energies

MDPI

Article

Metrics for Measuring Sustainable Product Design Concepts

Ji Han [1,*], Pingfei Jiang [2] and Peter R. N. Childs [3]

[1] School of Engineering, University of Liverpool, Liverpool L69 3BX, UK
[2] Department of Mechanical Engineering, Kingston University, London SW15 3DW, UK; p.jiang@kingston.ac.uk
[3] Dyson School of Design Engineering, Imperial College London, London SW7 2DB, UK; p.childs@imperial.ac.uk
* Correspondence: ji.han@liverpool.ac.uk

Abstract: Although products can contribute to ecosystems positively, they can cause negative environmental impacts throughout their life cycles, from obtaining raw material, production, and use, to end of life. It is reported that most negative environmental impacts are decided at early design phases, which suggests that the determination of product sustainability should be considered as early as possible, such as during the conceptual design stage, when it is still possible to modify the design concept. However, most of the existing concept evaluation methods or tools are focused on assessing the feasibility or creativity of the concepts generated, lacking the measurements of sustainability of concepts. The paper explores key factors related to sustainable design with regard to environmental impacts, and describes a set of objective measures of sustainable product design concept evaluation, namely, *material*, *production*, *use*, and *end of life*. The rationales of the four metrics are discussed, with corresponding measurements. A case study is conducted to demonstrate the use and effectiveness of the metrics for evaluating product design concepts. The paper is the first study to explore the measurement of product design sustainability focusing on the conceptual design stage. It can be used as a guideline to measure the level of sustainability of product design concepts to support designers in developing sustainable products. Most significantly, it urges the considerations of sustainability design aspects at early design phases, and also provides a new research direction in concept evaluation regarding sustainability.

Keywords: sustainability; design sustainability; conceptual design; concept evaluation; product design; sustainable product design

check for updates

Citation: Han, J.; Jiang, P.; Childs, P.R.N. Metrics for Measuring Sustainable Product Design Concepts. *Energies* **2021**, *14*, 3469. https://doi.org/10.3390/en14123469

Academic Editor: Edmundas Kazimieras Zavadskas

Received: 3 May 2021
Accepted: 8 June 2021
Published: 11 June 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The world population increased from 1 billion in 1800 to 7.8 billion in 2020 [1]. Although the world population growth rate is decreasing, it is predicted that the world population will reach 9.7 billion by 2064, subsequently declining to 8.8 billion in 2100 [2]. The population growth has led to global issues, such as overconsumption of resources and energy and pollution. Sustainability is a fundamental attribute playing an increasingly significant role in design nowadays, especially in product design, where it is considered a requirement for solving those global challenges [3].

In recent years, there has been an increasing focus on sustainable product developments due to environmental regulations and expectations of consumers [4]. It is imperative for modern firms and enterprises to consider sustainability in product design and development [5]. Sustainable development is often defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [6]. Sustainability commonly involves three interconnected pillars: social, economic, and environmental [7]. However, sustainability in design is primarily focused on environmental aspects [4]. Therefore, sustainable design is described as a design approach for reducing the environmental impacts throughout a product's entire life cycle [8–10].

Material extraction, manufacturing, use, and end of life of a product produced all have impacts on the environment [11]. It is therefore critical for designers, while designing new sustainable products, to select raw materials with the least environmental impact, influence manufacturers to minimise environmental damage, and consider an environmentally friendly manner of using and disposing of these products [12].

Conceptual design, which involves activities such as concept generation and assessment, is arguably the most significant stage in the design process. As an early stage in design, concept assessment has a powerful impact on the downstream activities, such as product production, use, and end of life [13–16]. It is a complex task involving decision making based on multiple criteria [13,14], which significantly saves product development cost and time, as well as raises awareness of design concept improvement opportunities. The decisions made have a critical influence on the environmental impact of a product, as well as performance, cost, reliability, and safety [17]. The decisions often have high impacts at the conceptual design stage, but decrease significantly as the design process progresses [16].

Environmental impacts occur throughout a product's entire life cycle, from raw materials, production, and use, to end of life, while the environmental impacts at different stages vary significantly among different products. For example, although both kettles and cameras are consumer electronics, kettles embody most of the environmental impacts at the use stage, while cameras, ignoring digital storage, embody most of the impacts at the production and raw material stages [18,19]. However, most of the environmental impacts are 'locked' into the product during early design stages, where the product concept is formed, functions and performance are determined, and materials and manufacturing processes are selected [20]. The 'lock-in' of environmental impacts is determined and cumulated throughout the product's life cycle [20]. Nevertheless, it is reported that 80% of sustainability impacts are decided at the design stage, involving both conceptual design and detailed design [11].

According to studies, Figure 1 indicates that the impact of decisions decreases, while the cumulative 'lock-in' environmental impact increases, as the product life cycle matures [16,20,21]. The figure shows the significance and advantages of addressing the sustainability issues of a product as early as possible in the design process, as it is challenging and costly to address sustainability issues at later stages [21,22]. For instance, it is easier to design an energy-efficient product rather than educating consumers to use the product in an energy-saving manner with the aim of reducing environmental impacts. Therefore, the opportunity to minimise a product's environmental impacts mainly exists in the preliminary design stage, especially in conceptual design where decisions have high impacts [23,24].

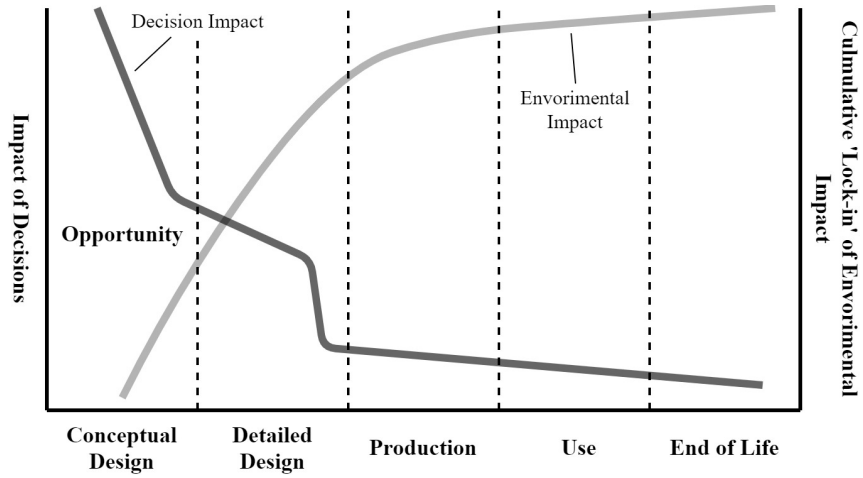


Figure 1. Opportunity in conceptual design for minimising cumulative 'lock-in' of environmental impact (adapted from [16,20]).

However, product design engineers generally focus on producing products that meet the required technical performance, aesthetics, durability, and cost demands [25], but lack awareness of the wider environmental impact of the design [12] (*Knowledge Gap 1*). For instance, Brundage et al. [26] indicated that there is a lack of communication between designers and manufacturers, which limits designers in reducing environmental impacts from a manufacturing perspective. It is also challenging to improve a product's sustainability once the product is designed [21,22] (*Knowledge Gap 2*). Therefore, there is a need to project later sustainability-related activities, such as manufacturing, use, and end of life, to early design stages to inform better decision making [27–29]. For example, a product designed for easy manufacturing and assembly could increase the chances of it being reused or recycled, leading to a reduction in environmental impacts [30]. Nevertheless, the majority of existing concept assessment methods or tools are used to evaluate the feasibility and creativity of the concepts generated at early design stages [31–37] (*Knowledge Gap 3*). Therefore, current concept assessment methods could not guarantee the generation of sustainable product design concepts, which embody minimum environmental impacts. These three knowledge gaps imply that there is a need to come up with an approach to measure the sustainability of design concepts, considering aspects of later activities in the product life cycle and therefore promoting a more sustainable design manner.

The paper aims to offer support to designers in generating sustainable design concepts by considering a wide range of aspects to minimise negative environmental impacts, ultimately leading to sustainable products. The primary objective of the paper is to answer the following research questions: (1) What are the critical factors related to sustainable design, particularly environmental impacts? (2). Is there a set of metrics that can measure sustainable product design concepts?

The remainder of the paper is organised as follows: the next section reviews the related work on sustainability and concept assessment. In Section 3, four metrics (*material*, *production*, *use*, and *end of life*) for measuring sustainable product design concepts are proposed with rationales and measurements. A case study demonstrating the application of the metrics is provided in Section 4, followed by discussion in Section 5 and conclusion in Section 6.

2. Related Work

2.1. Sustainable Product Design

Many methods and tools have been developed to support sustainable product design. Life cycle assessment (LCA) is most often used [38–41], which is a framework for calculating the environmental impacts of a product or service along its life cycle [42]. However, LCA methods are more suitable to be implemented at later design phases, as it often requires a large amount of data while the design of a product is more defined, of which materials, components, and processes are specified [43,44].

