD revisited & Research skills	Phase I (PDS)
2	CAD revisited & Research skills	
3	Design brief & Creativity/ Concept generation tools	
4	Evaluation and selection of Concept/ Concept design	Phase II (CDS)
5	Calculations / CAD model of concept	
6	Sustainability considerations / CAD model	
7	Materials and Manufacturing	Phase III (FDS, PS)
8	Design optimization/ costing/ sustainability	
9	Detail design/ GA drawings	
10	Finishing up and revisions/ Report writing	

The end of term examination was initially expected to be held in person, however, the unpredictability and restrictions surrounding the COVID 19 pandemic meant an online examination had to take place instead. As the examination was an online, open-book exam; two essay based, open-ended questions formed the exam that allowed room for discussion on the lines of the content taught in class. In the first question, the students were asked to analyse the evolution, current practices and future of engineering design and discuss the importance of engineering design in the context of sustainable development. The question expected the students to link the various tools and processes of engineering design such as design for total control, performance prediction and (or) smart manufacturing with principles, drivers, and legislation of sustainability. The second question was the application of the knowledge gained in class (demonstrated in Question 1 of the examination). The question asked students to propose the design of a product which had certain constraints and requirements. The students were expected to consider the entire life cycle (raw materials sourcing to disposal) and discuss how they would propose to design and manufacture the components of this product with the lowest possible environmental impact. The question expected design propositions in terms of sustainable sourcing, sustainable design techniques, sustainable manufacture, sustainable use and maintenance, and sustainable disposal while considering the constraints and requirements of the product provided in the exam question. The marking schemes for the examination questions are given in Table 3.

Table 3: Marking criteria used for the end of term online examination

Question 1 Marking criteria	Question 2 Marking criteria
General structure and flow of the essay	General structure, flow of the essay and use of high-quality sources
Principles, drivers, and legislation of sustainability clearly outlined	Proposed methods for sustainable sourcing
Design for total control considered providing a context for sustainable development	Proposed methods for sustainable design techniques
Themes of adoption of whole life approach clearly demonstrated	Proposed methods for design for sustainable manufacture
Strategic sustainable design and performance prediction given ample consideration	Proposed methods for design for sustainable use and maintenance
Critical thinking and relevance of arguments	Proposed methods for design for sustainable disposal
Use of high-quality sources	Consideration of the constraints and requirements highlighted

STUDENT OUTPUTS AND DISCUSSION

The aim of the two separate lecture sections was to provide students with a rounded view of product design from the perspective of the designer, the consumer as well as the company producing the product, covering all aspects of the Triple Bottom Line. An understanding of all three aspects has shown Triple Bottom Line to be a balanced and coherent construct of sustainable development (Epstein, 2008). As legislation and certification industry was also given attention, strategic sustainable design that catered to the societal, economic and environmental needs was evident from the student outputs. As an example, Figure 5 illustrates a student 's concept evaluation at a very early stage of product development. The evaluation and selection of the concept design already considers a myriad of socio-economic and environmental aspects such as, ease of maintenance, safety, market influence, etc. The concept selection clearly demonstrates an amalgamation of conventional engineering design principles with that of sustainable engineering.

Criteria	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6
Function	7	9	9	3	7	9
Cost	10	1	4	1	10	2
Sustainability	8	5	7	4	8	6
Reliability	8	9	6	10	8	7
Maintenance	10	10	6	2	9	4
Serviceability	8	5	6	2	8	6
Market influence	9	7	7	1	10	6
Ease manufacture	10	8	10	1	9	4
Safety	9	8	9	10	9	9
Limits	8	9	9	4	8	9
Aesthetics	7	7	7	4	7	5
Ease of use	10	9	9	3	10	6
Noise	6	5	6	2	6	3
Ergonomics	7	8	7	9	8	4
Weight	10	5	6	1	10	5
Total Scores	127	106	108	54	128	85

Figure 5: Product concept evaluation and selection. Evaluation table courtesy of Riten Patel (2021)

Some other student outputs to consider are the detailed designs produced (Figure 6) that clearly demonstrate forward thinking and modular designs that are easy to use and maintain, making them credibly sustainable. These designs are informed by similar concept selections as discussed.

