Integration of Axiomatic Design with Quality Function Deployment for Sustainable Modular Product Design

By

Arash Hosseinpour

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Department of Mechanical Engineering
University of Manitoba
Winnipeg, Manitoba

Abstract

Design is one of the most important stages in product development. Product design has experienced significant changes from concentrating on cost and performance to combining economic, environmental and societal considerations in design process. Sustainability is a new concept to balance economic, social and environmental aspects in product design. This research focuses on sustainable product design. The main challenging problem in the sustainable design is how the sustainable criteria can be used as quantitative metrics to evaluate products. This research integrates Axiomatic Design and Quality Function Deployment (QFD) concepts with Eco-design tools, such as Life cycle Assessment (LCA), to establish the quantitative metrics for sustainable product design. A novel wheelchair is designed as a case study in this research. Modularity is conducted to improve the wheelchair for the end of life cycle management.

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CHAPTER 1

Introduction

It is a well-known fact that design plays a leading role in product development. Product design is defined as a systematic and intelligent process for designers to generate, evaluate and specify designs of devices or processes, achieving users' needs and design objectives as well as satisfying a specified set of constraints [1]. A design format consists of shape, appearance, and structure of products. Function is considered as an important part of product design since the product will sell only if it operates as expected [1, 2].

1.1 Engineering design

Engineering design is creating and modifying of an idea, which leads to a product to satisfy customer requirements [3]. The core of the engineering design is creation, analysis, verification, validation, and presentation of a design solution [4]. The engineering design starts with solving a problem to meet customer requirements. In a brief overview, there are five stages in a design process [1]:

1- Determining the problem,

2- Gathering relevant information,

3- Providing and verifying possible solutions towards solving the problem,

4- Analyzing and selecting the best solution,

5- Validating the solution.

1.2 Shift from traditional design to sustainable design

Product design has witnessed dramatic and significant changes during the past decades. The objectives of the traditional design can be summarized as: durability, reliability, affordability, and aesthetic perspective of the product [1, 5]. However, in the last decade, product design experienced fundamental changes in its concept from focusing on performance, function and durability to some other factors such as being environmentally friendly, considering global warming, reducing energy consumption, and conducting end-of-product life cycle management such as reusing, recycling and remanufacturing [4, 6]. It should be noticed that while the traditional aspects of the design are important, both designers and consumers feel a sense of responsibility for natural environments and resources. These topics generate a new concept for product design, called sustainability [7]. Sustainability tries to satisfy today's needs using environmental, social and economic resources, without limiting the ability of future generations to meet their needs [5, 6].

1.3 Research objectives

The objective of this research is to develop a multi-criteria method for product design to map customer needs and sustainable requirements, from qualitative criteria into quantitative metrics, and improve the ability of product for ease of reusing, recycling and remanufacturing through the modularity. The sustainable attributes are usually stated as the qualitative outlines. This research integrates traditional and recent sustainable methods to identify and map both sustainable criteria and customer considerations from qualitative into the quantitative metrics, helping designers to establish sustainable design metric at the early stage of design.

1.4 Thesis structure

The literature survey is conducted in Chapter two to define the concept of sustainability, which examines the current research and studies for the sustainable design development. The framework and details of the research method, including the integration of traditional methodologies with the sustainable principles for product design and end of life cycle management, are described in Chapter three. The framework of the research method is shown in Figure 1-1. The research process consists of three stages as follows to provide a sustainable product with respect to both customer needs and sustainable requirements.

1- Mapping the customer needs and sustainable criteria into the functional requirements and design parameters using the axiomatic design,
2- Design process, including conceptual design, benchmarking, and improving the initial design based on sustainable metrics and details of benchmarks,
3- Improving the product for the end of life cycle management using modularity.

In Chapter four, the initial design of wheelchair is provided based on the concept derived from the sustainable requirements and customer needs. Because of limited data and details in designing of a wheelchair at the early stage of design, four wheelchairs are selected as benchmarks to find more details of design. In Chapter five, the initial design is improved based on the data and results of benchmarking. Chapter six discusses concluding remarks and contributions of this research.

