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A benchmark-based method for sustainable product design

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Abstract

Purpose – The purpose of this paper is to develop an effective approach to decide design details using benchmarking to capture the existing practice in sustainable design.

Design/methodology/approach – This paper reports a systematic method for sustainable product design. The method uses benchmarks as references searching for design details to achieve sustainable solutions. Quality function deployment is used to guide the search process for competitive products using benchmarking to meet quantitative targets of product and to increase knowledge for sustainable design.

Findings – The proposed method can meet both functional and sustainable requirements of product design. 18.55 percent reduction in carbon equivalent emissions is achieved compared to benchmarks in wheelchair design. The research reveals that when weight, material and number of components used in product decrease, environmental footprints and cost of the product improve.

Originality/value – The research improves the existing method of sustainable product design. Both sustainable requirements and functional demands of product are identified from qualitative criteria to quantitative metrics using benchmarking and the life cycle assessment.

Keywords Performance, Product design, Benchmarking, Quality function deployment, Knowledge management

Paper type Research paper

1. Introduction

Significant efforts have been made for sustainable product development by researchers and industries to reduce global warming and depletion of resources. It is required to consider minimizing environmental impacts of product in the design stage, which has been recognized as one of the most important practices for achieving product sustainability (Hwang *et al.*, 2013).

Considering product sustainable solutions in the design stage is called sustainable design which requires effectively dealing with both product functional attributes and environmental impacts in product design with the balance of economic, social and environmental aspects (Bereketli and Genevois, 2013; Remery *et al.*, 2012). Product performance is evaluated not only in durability, reliability, affordability, and aesthetic perspective, but also being environmentally friendly considering global warming, reducing energy consumption and conducting the end-of-product life cycle management such as reusing, recycling and remanufacturing (Yang *et al.*, 2012; Pialot *et al.*, 2012). Product designers need a sense of responsibility for natural environments and resources.

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Therefore, meeting functional requirements and sustainability is critical for product success in the current market. Products compete on the basis of not only price, functions and diversity, but also sustainability. Life cycle assessment (LCA) is commonly used to evaluate the environmental impact of a product or a system in its life cycle based on ISO-14040 (2006) and ISO-14044 (2006) of environmental management standards (Gmelin and Seuring, 2014). However, sustainability is not easy to achieve as it deals with complex factors (Kunz *et al.*, 2013). To understand the nature of design requirements in product development, quality function deployment (QFD) is an effective tool to systematically translate design expectations into functional requirements in product development (Ulrich, 1995; Bereketli and Genevois, 2013). QFD can translate product design requirements into engineering parameters, which provides a useful tool to understand design requirements. But QFD cannot provide the detail information for the sustainable analysis (Miguel, 2013). It is impossible to determine details of product components using QFD only in sustainable design. Many existing sustainable design methods lack the ability to generate technical details required in product design (Luthe *et al.*, 2013; Poel, 2007).

Benchmarking searches for the best practices that can lead to expected product performance through implementation of these practices by identifying the practice of industries and adapting solutions to address design requirements and priorities (Bogan and English, 1994). This research uses benchmarks as references searching for design parameters to achieve solutions of sustainability. QFD is expanded to guide the search process of competitive products using benchmarking to meet quantitative targets, and to increase design knowledge of sustainable product.

The benchmark-based method forms quantitative metrics for sustainable product design. The quantitative metrics are evolved using concepts of Axiomatic design (Suh, 2001) and QFD methods for the LCA. The proposed method maps sustainable criteria and functional requirements into design parameters for product details. In order to achieve sustainable solutions for a wheelchair design, four competitive wheelchairs are selected as benchmarks to find details of sustainable attributes in this research. Materials and mechanical structures of the wheelchair are decided based on the result of benchmarking. A sustainable wheelchair is finally designed using parameters obtained from the benchmarks. Following parts of the paper will first review the existing research and methods in sustainable design. Proposed methods will then be introduced in Section 3. Section 4 discusses a case study of the wheelchair design, followed by conclusions and further work in Section 5.

2. Literature review

Sustainable product is required to meet both functional and environmental-friendly requirements to achieve operational, economic and social objectives (Meybodi, 2013; Zink, 2014). Sustainability can be defined as the ability of a product or system to work continuously during its life cycle with the lowest level of impact to the environment (McLennan, 2004). Product design is one of the most important stages in sustainable product development. Design affects all stages of product life cycles from extracting raw materials to the end of product life. Among different scopes of sustainability, product design has the significant influence on product development from material selection, manufacturing and assembly processes to product distribution, use, reuse, recycle and disposal. It is noticed that although product design constitutes only 5-7 percent cost of whole product development, it can determine around 75 percent of the entire product life cycle cost (Ullman, 1992). Sustainable design provides solutions to reduce product environmental impacts. It is claimed that 80 percent of product environmental footprints is established in the design stage (Gilchrist *et al.*, 2012). Product design solutions have significant effects on the entire product life cycle (Bohm *et al.*, 2010).

One of the requirements in sustainable design is to reduce environmental footprints generated during product development (Graedel and Allenby, 2003; Lee and Park, 2005). The challenge is to evaluate product environmental footprints. Over the last decades, numerous methods have been developed for environmental and sustainable metrics (Pialot *et al.*, 2012; Murthy and Mani, 2012). Ramani *et al.* (2010) reviewed eco-design tools in four categories including checklist-based tools, QFD-based tools, LCA tools and integrated tools. Checklist-based tools evaluate the product environmental impact through a series of questions to guide sustainable design in the design process. These tools are qualitative to highlight environmental awareness (Bovea and Belis, 2012; Luttropp and Lagerstedt, 2006). Checklist tools are easy to use at the early stage of design, but they cannot provide design details.

QFD-based tools embed sustainable objectives in product design using methods of quality function deployment for environments. These tools collect customer requirements and environmental needs, and then try to correlate these needs with product and process specifications. They consider environmental requirements with product functions to achieve a balance between eco-design concepts for environmental concerns and economic aspects for consumer needs (Liu and Wang, 2011). The correlation of environmental-related design and consumer needs depends considerably on knowledge and experience of designers when using QFD-based tools (Masui *et al.*, 2003).

LCA tools find environmental impacts of a product or process based on the product interaction with environments through consuming materials and energy in different stages of the product life cycle. LCA evaluates environment impacts of product life cycles including raw materials production, manufacturing, distribution, product use and disposal. LCA aims to minimize the environmental impact of all phases of product life cycles, which requires the extensive data of the product and environments (Gmelin and Seuring, 2014). The conceptual design stage has incomplete information for LCA methods to use (Yang *et al.*, 2012).

Generally, LCA tools are costly and time-consuming as designers need accurate information and data of product life cycles to accomplish LCA (Guinée, 2002). It would be difficult to use this method at the early stage of design if detailed information of the final product is not available. Consequently, it is difficult to assess the environmental impact of a specific life cycle stage, a certain material, or a production flow (Koffler *et al.*, 2008).