Quality function deployment (QFD) is another popular approach for supporting sustainable product design. For instance, Bereketli and Erol Genevois [45] and Younesi and Roghanian [46] employed quality function deployment for environment (QFDE) to consider both environmental and economic aspects. Wu and Ho [47] and Ocampo et al. [48] came up with integrated QFD approaches to address uncertainties, ambiguities, and interdependencies of decision parameters. Although QFD-based approaches provide benefits, such as considering the voice of customers and logical organisation of information, it could be complex and time-consuming to process a large matrix and challenging to offer valid quantitative information [49,50].

In addition to LCA- and QFD-based tools, several other types of methods have been developed to support sustainable product design, such as CAD-integrated tools, diagram tools, checklists, and guidelines, as well as Design for X approaches [42]. However, most of these tools require training and experience to implement, and some require specific knowledge to interpret results in order to gain insights. More importantly, very few existing sustainability tools or methods are found to be capable of supporting designers in

sustainable product design at the conceptual design stage, concept assessment in particular, from the review conducted in this study.

2.2. Concept Assessment Methods

Concept assessment is often used to assess feasibility and creativity, and sometimes sustainability, aspects of design concepts in new product development. In this study, feasibility refers to whether a product produced could meet the design requirements, such as functional performance, business constraints, and customer needs. Creativity indicates the novelty, usefulness, and surprise of a design [51]. Sustainability refers to designing a product with minimum negative environmental impacts. Feasibility, creativity, and sustainability are not mutually exclusive; they can be interrelated when evaluating product design concepts. For example, the usefulness of a product is generally equivalent to the product's functional performance [51].

General multicriteria decision-making techniques are often used to assess design concepts, such as the Harris profile [31], Pugh matrix [34], and tabular evaluation matrix [37]. These methods often employ matrices consisting of a series of weighted criteria against which the design concept needs to be assessed. A ranking of the concepts with a quasi-quantitative measure of the advantages and disadvantages is provided to support the selection of the most suitable concept [37]. Although these methods could be used to assess creativity or sustainability depending on the criteria selected, they are mainly used to assess the feasibility of the concepts generated.

There also exist several other methods aimed at assessing the feasibility of design concepts generated. For instance, Davoodi et al. [35] applied the technique for order of preference by similarity to ideal solution (TOPSIS) to select the best concept based on the distance from ideal and non-ideal solutions. A shorter distance indicates a better design concept alternative, and vice versa. Goswami and Tiwari [52] suggested a framework to select the best design concept with the least risk by employing a Bayesian network methodology. Zhu et al. [15] and Tiwari et al. [13] proposed integrative methods by employing VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) to perform multicriteria decision analysis for selecting the best design concept. Shidpour et al. [14] indicated a multicriteria design concept evaluation method based on rough set theory for assessing the quantitative criteria of a product (such as costs) and fuzzy set theory for assessing the qualitative criteria (such as aesthetics). Rondini et al. [53] proposed a two-step importance–performance analysis (IPA)-based method, but focused on a product–service system. It is used for demonstrating the trade-off between customer value and provider value to direct design teams in progressing solution principles.

Creativity assessment methods aim at selecting the most creative concept and identifying creative designers and inventors [36]. The consensual assessment technique (CAT), proposed by Amabile [32], is known as the 'gold standard' in creativity assessment, which is grounded in the definition of creativity that 'the process by which something so judged (to be creative) is produced'. The CAT method often employs a group of experts in the domain in question to evaluate the creativity of a product.

However, human-judgement-criteria-based methods are most often used in product concept creativity assessment. For example, the Creative Product Semantic Scale (CPSS) [33,54,55] is a popular method for assessing design creativity. It involves three dimensions: novelty, resolution, and elaboration and synthesis, with associated subdimensions. Horn and Salvendy [56] indicated the use of novelty, affect, and importance, which are connected with consumer satisfaction, for assessing product design creativity. Sarkar and Chakrabarti [36] came up with a method for assessing creativity by evaluating the novelty and usefulness of a design concept. Novelty is assessed by using the SAPPhIRE model [57] and the function–behaviour–structure (FBS) model, while usefulness is assessed based on level of importance, rate of popularity of use, frequency of usage, and duration of use. Chiu and Shu [58] used novelty, usefulness, and cohesiveness to measure design concepts' creativity. Demirkan and Afacan [59] proposed three assessment factors related

to the shape, characteristics, and design principles of a product, respectively. Lee et al. [60] measured design creativity by using novelty, usefulness, aesthetics, and complexity. Srinivasan et al. [61] employed novelty and quality, while Starkey et al. [62] used usefulness and uniqueness for assessing the creativity of product design concepts.

In comparison with the methods for assessing the feasibility and creativity of product design concepts, a limited number of methods have been developed to evaluate the sustainability of product design concepts. For instance, Lindow et al. [63] presented an interdisciplinary method based on the combination of the house of quality and life cycle sustainability assessment, considering both product properties and sustainability indicators. However, this method requires a large amount of information to perform a complete assessment, which is time-consuming and expensive. Hassan et al. [64] came up with a systematic approach to assess the sustainability of alternative part configurations. It employs a weighted decision matrix to determine the sustainability scores of design configurations and an artificial neural network to measure the sustainability performance. However, this approach can only assess the sustainability of a single part of a product rather than the whole product. Turan et al. [65] developed a sustainability assessment model in product development to support designers in making better decisions before completing the final concept. The model integrates a green project management concept for guiding the sustainability assessment, a new scale of weighting criteria for easing the rating process, and rough–grey analysis for supporting decision making. The assessment model is designed specifically for the automotive industry, limiting its application.

A summary of the concept assessment methods for product design illustrated in this section is presented in Table 1, with highlights of whether the method is aimed at assessing feasibility, creativity, or sustainability. As shown in the table, the majority of the concept assessment methods are aimed at evaluating the feasibility or creativity aspects of the concept generated. Sustainability aspects in concept assessment have been overlooked by most researchers, and therefore, it is potentially worthwhile to explore a set of metrics for measuring sustainable product design concepts.

Table 1. Summary of concept assessment methods for product design.

Concept Assessment Methods	Year of Publication	Feasibility	Creativity	Sustainability
Harris [31]	1976	X		
Amabile [32]	1982		X	
O'Quin and Besemer [33]	1989		X	
Pugh and Clausing [34]	1996	X		
Horn and Salvendy [56]	2009		X	
Davoodi et al. [35]	2011	X		
Sarkar and Chakrabarti [36]	2011		X	
Chiu and Shu [58]	2012		X	
Chulvi et al. [54]	2012		X	
Demirkan and Afacan [59]	2012		X	
Lindow et al. [63]	2013			X
Goswami and Tiwari [52]	2014	X		
Lee et al. [60]	2015		X	
Zhu et al. [15]	2015	X		
Hassan et al. [64]	2016			X
Shidpour et al. [14]	2016	X		
Tiwari et al. [13]	2016	X		
García-García et al. [55]	2017		X	
Rondini et al. [53]	2017	X		
Turan et al. [65]	2017			X
Childs [37]	2018	X		
Srinivasan et al. [61]	2018		X	
Starkey et al. [62]	2019		X	

3. Metrics for Measuring Sustainable Product Design Concepts

Four metrics, *material*, *production*, *use*, and *end of life*, for measuring sustainable product design concepts are proposed based on existing studies on sustainable design and conceptual design. The four metrics are described in the following subsections with the underpinning rationales and measurements, respectively. However, it is challenging to determine the actual value of the negative environmental impacts caused at the conceptual design stage. As a result, to reflect the level of sustainability in a simple but effective manner, measurement scales of *low (0)*, *medium (1)*, and *high (2)* are employed to indicate sustainability attributes.

3.1. Material

The assessment of materials in sustainable product design concepts is of fundamental importance. Materials have direct impacts on products with regard to the origin, property, and use of materials. Origin of materials refers to where the materials, used in the components and parts of a product, are originally sourced, involving nonrenewable and renewable resources. Nonrenewable resources are limited in supply, which cannot be replenished or replaced, such as fossil fuels, minerals, and metal ores. Popular materials produced from nonrenewable resources involve fossil-based plastics, metals, and glasses, which are often used in product design. Renewable resources refer to those that can be easily regenerated. Materials that are renewable, such as bamboo, mushroom, natural rubber, wood, and cotton, are increasingly used in product design. An increasing number of sustainable materials are being developed by applying renewable resources. For example, bioplastics, which are less or minimally reliant on fossil fuel, are produced by using renewable plants, such as sugarcanes, corns, and potatoes. In addition, there is currently an emerging trend towards utilising waste materials for design. For instance, by-product waste materials (such as chicken feathers and bran), which are secondary products generated from production, are often used as raw materials.