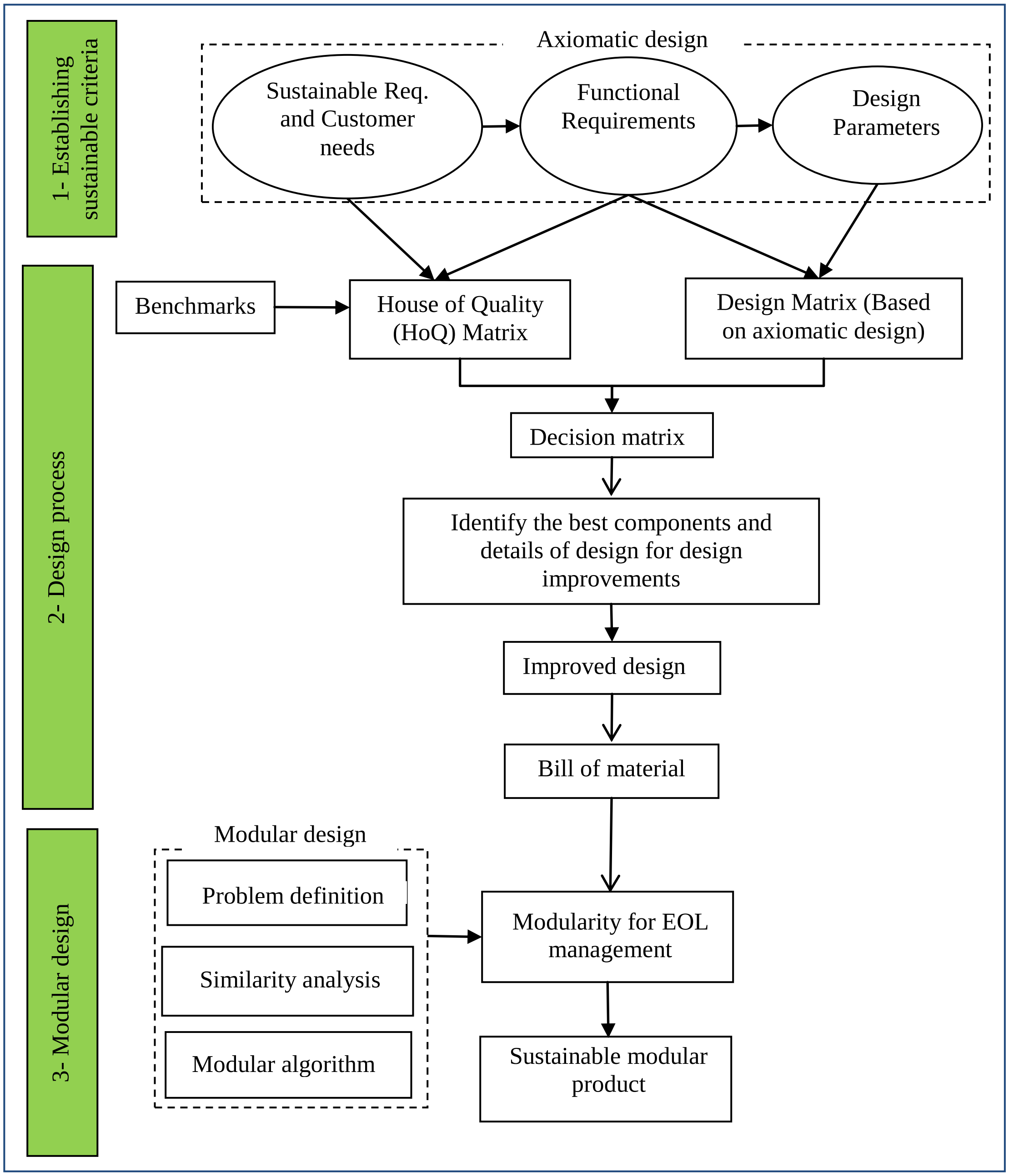


Figure 1-1. The research process

CHAPTER 2

Literature Review

2.1 Sustainability

The concept of sustainable development was first proposed by the world commission on environment and development in 1987 [6]. 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 [7]. It encompasses three elements: environment, economy, and social considerations [8]. These three elements, called the 'three pillars' of sustainability, have to be tuned and balanced with each other when a new product is designed or an existing one is improved [9].

Although environmental problems and global warming are very important issues, the sustainable development has to also consider economic and social aspects of industrial activities [6]. As shown in Figure 2-1, sustainability is the convergence of environmental, economic and social needs [10].