Multiple sources of uncertainty should be considered to achieve sustainable design solutions in the early product design process (Inoue *et al.*, 2012). Many of the existing LCA methods require precise and quantitative information which is not available during the product design phase (Remery *et al.*, 2012). Determining design details is difficult due to the uncertainty and imprecision of data given in the sustainable expectation. The extensive data are required to conduct a full LCA process (Gmelin and Seuring, 2014).

A lot of research efforts have been made recently for LCA-based methods. Mestre and Vogtlander (2013) proposed a LCA-based method for the eco-efficient value creation in four levels of project strategy, concept development, design implementation and product diffusion. The method aims at reducing the eco-burden of product, and enhancing the customer perceived value. The eco-burden is decided using LCA based on ISO 14040/44. The customer perceived value is based on the product price. LCA evaluates the product life cycle impact to environments based on the product function unit. The assessment can identify the possible areas of improvement. However, the final product may not be equal to the total of functional units. It has the limitation to guide designers to product improvement directions (Kim *et al.*, 2014).

Although the existing research considers different aspects of sustainable design by analyzing customer needs, sustainable metrics and design parameters, it does not provide a solution for designers to determine sustainable design details. LCA-based and QFD-based methods need detailed information and data as inputs and outputs which are ambiguous at the early stage of design. Eco-design requires considering environmental issues at beginning of product development process with effective tools for environmental rules and standards (Goepp *et al.*, 2014).

Current research activities try to integrate different eco-design methods together in order to improve sustainable design with detailed information and data. Integrated tools try to link eco-design tools using holistic approaches, such as using web-based assessment and education tools, combining the life cycle cost and LCA and using multi-criteria decision making (Čuček *et al.*, 2012). For example, Eddy *et al.* (2013) detailed a sustainability model by integration of LCA mathematical models and compatible life cycle cost models for product conceptual design. A three-phase QFD was proposed to identify and select eco-design improvement strategies considering both end user requirements and environmental stakeholder needs (Bereketli and Genevois, 2013). A modular upgradable architecture was proposed to enable the independent replacement of subsystems for extending useful life of subsystems and to lower total environmental impact (Agrawal and Ülkü, 2013). Design tools for determining life cycle strategies have also been developed. For example, Gmelin and Seuring (2014) linked sustainable factors and product development using a conceptual framework for a product life cycle view considering internal and external interactions and collaborations. However, most of these methods are primarily at the system level with fewer details for product design (Lee *et al.*, 2014).

Current approaches to assess the environmental impacts of product life cycles mainly focus on product detail design, which is not very useful in conceptual design (Eddy *et al.*, 2013). For a sustainable life cycle, decision making should occur in the early phase of the design process. However, the early phase contains multiple sources of uncertainty in describing design. The implementation of the sustainable development concept requires the use of appropriate methods and tools for product design (Inoue *et al.*, 2012).

Assessment of product impacts on environment needs information of material properties, product shape and size and manufacturing processes. However, these data are difficult to obtain in conceptual design process if without any references (Yang *et al.*, 2012). It is necessary to find product characteristics to be taken into account, and find ways to use them at beginning of product development.

Based on the literature reviewed, there is not an effective method to determine design details to achieve product sustainability at the product conceptual design stage. Traditional design often is a trial-and-error process, which is difficult to capture design solutions to pass them to other designers. It can be concluded that the existing research is limited to the consideration of general functional features of products rather than detailed design parameters of products due to difficulty in accessing detailed information of products in the early design stage (Kim *et al.*, 2014). It is important to have some references from the best design practice to support a design process (Inoue *et al.*, 2012).

Therefore, benchmarking is proposed to search for expected design solutions based on the existing products that have the best performance in the market. Benchmarking is a systematic approach to achieve targeted goals using the process of identifying, understanding and adopting the existing practices and processes (Panwar *et al.*, 2013). Benchmarking compares product and its competitive products in measured performance. Product details to achieve the expected performance can be obtained through the analysis. Main advantages of benchmarking can eliminate the trial and error process, speed up design improvement, and increase efficiency of developing new products (Bogan and English, 1994; Hong *et al.*, 2014).

Benchmarking has been used by many researchers and industries searching for the best solution both inside and outside the organization for product development or process improvement. Panwar *et al.* (2013) conducted a survey for 300 auto industries in India for adoption of the best practice through benchmarking. It was found that benchmarking is an important tool to gain knowledge of competitors for improving product design. Miguel (2013) reported importance of the QFD implementation using benchmarking in case studies of two companies. Customer satisfaction is improved through enhanced product and service quality. Vinayak and Kodali (2013) analyzed 127 QFD articles in order to identify the best practice of QFD models. In total, 36 steps of the QFD model were represented using House of Quality (HOQ).

A requirement-based benchmarking approach was proposed by Hamraz *et al.* (2013) to assess and improve the change prediction using the change prediction method (CPM) for engineering change management (ECM). The change requirements from the literature survey and industrial case studies are used as benchmarking criteria to assess the CPM for the best-in-class solutions. A decision support model was developed by Hong *et al.* (2014) for establishing benchmarks as a tool for the allocation of construction industry. Using the competitive analysis of benchmarking, product performance can be evaluated based on competitive products for performance ratings to decide the design priority.

There is one publication found that suggests using benchmarks for sustainable product details. Bernstein (2010) proposed a concept of function impact matrix (FIM) for integration of LCA, benchmarking and QFD to identify product environmental impacts. It is a concept for integrating qualitative and quantitative measures in the entire product life cycle. There are no details of the implementation and applications of the proposed FIM.

This paper proposes an approach to decide details of sustainable design parameters using benchmarking to capture the existing practice in sustainability. A multi-criteria approach is used to consider measures of traditional product design with environmental impacts. Based on the competitive benchmark analysis, the target performance for design requirements can be decided. The research uses axiomatic design and QFD principles to identify and map both sustainable requirements and function demands from qualitative criteria into quantitative metrics to develop sustainable solutions. LCA and benchmarking are integrated to compare and select the best design parameter of benchmarks based on the quantitative sustainable metrics. Finally, a sustainable wheelchair product is designed based on identified benchmark solutions.

3. Proposed methods

A basic challenge in sustainable product design is to assess and balance the product performance in durability, manufacturability, economic feasibility and environmental impacts (Bereketli and Genevois, 2013). It is necessary to have effective methods to evaluate, decide, analyze and optimize design for sustainable solutions. A framework for sustainable design is proposed in this research as shown in Figure 1. The method integrates QFD, benchmarking, and LCA to conduct the evaluation of environmental footprints of products and their components. QFD is used to map design requirements and functional specifications. The benchmarking provides data of the design specifications to decide product details for quantitative sustainable metrics. LCA checks the sustainable solutions, which is conducted for benchmark details such as the material processing of components to evaluate environmental footprints in manufacturing (Planchard and Planchard, 2012). The material, shape and dimension of components can then be determined based on details identified from the benchmarking analysis.

