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A quantitative method for sustainable product development

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Abstract: A quantitative measure-based method for the design and evaluation of sustainable products is proposed. The method uses multi-criteria in product design to meet sustainable requirements from qualitative criteria to quantitative metrics. The method integrates quality function deployment concepts with the life cycle assessment to establish a quantitative method for sustainable product development. It considers both customer needs and sustainable requirements by mapping these needs into design details using the axiomatic design and benchmarking methods. The method is applied in the wheelchair design. Four popular wheelchairs in the market are selected as benchmarks and are rated based on customer needs and sustainable criteria. The design matrix identifies the relationship of functional requirements and design parameters of the wheelchair. Compared to the best benchmark product, the proposed wheelchair can reduce costs by 13.8%, environment footprints 18.55%, mass 4.5%, and components 2.2%.

Key words: sustainability; product design; life cycle assessment; benchmarking

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Sustainability has become an important measure in product design and evaluation. The traditional design looks at products in durability, reliability, affordability, and aesthetic perspectives[1-2]. The sustainability requires products to meet expectation not only in traditional demands for functions and durability, but also being environmentally friendly considering global warming, reducing energy consumption, and the end-of-product life cycle management[3-4]. These topics generate new contents for product design, called design for sustainability [5].

Evaluation of sustainability for a product life cycle is called the product life cycle assessment (LCA) [6-7]. LCA is known as an analytical tool for the environmental assessment to examine resources and product footprints. LCA evaluates the environmental effect of a product from extracting resources, processing materials, manufacturing and production to distribution, use, and the final end-of-life cycle management [8].

It is noted that although product design takes up only 5%-7% cost in the entire product development, it can determine up to 75% of the total product life cycle cost[9]. It is claimed that 80% of product environmental footprints is established in the design stage [10-11]. Sustainable design provides a technical support to reduce the negative environmental impact. The challenge is to find an effective method to evaluate different aspects of sustainability in product design.

Over the last decades, numerous methods and tools in eco-design and sustainable development have been developed for the design for environment (DFE) [12-13]. Although there are various tools for the assessment of sustainable design, there is not a general solution to meet all aspects of the sustainable design. Some methods, such as eco-checklist [14-15], are easy to use at the early stage of design, but they cannot provide accurate results. On the other hand, methods such as LCA-based tools [16-17] need the detailed information and data for design inputs, which is ambiguous at the early stage of design and makes the sustainable assessment time-consuming and costly. Current research activities try to integrate different eco-design tools together, or integrate eco-design with other traditional methods of product design in order to improve the existing methods [18-20]. Consequently, a multi-criteria approach should be taken into account, which integrates traditional requirements in product design with relevant environmental aspects and impacts.

Although mapping customer requirements and sustainable needs into design details can provide the preliminary concept for a design, product information, such as material types, detailed size and geometry, and forms of assemblies and operation mechanisms, is required for the analysis of a sustainable product [21-22]. Benchmarking is a process to examine and compare similar products in the market for identifying the best product configuration and components of its kind [23]. The goal of benchmarking is to combine the best practical solution of each sub-function for eliminating trial and error, speeding up improvement processing, and increasing the efficiency in new idea development [24].

This research develops a multi-criteria method for product design to meet sustainable requirements from qualita-

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tive criteria to quantitative metrics. The method integrates traditional and sustainable methods to identify and map both sustainable criteria and customer requirements from the qualitative to quantitative measures for sustainable product design. Once customer needs and sustainable criteria are mapped from functional requirements to design parameters, a conceptual design of product can be formed. The conceptual design proposes the general structure of an intended product. To improve conditions of limited data and information available at the early stage of product design process, benchmarking is used as a cost-effective method to identify details of the sustainable measure.

1 Proposed Methods

Product design using quantitative sustainable measures is proposed as follows:

1) Establishing a house of quality (HoQ) matrix between sustainable needs and functional requirements for benchmarking sustainable measures.

2) Building a design matrix between the sustainable functional requirements and design parameters.

3) Forming a decision matrix for sustainable design.

4) Identifying details of the benchmarks for product details.

The sustainable design process starts with the identifying and mapping of sustainable needs, functional requirements, and physical properties based on the axiomatic design. HoQ is used to form links between sustainable needs and functional requirements, which determines the top-level of functional requirements based on sustainable requirements and customer demands. In the following step, the design matrix is built to link the functional requirements and physical properties. The decision matrix can then be established to link the HoQ and design matrices to determine the weight factors and priorities of the design. Selected benchmarks are analyzed to abstract similar components for the product detail.