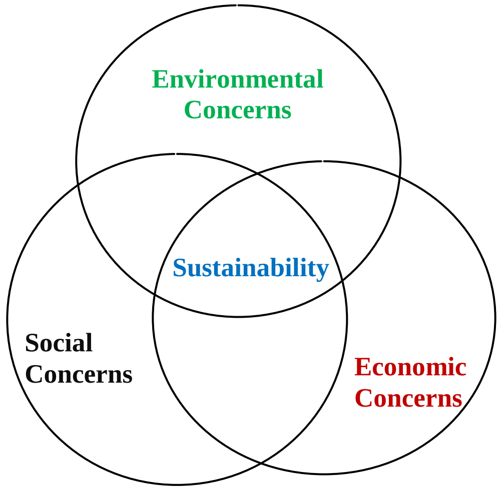


Figure 2-1. Sustainability areas [10]

2.1.1 Sustainable assessment

Evaluation of sustainability during the whole product life cycle is called life cycle sustainability assessment (LCSA) [10, 11]. The life cycle sustainability assessment can be calculated by an integration of environmental, social and economic effects of the product during its whole life cycle. The following scheme is used for evaluating the LCSA [11]:

$$LCSA=LCA + LCC + SLCA$$

Where LCA represents environmental life cycle assessment, LCC accounts for life cycle costing, and SLCA stands for the social life cycle assessment.

- Environmental assessment:

Environmental aspect of sustainability has become a controversial topic for researchers, manufacturers and governments. A lot of research and efforts have been conducted to evaluate the environmental impact of a product during its life cycle [12]. An environmental assessment over a portion or all of the life cycle of a product is known as

Life Cycle Assessment (LCA), which is used as a quantitative and standardized method [13]. LCA is the only internationally standardized environmental assessment method (ISO 14040-44), analysing the product from cradle to grave [13]. LCA is known as a holistic and analytical tool for the environmental management assessment to examine all inputs resources and output footprints (air emission, water toxicity, soil acidification, waste material and energy consumption) [11, 14]. LCA evaluates the environmental effect of generating a product from extracting resources, processing materials, manufacturing and production to distribution, use, and finally end-of-life cycle management such as reusing, recycling, remanufacturing or disposal [14].

- Economic assessment (Life cycle costing)

The second pillar of LCSA is life cycle costing (LCC). LCC is an assessment of all costs and expenses associated with the whole life cycle of a product, generated by suppliers, producers, users/consumers and those involved in the end of product life cycle [15]. LCC examines the total cost of making a product with considering manufacturing and production costs (from producer perspective) and the life cycle costs (from customer's perspective) [14]. The difficulty of using the LCC evaluation is the variety of different viewpoints from producer perspectives to the customer viewpoints. Fiksel et al. suggested five categories for the economic assessment of sustainability [15]:

- Direct costs, including raw material cost, labour cost and capital cost,
- Potentially hidden costs for recycling revenue and product disposition cost,
- Contingent costs for employee injury cost and customer warranty cost,
- Relationship costs including loss of goodwill and business interruption,
- Externalities for loss of ecosystem productivity and resources.

- Social assessment or social life cycle assessment

Companies should take responsibilities toward the social concerns such as safety, health of workforce, and ergonomics [16]. Social life cycle assessment (SLCA) tries to minimize harmful impacts of industrial activities to improve the social health [17]. SLCA addresses many different topics such as human rights, working conditions, employee's duties and responsibilities, standards of living, health, and wellbeing, safety and stability [13, 17]. A general scheme of the sustainable assessment is represented in Figure 2-2.

2.1.2 Scopes of sustainability

Sustainability covers the whole life cycle considerations of a product from raw material selections to the end of its life. Sustainability has many applications in the product development, such as sustainability for product design, sustainability for manufacturing, sustainability for assembly and disassembly, and sustainability for reusing and recycling [18].

a) Sustainability for design

Product design is one of the most prominent stages in sustainable development. Sustainable design affects all stages of the product life cycle from extracting the raw material to the end of its life cycle. One of the main controversial issues in the sustainable design is design for environment (DFE) to evaluate the level of environmental footprint of generating a product [18, 19]. DFE tries to make a product with the lowest level of environmental footprint, besides maintaining and making a balance along with the price, function and quality standards of the product [19]. The detail will be addressed in Section 2.2.