QFD is a common tool to integrate multi-requirements and criteria in a format to search for design solutions. The final selection of materials and design parameters is generally determined by functional requirements, feasibility and competitive performance with available manufacturing technologies.

The sustainable product design uses three processes: axiomatic design, benchmarking and detail analysis. Axiomatic design maps sustainable requirements and customer needs into functional requirements and then design parameters using QFD through identifying design needs in functional requirements and sustainable criteria. HoQ in QFD is expanded to include both functional and sustainable requirements. Benchmark products are decomposed into their subassemblies and components for the

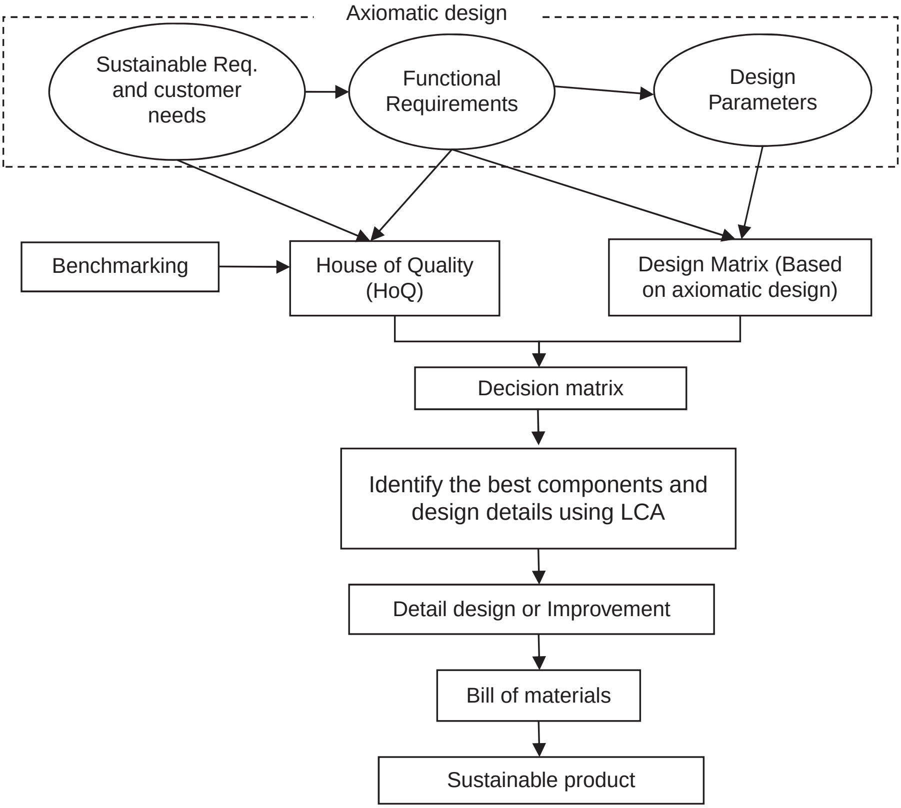


Figure 1.
Framework of sustainable design

comparison each other to find details leading to sustainability. Benchmark details are analyzed to find the best form of components for design priorities. Details of sustainable factors such as materials, component parameters to meet the sustainable and functional requirements can then be decided. SolidWorks, a computer-aided design (CAD) and computer-aided engineering (CAE) simulation tool, is used in the design analysis to obtain parameters of benchmark products. The finite elements analysis is also conducted to verify the design parameters. The detail processes are as follows.

1.1 Identification of CAs, FRs and DPs using axiomatic design

The first step of sustainable design is to identify sustainable requirements and customer needs (CAs). QFD can be used to develop product details when function requirements (FRs) and design parameters (DPs) are identified. However, QFD cannot determine details of design parameters to meet design requirements. QFD needs other tools such as axiomatic design to search for the solution. Axiomatic design is integrated with the QFD to determine the minimum set of design requirements of product.

Axiomatic design converts customer needs into functional requirements (Suh, 2001). Customer needs are mapped into functional requirements (FRs). FRs are then mapped into design parameters (DPs). Process variables (PVs) are defined by mapping DPs into process details. These mappings can be represented using matrices (Ulrich, 1995). When FRs are defined, DPs can be searched to satisfy FRs. A diagonal matrix leads to the uncoupled design to meet requirements with independent elements. Consequently, each FR can be satisfied by one DP. Otherwise, there would be more than one DP required to satisfy one FR. Axiomatic design can guide the search to adopt design demands such as sustainable requirements with proper functions and design parameters.

1.2 Mapping sustainable CAs, FRs and DPs

This step maps customer needs from functional domain to physical domain with sustainability criteria. As shown in Figure 2, sustainable criteria are added to traditional function needs, which are then mapped into proper functional requirements and design parameters.

The entire sustainable need should be considered with both traditional and sustainable attributes of product such as being durable, easy to use, inexpensive, safe, easy to maintain and environmentally friendly. Based on axiomatic design, FRs are identified as the minimum set of independent requirements to meet all of CAs. Customer requirements are mapped into functional requirements (FRs) which is then mapped to physical design parameters of product (Kim *et al.*, 2014).

This process determines engineering characteristics of product to satisfy CAs. Once all of FRs are defined, DPs can be determined for FRs. DPs decide physical solutions of FRs. The correlation of FRs and DPs is identified to maintain equal numbers of DPs and FRs for an ideal design.

Once function needs and sustainable criteria are identified and mapped into FRs and DPs, an initial design can be formed. The initial design represents a general structure of the proposed product. However, because of limited data and product information at this stage of design process, benchmarking is used to decide design details.

1.3 HoQ for sustainable CAs and FRs

HoQ is a visualized tool of QFD. It is used to establish the relationship matrix between CAs and FRs as shown in Figure 3. CAs are mapped into FRs based on the technical feasibility. The preference of FRs for CAs can be defined in different scores. If there is

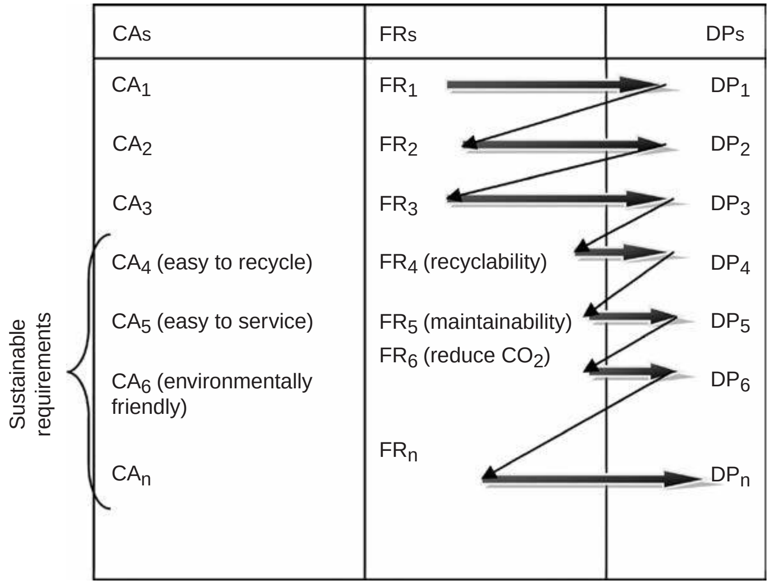
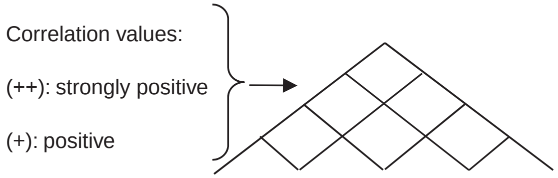


