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Using Taxonomy for Supporting Sustainable Product Design Concept Analysis

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Abstract

Sustainability, which involves environmental, social and economic dimensions, is playing an increasingly significant role in product design, of which the environmental dimension is currently the primary focus. Many studies have explored the use of methods or tools, such as life cycle assessment and quality function deployment, to support sustainable product design. However, more studies are needed to explore the associations between product design activities and sustainability, particularly at the conceptual design stage where decisions have high impacts. Therefore, this paper proposes a new approach using taxonomy for sustainable product design concept analysis. It aims to provide new insights for addressing sustainability issues by employing computational techniques, such as natural language processing and ontologies, at early design stages. The approach involves sustainability knowledge capture, knowledge expansion, taxonomy formalisation, and sustainability analysis. A case study has been conducted to demonstrate the workflow of the taxonomy approach and indicate its viability in an education setting.

Keywords: Sustainability, Sustainable Design, Product Design, Taxonomy

1 Introduction

Overconsumption of resources, pollution, and climate change have caused significant global challenges. Although several strategies have been set in the recent COP26 (UN Climate Change Conference UK 2021) to tackle some of these issues, such as speeding up the switch to electric vehicles, encouraging investment in renewables, protecting and restoring ecosystems, more efforts are needed. Products, from raw material selections, manufacturing and distribution system choices, to uses and disposals, are significant factors that are closely related to these global issues.

Since the early 1990s, a number of frameworks have emerged to support sustainability in product design, such as eco-design, green design, cradle-to-cradle design, and emotionally durable design (Clark et al., 2009; Ceschin & Gaziulusoy, 2016). In recent years, sustainability is playing an increasingly important role, due to environmental regulations and growing customer demands and expectations (Fargnoli et al., 2014; Zhou et al., 2021). Sustainability or sustainable development is often described as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). Although sustainability involves environmental, social and economic dimensions, it is primarily focused on the environmental dimension in product design (Fargnoli et al., 2014; Purvis et al., 2019). Thus, sustainable product design is an approach used for developing a product with minimal negative environmental impacts throughout its entire life cycle (He & Gu, 2016).

It is revealed that 80% of a product's environmental impacts are determined at the design stage where the detailed product concept is formed including the selection of materials and manufacturing processes (Lewis et al., 2017; Ahmad et al., 2018). While the product life cycle matures, the environmental impacts will cumulate but the decision impacts will decrease (Wang et al., 2002; Lewis et al., 2017). In other words, it is challenging to address sustainability issues of a product after the design stage, as decisions will only have limited impacts on the product's sustainability performance. Therefore, it is beneficial to tackle the sustainability issues and minimise the environmental impacts of a product at the design stage, especially in conceptual design (Han et al., 2021), which is more effective and efficient. However, design concepts can be many and varied as they start from individual imagination. Many attempts have been made to quantify the process but all suffer from the same issue that there are too many options which often makes the process null and void. Besides, in a recent study, Jiang et al. (2021) revealed that current research failed to establish associations between product design activities and sustainability through a bibliometric review of over 7000 academic publications concerning sustainable product design. The study indicated that the lack of design research for supporting sustainable product design has led to challenges in producing products that are more sustainable.

In order to support design engineers, particularly students, in sustainable product design at the conceptual stage, this paper proposes a taxonomy approach for analysing the sustainability aspects of product design concepts and ultimately leading towards sustainable products. It aims to provide new insights into how computational techniques could be employed to address sustainability issues at early design stages, and facilitate the future research direction of AI for sustainable design.

2 Sustainable Product Design

Sustainability issues of a product need to be addressed as early as possible in the design process, whereas most of the sustainability support tools can only be employed at late design stages (Jiang et al., 2021). For example, life cycle assessment, which is the most often used tool for supporting sustainable product design (Deng et al., 2016), measures the environmental impacts of a product along its life cycle (Rossi et al. 2016). It is commonly applied at late design stages when a large amount of information is available, including the materials, components, manufacturing processes and functions of a product (Millet et al., 2007). However, this has limited the capability and applicability of life cycle assessment. Besides, designers need to be equipped with the skills and knowledge to use life cycle assessment to interpret the results and produce useful insights for supporting sustainable design. Several tools exist for supporting sustainable product design in the early stages of design, such as quality function deployment (QFD). QFD was originally developed for quality control and it is often used to address sustainability issues (Bereketli & Erol Genevois, 2013; Masui, 2013). It could be applied to address uncertain and ambiguous decision parameters, consider the voice of customers, and organise information in a logical manner (Wu & Ho, 2015). However, it is challenging and time-consuming to analyse a large quality function deployment matrix involving valid quantitative information (Olewnik & Lewis, 2008). Only a limited amount of information is available at the early design stages, which makes QFD inappropriate for supporting conceptual design.

