ENGINEERING LEARNING OF SUSTAINABLE PRODUCT LIFECYCLE THROUGH CDIO

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ABSTRACT

Sustainable development is an optional CDIO (Conceive, Design, Implement, Operate) standard in the engineering curriculum, however, due to the impact of climate change on society and the environment, sustainability is now seen as a crucial aspect of learning. Engineering has contributed to climate change through non-sustainable solutions, so it is important to implement a sustainable CDIO standard in the engineering curriculum. In the UK, the Engineering Council already requires engineering-accredited courses to embed sustainability into the engineering curriculum, learning, practice and assessment following the UNESCO sustainability goals. This means that the engineering curriculum is required to provide learning opportunities for students to engineer sustainable solutions that are fit for all of society. This paper illustrates how the optional CDIO standard: sustainable development has been implemented in a second-year capstone project module The module challenges students to research and develop a low-carbon footprint product for World Rugby The module placed learning emphasis on a diamond TQM+ paradigm (Time, Quality, Management, Sustainability, Health & Safety) and challenged students to consider environmental impact and circular economy solutions. The paper reports on student learning, challenges, and successes in satisfying this diamond TQM+ paradigm to engineer sustainable rugby equipment (products, clothing, footwear, PPE) solutions and opportunities for further student learning development.

KEYWORDS

Engineering Education, Capstone Project, TQM+, UNSECO Goals, Earth Charter, Optional Standard: Sustainable Development

INTRODUCTION

Malmqvist et al (2017) demonstrated that there is a clear need for engineering graduates to have competencies in sustainable development, this was further developed by Malmqvist et al (2019) and recommended by Malmqvist (2019) for adoption by CDIO Council as optional CDIO standard sustainable development. Rosen et al (2021) reported on the pilot implementation of the optional standard and assessment rubrics to be used when implementing optional CDIO standard sustainable development as a starting point for implementation in the curriculum. Dubova et al. (2020) embedded this optional standard into metallurgical education to challenge students to consider and justify material selection in CDIO projects on sustainable considerations.

In reality, any CDIO project students have historically been challenged at the concept and design stage to consider the time (manufacture/fabricate), quality (fitness to requirements) and cost (materials and manufacture), Clausen (2018) highlighted that CDIO projects have the opportunity encapsulate TQM and Lean Management. However, TQM and Lean Management neglect sustainability and safety considerations. Hamdan et al (2021) demonstrated the adoption of more manufacturing corporate social responsibility (CRP) focus enables a business to address and align different TQM and Corporate Green Performance (CGP) considerations. Santos et al (2019) safety management systems (SMS) can be adopted well under a TQM approach in particular to address unsafe working conditions, (Álvarez-Santos, 2018). However, safety is an important consideration at each stage of the CDIO project to generate a new product, addressing the safety from an end user perspective at conceiving, designing and operating a new product, also safe manufacture and fabrication at the implementation stage. This has been very much taken to heart by the construction industry as safety is part of construction site TQM strategy leads to improve quality of construction in terms, also site planning, organization, coordination, and profit, (Husin, 2008).

Adopting the TQM approach with a focus on producing quality products in a safe approach and applying environmental and societal considerations can increase a business's bottom line (Mohan et al, 2004), Therefore for businesses not only on moral and ethical grounds a Time, Quality and Management (TQM+) diamond paradigm approach offers a more sustainable business economic health than traditional TQM triangle. As engineers conceive, design, implement and operate new products for a business, the next generation engineers need learning opportunities to apply the TQM+ diamond paradigm considering during a CDIO project the;

- time to produce and recycle,
- cost to manufacture, deliver, recycle/end of life,
- quality of the processes and product lifespan
- health and safety of the product, manufacture and recycle/end of life,
- sustainability resources, materials products and recycling/end-of-life.