Figure 2.
Mapping CAs, FRs and DPs based on the sustainability



		Functional requirements				Rating for benchmarks		
Customer requirement	Importance rate	FR_1	FR_2	FR_j	FR_m	1	2	3
CR_1	d_1	a_{11}	a_{12}	a_{1j}	a_{1m}	B_{11}	B_{12}	B_{13}
CR_2	d_2	a_{21}	a_{22}	a_{2j}	a_{2m}	B_{21}	B_{22}	B_{23}
CR_i	d_i	a_{i1}	a_{i2}	a_{ij}	a_{im}	B_{i1}	B_{i2}	B_{i3}
CR_n	d_n	a_{n1}	a_{i2}	a_{nj}	a_{nm}	B_{n1}	B_{n1}	B_{n1}
Absolute weight		w_1	w_2	w_j	w_m			
Relative weight		r_1	r_2	r_j	r_m			

Figure 3.
House of Quality

no relation between a CA and a FR, their intersection element is blank. The house roof, called the correlation matrix, is used to determine the impact of functional requirements on each other. The correlation of functions can be strongly positive to strongly negative. Based on the correlation matrix, designers can eliminate physical contradictions of function requirements. Once the relationship matrix is completed, absolute and relative weights of each FR can be calculated to determine FR priorities of design (Poel, 2007):

$$\text{Absoluteweight}: W_j = \sum\nolimits_{i=1}^{n} a_{ij}\, di,\ \text{Relative weight}:\ rj = (w_j)/(\sum\nolimits_{i=1}^{m} w_j)$$

where w_j is the absolute weight of each function, a_{ij} is the relationship value between CAs and FRs, d_i is importance of the ith customer demand, and r_j is a relative weight of each function.

In Figure 3, right columns of HoQ represent the rating of benchmarks for identifying the best performance (Abele *et al.*, 2005). Although rating benchmarks brings valuable data about specifications of product to meet function needs, it does not provide details of design and components to satisfy FRs and sustainable criteria. Consequently, in order to find details of benchmarks, design matrix and decision matrix are established to determine the sustainable metrics.

1.4 Design matrix for sustainable FRs and DPs

When mapping FRs and DPs is completed, a design matrix is formed to identify the correlation between FRs and DPs. Design matrix provides a visual solution to ensure that the design obliges the independence axiom. As shown in Table I, Values of 1 and 0 are used to determine the correlation of FRs and DPs. When DP satisfies FR, the element is 1. If there is no correlation between DP and FR, the element is 0. The final score of each function is determined by adding values of its related row.

1.5 Decision matrix for sustainable metrics

To link HoQ and the design matrix, the decision matrix is used to find the final weight factor for each FR based on results of HoQ and design matrices. The decision matrix provides quantitative measures to identify, analyze, and rank the importance of data. As shown in Table II, relative weights of each function, derived from the HoQ matrix, are listed in the second row. The total scores of each function, calculated from the design matrix, are in the third row. The final weight factor of each FR is calculated as follows, they are listed in the last row in Table II (Zhao, 1994).

DPs FRs	DP_1	DP_2	DP_3	DP_i	DP_n	Final score
FR_1	1	0	0	0	0	S_1
FR_2	x	1	0	0	0	S_2
FR_3	x	x	1	0	0	S_3
FR_i	x	x	x	1	0	S_i
FR_n	x	x	x	x	1	S_n

Table I.
General format of decision matrix

FRs Scores	FR_1	FR_2	FR_3	FR_4	FR_5	FR_i	FR_n
Relative weight (HoQ-Matrix)	R_1	R_2	R_3	R_4	R_5	R_i	R_n
Score (design- matrix)	S_1	S_2	S_3	S_4	S_5	S_i	S_n
Final weight factor	F_1	F_2	F_3	F_4	F_5	F_i	F_n

Table II.
Decision matrix

Final weight factor: $F_i = R_i \times S_i$, (i = 1, 2, 3, … n)

Final weight factors determine the design priority based on mapping needs and parameters. The priorities are used in the next phase in sustainable design metrics to compare and select the best sustainable components from different benchmarks.

1.6 Product footprints

Čuček *et al.* (2012) investigated measures and definitions associated with LCA tools for footprint evaluation through review scientific databases and Internet sources. They concluded that environmental footprints can be measured by carbon footprint (CF), water footprint (WF), energy footprint (ENF), emission footprint (EMF), nitrogen footprint (NF), land footprint (LF), and /or biodiversity footprint (BF) based on product or process applications.

Lehtinen *et al.* (2011) analyzed over 25 existing LCA-related tools including GaBi and SimaPro, and concluded that LCA is a powerful tool but no universally agreed methodology exists. Some of these tools are available under license and incorporate extensive databases but cannot strictly provide complete transparency due to commercial restrictions. Some difficulties in applying these LCA tools into particular products include the method complexity and lack of data. This research uses LCA tools and measures provided in SolidWorks 2013 to assess product footprints including air acidification, carbon footprint, and water emission.

1.7 Design based on benchmarking

Component benchmarking is conducted based on results of the decision matrix, which provides the quantitative sustainable metrics to find data and design details. The benchmarks, selected for details of HoQ, are decomposed into their subassemblies and components for the comparison based on priorities and weight factors for components of sustainable product. LCA is conducted for all benchmarks to find their environment footprints. The benchmark products are modeled to evaluate design solutions according to materials, manufacturing process, energy usage, and product footprints (Planchard and Planchard, 2012). The benchmarking results provide data and details for the new design. The material, shape and size of components can be determined for the product design. Based on materials and design parameters identified, the finite element analysis can also be conducted for the design analysis.

4. Case study

A wheelchair is designed in the case study to verify the proposed method for sustainable product design. The wheelchair is a chair with wheels moving people who have walking difficulties. There is a variety of wheelchairs in the market, they can be classified in three groups: manual wheelchairs moved by turning the rear wheels using user hands, powered or motorized wheelchairs driven by electrical motors, and sport wheelchairs designed for disabled athletes (Karp, 1998). Four powered wheelchairs are selected as benchmarks for the sustainability assessment according to functional, economic and technical targets of design requirements. These benchmarks are wheelchairs that are widely used in the market with the expected quality and affordability.