Toxicity, recyclability, and biodegradability are the main indicators of material sustainability properties. A material that is recyclable or biodegradable and nontoxic is often preferred, while materials that are toxic and neither recyclable nor biodegradable should be avoided in product conceptual design.

The use of material in a product refers to the volume/weight of materials and the number of types of materials involved. Using less volume/weight of materials contributes to a positive environmental impact, as it consumes less amount of resources and energies from material sourcing and production, to product end of life. The more types of materials used will increase a product's complexity, which will lead to more negative environmental impacts throughout the product's life cycle, as it increases the difficulties in product production and end of life. Therefore, determining which material(s) to use and identifying how the material(s) are used in a product design concept are strongly associated with the product's sustainability performance.

Measurement of Material

In the conceptual design stage, information such as material origins, material properties, and the use of materials needs to be determined to assist designers with evaluation. As suggested previously, *low (0)*, *medium (1)*, and *high (2)* are used to indicate sustainability attributes. For example, if the origin of one type of material used is a promising renewable source, then a rating of *high*, a score of *2*, will be given. Similar principles apply to material properties. For example, if the material is toxic, cannot be recycled, or is biodegradable, then a rating of *low*, a score of *0*, will be given. The use of materials includes the weight/volume of materials and the number of types of materials used. Regardless of material origins, lesser volume/weight and fewer types of materials used will lead to less negative environmental impacts. However, it is difficult to judge the absolute quantity (weight/volume) of materials needed for a concept; therefore, this attribute refers to the potential for material quantity reduction at the time when the concept is evaluated.

For instance, if the volume/weight of materials of a product concept could be easily reduced without affecting the structure and performance of the product, a *high (2)* score will be given.

Table 2 summarises the attributes to consider for material sustainability and provides a brief explanation of each level to inform rational decision making. An equation is then developed to quantify the *material* sustainability, as shown in Equation (1).

$$Metric_{Material} = \frac{9 \times \left(\frac{\sum_{i=1}^{N} (M_1 + M_2) \times M_3}{N} \right)}{8} + 1 \quad (1)$$

Table 2. Attributes for measuring concept *material* sustainability.

Attributes	Symbol	Low = 0	Medium = 1	High = 2
Material origin	M_1	Nonrenewable (e.g., fossil-based plastics, metal, glass)	Hybrid (e.g., bioplastics, by-product waste materials)	Renewable (e.g., bamboo, wood, natural rubber)
Material property	M_2	Toxic, neither recyclable nor biodegradable	Either toxic or nontoxic, either recyclable or biodegradable	Nontoxic, can be easily reused or recycled
Use of material—quantity	M_3	Poor potential for material quantity reduction	Fair potential for material quantity reduction	Good potential for material quantity reduction
Use of material—type	N	*Not Applicable*		

In Equation (1), i refers to the ith type of material used in a concept. A multiplier is used to correlate attributes that have aggregated effect. For example, *material original* (M_1) and *use of material—quantity* (M_3) have a clear aggregated effect; hence, they are multiplied together. These aggregated effects are added together and then divided by the number of material types N to indicate the overall *material* sustainability, which will vary between *0* and *8*. In order to yield an accessible result, a scaling process is performed to ensure that the final score is within the range of *1* to *10*, in which *1* means *poor* and *10* means *excellent* with regard to sustainability.

3.2. Production (Manufacturing and Assembly)

Producing products in a sustainable manner, such as conserving resources, consuming less energy, and generating less pollution and waste, leads to minimum negative environmental impacts. However, production is a complex process where many design details are determined at the detailed design stage rather than the conceptual design stage. Therefore, only aspects related to manufacturing and assembly are discussed in this paper. Design for manufacturing and assembly (DFMA) is an effective approach to achieve sustainable production. This study extracted core DFMA considerations, for ease of assembly and manufacturing, to measure sustainable production aspects of design concepts, as shown in Table 3. Minimising the number of parts in a practical manner, as well as using more standardised parts/components and fewer unique parts/components, could reduce inventory cost, process time, and so on. Designing parts for ease of assembly involves better presentation (such as avoiding too large or too small items and employing symmetric features), easy handling (such as avoiding oversize, sharp, slippery, heavy, and fragile items), mistake proofing (such as using symmetric or asymmetric features to prevent parts from being assembled in wrong orientations), and efficient insertion (such as employing self-aligning/locating features). Suitable fabrication methods refer to the identification of the most appropriate technology/process based on the material selected to minimise excessive operations, such as polishing and fine machining.

Table 3. DFMA considerations for sustainable product design concepts.

DFMA Considerations	Explanations
Minimum number of parts	The practical minimum number of parts for both manufacturing and assembly.
Parts/components standardisation	The number of standardised parts/components and unique parts/components.
Parts assembly	Parts presentation, handling, mistake proofing, and insertion for ease of assembly.
Suitable fabrication methods	Cost- and energy-effective technology/process for ease of manufacturing.

Measurement of Production

Production details, such as manufacturing methods, manufacturing parameters, and assembly procedures, can be difficult to determine at the conceptual design stage. However, designers are encouraged to consider these attributes with respect to sustainability to steer towards a more sustainable outcome. A similar approach explained in 3.1.1 is adopted here, for example, a *low* rating, a score of *0*, will be given if a concept requires a considerable number of customised parts/components, implying that more negative impacts are created during production. An explanation of levels for each production attribute is provided in Table 4. It is worth noticing that these production attributes are concept dependent, and this therefore requires subjective judgement, for instance, whether adequate standardisation has been achieved. In addition, unlike the types of materials, it is also challenging to evaluate each individual part/component with respect to standardisation, fabrication, and assembly; therefore, here they are considered holistically at the concept level. An equation is then developed to quantify the sustainability with respect to production, as shown in Equation (2).

$$Metric_{Production} = \frac{9 \times (P_1 \times P_2 + P_3) \times P_4}{12} + 1 \quad (2)$$

Table 4. Attributes for measuring concept *production* sustainability.

Attributes	Symbol	Low = 0	Medium = 1	High = 2
Balance between number of parts and their complexity	P_1	Poor balance (e.g., contains too many parts or too complicated parts)	Fair balance (e.g., contains few parts but is complicated)	Good balance (e.g., contains few simple parts)
Parts standardisation	P_2	The concept requires a considerable degree of customisation	The concept has a reasonable degree of potential to be standardised	The concept can benefit significantly by using standardised components
Parts design for assembly	P_3	Poor potential for assembly optimisation	Fair potential for assembly optimisation	Good potential for assembly optimisation
Suitable fabrication method	P_4	Excessive operations needed (e.g., polishing, fine machining)	Partial excessive operations needed	No excessive operations needed

Similar to *material*, the aggregated effect for *production* attributes is considered here. This is again reflected on the multiplier. For example, *balance between number of parts and their complexity* (P_1) is closely related to *part standardisation* (P_2), while *suitable fabrication method* (P_4) will amplify their effect, hence, $P_1 \times P_2 \times P_4$. The equation leads to an overall score for *production* sustainability, which will vary between *0* and *12*. A similar scaling process is performed to ensure that the final rating will yield a value between *1 (poor)* and *10 (excellent)*.

3.3. Use

The use of a product pertains mainly to the amount of time the product is owned and operated by its user. A product's lifetime starts from when it is acquired to when

the product is discarded, which is primarily determined at the conceptual design stage. Functional obsolescence, maintenance prevention, and aesthetic obsolescence are the main reasons that lead to the end of life of a product. In early studies, product lifetime extension was employed to reduce resource consumptions and waste productions by means such as ease of repair and upgrade. However, a longer life span of a product does not necessarily indicate that the product is more resource and waste efficient. For instance, longer lifetime products usually consume more resources in material and production. These extra resources are wasted if a product's lifetime is longer than the time of the product being needed by the user. Therefore, product lifetime optimisation, where a balance between extending and shortening the lifetime and use time is achieved, should be used as an effective strategy to minimise the negative environmental impacts of products. For example, less durable materials should be used for short-life or temporary products and parts. Another strategy to decrease environmental impacts at the use stage is to reduce the product's resource or energy consumption. For example, LED lights consume much less electrical energy in comparison with incandescent lights, but produce the same illumination. Therefore, LED lights should be used rather than incandescent lights while designing products with illumination features.

Measurement of Use

As described previously, the balance between product use time and lifetime needs to be considered during the conceptual design stage. An ideal scenario would be when the product use time is identical to its lifetime, implying that the product enters its end-of-life stage immediately after the use stage. Therefore, the ratio between product lifetime and use time is an attribute to consider, as shown in Table 5. Despite various product categories being evaluated, the product use time and lifetime balance can be determined in a unified way, meaning that the difference between them should always be minimised. For example, the perfect balance for a disposable coffee cup is that it can be recycled right after people finish their drinks. For a mobile phone, the ideal case would be that it can be recycled right after it breaks or when people get a new one rather than sitting in a drawer. It is possible to use objective values to determine the thresholds (*low*, *medium*, and *High*) of *product use time/lifetime* (U_1), but they would be largely dependent on the products themselves. Therefore, subjective descriptors, such as 'significantly shorter/longer', are employed.