Taxonomies are often used in design to classify or organise information to facilitate design concept analysis (Wodehouse & Ion, 2010). Therefore, taxonomies could potentially be used to address the limitations of the existing sustainability support tools, while a taxonomy approach for analysing sustainable product concepts is needed.

Han et al. (2021) proposed four metrics for measuring sustainable product design concepts, which involves material, production, use and end of life, as shown in Table 1. Each of the metrics involves a set of attributes and corresponding measurement equations. For instance, 'Material' involves attributes such as 'Material Origin', 'Material Property', and 'The Use of Material'. 'Material Origin' is determined by whether nonrenewable, hybrid, and/or renewable materials are used; 'Material Property' is decided by whether the materials are toxic, recyclable and/or biodegradable; and 'The Use of Material' is dependent upon the quantity and number of types of materials used. The four metrics together with the corresponding attributes have been employed in a case study by Han et al. (2021) which indicated its effectiveness and usefulness. The comprehensiveness and hierarchy of the metrics have thereby indicated the potential of forming a hierarchical taxonomy for sustainable product concept analysis.

Table 1. Metrics for measuring sustainable product design concepts (adapted from (Han et al. 2021))

Metrics	Attributes
Material	Material Origin; Material Property; The Use of Material – Quantity; The Use of Material – Type.
Production	Balance between the Number of Parts and Complexity; Parts Standardisation; Parts Design for Assembly; Suitable Fabrication Method.
Use	Product Use Time/Lifetime; Energy Consumption during Use; Robustness, Reliability and Maintenance.
End of Life	Reuse; Recycling, Remanufacturing and Repair; Ease of Disassembly; Disposal.

3 A Taxonomy Approach for Sustainable Product Design Concept Analysis

3.1 The Structure of the Taxonomy

According to the best knowledge of the authors, there are no ready-available taxonomies, which could comprehensively capture the sustainability-related explicit knowledge of a product design concept and effectively present the knowledge in a hierarchical structure, for supporting sustainable product design concept analysis. Therefore, a 3-Level hierarchical sustainable product design concept analysis taxonomy is proposed based on the study by Han et al. (2021), as shown in Figure 1, prior to proposing the taxonomy approach for analysing sustainable product design concepts.

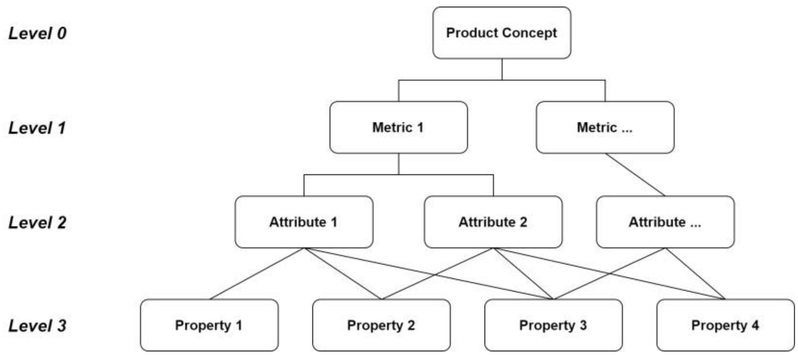


Figure 1. Structure of the Taxonomy for Sustainable Product Design Concept Analysis