This paper will illustrate how the optional CDIO Standard: Sustainable development and facilitating the students to adopt a TQM+ diamond paradigm approach enabled the students to address conceiving, designing, implementing, and operating a low carbon footprint product for World Rugby. The students were challenged to research rugby equipment (products, clothing, footwear, PPE), and identify opportunities for product improvements or opportunities for new products within the World Rugby equipment performance constraints. The students were challenged to CDIO new products in terms of time (produce), quality (lifespan of the product), management (costs both in terms of financial and carbon footprint), sustainability (sustainable raw materials, manufacture process and end-of-life (recycle/reuse)) and health & safety (as PPE). Essentially challenging the students to conceive, design, implement and operate new Rugby PPE products that satisfy the TQM+ diamond paradigm. The paper will report on student learning, challenges, and successes in satisfying the diamond TQM+ paradigm to engineer sustainable rugby equipment (products, clothing, footwear, PPE) solutions. Identifying in particular, where students demonstrated learning well in engineering sustainable solutions. It also illustrates the aspects of the product lifecycle design and implementation that the students found challenging, which is difficult for students to research and complete and therefore requires further student learning development.

PRODUCT LIFE-CYCLE MODULE

The module is a second-year module of a biomedical, mechanical and product design engineering degree course, and is 40 credit (20 ECAT) module. The module aims to provide students with an overview of complex product life cycles from raw materials to end of life taking into consideration the wider social, environmental, business and financial contexts of the engineering solution and the role of a professional engineer operating within the field of mechanical related engineering, with particular attention to their legal, safe and ethical responsibilities. The module learning outcomes, the students by the end of the module should be able to:

1. Apply appropriate design methodology, engineering analysis methods and engineering management to conceive, design, rapid prototype/simulate and evaluate the operation of a heuristic product solution;
2. Evaluate data and solve basic fiscal and engineering mathematical computations/modelling to support a conceptual engineered solution for a problem typically sourced from the industry;
3. Produce technical data sheets and drawings to support the manufacture and assembly of a product using a computer software tool; and
4. Understand the wider legal, social, political and ethical context of a product and its lifecycle and the professional responsibilities of the engineer.

The module was designed to build upon the student's first-year learning and in particular first-year capstone project module, providing an opportunity for students to develop and apply their technical and non-technical skills to solve a mechanical engineering-related problem typically sourced from the industry. The module approaches developing these skills through a process of engineering in practice, continuous professional development (CPD) and assessment for learning. The students are to undertake a lifecycle and risk assessment study project in pairs or a team of students. The timetable is a mix of engineering degree courses, for example, one tutorial group consisted of biomedical engineering and mechanical engineering students. The students self-selected their groups.

The projects are identified by industry in this case on behalf of World Rugby to examine opportunities for more sustainable Rugby PPE. Students are challenged to identify what has the potential to be improved on sustainability grounds Rugby PPE, students are encouraged to examine in detail and map out the life cycle of the product. The groups are encouraged to break the product down into its principal components and trace them back to the raw materials and likely country of origin. The students are encouraged to select a product that currently has significant health, social or ethical aspects associated with at least one part of their manufacture. The students are to conceive, design, implement and operate more sustainable product solutions.

The students throughout the project explore the engineering design methodologies, design thinking, systems thinking from engineering design, material selection, simulation/prototype and evaluate the operation of the product taking into account health and safety, commerce, sustainability and business management considerations, essentially diamond TQM+ paradigm. They are also required to consider the users of the product and how it might be made more suitable for different groups of users, for inclusive solutions for all of society. The students present their final results and personal reflections on the project in the form of a presentation and report illustrating the estimation of raw material costs, health and safety, end-of-life environmental impact etc.

The module provides a learning opportunity on the full engineering product or systems lifecycle, the role of other professionals and processes in the product lifecycle for example the engineering industry and government(s), marketing, finance (cost estimation, budgeting and forecasting), environment, efficiencies, end of life, carbon footprint, maintenance, sustainability, ethics, risks, hazards, health and safety.