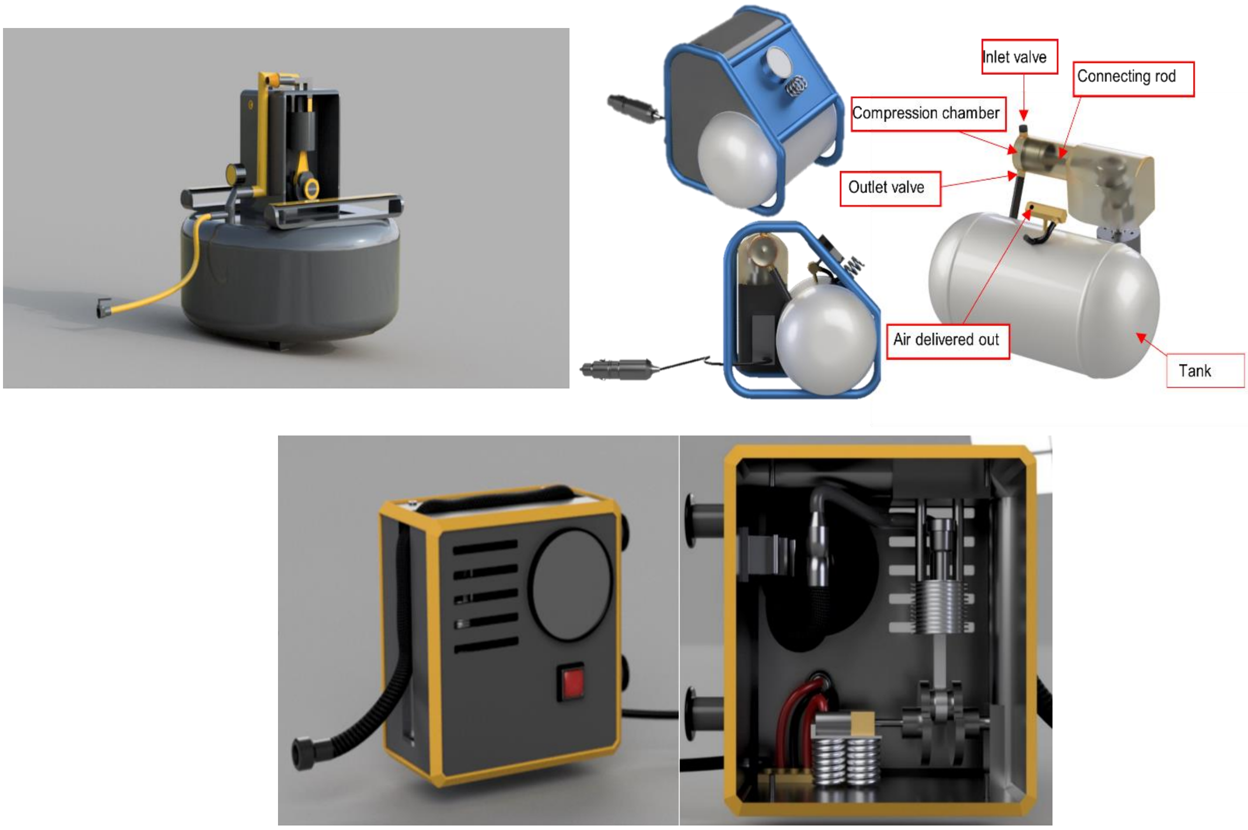
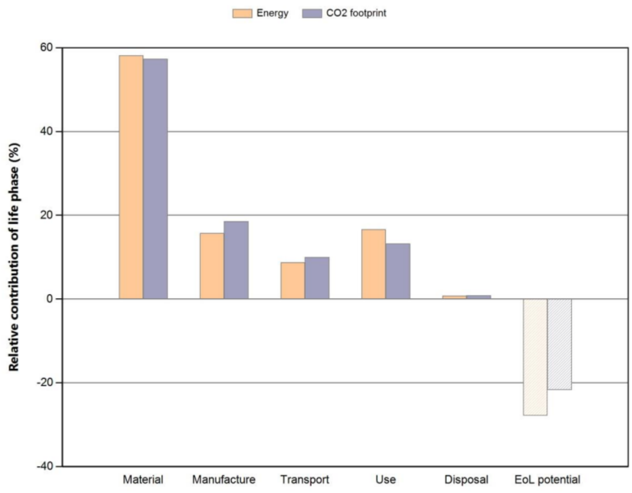