As shown in Figure 1, Level 0 is the master level of the taxonomy, indicating a product design concept. Level 1 of the taxonomy refers to the metric level of the product design concept, which involves four metrics: 'Material', 'Production', 'Use' and 'End of Life'. These four metrics cover the main phases of the entire life cycle of a product, from material selection and extraction, product manufacturing and assembly, the use of the product, to when the product needs to be discarded. Level 2 refers to the attribute level of the product concept. From metric level (Level 1) to attribute level (Level 2), it follows a one-to-many correspondence. In other words, one metric consists of several specific attributes. For example, the 'End of Life' metric is composed of four attributes, including 'Reuse', 'Recycling, Remanufacturing and Repair', 'Ease of Disassembly', and 'Disposal'. As indicated in Table 1, 'Material' involves four attributes, 'Production' involves four attributes, 'Use' involves three attributes and 'End of Life' involves four metrics. Level 3 is the property (such as the specific materials used in a product) level of the product concept, which connects with the attribute level (Level 2) in a many-to-many correspondence. That is, one property could relate to several attributes, while one attribute could also relate to several properties. Using a battery-powered radio-controlled car as an example, the 'Material Origin' attribute is related to product properties such as the PLA shell and the rubber tyres, while the battery property could be associated with attributes such as 'Parts Standardisation' and 'Energy Consumption during Use'.

3.2 The Taxonomy Approach

The concept underpinning the taxonomy approach for analysing sustainable product design concepts is depicted in Figure 2. The approach is aimed at capturing the sustainability-related properties of a product from a piece of text, which describes the product design concept, and formalising them into the sustainable product design concept analysis taxonomy for further sustainability analysis by humans or computers. The approach involves four main steps as indicated below:

1. Extracts sustainability-related knowledge (product properties) from a piece of product concept description text, for example, could be design specifications or concept annotations This step could be accomplished through using part-of-speech (POS) tagging techniques to extract noun words and noun phrases from the text. Alternatively, natural language process (NLP) techniques, especially deep neural network based ones such as Generative Pretrained Transformer (GPT) (Brown et al., 2020) and BERT (Devlin et al., 2018), could be used to better understand the text and extract words and phrases with the awareness of context.
2. Populates the sustainability-related knowledge captured. The words and phrases extracted could be limited to comprehensively cover all the knowledge needed for sustainability analysis. Using the preceding radio-controlled car as an example, one of the noun phrases extracted from its description, from the product website or user manual, could be 'electric motor'. An electric motor involves components such as rotor and stator, which could not be captured in a direct manner but are related to the sustainability of the product. Therefore, existing ontologies, such as common-sense WordNet (Miller, 1995) and ConceptNet (Speer et al., 2017) as well as technical TechNet (Sarica et al., 2020) and B-Link (Shi et al., 2017), could be used to expand the knowledge captured.
3. Formalises the knowledge into the sustainable product design concept analysis taxonomy. This step involves associating the product properties (sustainability-related knowledge) captured and populated (Level 3 taxonomy) with corresponding attributes (Level 2 taxonomy). Using the radio-controlled car example, properties such as 'electric motor' and 'bearings' could be associated with attributes such as 'part standardisation'. Several approaches can be employed to accomplish the task, of which leveraging the use of the relationships between entities in existing ontologies to construct the associations is less

expensive and time-consuming. However, it is possible that certain relationships are not included in existing ontologies.

4. Analyses the sustainability of the product design concept. Once the sustainable product design concept analysis taxonomy is created, the taxonomy could be analysed by humans (4.1) or computers (4.2) employing the measurements indicated in the study by (Han et al., 2021) for both the attribute level (Level 2) and metric level (Level 1). However, human judgement and knowledge are needed for human analysis. While a database needs to be created, containing the sustainability scales of different properties regarding different attributes, to support the computational analysis.