This paper presents the academic qualitative analysis of the student group submissions, in applying a TQM+ diamond paradigm to CDIO sustainable World Rugby equipment. The module results identify common learning themes and challenges of satisfying the TQM+ diamond paradigm. This paper highlights the range of the student's research and focus, in particular, analyses the quality of the student material selection for their choice of equipment using the TQM+ paradigm.

MODULE RESULTS

The students were introduced via a mini-lecture to World Rugby and their requirements concerning equipment, the type, performance constraints and low carbon footprint product. The students pursuing different degree pathways such as Biomedical, Mechanical and Product Design engineering were given the freedom to pick and research their problem. The students were encouraged to focus on equipment relevant to their degree and their engineering interests. This led to a plethora of choices (Table 1) and student engagement which may not have resulted if a specific problem.

Table 1: Summary of projects undertaken and team composition.

Focus of Project	**Student Degree pathway**	**Number of students**
Rugby Ball bladder	Mechanical Engineering, Mechanical Engineering-Advanced Manufacture and Mechanical Engineering-Building Services	7- two groups of 3 & 4 respectively
Studs used in boots	Mechanical Engineering, Mechanical Engineering-Advanced Manufacture and Biomedical Engineering	8 – two groups of four each
Leather vs Synthetic leather used in boots	Mechanical Engineering	3
Rugby Body Padding	General Engineering and Mechanical Engineering-Advanced manufacture	4
Design and efficacy of a Mouthguard	Biomedical Engineering	4
Spoke guards used in wheelchair rugby	Biomedical Engineering	4
Breast Padding	Biomedical Engineering	2
Rugby Scrum CAP	Mechanical Engineering, & Product Design Engineering	6 - two groups of three each
Protective Gloves in Wheelchair Rugby	Product Design Engineering	3
Protective goggles	Product Design Engineering	3
Rugby Tackling Machine	Mechanical Engineering	3

Multiple research projects were carried out in understanding the lifecycle of rugby balls (Figure 1), materials used in the shoe upper (excluding the sole) (Figure 2), tackling and scrum training equipment, PPE such as Headgear and Shin pads, and some biomedical students even looked at mouthguards and wheelchair rugby.

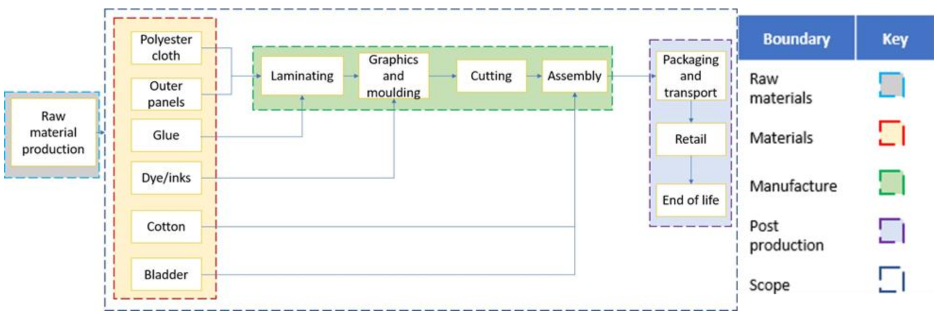

Figure 1: Scope of the lifecycle analysis carried out by the students studying rugby balls.