The first step of the wheelchair design identifies customer needs including being stable, comfortable, light weight, inexpensive, durable and eco-friendly. Sustainability requires a balance between product cost, durability and low environmental footprints (Willard, 2002). Once customer needs are identified, functional requirements are mapped to satisfy CAs. Based on the axiomatic design, the functional requirements are grouped into independent sets to meet the demand. By mapping CAs into FRs, wheelchair functions can be identified. The initial demand of the wheelchair is to carry a user (CA.1) which leads to the top level of customer needs as shown in Figure 4. CA.1 is satisfied by a moving system (FR.1), which is mapped to the wheels (DP.1). In the second level, in order to have an automatic wheelchair (CA.2), wheels should be operated by power (FR.2), which needs electrical motors (DP.2), and so on. FRs and DPs can then be finalized following these mapping processes. In order to consider different aspects of sustainable requirements, design metrics are rated based on weight factors of product requirements.

A conceptual design of wheelchair can now be formed to meet identified requirements, such as the chair with a seat supporting user body, wheels using an automatic moving system, and the adjustable back rest, etc. A conceptual design of the wheelchair can be drafted with frame, seat, back rest, leg rest, wheels and other components, including some details such as driving wheelchair using electrical motors, flexible back and leg rests that can be folded or un-folded as a chair or bed. To fold and unfold components, the power-seat mechanism can be used (Woude *et al.*, 1989). The arm rests can be adjustable for different heights. However, some details are still unknown for further design needs including components material, shape and size, component structure and mechanism to meet sustainable and functional requirements. In order to find details of design parameters, benchmarking is conducted.

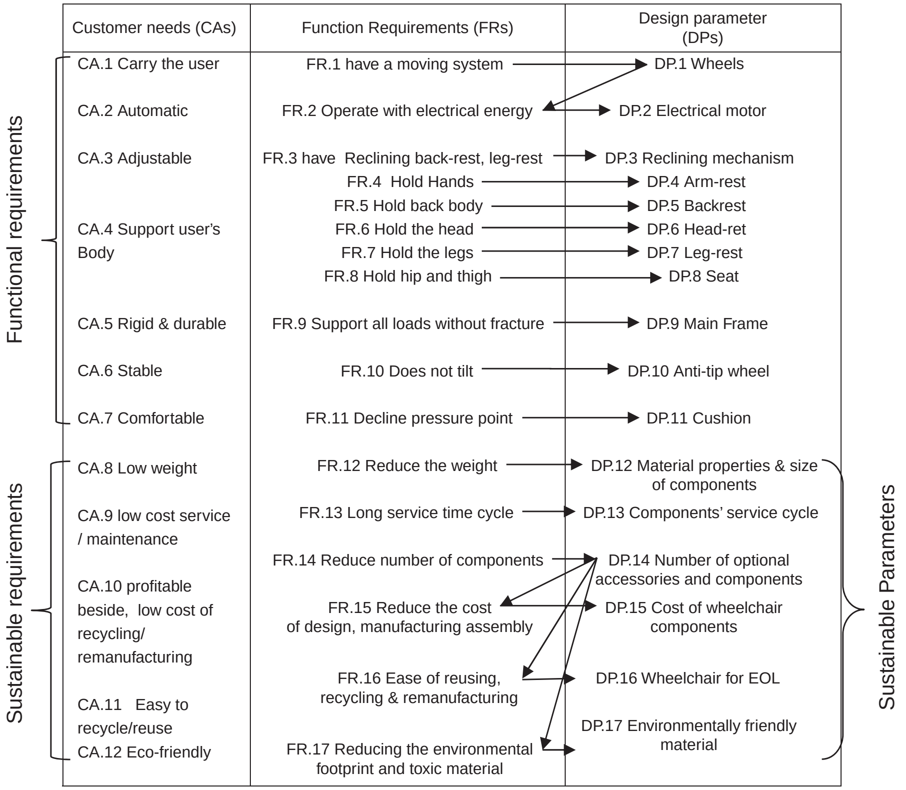


Figure 4.
Mapping CAs, FRs and DPS for wheelchair design

Four benchmark wheelchairs are rated for comparison in a HoQ to link customer needs and sustainable considerations with functional requirements. Four benchmarks are entitled as Wheelchairs A to D. They are similar in functions and prices. Table III shows specifications of the wheelchairs.

When CAs, FRs and DPs of wheelchairs are identified, HoQ is formed with customer needs and functional requirements as shown in Figure 5. The relationship of CAs and FRs can be weak (with value $\Delta = 1$), medium (with value ○ = 3), or strong (with value ◎ = 5). To determine the score of each FR, the importance score is multiplied by the value of related cells. The numbers are added up in their respective columns to determine the score of each FR. For example, reducing the number of components (FR.13) makes the wheelchair light in weight (CA.8) and the product cost change (CA.9). Hence, the weight of reducing "number of components" (FR.13) is $3\times5+5\times3 = 30$. The roof of HoQ, called the correlation matrix, shows functional requirements to impact each other. The relative weight factor of wheelchairs is calculated by dividing each weight with the total score. For example, a weight factor to reduce the number of components (FR.13) is $(30/371)\times100 = 8$ percent.

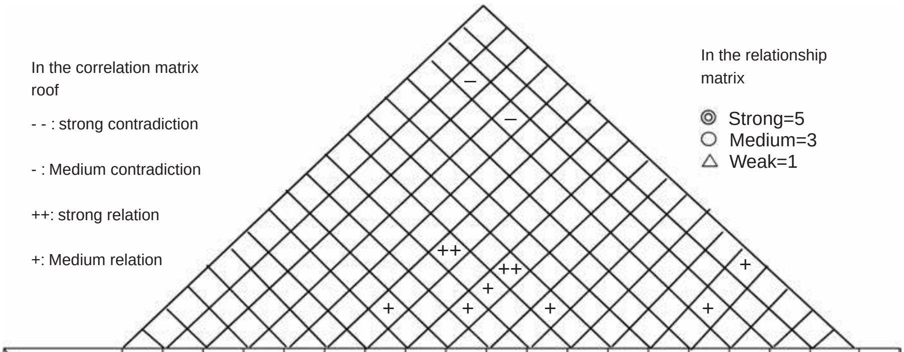
As shown in Table IV, four benchmarks are rated based on contents of HoQ shown in Figure 5. For instance, for being automatically driven, wheelchairs use an electrical device. Wheelchair D is equipped with electrical reclining back-rest mechanism, wheelchair B has a manual reclining mechanism, and wheelchairs A and C have fixed one. Therefore, their rates are different as shown in the second row, the automatic operation.