In this research, sustainable criteria are added to the traditional customer needs. They are mapped from functional requirements to design parameters. Functional requirements are established based on the sustainable needs identified from both traditional and sustainable attributes of a product such as being durable, easy to use, inexpensive, safe, easy to maintain and environment friendly. Based on the axiomatic design, functional requirements are identified as the minimum set of independent requirements to meet all of customer needs, which determines the engineering characteristics of a product. Once all of functional requirements are defined, the design parameters can be determined with respect to functional requirements. Design parameters are the physical solutions of the functional requirements.

Without references, it is difficult to decide design details due to the lack of knowledge and data in the conceptual design. Therefore, some similar products are selected from the market as benchmarks. The benchmarks are decomposed into subassemblies and components for detail analysis based on the priorities and weight factors derived from the design matrix. LCA can be used to assess the environmental footprints of the benchmarks. The result of benchmarking provides details for the product design.

While rating of the benchmarks brings valuable data for the design specifications, it does not provide the details of design and components to satisfy functional requirements and sustainable criteria. Consequently, in order to compare details of benchmarks, the design matrix and decision matrix are combined to determine the sustainable metrics. In order to find data and details of the product design, components of benchmarks are compared based on the results of the decision matrix, which provides the quantitative sustainable measures.

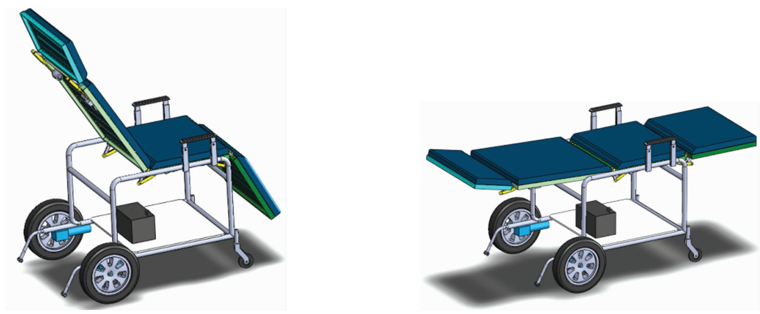
The benchmarks and their components are modelled using CAD tools based on the product manufacturer's specifications. Components among the benchmarks can then be compared for the best sustainable performance to be applied for the new product. LCA is conducted in the comparison for all benchmarks to determine the environment footprints. Benchmark models are evaluated according to materials used, the manufacturing process, energy usage, carbon footprints, water toxicity, and soil acidification. Materials, component sizes, and component forms can be finally determined for the product detail using the benchmarking solution.

2 Case Study

A wheelchair is designed using the proposed method to meet both functional and sustainable needs as shown in Fig. 1. The wheelchair is a chair with wheels to move people who have walking difficulties. The design starts at mapping customer needs and sustainable requirements into design parameters by identifying and converting these needs from qualitative criteria to quantitative parameters. QFD is used to develop product characteristics after the function requirements and design parameters are identified. However, QFD cannot determine details of functions and design parameters that are required to meet the design requirements, or to determine the function requirements and design parameters without conflicts. Consequently, the axiomatic design is integrated with the QFD to determine the minimum set of design characteristics without conflicts in the product. Customer needs are first mapped into functional requirements, and the functional requirements are then transformed into design parameters to determine the design details of the wheelchair.

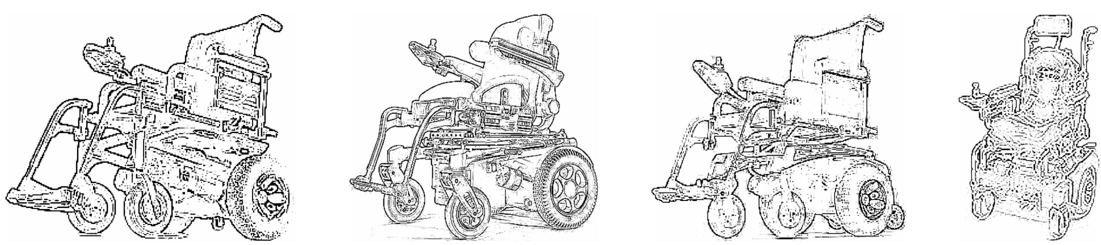
To provide details of the wheelchair at the early design stage, four wheelchairs are selected as benchmarks as shown in Fig. 2. These benchmarks are popular wheelchairs in the market with competitive function and price. The four selected wheelchairs are similar in functions and applications to the proposed design.