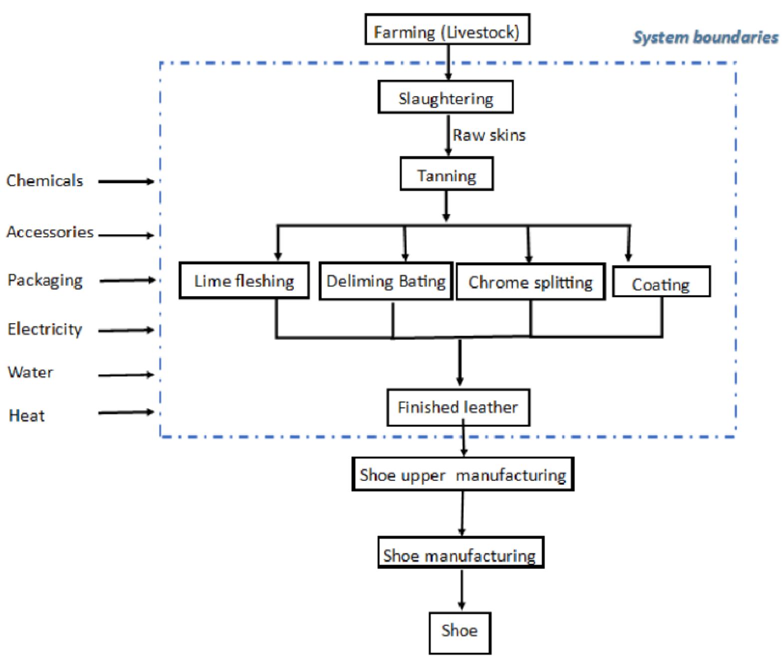

Figure 2:System boundaries for the study of leather used in making shoes.

Each group adopted different methods to evaluate the material selection for the equipment and satisfy the TQM+ paradigm, as shown in Table 2, in particular, the comparisons between material choice for a piece of equipment had on environmental impact, that is CO2 emissions. Some groups looked at different materials and carried out an analysis of a range of engineering and environmental factors (Table 3)

Table 2: Table Methods of material comparison selected to satisfy the TQM+ paradigm

Project	Material	CO2e	Water Consumption(l)	Manufacture process
Rugby Ball	Butyl Rubber	28 kg		Fabric Production- Molding- Laminating Assembly
	Natural Rubber	14 kg		
Studs	12- Aluminum Stud	0.29-1.14 kg		Casting + Processing
	12- Zinc Alloy Stud	0.31-0.954 kg		
Scrum Cap	EVA - Ethylene Vinyl Acetate	7.054-70.321 kg		Laser Cutting-Molding and then stitching together
	PE- Polyethylene	5.274 g		
Boot Leather	Natural Leather	773.5 g	0.17	As explained in Figure 2
	Synthetic Leather	274.5 g	104	
Breast Padding	EVA - Ethylene Vinyl Acetate	2.364 kg	1.29	Fabric cutting- assembly with foam to sowing for completion
	PE- Polyethylene	2.843 kg	1.87	
Mouthguards	EVA - Ethylene Vinyl Acetate	5.05 ± .24 kg	2.66-2.94	Material Extraction and Moulding
	PE+EVA	5.26 ± .26 kg	2.74-2.89	

Table 3: One group’s alternative material Analysis to satisfy the TQM+ paradigm

Environmental and Engineering Parameters studied for a spoke guard			
Material	**Yield Strength (MPa)**	**Price (GBP/kg)**	**Carbon Footprint kgCO2E**
Bamboo	39.9	1.425	1.057
Aluminum	163	1.56	8.845
PLA	36	2.6	2.79
PVC	55.5	1.865	1.855
TPU	39	2.42	3.21
PET	67.5	0.94	2.68
PE	23.45	1.1	1.86

Interesting further observations of the student’s analysis of the carbon footprint of a product lifecycle also fed into the material selection. One group of students studying the rugby ball calculated and reported an increase of 31% in the carbon footprint when comparing a synthetic rubber ball (Butyl) to a natural rubber rugby ball (Figure 3).