Table 5. Attributes for measuring concept *use* sustainability.

Attributes	Symbol	Low = 0	Medium = 1	High = 2
Product use time/lifetime	U_1	Product lifetime is significantly shorter/longer than product use time	Product lifetime is fairly shorter/longer than product use time	Product lifetime is almost identical to product use time
Energy consumption during use	U_2	The concept consumes a significant amount of energy	The concept consumes a fair amount of energy	The concept consumes a slight amount of energy
Robustness, reliability, and maintenance	U_3	The concept requires a significant amount of resource to maintain/service	The concept consumes a fair amount of resource to maintain/service	The concept consumes a slight amount of resource to maintain/service

Energy consumption during use directly indicates the energy efficiency; hence, it is used as the second attribute. Different products can vary significantly; hence, it would be difficult to judge without considering the product category. As a result, it would be beneficial to develop a lookup table by collecting data of day-to-day products and come up with a range of specific values for energy consumption for different product categories. By this, the designer could make judgements by referring to the table more easily. However, it is time-consuming to construct such a lookup table, and therefore, subjective descriptors are used for *energy consumption during use* (U_2) in this study. Robustness, reliability, and

maintenance are treated as the third attribute to indicate sustainability. For example, if a design is more robust, reliable, and easy to maintain, it is then unlikely to cause a significant negative environmental impact due to malfunctioning and servicing. Equation (3) is then developed to quantify the *use* sustainability. Again, the aggregated effect of attributes is considered here and denoted by multipliers. For example, the effect of *energy consumption during use (U_2)* will be amplified by the *product use time/lifetime (U_1)*, hence $U_1 \times U_2$ in the equation. The same scaling process is applied to ensure that the final sustainability score falls between *1* and *10*.

$$Metric_{Use} = \frac{9 \times U_1 \times (U_2 + U_3)}{8} + 1 \quad (3)$$

3.4. End of Life

End of life refers to a product that is at the end of its life cycle, where the product needs to be discarded. End-of-life approaches, such as recycling, reuse, repair, and remanufacturing, are considered more sustainable than conventional disposal methods involving incineration and landfill. Employing biodegradable materials and using waste-to-energy technologies are often used to decrease the negative impacts caused by product disposals, such as landfill and incineration. However, product disposal still leads to issues, such as pollutions and contaminations, and therefore is considered unsustainable. Recycling is a process of converting a disposed product into new materials or objects; reuse involves the action of using the product or parts of the product, without changing the structures, for original and new purposes; repair refers to the replacement of nonfunctional or damaged parts of the product; and remanufacturing means returning the product to a 'like-new' condition. Product disassembly is often needed and considered a significant process in product end of life, even for landfill and incineration. Ease-of-disassembly tactics, such as employing detachable joints, using standardised fasteners, minimising the number of fasteners, and avoiding glues, should be considered at the conceptual design stage to contribute to sustainable product end of life. In addition to ease of disassembly, strategies such as using compatible materials, employing modular parts, ease of identification and inspection, and ease of sorting could also support product end-of-life processing for better environmental performance.

Measurement of End of Life

Compared with recycling, remanufacturing, and repair, reuse requires the least resource and, therefore, is listed as an individual attribute. Recycling, remanufacturing, and repair all require further handling and processing, which consumes more energy and materials; hence, they are categorised together. Some parts of a product are inevitably not reusable, recyclable, remanufacturable, or repairable and need to be disposed of. As a result, the environmental impact caused by disposal needs to be considered. A product at its end of life often requires disassembling to obtain the parts to be reused, recycled, remanufactured, repaired, or even disposed of. Therefore, the degree to whether the concept is easy to disassemble at its end of life is another important attribute. Table 6 presents a summary of the explanations for the attributes discussed. Similar to other metrics, the potential aggregated effect is represented by multipliers of attributes; for example, in order to *reuse (E_1)*, *recycle*, *remanufacture*, *and repair (E_2)* and *dispose (E_3)* the components of a product, the *ease of disassembly (E_4)* of the product is critical. Equation (4) with a scaling operation was developed for the *end-of-life* sustainability.

$$Metric_{EOL} = \frac{9 \times (E_1 + E_2 + E_3) \times E_4}{12} + 1 \quad (4)$$

Table 6. Attributes for measuring concept *end-of-life* sustainability.

Attributes	Symbol	Low = 0	Medium = 1	High = 2
Reuse	E_1	Poor potential for reuse	Fair potential for reuse	Good potential for reuse
Recycling, remanufacturing, and repair	E_2	Poor potential for recycling and remanufacturing	Fair potential for recycling and remanufacturing	Good potential for recycling and remanufacturing
Disposal	E_3	Significant impact due to disposal	Moderate impact due to disposal	Little impact due to disposal
Ease of disassembly	E_4	Poor potential for disassembly optimisation	Fair potential for disassembly optimisation	Good potential for disassembly optimisation

3.5. The Four Metrics

Material, *production*, *use*, and *end of life* are the four metrics, involving 15 attributes, proposed for measuring sustainable product design concepts. A summary of the metrics is depicted in Figure 2. The four metrics proposed could be used individually to measure specific aspects of a product design concept's sustainability, and integrated to provide insights into the concept's overall sustainability. Equations (1)–(4) are developed to indicate the degree of sustainability, from *poor (1)* to *excellent (10)*. A demonstration of utilising the four metrics in a systematic manner for measuring sustainable product design concepts is presented in Section 4.

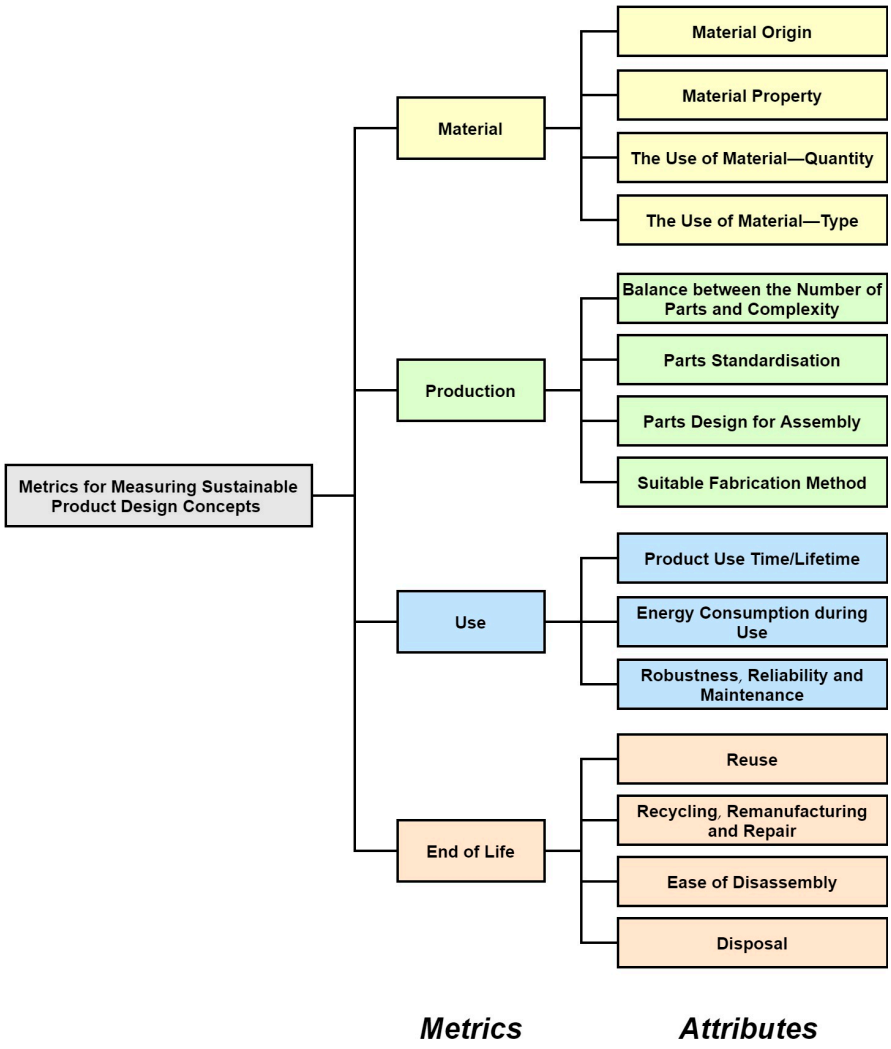
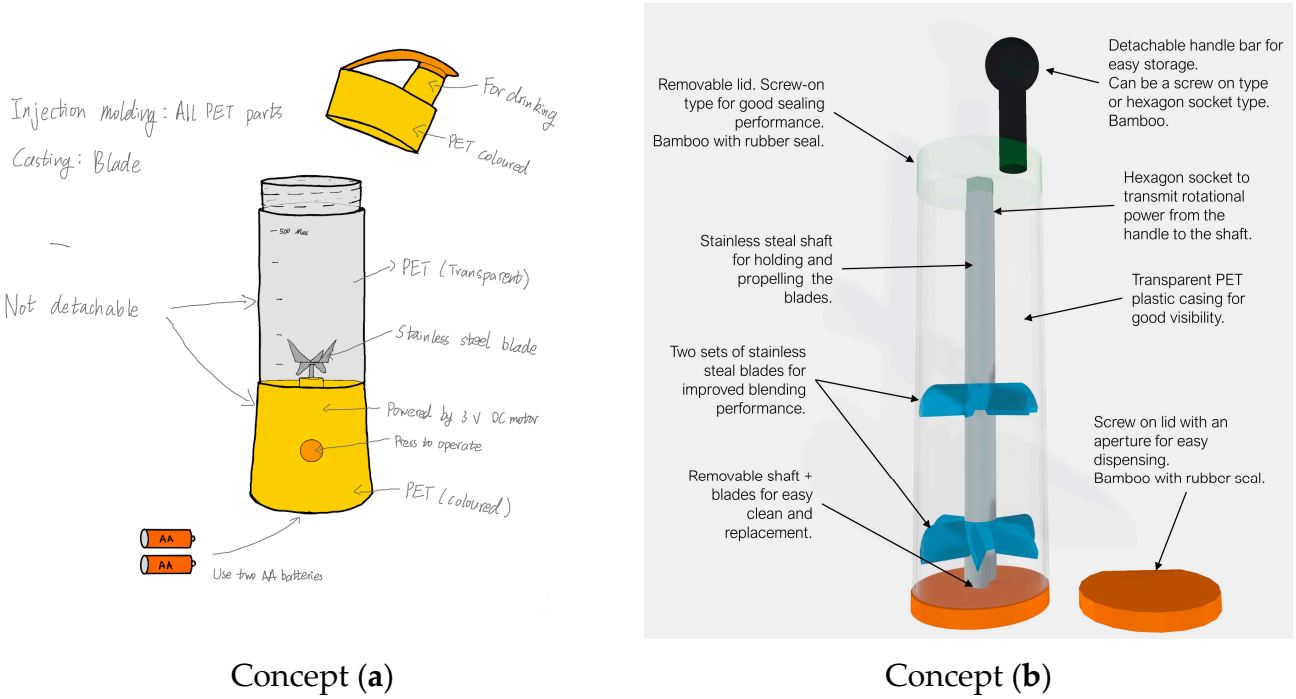