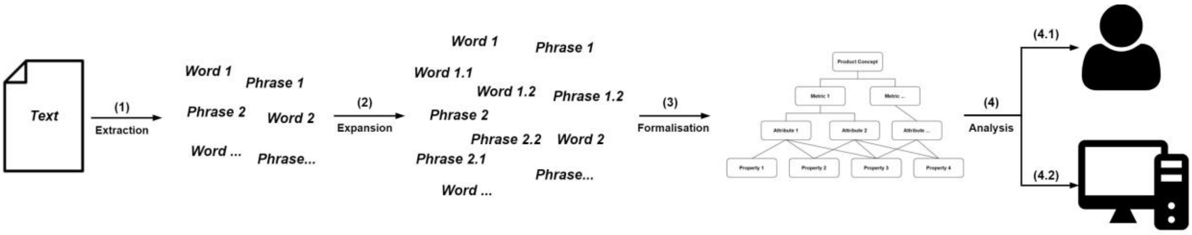
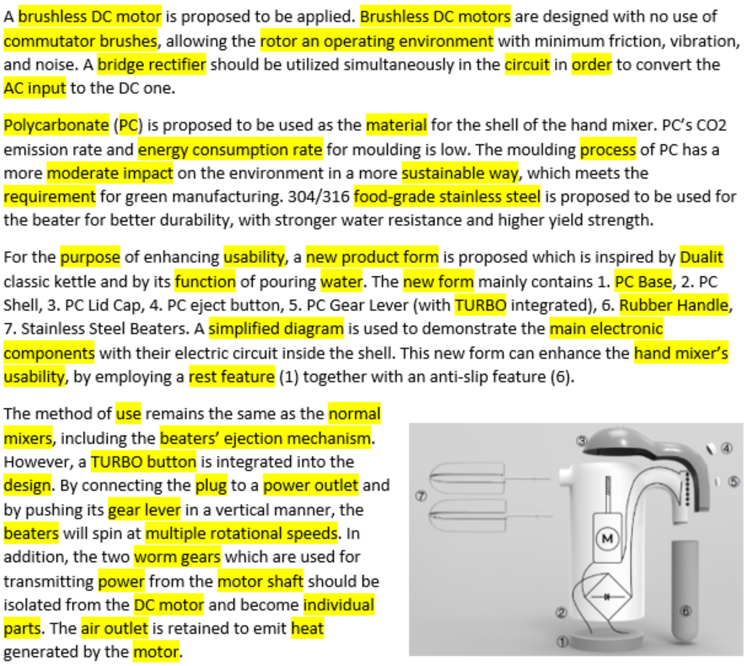


Figure 2. The Taxonomy Approach for Sustainable Product Design Concept Analysis

4 Case Study and Discussion

A case study is conducted to demonstrate the process of the taxonomy approach proposed in an education setting. As shown in Figure 3, a piece of text describing a sustainable hand mixer concept is used. The text is extracted from a student's coursework aiming to redesign an existing hand mixer to improve its sustainability. Please note that the CAD model in the figure is to help readers better comprehend the design concept. As indicated in the figure, the highlighted noun words and phrases are the product properties captured by using a POS tagging algorithm developed by the authors. However, there are several noise data, such as 'order' and 'material', which need to be removed. Besides, several phrases, such as 'moulding process', have been recognised as individual words, such as 'process', which might affect the accuracy of further analysis. Therefore, using the advanced NLP techniques indicated in the preceding to extract key words and phrases could potentially solve the issues.



A brushless DC motor is proposed to be applied. Brushless DC motors are designed with no use of commutator brushes, allowing the rotor an operating environment with minimum friction, vibration, and noise. A bridge rectifier should be utilized simultaneously in the circuit in order to convert the AC input to the DC one.

Polycarbonate (PC) is proposed to be used as the material for the shell of the hand mixer. PC's CO2 emission rate and energy consumption rate for moulding is low. The moulding process of PC has a more moderate impact on the environment in a more sustainable way, which meets the requirement for green manufacturing. 304/316 food-grade stainless steel is proposed to be used for the beater for better durability, with stronger water resistance and higher yield strength.

For the purpose of enhancing usability, a new product form is proposed which is inspired by Dualit classic kettle and by its function of pouring water. The new form mainly contains 1. PC Base, 2. PC Shell, 3. PC Lid Cap, 4. PC eject button, 5. PC Gear Lever (with TURBO integrated), 6. Rubber Handle, 7. Stainless Steel Beaters. A simplified diagram is used to demonstrate the main electronic components with their electric circuit inside the shell. This new form can enhance the hand mixer's usability, by employing a rest feature (1) together with an anti-slip feature (6).

The method of use remains the same as the normal mixers, including the beaters' ejection mechanism. However, a TURBO button is integrated into the design. By connecting the plug to a power outlet and by pushing its gear lever in a vertical manner, the beaters will spin at multiple rotational speeds. In addition, the two worm gears which are used for transmitting power from the motor shaft should be isolated from the DC motor and become individual parts. The air outlet is retained to emit heat generated by the motor.