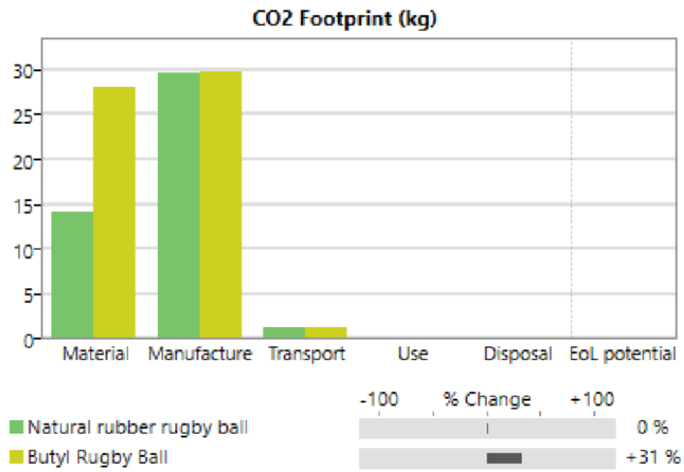

Figure 3: Student carbon footprint comparison for a Butyl rugby ball in comparison to a natural rubber rugby ball.

Another group researching the product lifecycle of mouthguards compared in addition to material environmental impact (Table 2) they also studied potential materials' physical properties such as toughness/hardness, impact test properties and performance against bacteria and porosity for permeation of saliva. Students researching the scrum caps produced an interesting analysis of the amount of CO2e used/emitted during the product lifecycle of a headgear made out of EVA (Table 4). Results show that almost 98% of the impact on the environment came from the use of water.

Table 4: Values of CO2e for lifecycle analysis of a Rugby headgear made of EVA

Property	Value (gCO2E)
Primary Embodied Energy	298.78
Primary Material CO2 footprint	289.85
Polymer Moulding	64.53
Water Usage	69207.00
Material Processing	93.50
Recycling and Combustion	358.40
	70312.06

Students studying the padding material used in the body padding reported that:

> "*A change in foam to an eco-friendlier option known as eco-foam, this option reduces the CO2e impact by 14% and is fully recycled and recyclable*".

From the academic perspective, the student's academic performance is shown in Table 5. The results for individual assessment show a 91% first-time pass rate while the take-home exam shows a 90 %

first-time pass rate. The overall pass rate for the first-time sit is 90% which is higher than the UK norms and illustrates that the majority of students demonstrated meeting all the module learning outcomes and engaged in the module learning.

Table 5: Pattern of student grades following the 4 assessments – 3 coursework and 1 exam and a total of 47 students

Commented [AN1]: We number of students studying the module please

	Coursework	Exam	Overall
Min – Max	15-84	8-96	12-85.5
Mean	57.8	63.75	55.75
Standard Deviation	17.6	22.7	19.2
Pass %	91	90	90

MODULE RESULTS DISCUSSION

While all students presented their findings about the impact of the product studied only 3 out of 14 groups included other parameters such as water requirements and other measures of environmental impact. All the groups investigated the problem from environmental and engineering perspectives as well as creating a total framework which helped them understand and apply their learning to meet the TQM+ paradigm for their projects.

One of the first findings of this module CDIO project was that the students enjoyed having their area of focus and research.

"*it allowed us to find problems and focus on a product of our choice*". Student Survey Feedback

The module brief was designed to provide an industry-sourced CDIO project with appropriate challenge, and stretch, and provided project choice through the selection of Rugby equipment. This empowered the students in choosing a rugby product that would be more aligned with their degree. The biomedical engineering students were able to pick research studies focused on injury prevention such as mouthguards or even looking at Paralympic rugby where the students focused on rugby wheelchairs. Usually with a CDIO project, when sourced from industry, the problem statement is already defined and limits the student scope (especially if the teaching being carried out is across different pathways). The students were required to investigate a product not only from an environmental perspective but also from cost, quality, time to manufacture and health and safety perspective, the TQM+ paradigm. Essentially the students were needing to gauge what improvement could they achieve concerning sports, health and safety performance of the product as well as reduce its environmental impact.

Work done by the students shows an increase in their understanding of life cycle assessments add and perception of the pact of engineering on the environment. Some of the reports submitted highlighted the learnings of the students, where the students identified that for certain products the use of water is the highest contributor to the environmental impact. This led to the identification of other products and processes, such as everyday clothing and the washing/laundry pattern, which the students use, and the realisation of the environmental impact everyday activities may have. The learnings from the project have helped students understand not only the implications in design and manufacture but also have understood the implications in their daily life.