To rate four benchmarks based on the customer needs and sustainable criteria, these wheelchairs are evaluated in HoQ to compare their performance. The HoQ identifies the relationship among customer needs, sustainable criteria, and functional requirements. Also, general specifications of the benchmarks are compared based on customer needs. However, using HoQ only is not sufficient to provide details of the benchmarks. For instance, in order to know the environmental footprints, recyclability and maintainability of the benchmarks, their components are evaluated by introducing a decision matrix as shown in Tab. 1.



(a) (b)

Fig. 1 Proposed wheelchair. (a) Folded position; (b) Unfolded position



(a) (b) (c) (d)

Fig. 2 Selected wheelchairs for benchmarking. (a) Wheelchair A; (b) Wheelchair B; (c) Wheelchair C; (d) Wheelchair D

Tab. 1 Decision matrix for wheelchairs based on HoQ and design matrix

Design requirement	Relative weight based on HoQ	Score based on design matrix	Final weight factor	Importance rank
Moving system	7.2	1	7.2	6
Operating electricity	2.7	2	5.4	8
Reclining back-rest	4	1	4	9
Holding Hands	4	1	4	9
Holding back body	6.7	1	6.7	7
Holding the head	1.3	1	1.3	10
Holding Legs	4	1	4	9
Holding hip and thigh	6.7	1	6.7	7
Supporting all loads	5.4	1	5.4	8
Without tilt	5.4	1	5.4	8
Declining the pressure point	5.4	1	5.4	8
Reducing the mass	4	2	8	5
Long service time cycle	6.7	2	13	4
Number of components	8	2	16	3
Reduced cost	9.1	3	27	1
Ease of reusing and recycling	9.4	2	19	2
Environmental factor	8	2	16	3

The decision matrix provides the final weight factor to determine the importance of sustainable measures. The measures are ranked based on their weight factors in Tab. 1. Cost, environmental footprints, number of components, mass, service time, and ease of reusing, recycling, and remanufacturing are important measures for the parameters and sustainable design of wheelchairs. The priorities identified in the decision matrix are used in the next phase to compare the benchmarks for the best component of the proposed wheelchair.

Benchmark wheelchairs can be ranked in the HoQ. However, the benchmark details, such as environmental footprints, number of components, recyclability, and maintainability, are not analyzed in the HoQ. In order to evaluate details of the benchmarks, the four wheelchairs are broken down into their components. The specifications of each wheelchair, including material, size, cost, number of components and service time, are obtained from the specifications provided by the product manufacturers. The benchmarks' components are modelled in SolidWorks 2013 to evaluate their mass and environmental footprints. For example, components used in Wheelchair A are modelled as shown in Fig. 3. The main materials used in the wheelchairs are steel, aluminium, ABS, composite, and rubber. Wheelchairs A and C use a fixed back-rest; Wheelchairs B and D are equipped with a reclining back-rest. Wheelchair B has a manual reclining back-rest and Wheelchair D uses the powered reclining seat. Wheelchair A uses a solid tire in its front wheels; the other three wheelchairs have a pneumatic tire. The height of the arm rests and the position of the leg-rests in Wheelchairs A and C are adjustable while these components are fixed in the other two wheelchairs.

In order to calculate the mass and environmental footprints of components, the benchmarks are evaluated in detail. The environmental footprints can be classified as 1) Air acidification, which is typically measured in units of kg sulphur dioxide equivalent (SO_2), 2) Carbon footprint, which is measured in units of kg carbon dioxide equivalent (CO_2), 3) Water emissions, which are measured in units of kg phosphate equivalent (PO_4)[8,25]. SolidWorks 2013 Sustainability provides tools to decide the air acidification, carbon footprint, and water emissions based on the material, manufacturing process, transportation, and the end of product life cycle. As this research focuses on the design, the environmental footprints are calculated based on the material, geometry, and life time of the wheelchair components.