Figure 3. The description text of the sustainable hand mixer design concept

After cleaning the words and phrases captured, TechNet and ConceptNet are used in a mixed manner to populate the sustainability-related knowledge. ConceptNet contains common-sense terms and relations, while TechNet is technology and engineering-focused. Therefore, the use of both TechNet and ConceptNet could be beneficial for acquiring both common-sense and technical knowledge for more comprehensive sustainability analysis. To be more specific, the properties captured are employed in TechNet and ConceptNet to explore the knowledge associated, and select the most appropriate ones. However, some of the properties captured are not contained in ConceptNet and/or TechNet, of which these terms are modified to enable the property population process. For example, 'stainless steel' is used instead of 'food-grade stainless steel'. As shown in Table 2, 36 product properties in total, 12 captured properties selected and 24 populated properties, are identified for constructing the sustainable product design concept analysis taxonomy.

Table 2. The properties of the sustainable hand mixer design concept

Properties Captured	**Properties Populated**
AC input	ac, ac power supply
beater	beater head, beater rod
bridge rectifier	rectifier circuit, filter capacitor
brushless DC motor	stator, dc, rotor
circuit	wiring, capacitor, switch
food-grade stainless steel	corrosion resistant, high strength, casting
gear lever	gear, gearbox
motor	motor shaft
new product form	shape, aesthetic
plug	cord, connector
polycarbonate	recycle
rubber handle	natural material

The properties are then associated with the corresponding attributes manually to formalise the sustainable knowledge of the hand mixer design concept into the taxonomy, as shown in Figure 4. The hand mixer design concept taxonomy is then analysed manually, due to the lack of an existing and available 'property – sustainability scale' database for computational analysis. The sustainability measurements proposed by Han et al. (2021) are employed to perform the sustainability analysis of the hand mixer design based on the taxonomy constructed only. As suggested by the sustainability measurements, a scale ranging from 'poor (0)', 'fair (1)', to 'good (2)' are used to indicate the level of sustainability of the attributes. Scaling processes were introduced into the measurements and each metric will receive a final score within the range of '1 (low)' to '10 (high)' regarding the sustainability level. This is to effectively reflect the sustainability level of each metric in a simple manner. However, as presented in Figure 4, several attributes, including 'Parts Design for Assembly', 'Reuse', 'Ease of Disassembly' and 'Disposal', are not connected with any product properties. This reveals that the student, who came up with the hand mixer design concept, might have not considered these sustainability attributes in the design. Thereby, these four attributes will receive 'poor (0)' scores.