Figure 2. Metrics and attributes for measuring sustainable product design concepts.

4. Case Study

A case study was conducted to demonstrate the application of the metrics explored. Two design concepts of portable blenders, as shown in Figure 3, were used in the case study for sustainability measurement by a design expert by employing the four metrics, *material*, *production*, *use*, and *end of life*, and associated measurements illustrated previously. The two blender concepts were generated, respectively, by two novice design engineers, who participated in the case study voluntarily with high levels of interest. To be more specific, the two design novices were asked to come up with a conceptual design of a portable blender and present the concept using sketches or CAD drawings with annotations. The key product design specifications of the portable blender design were provided to the two design novices to guide them in the conceptual design stage, as shown in Table 7. The design novices signed up with standard case study protocols to provide permission to use their design concepts in this publication and related analysis.



Concept (**a**) Concept (**b**)

Figure 3. Portable blender concept (**a**) and (**b**).

As shown in Figure 3, concept (a) is a portable blender powered by a 3 V DC motor using two AA batteries. The body part of the blender consists of a jug section and a base section, but they are not detachable. The base section is used to house the blade, motor, AA batteries, and other associated electronic components, while the jug section is for containing ingredients, such as fruits and vegetables. A cap is designed with a spout lid, which is screwed on the jug during blending and drinking. PET (polyethylene terephthalate) was selected to produce the cap, jug, and base, while injection moulding was selected as the manufacturing process. Stainless steel was selected for manufacturing the blade via casting. Concept (b) is a manually powered handheld design without the need for batteries or AC/DC power supply. It consists of a lid and a body section. There are two lids: One is for sealing the container body properly while providing interface for attaching the handle bar. Another lid can be used when the blending is finished, and it has an aperture for easy dispensing. The body section contains a transparent PET container with stainless steel shaft and two sets of blades. The steel shaft and blades can be removed completely for easy cleaning and replacement.

Table 7. Key product design specifications.

Function	• To process nuts, fruits, and vegetables into liquid. • The blender should be able to operate without plugging into a power socket.
Performance	• The needed operating time should be within 30 s. • The residual particles should not exceed 3 mm in diameter. • The blender needs to be easy to clean.
Safety	• The blender should not possess risks of causing injuries at any time.
Purpose market	• For outdoor use (e.g., travel, hiking, and picnic).
Quantity	• For product trial, 300 units are expected.
Quality and reliability	• Food hygiene standard has to be met. • The blender should withstand high/low pressure, shock, dust, and water.
Cost	• Should not cost more than a conventional juice blender.
Size and weight	• The blender should be easy to carry with one hand. • The weight should not exceed 2 kg.
Life span	• The blender should last at least 6 months with daily use.
Recycle	• The blender should be easy to recycle at its end of life.
Environment	• The blender should cause minimum environmental impact across its entire life cycle (e.g., service life and end of life).

Evaluation and Results

The design expert, with over 8 years of experience in design engineering, participated voluntarily in the case study to assess the sustainability of the two portable blender concepts. Prior to starting the assessment, explanations of the metrics and instructions for using the equations were provided to the design expert. The results of the evaluation are shown in Table 8. For instance, for the *material* metric of concept (a), four types of materials, PET, stainless steel, battery, and motor, were included in the evaluation. PET was the material used for the cap, base, and jug, while stainless steel was used for the blade of the blender. The motor and battery are not strictly materials, as they have multiple components and features involving many types of materials. However, it is challenging, as well as time-consuming, to consider all materials used for fabricating a motor and battery. Therefore, components such as a motor and battery, which contain multiple materials, are considered individual types of materials to ease the evaluation process. For the *material origin* (M_1) attribute, PET, stainless steel, battery, and motor were all produced using nonrenewable resources, such as fossil fuels and minerals, and therefore, *low* scores of *0* were given. For the *material property* (M_2) attribute, PET is a recyclable material but is toxic to the environment; thus, a *medium (1)* score was given. Stainless steel is a nontoxic and recyclable material, therefore achieving a *high (2)* score. Both the battery and motor contain materials that are nonrecyclable and toxic, therefore receiving *low (0)* scores. For the *use of material—quantity* (M_3) attribute, both PET and stainless steel have fair potentials for material quantity reduction, such as reducing the thickness of the wall or the size of the blade, and were therefore assigned *medium (1)* scores. There are poor potentials to reduce material quantities for both the battery and motor; thus, *low (0)* scores were given. As a result, concept (a) achieved a *material* metric score of 1.84 according to Equation (1). The measurements of the other metrics of concept (a), as well as the sustainability measurement of concept (b), are depicted in Table 8.

Table 8. Evaluation of the two blender concepts.