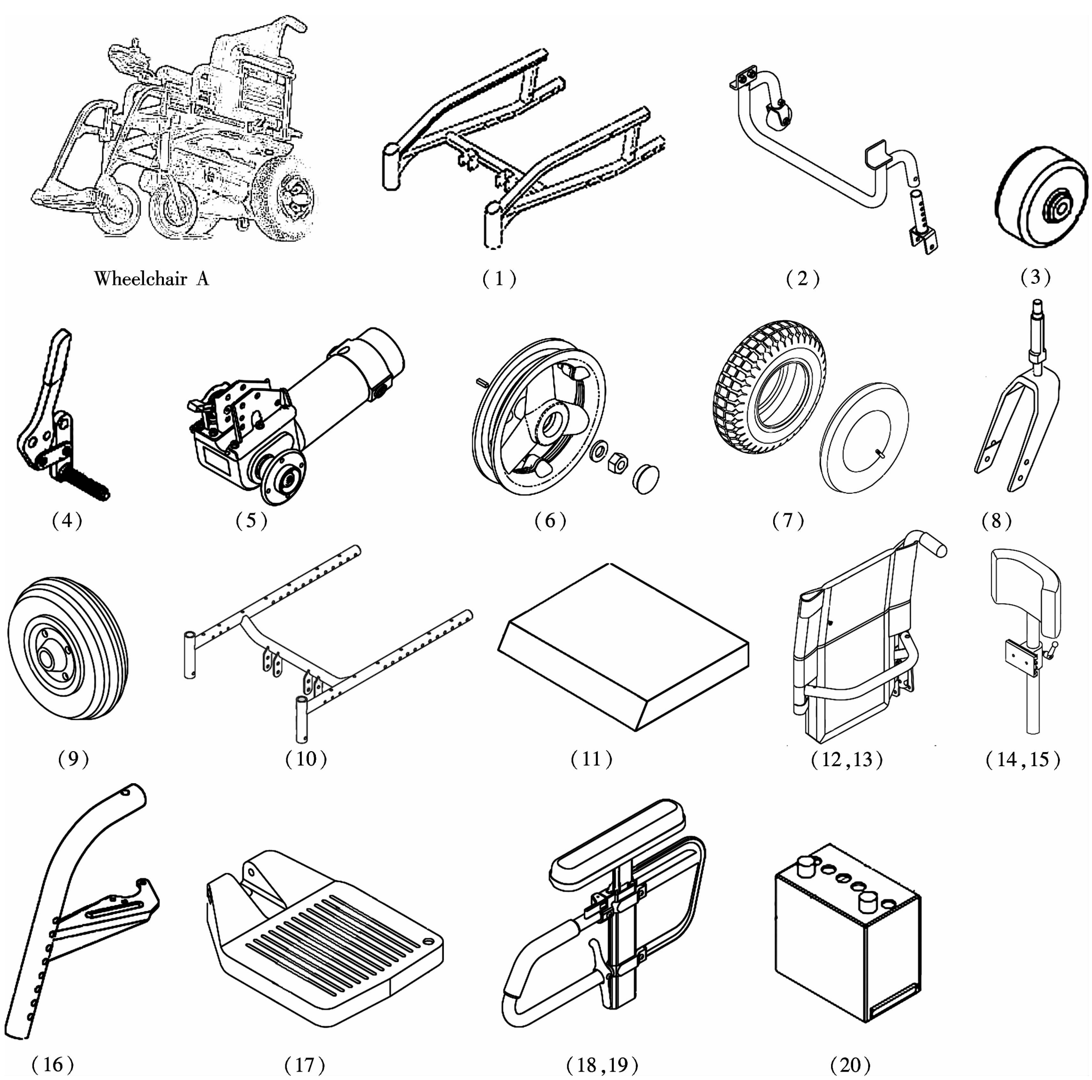


Fig. 3 Components of Wheelchair A

Taking the seat frame of Wheelchair A as an example for evaluation of its mass and environmental footprints, Aluminium T6 is the material used, and the duration of the expected life time is 5 years. The mass of the seat frame can be found based on its geometry and material, which is 4.15 kg. Total environmental footprints of the seat frame are measured using the mass (kg) of emissions produced in the process. Although the emission contents may be different, it is assumed that these emissions have equal impact on environments in evaluation of each effect on them based on their weights to find the most critical factor. The total environmental footprint of the seat frame can therefore be calculated based on its air acidification, carbon footprint, and water emissions as follows:

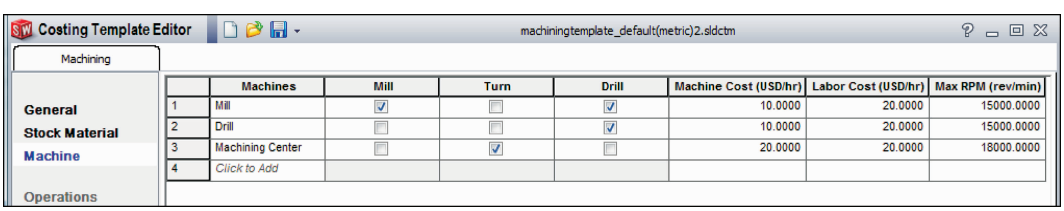
Total environmental footprints of the seat frame (kg) = Air acidification (kg SO_2) + Carbon footprint (kg CO_2) + Water emissions (kg PO_4) $= 0.376 + 55 + 0.012 = 55.38$ kg

This calculation shows that the major environmental footprint belongs to the carbon footprint, which is the main factor in global warming. The same evaluation is conducted on all components of the four wheelchairs. Based on the evaluation of the benchmarks for their components, the best components are selected for the design details of the proposed wheelchair.

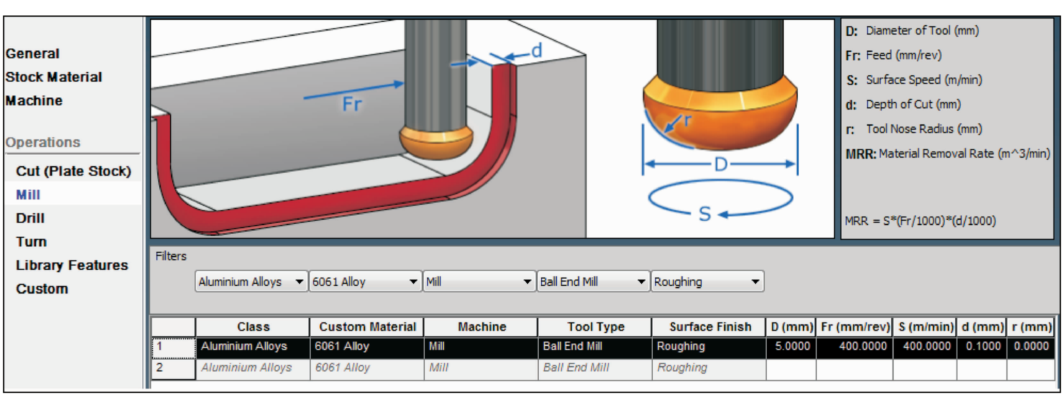
Costs of raw materials and manufacturing processes are evaluated based on an assumption that all components are manufactured in the same industry. The parameters and standards of manufacturing processes are considered consistently for all components. SolidWorks 2013 is used as a tool to decide the manufacturing cost. Taking the head rest gripper of Wheelchair A as an example (Part 15 in Fig. 3), the cost of raw materials and manufacturing processes are evaluated as follows.

There are two manufacturing operations to process the head rest gripper, the milling process for top and side surfaces, and the drilling hole of the gripper. As shown in Fig. 4, manufacturing parameters are selected in SolidWorks 2013 for milling and drilling processes based on the ISO metric standard. The labor cost and machine setup cost are assumed to be 10 USD/h and 20 USD/h, respectively. The material of the gripper is Al 6061 T6. The price of the raw material is 13.71 USD. As shown in Fig. 5, the milling cost of top and lateral surfaces is 4.48 USD, and the cost of the 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 the manufacturing process to make a head rest gripper is 27.02 USD. The total cost of the gripper including 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 of the costs represents the cost of assembling, packing, distributing and profits of the company. The same evaluation is conducted for all components of the benchmarks.