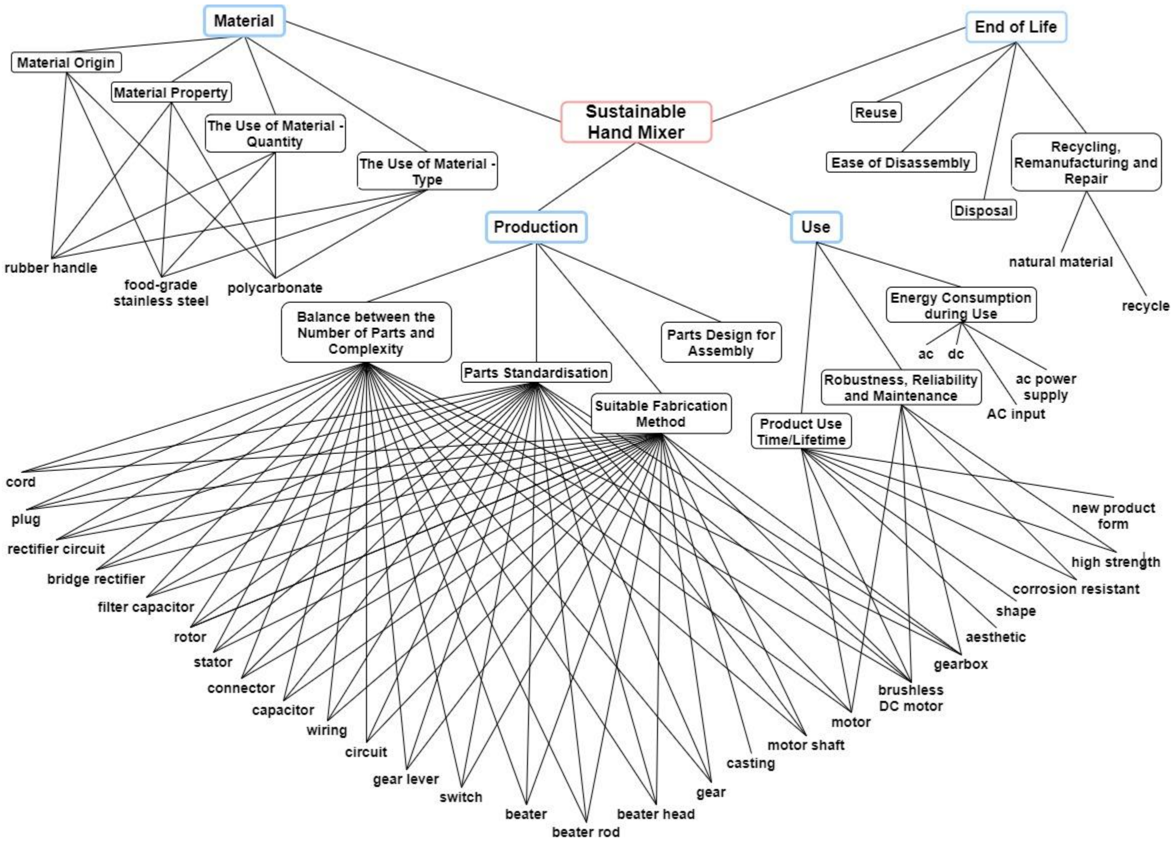


Figure 4. The Taxonomy of the sustainable hand mixer design concept

The results of the evaluation are presented in Figure 5 with the reasons underpinning. As shown in the figure, the sustainable hand mixer design (described in Figure 3), has achieved 4 in 'Material' metric, 1 in 'Production', 5.5 in 'Use', and 1 in 'End of Life', with an average sustainability score of 2.9. The average sustainability score has indicated a relatively low level of sustainability of the product design concept. The 'Material' and 'Use' metrics of the design are at fair sustainability levels, while the 'Production' and 'End of Life' metrics are at very low sustainability levels. In terms of the 'Production' metric, the 'Balance between the Number of Parts and Complexity' was assigned a 'poor (0)' score as the design is fairly complicated and involves many different parts, while the 'Parts Design for Assembly' was also rated a 'poor (0)' score as the attribute was not considered. Thus, the student needs to reduce the number of parts and the complexity of the design, as well as consider the assembly aspects, to improve the sustainability level of the 'Production' metric. With regard to 'End of Life', only the 'Recycling, Remanufacturing and Repair' attribute was considered. Thus, the student needs to explore other 'End of Life' related aspects to improve its sustainability level.

As indicated in the preceding, several attributes were identified as 'has not been considered'. One could argue that this might be because that sustainable hand mixer design concept taxonomy constructed has omitted the relevant product properties. Such product properties might have not been captured from the product concept description text and/or might have not been associated with these attributes. However, this provides designers with the opportunity to consider these attributes for further product sustainability improvements. Therefore, the hand mixer design concept description, as shown in Figure 3, was provided to a human expert for further analysis. The expert confirmed that the design concept description text does not contain any information related to 'Parts Design for Assembly', 'Reuse', 'Ease of Disassembly' and 'Disposal' attributes. This shows that the hand mixer taxonomy constructed could truly reflect the sustainability-related knowledge contained in the description text to some extent.

Metrics	Attributes	
Material (M)	Material Origin (M1)	rubber handle - 2; food-grade stainless steel - 0; polycarbonate - 0.
	Material Property (M2)	rubber handle - 2; food-grade stainless steel - 2; polycarbonate - 1.
	The Use of Material – Quantity (M3)	rubber handle - 1; food-grade stainless steel - 1; polycarbonate - 2.
	The Use of Material – Type (N)	3
$\mathbf{Metric_M} = \frac{9 \times \left(\frac{\sum_{i=1}^{N}(\mathbf{M_1} + \mathbf{M_2}) \times \mathbf{M_3}}{\mathbf{N}}\right)}{8} + 1 = 4$		
Production (P)	Balance between the Number of Parts and Complexity (P1)	Involves many different parts, fairly complicated design - 0
	Parts Standardisation (P2)	Some parts, e.g. motor and gearbox, can benefit from standard components, while some others might need customisation - 1
	Parts Design for Assembly (P3)	This attribute has not been considered - 0
	Suitable Fabrication Method (P4)	Partial excessive operations needed -1
$\mathbf{Metric_P} = \frac{9 \times (\mathbf{P_1} \times \mathbf{P_2} + \mathbf{P_3}) \times \mathbf{P_4}}{12} + 1 = 1$		
Use (U)	Product Use Time/Lifetime (U1)	The design lifetime of the hand mixer should be close to its use time - 2
	Energy Consumption during Use (U2)	ac power is used and converted into dc power - 1
	Robustness, Reliability and Maintenance (U3)	Several components, e.g., motor and gearbox, will require a fair amount of resource to maintain/service), while other components are strong and robust - 1
$\mathbf{Metric_U} = \frac{9 \times \mathbf{U_1} \times (\mathbf{U_2} + \mathbf{U_3})}{8} + 1 = 5.5$		
End of Life (E)	Reuse (E1)	This attribute has not been considered - 0
	Recycling, Remanufacturing and Repair (E2)	Certain material(s) is natural and/or can be recycled - 1
	Disposal (E3)	This attribute has not been considered - 0
	Ease for Disassembly (E4)	This attribute has not been considered - 0
$\mathbf{Metric_E} = \frac{9 \times (\mathbf{E_1} + \mathbf{E_2} + \mathbf{E_3}) \times \mathbf{E_4}}{12} + 1 = 1$		