Metrics	Attributes	Concept (a)	Concept (b)
Material	Material origin (M_1)	• PET—0 • Stainless steel—0 • Battery—0 • Motor—0	• Bamboo—2 • Rubber—2 • Stainless steel—0 • PET—0
	Material property (M_2)	• PET—1 • Stainless steel—2 • Battery—0 • Motor—0	• Bamboo—1 • Rubber—1 • Stainless steel—2 • PET—1
	Use of material—quantity (M_3)	• PET—1 • Stainless steel—1 • Battery—0 • Motor—0	• Bamboo—1 • Rubber—0 • Stainless steel—1 • PET—1
	Use of material—type (N)	4	4
	Material metric	$Metric_{Material} = \frac{9\times\left(\frac{\sum_{i=1}^{N}(M_1+M_2)\times M_3}{N}\right)}{8} + 1 = \frac{9\times\left(\frac{(0+1)\times1+(0+2)\times1+(0+0)\times0+(0+0)\times0}{4}\right)}{8} + 1 = 1.84$	$Metric_{Material} = \frac{9\times\left(\frac{\sum_{i=1}^{N}(M_1+M_2)\times M_3}{N}\right)}{8} + 1 = \frac{9\times\left(\frac{(2+1)\times1+(2+1)\times0+(0+2)\times1+(0+1)\times1}{4}\right)}{8} + 1 = 2.69$
Production	Balance between the number of parts and complexity (P_1)	Simple design, only a few simple parts—2	Simple design, only a few simple parts—2
	Parts standardisation (P_2)	Motor, battery, and gearbox can benefit from standard components—2	All components require customisation—0
	Parts design for assembly (P_3)	Good potential for assembly optimisation—2	Good potential for assembly optimisation—2
	Suitable fabrication method (P_4)	No excessive operations needed—2	Partial excessive operations needed—1
	Production metric	$Metric_{Production} = \frac{9\times(P_1\times P_2+P_3)\times P_4}{12} + 1 = \frac{9\times(2\times2+2)\times2}{12} + 1 = 10$	$Metric_{Production} = \frac{9\times(P_1\times P_2+P_3)\times P_4}{12} + 1 = \frac{9\times(2\times0+2)\times1}{12} + 1 = 2.5$
Use	Product use time/lifetime (U_1)	The design lifetime should be close to its use time—2	The design lifetime should be close to its use time—2
	Energy consumption during use (U_2)	Needs AA batteries to power—1	Manually operated, no other energy required—2
	Robustness, reliability, and maintenance (U_3)	Internal components for the base (e.g., motor and gearbox will require a fair amount of resource to maintain/service)—1	All components are easy to maintain—2
	Use metric	$Metric_{Use} = \frac{9\times U_1\times(U_2+U_3)}{8} + 1 = \frac{9\times2\times(1+1)}{8} + 1 = 5.5$	$Metric_{Use} = \frac{9\times U_1\times(U_2+U_3)}{8} + 1 = \frac{9\times2\times(2+2)}{8} + 1 = 10$
End of Life	Reuse (E_1)	Battery, motor, and gearbox have fair potential to be reused—1	Poor potential for reuse as all components are custom-made—0
	Recycling, remanufacturing, and repair (E_2)	PET plastic, steel blades, and batteries can be recycled (i.e., fair potential for recycling and remanufacturing)—1	PET plastic, steel shaft, and blades can be recycled; bamboo can be remanufactured—2
	Disposal (E_3)	Batteries and motors will cause moderate impact due to disposal—1	All components will have little impact due to disposal—2
	Ease of disassembly (E_4)	Blender base that contains battery, motor, and gearbox will be difficult to disassemble—1	All components are easy to remove—2
	End-of-Life metric	$Metric_{EOL} = \frac{9\times(E_1+E_2+E_3)\times E_4}{12} + 1 = \frac{9\times(1+1+1)\times1}{12} + 1 = 3.25$	$Metric_{EOL} = \frac{9\times(E_1+E_2+E_3)\times E_4}{12} + 1 = \frac{9\times(0+2+2)\times2}{12} + 1 = 7$

An overview of the product concept sustainability assessment results of concepts (a) and (b) is shown in Figure 4, including the results of the four metrics and the average sustainability score. As shown in the figure, concept (a) achieved 1.84 in *material* metric, 10 in *production* metric, 5.5 in *use* metric, and 3.25 in *end-of-Life* metric, with an average sustainability score of 5.15. Concept (b) achieved *material*, *production*, *use*, and *end-of-life* metric scores of 2.69, 2.5, 10, and 7, respectively, with an average sustainability score of

5.55. Based on the results, although the average sustainability scores of concepts (a) and (b) are at a similar level, their metric scores are different. For example, concept (a) outperforms concept (b) in terms of *production*, as it employs standard components and requires no excessive fabrication operations, as presented in Table 8. However, concept (b) has higher scores in *material*, *use*, and *end-of-life* metrics in comparison with concept (a) due to features such as using renewable and less toxic materials, employing manual operation, and being easy to maintain, recycle, remanufacture, and disassemble.

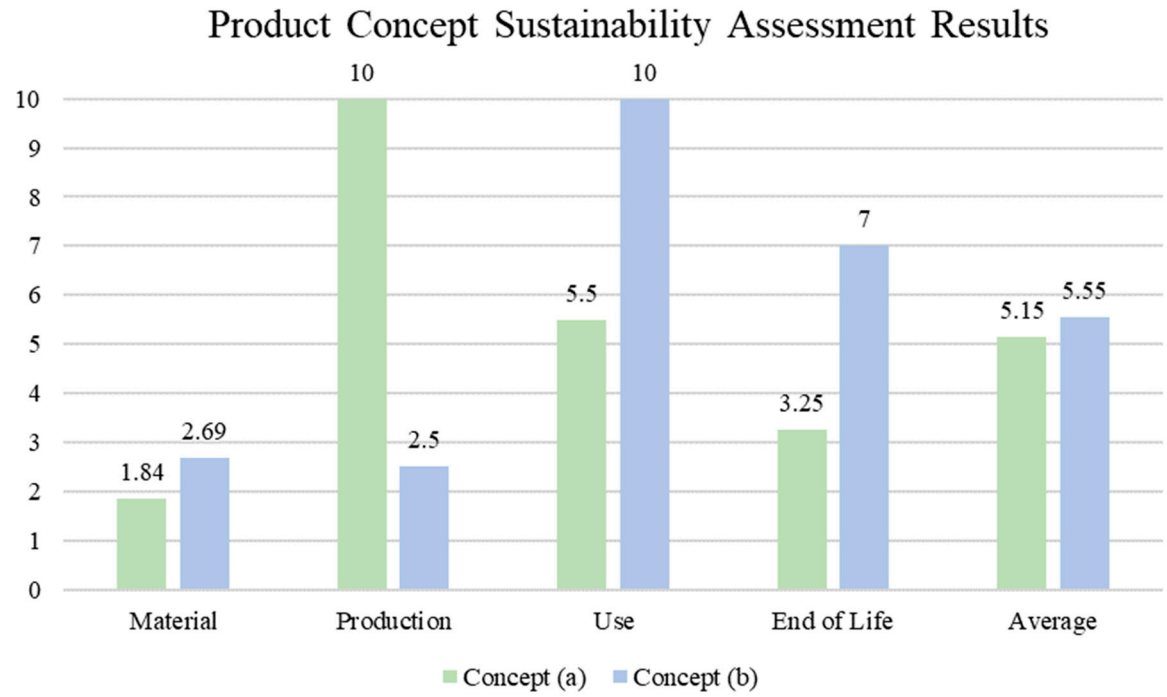


Figure 4. Product concept sustainability assessment results—concepts (**a**) and (**b**).

In addition to the comparison, the sustainability assessment results also indicate sustainability improvement directions for each concept. For example, concept (a) achieved poor performance in the *material* metric, especially the *material origin* (M_1) attribute, as shown in Table 8. Therefore, using renewable materials, such as recycled glass, to replace the use of PET for producing the jug of the blender could potentially increase the sustainability score of the concept regarding the *material* metric. Concept (b) has poor performance in *production*, of which the *parts standardisation* (P_2) attribute is given a *low (0)* score, and the *suitable fabrication method* (P_4) attribute is given a *medium (1)* score. Therefore, using a standardised rotating handle with shaft that is available on the market will reduce the number of customisation parts and the excessive fabrication operations needed, which could potentially improve the *production* score. Other improvement strategies could be inferred to increase the scores of the remaining sustainability metrics of the two concepts.

5. Discussion

Four metrics, *material*, *production*, *use*, and *end of life*, are proposed in this study for measuring sustainable product design concepts. The corresponding attributes with associated measurement equations could be used to identify the sustainability level of a concept, with regard to the four metrics, in a quantitative manner. The attribute scores, *low (0)* to *high (2)*, applied are in the simplest form possible to provide the most straightforward indication of attribute sustainability. The equations developed aim to indicate the sustainability of each metric by using multipliers to link attributes that have aggregated effects, for instance, *material origin* and *use of material—quantity*, and using summation to indicate the cumulative effects of the attributes. The equations developed and used are not necessarily the final

forms, and modifications can be envisaged. For example, different weights can be assigned to attributes within a metric, referring to different product design applications, to better indicate concept-specific sustainability. The major advantage of using equations is making quantitative comparisons between different concepts. The designer is able to obtain instant results of concept sustainability based on the scores. More significantly, scores for different metrics allow an indication of sustainability improvement directions. For instance, if a product design concept received a poor sustainability evaluation rating for a metric, the designer could explore which attribute(s) of the metric has low ratings and then modify the design concept accordingly for sustainability improvements.

This study has three implications. First, the four metrics identified for measuring product design concepts could effectively improve a product's sustainability level at a lower cost in comparison with addressing sustainability issues at later stages. Solving sustainability issues once a product is designed or at late design stages is challenging and expensive [21,22], whereas decisions made at the conceptual design stage have high impacts on minimising the negative environmental impacts on downstream activities, such as material, production, use, and end of life [13–16]. The second implication is that the study has raised the significance of addressing sustainability issues at the conceptual design stage. Many design features related to product sustainability or environmental impacts are not often considered by design engineers, as they generally focus on cost, performance, and durability [12,25,26]. This could result in products' lack of sustainability considerations, while the introduction of the four metrics for assessing the sustainability of product concepts has the potential to foster designers in considering sustainability design features during conceptual design. The third implication is the need for more and better sustainability concept assessment tools. The review conducted in this study reveals that the majority of existing concept assessment methods or tools are aimed at assessing the feasibility or creativity aspects of product design concepts. Although a few methods exist for evaluating the sustainability of product design concepts, these methods are limited in use [63–65]. The metrics for measuring sustainable product design concepts proposed in this study have an extensive application scope in practice, which could also be utilised as a theoretical foundation for developing advanced sustainability concept evaluation tools.