The materials and component structures are decided based on the benchmarks. When a component material is decided, its manufacturing methods can be selected to meet the requirements of the material process. The metal material uses mainly the metal cutting process. The non-metal (Abs, composite, rubber, etc.) components can be produced using injection molding, rubber molding,



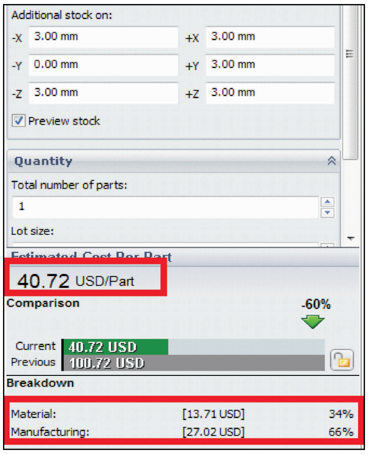
(a)



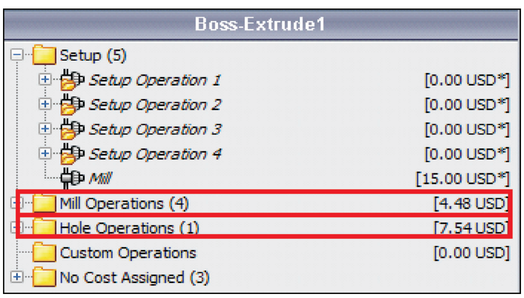
(b)

Fig. 4 Manufacturing parameters selection based on the ISO metric standard in SolidWorks 2013. (a) The setup cost and labor cost of different manufacturing processes; (b) Milling parameters based on the raw material and milling tool selection

3D printing, or other manufacturing methods. The related emissions can be similarly calculated.



(a)



(b)

Fig. 5 Evaluation of the raw material, milling and drilling costs. (a) Material cost and total manufacturing cost; (b) Milling and drilling costs

Using the details obtained from benchmarking, the final design is decided for the proposal wheelchair. Compared to the best benchmark product, the proposed wheelchair can reduce costs by 13.8%, environment footprints 18.55%, mass 4.5%, and components 2.2%.

The comparison of the benchmark wheelchairs and the proposed wheelchair reveals that there is a link between cost, the number of components, environmental footprints, and mass for a sustainable design. As the mass, material, and number of components decrease, environmental footprints and the cost of the final product improve. The design complexity and the number of components to satisfy each desired function have direct effect on the cost and environmental footprints.

For example, the main function of the back-rest in wheelchairs is to support the mass of the back of the body. All wheelchairs except Wheelchairs A and C have a fixed back rest. Wheelchair D is equipped with an automatic reclining back rest, which allows the user to set the back rest at different angles. However, the electric reclining back rest needs more materials and components than a fixed one, resulting in more cost and environmental impact. In addition, based on the axiomatic design, the minimum set of functions should be determined to satisfy the intended requirements of an ideal product. Consequently, the minimum set of functions, components, and materials should be identified to obtain a sustainable design.

The material selection has a direct effect on the cost, mass, 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 footprints than PUR and ABS do. Also, it is more expensive than ABS. Consequently, using ABS, as the solid tire of an anti-tip wheel, generates less environmental footprints with a lower cost and less mass than PUR and rubber.

3 Conclusions and Further Work

This research identifies customer needs and sustainable criteria for functional requirements and design parameters based on the house of quality for a wheelchair design. Four wheelchairs were selected as benchmarks and were rated based on customer needs and sustainable criteria. The design matrix identified the relationship of functional requirements and design parameters of the wheelchair. The decision matrix links the house of quality and design matrix. The functional requirements are ranked based on the customer needs and sustainable requirements. The result of the decision matrix identifies the priorities of the wheelchair design. Details of the benchmarks are analyzed based on the priorities of design. The best components in the benchmark wheelchairs are selected for the proposed wheelchair. Further research will consider the entire product life cycle to achieve the complete product sustainability including sustainability for manufacturing, sustainability for assembly and disassembly.

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一种量化的可持续产品发展方法

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摘要:提出了基于量化的可持续产品设计和评估方法. 该方法使用产品设计的多标准来满足可持续产品从定性到定量的设计要求. 建立的可持续发展产品定量方法集成了质量功能展开的概念与生命周期评估方法. 它同时考虑客户需求和可持续发展的要求,并通过公理设计映射和基准测试方法将这些需求变为设计细节. 将提出的方法应用在轮椅设计中. 其设计基准选用了 4 种常用的轮椅并将其根据客户需求和可持续要求评级. 设计矩阵用来确定轮椅功能要求和设计参数的关系. 与最好的基准产品相比,所设计的轮椅可以降低成本 13.8%,环境足迹 18.55%,质量 4.5%,以及组件数量 2.2%.

关键词:可持续性;产品设计;生命周期评估;基准测试

中图分类号:TB21,TB472