Figure 5. Sustainability analysis of the hand mixer design based on the taxonomy constructed

However, please note that this paper is primarily aimed at exploring a taxonomy approach in a manual manner to analyse sustainable product design concepts and indicating its potential viability to be implemented employing computational means, rather than examining the effectiveness and validity of the approach. Thereby, the case study conducted is to deliver useful insights into the proposed approach, and demonstrate how the approach can be used to guide designers in generating sustainable product design concepts. The case study has also demosonstrated the potential of using such an approach to develop students' understanding and implementation of sustainable product design during early design stages.

There are two main limitations of this study. First, the metrics used for sustainability analysis involve 'Material', 'Production', 'Use' and 'End of Life' which cover the main phases of the entire life cycle of a product, while other phases that have sustainability impacts, such as sales and distribution, were not considered. Revised versions of the sustainability analysis metrics and taxonomy are thereby needed to include all phases, which have sustainability impacts, to provide a more comprehensive sustainability analysis of product design concepts. Second, the sustainability assessment outcomes are depended upon the piece of text used that describes the product design concept. Moreover, it is very unlikely that two or more engineering designers (or students) describing the same design concept would deliver identical text descriptions with identical noun words and phrases, due to the individual author’s experience, interest and competence. Thus, the POS tagging algorithm will deliver different results for the same design concept. Therefore, advanced NLP techniques, such as GPT and BERT, could be used to enhance document exploration, derive higher quality vectoral representations, better detect engineering entities, and enable the derivation of engineering-focused relations (Han et al., 2022). This would facilitate the extraction of sustainability-related knowledge from design concept descriptions, lead to more reliable results than POS tagging, and ultimately reduce the dependency on the quality of the description text used.

5 Conclusions

Sustainable product design plays an increasingly important role in the world nowadays. However, there is currently a lack of design research for supporting sustainable product design. It is revealed in previous studies that addressing sustainability issues at the conceptual design stage is more effective and efficient. Therefore, this paper has proposed a taxonomy approach for sustainable product design concept analysis. The approach involves the construction of a three-level taxonomy, by capturing sustainability-related knowledge from design concept description texts, populating the knowledge captured, and formalising the knowledge into the taxonomy, for computational or human analysis. A case study has been conducted to demonstrate the workflow of the taxonomy approach proposed and indicate its viability in an education setting. It shows the potential of utilising such an approach to support students in learning sustainable product design.

However, in the current formula of the taxonomy approach, the details of each step, such as which computational models and approaches to use, have not been determined. Therefore, further studies are planned to explore the most appropriate computational approaches and models for realising the taxonomy construction process. Besides, a database containing the sustainability scales of different product properties regarding corresponding product attributes is planned to be created to support both human and computational analysis.

This study is only a first step in exploring the use of a taxonomy approach for supporting the analysis of sustainable product design concepts. It has four significant contributions to the intersection of design, sustainability and data science. First, it serves as a guide to measuring the sustainability of product design concepts by analysing description texts and constructing taxonomies. Second, it supports the development of engineering and design students' mindsets regarding sustainable product design. Third, it provides new insights into the development of computational sustainable design concept evaluation tools. Fourth, it raises the significance of sustainable product design research and invites further studies to investigate advanced approaches, methods and tools for supporting sustainable product design.

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