The next step determines design parameters of the wheelchair. Cost, environmental footprints, number of components, weight, service time, and ease of reusing, recycling, and remanufacturing are important parameters for sustainable products. Four benchmarks are ranked for these measures in the HoQ. However, the product details, such as environmental footprints, number of components, recyclability, maintainability, are not included in the HoQ. In order to evaluate details of benchmarks, four benchmarks are modeled using SolidWorks for detailed components used in each benchmark.

To find specifications of benchmarks, such as material, size, cost, number of components and processing time, benchmark wheelchairs are modeled to evaluate their environmental footprints. Figure 6 shows components modeled for benchmark B. Main materials used in the wheelchairs are steel, aluminum, Abs, compositeand rubber. Wheelchairs A and C use a fix back-rest; Wheelchairs B and D are equipped by reclining back-rest. Wheelchair B uses the manual reclining back rest and Wheelchair D has a powered reclining seat. While Wheelchair A uses the solid tire in front wheels, the other three wheelchairs use the pneumatic tire. The height of arm rests and the

Table III. Specifications of four benchmarks

Wheelchair Specification	Wheelchair A	Wheelchair B	Wheelchair C	Wheelchair D
Cost (USD)	5,298	6,440.7	6,923.7	7,003.7
Weight (Kg)	35.5	45.3	41.6	51.2
Speed (Km/h)	8	9.2	10	8
Battery	12 V/34 Ah	12 V, 55 Ah	12 V, 42 Ah	12 V, 65 Ah
Reclining back rest	N/A	Manual recliner	N/A	Power recliner
Seat size (L-W)	16-17 inch	17-17 inch	17-18 inch	17-17 inch
Beck rest height	18 inch	17 inch	18 inch	19 inch



FRs / CAs	Importance score	1. Moving system	2. Electrical energy	3. Reclining back-rest	4. Hold Hands	5. Hold back body	6. Hold the head	7. Hold legs	8. Hold hip and thigh	9. Support all loads	10. Does not tilt	11. Pressure point	12. Reduce the weight	13. Service time cycle	14. NO. of components	15. Reduce the cost	16. Reducing,/recycling	17. Environmental footprints	Total
1- Carry user	5	◎ =5																	
2- Automatic	2	△ =1	◎ =5																
3- Adjustable	3			◎ =5															
4- Support user's Body	5				○ =3	◎ =5	△ =1	○ =3	◎ =5										
5- Rigid & durable	5									◎ =5									
6-Stable	4										◎ =5								
7-Comfortable	4											◎ =5							
8-Low weight	3												◎ =5		◎ =5				
9-Low cost service/ maintenance	5													◎ =5		△ =1			
10- profitable and low cost recycling/	5														○ =3	◎ =5	○ =3		
11-Easy to recycle/reuse	4															△ =1	◎ =5		
12-Eco-friendly	5																	◎ =5	
Absolute score		27	10	15	15	25	5	15	25	25	20	20	15	25	30	34	35	30	37 1
Relative score		7.2	2.7	4	4	6.7	1.3	4	6.7	5.4	5.4	5.4	4	6.7	8	9.1	9.4	8	100

Figure 5.
House of quality for wheelchair design

position of leg-rests in Wheelchairs A and C are adjustable while these components are fixed in the other two wheelchairs.

Components specifications are obtained from these models as shown in Table V. Based on the comparison, the component with the best performance is selected as the reference in design of shape, size and material of the component used in new product. In order to find the weight and environmental footprints of each component, the

Table IV.
Available comparisons from HoQ

		Rating of the four Benchmarks in HoQ Importance score: 1: lowest, 5: highest				
CAs	Score	1	2	3	4	5
1. Carry user	5					A, B, C, D
2. Automatic control	2			A, C	B	D
3. Adjustability	3		A	C	B	D
4. Support user's Body	5			A	D	B, C
5. Rigid and durability	5			A, B	C	D
7. Comfortable in use	4			A, C	D	B
8. Low weight	3	D	B	C	A	
10. Profitability	5	D	C	B	A	

benchmarks are evaluated using the SolidWorks sustainability package for environmental impacts of wheelchair components.

Sustainability indicators, air acidification, carbon footprint and water emission, are chosen as measures for product environmental impacts. These indicators are related to sustainability dimensions and can be calculated quantitatively using functions provided in SolidWorks. They are factors of greenhouse gases and related to climate change. Where air acidification is measured in unit of kg sulphur dioxide equivalent (SO_2), carbon footprint is measured in unit of kg carbon dioxide equivalent (CO_2), and water emission is measured in unit of kg phosphate equivalent (PO_4) (Finkbeiner *et al.*, 2010).

Air acidification, carbon footprint, and water emission of wheelchair components are calculated based on the extraction of materials, manufacturing process, transportation and the end of life cycle. The environmental footprint is calculated based on material, product geometry and life time. Material types and the use duration of components are evaluated. For example, the seat frame of Wheelchair A is evaluated for environmental footprints as shown in Figure 7. Aluminum T6 is used as the material, and the use duration is assumed for 5 years. The weight of the seat frame is 4.15 Kg. The total environmental footprint of the seat frame is calculated based on the air acidification, carbon footprint, and water emission as follows: Total environmental footprint of the seat frame (kg) = air acidification (kg SO_2)+ Carbon footprint (Kg CO_2)+ Water emission (Kg PO_4) = 0.376+55+0.012 = 55.38 Kg.

The result shows that the main environmental footprint is carbon footprint, which is a main factor of the global warming. The same evaluation is done for all components of the four benchmark wheelchairs. The sale price of each component of the four benchmarks is based on manufacturer data. Sale price is affected by factors such as cost of raw materials, manufacturing processes, labor, assembly, packing, and distribution. Raw materials and manufacturing processes are evaluated in detail, other expenses are considered as the rest cost in this study based on available data. It is assumed that components are manufactured in the same industry. Parameters and standards of manufacturing processes are considered consistently for all components (Ben-Arieh, 2000). The price of raw materials is based on data from an online metal company. For example, the head rest gripper cost of Wheelchair A is obtained based on raw materials and manufacturing processes as follows.

For the head rest gripper, two manufacturing operations are used to make the head rest gripper: a) milling process for top and side surfaces, and b) drilling for holes of the gripper. The material removal rate for each manufacturing process can be calculated.