Figure 6: Detailed designs of the motor driven air compressor. Images top-left, top right and bottom courtesy of Sam Hunt (2021), Jarrod Greenwood (2021) & Jonny Cox (2021), respectively

In addition to considering socio-economic and the environmental factors for the concept and detailed designs, the students also conducted comprehensive eco-audits at various stages of the product development with several materials/manufacturing processes. The eco-audits helped the students define sustainability metrics that were illustrated in Figure 4. An example of a product eco-audits using Ansys Granta is shown in Figure 7. The objective of these eco audits was to minimize the energy consumption at each stage by as much as possible. Again, benchmarks for energy consumption/reduction were not prescribed, instead only methods such as sustainable sourcing, modular design and 4Rs end-of-life disposal methods were suggested (among others) during seminars for students to make an informed yet completely independent decisions.



Energy details   CO2 footprint details

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	25.1	58.1	1.55	57.3
Manufacture	6.79	15.7	0.501	18.5
Transport	3.75	8.7	0.27	10.0
Use	7.17	16.6	0.357	13.2
Disposal	0.34	0.8	0.0238	0.9
Total (for first life)	**43.1**	**100**	**2.7**	**100**
End of life potential	-12		-0.586	

Figure 7: Eco-audit of the product developed. Image courtesy of James Cree (2021).

Most students demonstrated a significant engagement with the design for total control approach and demonstrated clear adoption of the Triple Bottom Line framework throughout the product development lifecycle. This was further exhibited in the examinations where most students linked the various tools and processes of engineering design such as design for total control, performance prediction and (or) smart manufacturing with principles, drivers, and legislation of sustainability. These claims are backed by the high student attainment where 82% of the students achieved an Upper Second or First - Class grade that represent 'very good' and 'excellent' attainment, respectively. In the examination 90% of the students achieved an Upper Second or First - Class grade. These project and examination results are illustrated in Figure 8.