However, the metrics proposed are aimed at recommending design changes at the conceptual design stage, and it might be challenging to suggest final determinations. It therefore requires the designer or evaluator who uses the metrics for evaluation to possess sufficient knowledge and experience in sustainable design and decision-making skills to yield final design decisions. Further explorations, such as conducting more practical case studies, are needed to examine how well the four metrics represent sustainability to increase the metrics' suitability for conceptual design and to improve the measurement equations.

6. Conclusions

Sustainability plays an increasingly significant role in modern product design and development, while it is indicated that most of the negative environmental impacts are determined at early design stages, such as conceptual design. However, the review of prior literature showed that most of the existing concept evaluation methods are geared to measure the feasibility or creativity of concepts generated rather than the sustainability. The lack of measurements of sustainability at the conceptual design stage often leads to nonsustainable products, which result in negative environmental impacts. Therefore, this paper explored the key sustainable design elements and propose a set of metrics for measuring sustainable product design concepts. The four metrics identified, *material*, *production*, *use*, and *end of life*, associated with corresponding attributes and measurement equations, can support designers in producing sustainable design concepts, ultimately leading to sustainable products with minimal negative environmental impacts. Although this paper aims at assessing the environmental aspects of sustainable product design concepts, products produced also impact both the social and economic dimensions of

sustainability through manufacturing, use, and end of life, which contribute to both employability and value creation [66].

The paper is the first study to explore metrics for evaluating product design sustainability at the conceptual design stage. It delivers three significant contributions to engineering design, sustainability, and energy research communities. First, it serves as a guideline to measure the level of sustainability of design concepts for supporting sustainable product design in a quantitative manner. Second, it urges design practitioners and researchers to look into the importance of considering sustainable design aspects at early design stages. Finally, the study offers new research insights into exploring sustainable concept evaluation and can be used as an infrastructure to develop future concept evaluation tools.

Author Contributions: Conceptualization, J.H., P.J., and P.R.N.C.; methodology, J.H. and P.J.; investigation, J.H. and P.J.; writing—original draft preparation, J.H. and P.J.; writing—review and editing, J.H., P.J., and P.R.N.C.; supervision, P.R.N.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available in this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Parker, J.; Simpson, G.D. A Theoretical Framework for Bolstering Human-Nature Connections and Urban Resilience via Green Infrastructure. *Land* **2020**, *9*, 252. [CrossRef]
2. Vollset, S.E.; Goren, E.; Yuan, C.-W.; Cao, J.; Smith, A.E.; Hsiao, T.; Bisignano, C.; Azhar, G.S.; Castro, E.; Chalek, J.; et al. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: A forecasting analysis for the Global Burden of Disease Study. *Lancet* **2020**, *396*, 1285–1306. [CrossRef]
3. Mesa, J.; Maury, H.; Arrieta, R.; Corredor, L.; Bris, J. A novel approach to include sustainability concepts in classical DFMA methodology for sheet metal enclosure devices. *Res. Eng. Des.* **2018**, *29*, 227–244. [CrossRef]
4. Fargnoli, M.; de Minicis, M.; Tronci, M. Design Management for Sustainability: An integrated approach for the development of sustainable products. *J. Eng. Technol. Manag.* **2014**, *34*, 29–45. [CrossRef]
5. Chiu, M.-C.; Chu, C.-H. Review of sustainable product design from life cycle perspectives. *Int. J. Precis. Eng. Manuf.* **2012**, *13*, 1259–1272. [CrossRef]
6. WCED. *Our Common Future*; Oxford University Press: Oxford, UK, 1987. Available online: https://archive.org/details/ourcommonfuture00worl/page/n5/mode/2up (accessed on 8 June 2021).
7. Purvis, B.; Mao, Y.; Robinson, D. Three pillars of sustainability: In search of conceptual origins. *Sustain. Sci.* **2019**, *14*, 681–695. [CrossRef]
8. He, B.; Gu, Z. Sustainable design synthesis for product environmental footprints. *Des. Stud.* **2016**, *45*, 159–186. [CrossRef]
9. Vallet, F.; Eynard, B.; Millet, D.; Mahut, S.G.; Tyl, B.; Bertoluci, G. Using eco-design tools: An overview of experts' practices. *Des. Stud.* **2013**, *34*, 345–377. [CrossRef]
10. Chen, C.; Zhu, J.; Yu, J.-Y.; Noori, H. A new methodology for evaluating sustainable product design performance with two-stage network data envelopment analysis. *Eur. J. Oper. Res.* **2012**, *221*, 348–359. [CrossRef]
11. Ahmad, S.; Wong, K.Y.; Tseng, M.L.; Wong, W.P. Sustainable product design and development: A review of tools, applications and research prospects. *Resour. Conserv. Recycl.* **2018**, *132*, 49–61. [CrossRef]
12. Howarth, G.; Hadfield, M. A sustainable product design model. *Mater. Des.* **2006**, *27*, 1128–1133. [CrossRef]
13. Tiwari, V.; Jain, P.K.; Tandon, P. Product design concept evaluation using rough sets and VIKOR method. *Adv. Eng. Inform.* **2016**, *30*, 16–25. [CrossRef]
14. Shidpour, H.; Da Cunha, C.; Bernard, A. Group multi-criteria design concept evaluation using combined rough set theory and fuzzy set theory. *Expert Syst. Appl.* **2016**, *64*, 633–644. [CrossRef]
15. Zhu, G.-N.; Hu, J.; Qi, J.; Gu, C.-C.; Peng, Y.-H. An integrated AHP and VIKOR for design concept evaluation based on rough number. *Adv. Eng. Inform.* **2015**, *29*, 408–418. [CrossRef]
16. Wang, L.; Shen, W.; Xie, H.; Neelamkavil, J.; Pardasani, A. Collaborative conceptual design—State of the art and future trends. *Comput. Aided Des.* **2002**, *34*, 981–996. [CrossRef]
17. Hsu, W.; Liu, B. Conceptual design: Issues and challenges. *Comput. Aided Des.* **2000**, *32*, 849–850. [CrossRef]
18. Marcinkowski, A.; Zych, K. Environmental Performance of Kettle Production: Product Life Cycle Assessment. *Manag. Syst. Prod. Eng.* **2017**, *25*, 255–261. [CrossRef]
19. WRAP. Environmental Assessment of Consumer Electronic Products. Available online: http://archive.wrap.org.uk/sites/files/wrap/Environmental%20assessment%20of%20consumer%20electronic%20products.pdf (accessed on 25 May 2021).