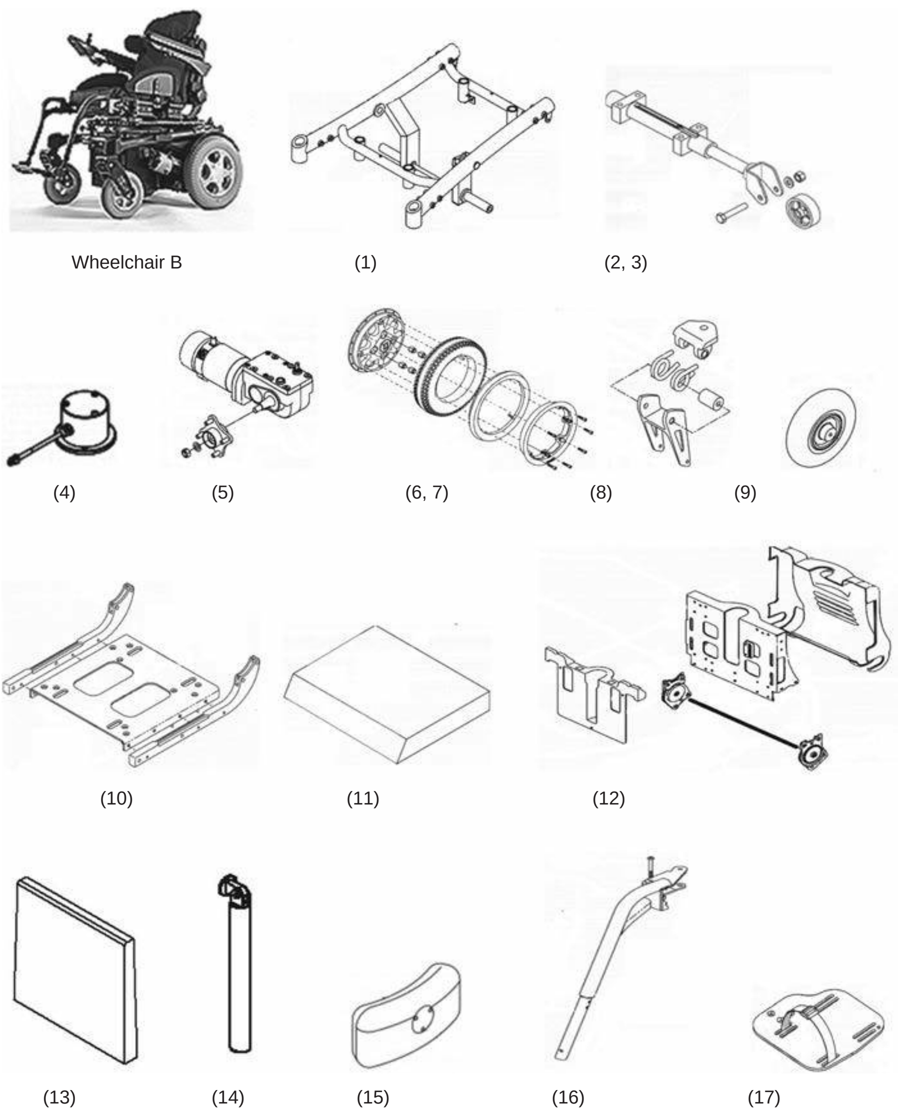


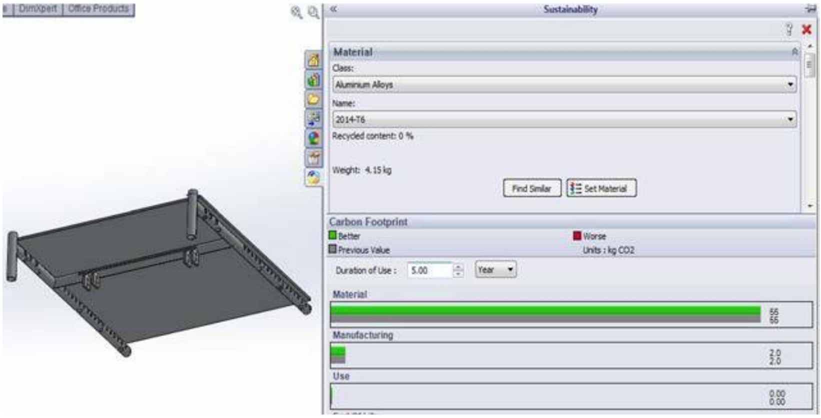
Figure 6.
Modeling details of benchmark B

Manufacturing parameters are selected for milling and drilling processes based on ISO metric standard. The labor cost and machine set up cost are assumed as 10 USD/hr and 20 USD/hr, respectively. The material of the gripper is Al 6061 T6. The cost of the raw material is 13.71 USD. The milling cost of top and lateral surfaces is 4.47 USD, and the cost of drilling operation is 7.54 USD based on the selected parameters of milling and drilling processes. The set up cost for all milling and drilling operations is 15 USD. The total cost of manufacturing process to make a head rest gripper is 27.02 USD. The total cost of the gripper including the raw material and manufacturing process is 40.72 USD. The sale price of this component is 116.87 USD. The rest cost is 116.87-40.72 = 76.15 USD. The rest cost represents the cost of

Table V.
Specifications of benchmark B

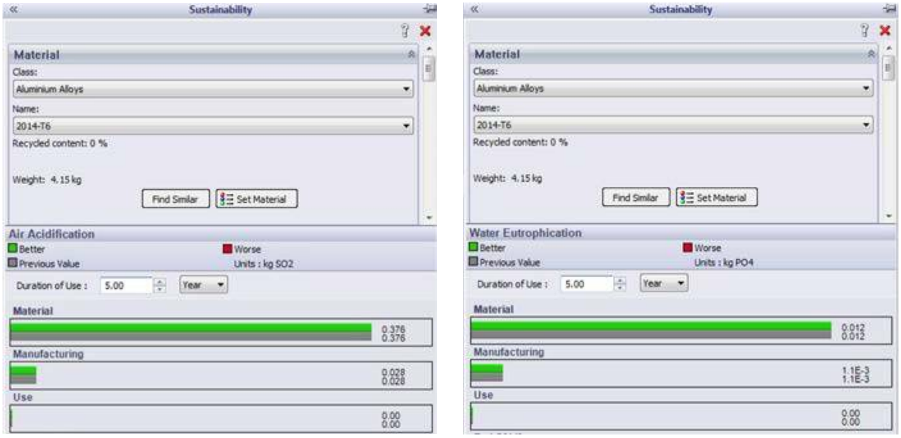
No.	Benchmark B	Sale price (USD)	Making cost (USD) Raw material	Manu	Others	Material	Number of component	Service time (year)	Weight (Kg)	Environmental footprint (Kg)
1	Base Frame	1,378	273.42	201.32	903	Al T6 ABS	14	1	7.1	71.45
2	Anti-tip structure	50	4.3	12.7	33	Al T6 6061	6	1/4	0.74	8.3
3	Anti-tip wheel	29	6.22	9.93	12.8	Rubber	1	1/4	4.35	12.2
4	Wheel brake	502	73.6	192.43	236	Al, St, ABS	4	1/12	0.63	1
5	Motor package	1,174	196	456.31	521	Al, Cu, St	14	1/4	7.5	1.77
6	Wheel rim	92	42.3	26.28	23.4	Al T6 6061	5	1/12	4.64	53.36
7	Drive wheel	58	15.32	21.75	21	Rubber	2	1/12	6.47	2.11
8	Front suspension fork	286	33.25	62.2	190	Al T6 6061	14	1/4	0.74	8.51
9	Casterand tire	50	13.25	18.7	18.0	Rubber and ABS	2	1/12	5.88	10.2
10	Seat frame	745	106.42	151	487	Aluminum	27	1	3.63	37.7
11	Seat cushion	100.9	12.6	16.8	71.5	Foam	2	1	0.15	0.72
12	Manual recliner back rest	382	54.7	76.4	251	Al, ABS	14	1/4	4.12	43.36
13	Back rest cushion	150	18.7	25	106	Foam, fabric	2	1	0.17	0.338
14	Head rest-structure	200	27.5	43.1	129	Steel	14	1/4	0.13	0.27
15	Headrest-pad	45	5.6	7.64	31.7	Foam, Fabric	1	1	0.05	0.065
16	Swing -away	314	39.2	62.8	212	Al T6 6061	13	1/4	1.46	5.29
17	Footrest	121.9	17.28	26.71	77.9	Al T6 6061	15	1/4	1.35	15.5
18	Armrest structure	465	54.42	97.3	313	Al, St	25	1/4	1.59	6.78
19	Armrest pad	22.5	2.8	3.82	15.8	Foam, fabric	1	1	0.025	0.035
20	Battery	139	17.3	29.5	92.2	Lead, sulfuric acid, ABS	12	4	17.01	18.41
Total		6,304	1,014.18 2,525.87	1,511.69	3,768		188		54.91	204.418