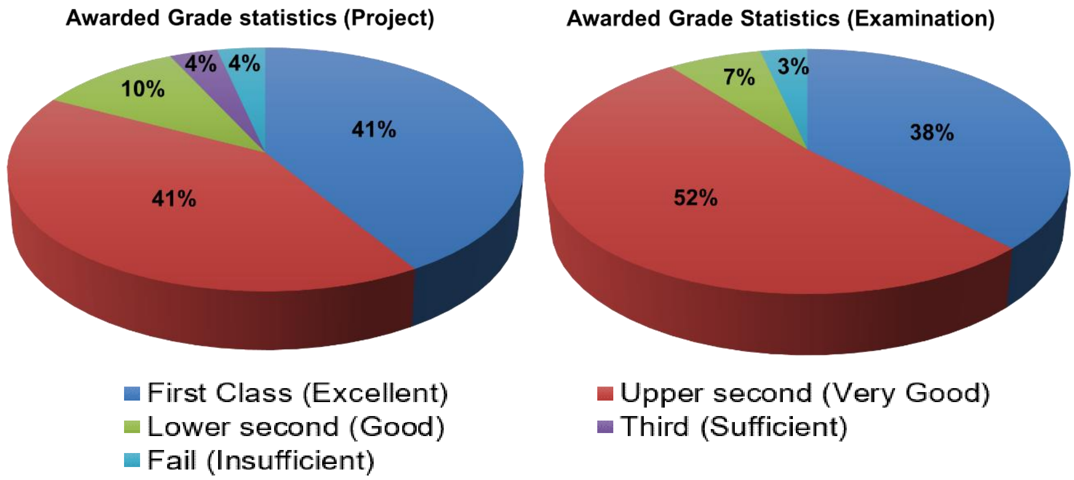


Figure 8: Student attainment in the project (left) and final examination (right)

Methods of embedding sustainability in engineering cannot be prescriptive as it is extremely subjective; tools and knowledge can be transferred, however sustainability in engineering design requires a change in mindset (Johnson & Gibson, 2014). As demonstrated, sustainability was not prescribed at end of life/disposal of the product, rather sustainability was encouraged throughout the product lifecycle. The focus was moved away from the rather dominant view of sustainability as an end-of-life consideration to a more holistic approach considered at each stage of product development. The probes during the seminars of how any aspect of design affected profit, people or planet at any stage reiterated the importance of being mindful of the Triple Bottom Line. This change was further reinforced by the exam questions that emphasized a whole life sustainability model.

The effectiveness of interactive lecturing for students with diverse science backgrounds has already been reported (Ernst & Colthorpe, 2007) and this was used for the current module. The in-class discussions and the variety of case studies allowed students to think critically and creatively while the flipped classroom seminars promoted active learning. Flipped classrooms have shown to encourage students to take responsibility of their own learning and engage in active learning (Lai & Hwang, 2016). Crucially, students have also shown in the past to appreciate flipped classrooms (Cronhjort & Wuerlander, 2016) as they can optimise the use of their time (Cheah & Sale, 2017) and work flexibly at essentially any location (McDonald & Smtih, 2013). The product design workbook was very well received as it provided opportunities for peer assisted and collaborative learning. It also provided an opportunity for the instructor to tune into student thinking; this has shown to make it possible to identify any misconceptions or lack of understanding (Cheah & Sale, 2017). The end-of-term module survey had very high scores of 4.7, 4.8, 4.6 and 4.6 out of 5 for student's *'Overall Satisfaction', 'Feedback on module teaching', 'Assessment and Feedback'* and *'Module Organisation and Resources'* which is a testament to the effectiveness of the teaching methods adopted. Most of the students had very positive and encouraging comments where some appreciated the skills learnt as in *"This module has proved the most valuable module so far across all years because of the skills learnt and their use in the world of engineering and product development"* while others appreciated the teaching methods, as demonstrated by the following comment: *"I like the focus on student interaction and questioning to help move seminar sessions along"*

CONCLUSION

The teaching and assessment methods adopted for a third-year engineering module at NTU have been presented here. The module is an introductory course for all engineering courses at NTU to product development and how to embed sustainability in design, with a special consideration of the Triple Bottom Line. CDIO standard informed the development of the module, specifically standards 1 – 3 & 5, 7 and 8 were demonstrated in this paper via module delivery methods and discussion of results. A key area of focus in the delivery was student engagement and active learning, ensuring that sustainable education was not prescriptive. Excellent feedback via module surveys and student attainment demonstrates the success of the module and the variety of tools used by students to integrate sustainable development in engineering design was confirmation that learning outcomes were met successfully. Despite the positive feedback, the module has room for improvement, specifically in replacing online examinations with a more conventional coursework that can perhaps test eco-auditing abilities of the students. The coursework could also provide an opportunity for a group project that can tie into and compliment the individual product design project while further encouraging collaborative learning.

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BIOGRAPHICAL INFORMATION

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