As part of the module, the students, under the guidance of the technical team, also used energy meters (PM001-C, Maxcio, Ningbo Qiyue Electronics Company LTD, China) to understand the carbon footprint of different components/processes in a manufacturing setup/process. During the experiments, students were able to calculate total power usage that was then converted to GHG emission equivalency. During the experiments carried out, while looking at all the energy consumption the students were able to relate to the energy wastage that occurs and identify sources of energy losses. The students were also able to correlate the energy losses noted by comparing them to their experiences with the increase in energy bills in the UK.

Along with all the positive learning outcomes, there was a lot of feedback from the students which would help improve the Engineering Product lifecycle module in the long run. The main feedback received was

> "*More hands-on working to be provided to improve engagement*".

The other feedback received at the end of the module review survey was:

> "*More hands-on practical sessions would be beneficial as it was mostly sitting in a classroom on a computer*".

The module content is comparatively more theoretical than other traditional engineering modules such as material testing, machine shop, and computer-aided design.

The module team has worked on the feedback received and has carried out more statical research this year to understand how student engagement can be improved. To improve student interaction, not just in the classroom but also with the module documentation, the module team is going to try and incorporate different methods of signposting information- through emails, announcements and interactive quizzes while monitoring the interaction information to gauge what works best. In the past, the author has noticed an increased enthusiasm and animated discussion whenever a little quiz or competitive questioning is carried out (O'Neill, 2020; Zhang & Yu, 2021). The module teams also plan to carry on investigating different techniques used by other researchers and academics to enhance student engagement and also understand what student engagement might look like rather than just hours spent on the module website (Hu & Li, 2017; Kennedy, 2020).

The work done by the students resulted in an improved understanding of the impact of engineering on the environmental impact of the product and showed that a TQM+ paradigm approach to product lifecycle is needed. The layout of the assessments-coursework showing the planning and the report presenting the final work also provides the students with a logical approach which helps them obtain feedback and provides a structure which supports engaged learning and systematic improvement in the quality of the work produced. The strategies followed in this module have been shown to provide the students with an experience to not only Design, Implement and Operate the solution but also focus on Conceiving the problem. This holistic CDIO approach has led to students improving the existing engineering solutions for able-bodied and Paralympic rugby while also improving its impact on the environment.

While this project may only be looking at products which are minute in comparison to the global climate change crisis, however, it helps provide the students with a complete understanding of the engineering of a product and product lifecycle environmental impact. While this may not lead to solving the climate crisis in the short term, however, it equips the next generation of engineers to engineer more sustainable products. This model is a polycentric approach that ensures everyone involved in engineering products and product lifecycle contributes to improvements and understanding of environmental implications (Ostrom, 2009: Lui, 2010) This project has helped the students understand the TQM+ paradigm, that is the implications of cost, quality, processing, packaging and transport, logistics of materials and overall production which impacts the product's health and safety and sustainability.

CONCLUSION

The engineering product lifecycle module has been shaped to allow students to pick a product in Rugby equipment (products, clothing, footwear, PPE) to analyze and improve its design with an eye on the sustainability of the product by carrying out a lifecycle analysis. Through this year-long module, the students have analyzed different rugby products such as rugby balls, shoe leather, studs, body padding, scrum training equipment and other PPE such as shin pads and scrum hats. The students were able to analyze different energy uses during a manufacturing process and convert it to emissions in the form of CO_2e. The students have produced detailed reports on different solutions for each problem and produced comparisons which show how the changes or improvements have affected the sustainability of the product. The student solutions balancing the TQM+ diamond paradigm satisfy the tangible considerations of:

- time
- cost
- quality
- health and safety
- sustainability

The findings from the module also show that students can relate the findings of their research to their personal lives and other projects. The module team will keep running the project for a couple of years to provide the students with an opportunity to select a project and analyse it to satisfy the diamond TQM+ paradigm.

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