(a) Carbon footprints



Material
Class: Aluminium Alloys
Name: 2014-T6
Recycled content: 0 %
Weight: 4.15 kg

Carbon Footprint
🟩 Better
▨ Previous Value
🟥 Worse
Units : kg CO2
Duration of Use : 5.00 Year
Material 55 55
Manufacturing 2.0 2.0
Use 0.00 0.00



(b) Air acidification

Material
Class: Aluminium Alloys
Name: 2014-T6
Recycled content: 0 %
Weight: 4.15 kg

Air Acidification
🟩 Better
▨ Previous Value
🟥 Worse
Units : kg SO2
Duration of Use : 5.00 Year
Material 0.376 0.376
Manufacturing 0.028 0.028
Use 0.00 0.00

(c) Water emission

Material
Class: Aluminium Alloys
Name: 2014-T6
Recycled content: 0 %
Weight: 4.15 kg

Water Eutrophication
🟩 Better
▨ Previous Value
🟥 Worse
Units : kg PO4
Duration of Use : 5.00 Year
Material 0.012 0.012
Manufacturing 1.1E-3 1.1E-3
Use 0.00 0.00

Figure 7. Environmental footprints of the seat frame

assembling, packing, distributing of the product. The same process is conducted for all components of the four benchmarks.

Following above processes, specifications of benchmark wheelchairs including the sale price, cost of processing components, materials, number of components, service time, weight, and environmental footprint are found. After identifying specifications of the benchmarks, their components are compared based on the metrics and weight factors, derived from the decision matrix. For example, for the chair frame, the amount of cost, the number of components, weight, processing time, and environmental footprints of the four frames of wheelchairs are multiplied by their weight factors. The result shows that frame A-1 has the lowest cost, the least components, weight, and environmental footprints and the longest service time. The same evaluation is conducted for all of the rest components. The best solution is then identified for the wheelchair design.

A sustainable wheelchair is proposed based on the best solution of the benchmarking analysis. Figure 8 shows the design of the proposed wheelchair. The cost, number of components, weight, and environmental footprints of the four benchmarks and the proposed wheelchair are compared in Table VI.

Based on the comparison, wheelchair A has the least price, the lowest level of environmental footprint, and least number of components and weight among the four benchmarks. The cost of the proposed wheelchair is 13.08 percent lower than that of wheelchair A. There is 18.55 percent reduction of the environmental footprint for the proposed wheelchair compared to the best benchmark Wheelchair A. Also, the weight

Figure 8.
Proposed sustainable wheelchair

Table VI.
Comparison of four benchmarks and the proposed wheelchair

Metrics		Making Cost (USD)					
Item	Sale price (USD)	Raw material	Manufacturing	Rest	Number of components	Weight (Kg)	Environmental footprint (Kg)
Wheelchair A	5,097.0	770.51 1,981.85	1,211.34	3,115	179	35.84	156.86
Wheelchair B	6,440.7	1,014.18 2,525.87	1,511.69	3,914	188	54.91	204.41
Wheelchair C	6,923.7	1,042.6 2,578.98	1,536.36	4,232	178	45.56	1,778
Wheelchair D	7,003.7	1,070.8 2,655.5	1,584.66	4,368	206	51.28	279.08
Proposed wheelchair	4,370.8	699.61 1,802.58	1,102.97	2,568	177	37.55	126.07

and number of components of the proposed wheelchair are decreased by 4.5 and 2.2 percentages, respectively.

5. Conclusions and further work

This research proposed a quantitative method for sustainable product design considering both traditional and sustainable aspects of requirements. It is a multi-criteria method with the integration of axiomatic design and QFD. A sustainable wheelchair is designed based on the details derived from the benchmarking. LCA is conducted for components to evaluate their environmental footprints. From the environmental perspective, 18.55 percent reduction in carbon equivalent emissions has been achieved compared to the benchmarks.

The comparison of the benchmarks and the proposed wheelchair reveals that there is a link between cost, number of components, environmental footprints, and weight for a sustainable design. As the weight, material and number of components decrease, the environmental footprints and cost of the product improve. This solution is in accordance with the research done by Gilchrist *et al.* (2013). The design complexity and the number of components to meet the desired function have direct impacts on the cost and environmental footprints. For example, the main function of the back-rest in wheelchairs is to support the weight of the back body. The electric reclining back-rest needs more material and components than a fix one, resulting in more cost, weight and environmental impacts. Therefore, it is ideal using the minimum set of components to satisfy intended requirements of a product. Therefore, the minimum set of components and materials should be identified to obtain sustainable design. The other parameter in the sustainable design is material selection. Material selection has a direct effect on the cost, weight, and environmental footprints. For instance, the solid tire of anti-tip wheels can be made up of rubber, Plastic PUR, or ABS. Rubber generates more environmental footprint than PUR and ABS. Also, it is more expensive than ABS. Therefore, using ABS, as the solid tire of an anti-tip wheel, generates less environmental footprints with the lower cost and less weight than using PUR and rubber.

Keeping balance between environmental optimization, technical feasibility and economic efficiency remains a challenge. For example, increasing surface finish on the wheelchair seat and arms will increase the cost, but the wheelchair will require less maintenance. In pricing, it may believe that the choice of lower market prices will be the affordability of product for the majority of users. However, the price policy is driven not only by necessary economic success, but also by a holistic understanding of sustainability. This research only focuses on the design and material processing. The sustainability for product assembly and disassembly are not discussed. Further research will consider the entire product life cycle to achieve the complete product sustainability.

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