20. Lewis, H.; Gertsakis, J.; Grant, T.; Morelli, N.; Sweatman, A. *Design+ Environment: A Global Guide to Designing Greener Goods*; Routledge: London, UK, 2017.
21. Ramani, K.; Ramanujan, D.; Bernstein, W.Z.; Zhao, F.; Sutherland, J.; Handwerker, C.; Choi, J.-K.; Kim, H.; Thurston, D. Integrated Sustainable Life Cycle Design: A Review. *J. Mech. Des.* **2010**, *132*, 091004. [CrossRef]
22. Birch, A.; Hon, K.K.B.; Short, T. Structure and output mechanisms in Design for Environment (DfE) tools. *J. Clean. Prod.* **2012**, *35*, 50–58. [CrossRef]
23. Ruy, M.; Alliprandini, D.; Scur, G. Environmental assessment in the conceptual design phase of new product development. *Int. J. Sustain. Des.* **2019**, *3*, 182–204. [CrossRef]
24. Hallstedt, S.I. Sustainability criteria and sustainability compliance index for decision support in product development. *J. Clean. Prod.* **2017**, *140*, 251–266. [CrossRef]
25. Yang, C.J.; Chen, J.L. Accelerating preliminary eco-innovation design for products that integrates case-based reasoning and TRIZ method. *J. Clean. Prod.* **2011**, *19*, 998–1006. [CrossRef]
26. Brundage, M.P.; Bernstein, W.Z.; Hoffenson, S.; Chang, Q.; Nishi, H.; Kliks, T.; Morris, K.C. Analyzing environmental sustainability methods for use earlier in the product lifecycle. *J. Clean. Prod.* **2018**, *187*, 877–892. [CrossRef]
27. Kravchenko, M.; Pigosso, D.C.A.; McAloone, T.C. Developing A Tool to Support Decisions in Sustainability-Related Trade-Off Situations: Understanding Needs and Criteria. *Proc. Des. Soc.* **2020**, *1*, 265–274. [CrossRef]
28. Gagnon, B.; Leduc, R.; Savard, L. From a conventional to a sustainable engineering design process: Different shades of sustainability. *J. Eng. Des.* **2012**, *23*, 49–74. [CrossRef]
29. McAloone, T.C.; Pigosso, D.C.A. Ecodesign Implementation and LCA. In *Life Cycle Assessment: Theory and Practice*; Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 545–576.
30. Suhariyanto, T.T.; Wahab, D.A.; Rahman, M.N.A. Product Design Evaluation Using Life Cycle Assessment and Design for Assembly: A Case Study of a Water Leakage Alarm. *Sustainability* **2018**, *10*, 2821. [CrossRef]
31. Harris, J.S. New product profile chart. *Chemtech* **1976**, *6*, 554–564.
32. Amabile, T.M. Social psychology of creativity: A consensual assessment technique. *J. Personal. Soc. Psychol.* **1982**, *43*, 997–1013. [CrossRef]
33. O'Quin, K.; Besemer, S.P. The development, reliability, and validity of the revised creative product semantic scale. *Creat. Res. J.* **1989**, *2*, 267–278. [CrossRef]
34. Pugh, S.; Clausing, D. *Creating Innovtive Products Using Total Design: The Living Legacy of Stuart Pugh*; Addison-Wesley Longman Publishing Co., Inc.: Boston, MA, USA, 1996.
35. Davoodi, M.M.; Sapuan, S.M.; Ahmad, D.; Aidy, A.; Khalina, A.; Jonoobi, M. Concept selection of car bumper beam with developed hybrid bio-composite material. *Mater. Des.* **2011**, *32*, 4857–4865. [CrossRef]
36. Sarkar, P.; Chakrabarti, A. Assessing design creativity. *Des. Stud.* **2011**, *32*, 348–383. [CrossRef]
37. Childs, P.R.N. *Mechanical Design Engineering Handbook*, 2nd ed.; Butterworth-Heinemann: Oxford, UK, 2018.
38. Yung, W.K.C.; Chan, H.K.; So, J.H.T.; Wong, D.W.C.; Choi, A.C.K.; Yue, T.M. A life-cycle assessment for eco-redesign of a consumer electronic product. *J. Eng. Des.* **2011**, *22*, 69–85. [CrossRef]
39. Mestre, A.; Vogtlander, J. Eco-efficient value creation of cork products: An LCA-based method for design intervention. *J. Clean. Prod.* **2013**, *57*, 101–114. [CrossRef]
40. Deng, C.; Wu, J.; Shao, X. Research on eco-balance with LCA and LCC for mechanical product design. *Int. J. Adv. Manuf. Technol.* **2016**, *87*, 1217–1228. [CrossRef]
41. Civancik-Uslu, D.; Puig, R.; Voigt, S.; Walter, D.; Fullana-i-Palmer, P. Improving the production chain with LCA and eco-design: Application to cosmetic packaging. *Resour. Conserv. Recycl.* **2019**, *151*, 104475. [CrossRef]
42. Rossi, M.; Germani, M.; Zamagni, A. Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. *J. Clean. Prod.* **2016**, *129*, 361–373. [CrossRef]
43. Wisthoff, A.; Ferrero, V.; Huynh, T.; DuPont, B. Quantifying the Impact of Sustainable Product Design Decisions in the Early Design Phase Through Machine Learning. In Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Charlotte, NC, USA, 21–24 August 2016.
44. Millet, D.; Bistagnino, L.; Lanzavecchia, C.; Camous, R.; Poldma, T. Does the potential of the use of LCA match the design team needs? *J. Clean. Prod.* **2007**, *15*, 335–346. [CrossRef]
45. Bereketli, I.; Erol Genevois, M. An integrated QFDE approach for identifying improvement strategies in sustainable product development. *J. Clean. Prod.* **2013**, *54*, 188–198. [CrossRef]
46. Younesi, M.; Roghanian, E. A framework for sustainable product design: A hybrid fuzzy approach based on Quality Function Deployment for Environment. *J. Clean. Prod.* **2015**, *108*, 385–394. [CrossRef]
47. Wu, Y.-H.; Ho, C.C. Integration of green quality function deployment and fuzzy theory: A case study on green mobile phone design. *J. Clean. Prod.* **2015**, *108*, 271–280. [CrossRef]
48. Ocampo, L.A.; Labrador, J.J.T.; Jumao-as, A.M.B.; Rama, A.M.O. Integrated multiphase sustainable product design with a hybrid quality function deployment—Multi-attribute decision-making (QFD-MADM) framework. *Sustain. Prod. Consum.* **2020**, *24*, 62–78. [CrossRef]
49. Olewnik, A.; Lewis, K. Limitations of the House of Quality to provide quantitative design information. *Int. J. Qual. Reliab. Manag.* **2008**, *25*, 125–146. [CrossRef]

50. Abu-Assab, S. Quality Function Deployment in New Product Development. In *Integration of Preference Analysis Methods into Quality Function Deployment: A Focus on Elderly People*; Abu-Assab, S., Ed.; Gabler Verlag: Wiesbaden, Germany, 2012; pp. 47–68.
51. Han, J.; Forbes, H.; Schaefer, D. An exploration of how creativity, functionality, and aesthetics are related in design. *Res. Eng. Des.* **2021**, 1–19. [CrossRef]
52. Goswami, M.; Tiwari, M.K. A predictive risk evaluation framework for modular product concept selection in new product design environment. *J. Eng. Des.* **2014**, *25*, 150–171. [CrossRef]
53. Rondini, A.; Bertoni, M.; Pezzotta, G. An IPA Based Method for PSS Design Concept Assessment. *Procedia CIRP* **2017**, *64*, 277–282. [CrossRef]
54. Chulvi, V.; Sonseca, Á.; Mulet, E.; Chakrabarti, A. Assessment of the Relationships Among Design Methods, Design Activities, and Creativity. *J. Mech. Des.* **2012**, *134*, 111004. [CrossRef]
55. García-García, C.; Chulvi, V.; Royo, M. Knowledge generation for enhancing design creativity through co-creative Virtual Learning Communities. *Think. Ski. Creat.* **2017**, *24*, 12–19. [CrossRef]
56. Horn, D.; Salvendy, G. Measuring consumer perception of product creativity: Impact on satisfaction and purchasability. *Hum. Factors Ergon. Manuf. Serv. Ind.* **2009**, *19*, 223–240. [CrossRef]
57. Chakrabarti, A.; Sarkar, P.; Leelavathamma, B.; Nataraju, B.S. A functional representation for aiding biomimetic and artificial inspiration of new ideas. *Artif. Intell. Eng. Des. Anal. Manuf.* **2005**, *19*, 113–132. [CrossRef]
58. Chiu, I.; Shu, L.H. Investigating effects of oppositely related semantic stimuli on design concept creativity. *J. Eng. Des.* **2012**, *23*, 271–296. [CrossRef]
59. Demirkan, H.; Afacan, Y. Assessing creativity in design education: Analysis of creativity factors in the first-year design studio. *Des. Stud.* **2012**, *33*, 262–278. [CrossRef]
60. Lee, J.H.; Gu, N.; Ostwald, M.J. Creativity and parametric design? Comparing designer's cognitive approaches with assessed levels of creativity. *Int. J. Des. Creat. Innov.* **2015**, *3*, 78–94. [CrossRef]
61. Srinivasan, V.; Song, B.; Luo, J.; Subburaj, K.; Elara, M.R.; Blessing, L.; Wood, K. Does Analogical Distance Affect Performance of Ideation? *J. Mech. Des.* **2018**, *140*, 071101. [CrossRef]
62. Starkey, E.M.; Menold, J.; Miller, S.R. When Are Designers Willing to Take Risks? How Concept Creativity and Prototype Fidelity Influence Perceived Risk. *J. Mech. Des.* **2019**, *141*, 031104. [CrossRef]
63. Lindow, K.; Woll, R.; Stark, R. Developing Sustainable Products: An Interdisciplinary Challenge. In Proceedings of the 4th International Conference on Research into Design (ICoRD'13), Tamil Nadu, India, 7–9 January 2013; pp. 517–527.
64. Hassan, M.F.; Saman, M.Z.M.; Sharif, S.; Omar, B. Sustainability evaluation of alternative part configurations in product design: Weighted decision matrix and artificial neural network approach. *Clean Technol. Environ. Policy* **2016**, *18*, 63–79. [CrossRef]
65. Turan, F.M.; Johan, K.; Nor, N.H.M.; Omar, B. Sustainability Assessment Model in Product Development. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *226*, 012021. [CrossRef]
66. Tarne, P.; Traverso, M.; Finkbeiner, M. Review of life cycle sustainability assessment and potential for its adoption at an automotive company. *Sustainability* **2017**, *9*, 670. [CrossRef]