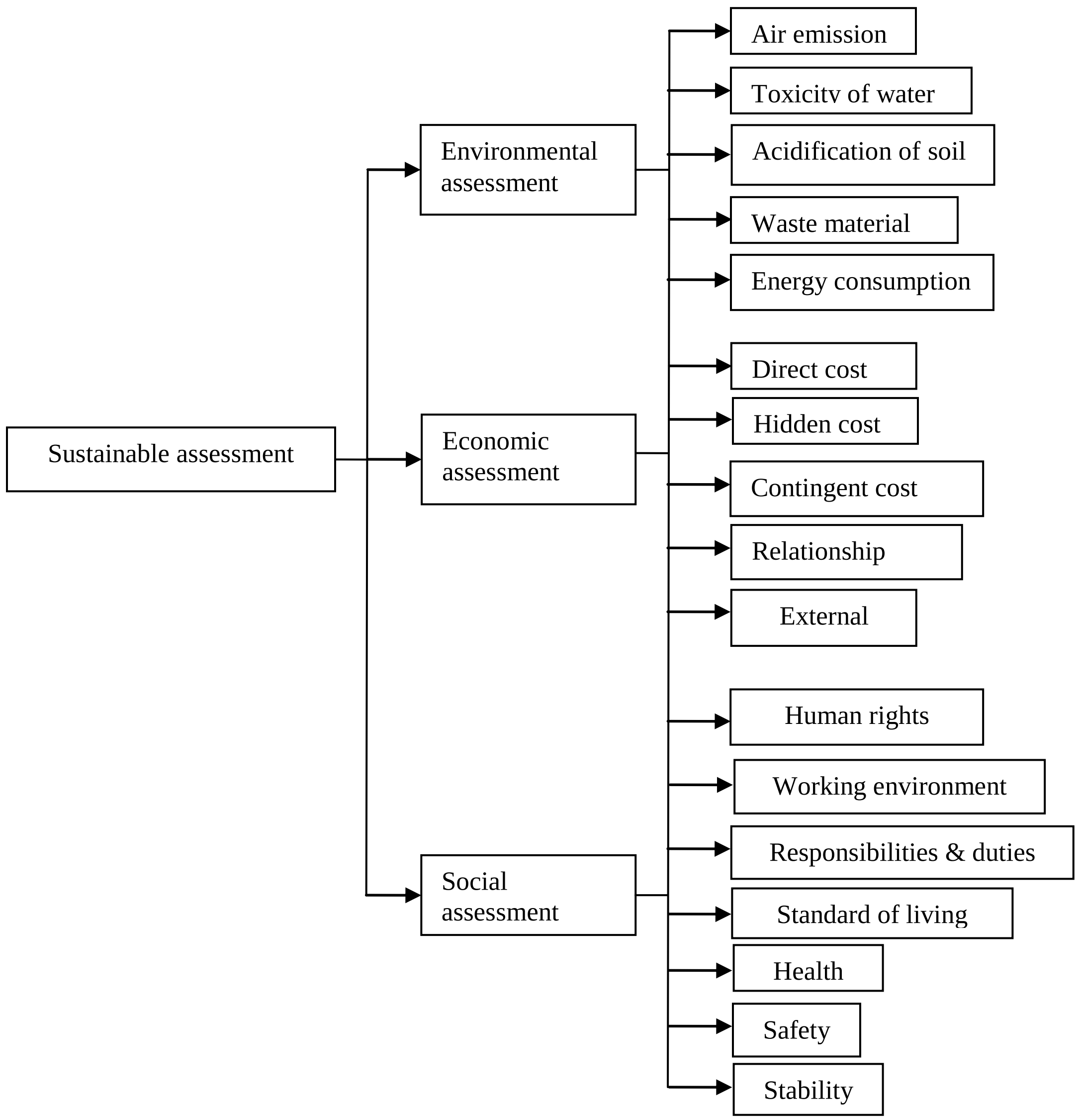


Figure 2-2. Sustainable assessment scheme

b) Sustainability for manufacturing

Manufacturing process accounts for the main stage in consuming resources and generating industrial pollution [18]. Traditional manufacturing processes focus on high performance and low cost with little attention paid to the environmental impact [20]. However, sustainable manufacturing tries to minimise manufacturing consumption, cost and environmental footprint by: 1) process improvement and optimization, 2) green manufacturing process development (such as using laser-based cutting instead of oxy-fuel cutting), and 3) eco-process planning [21, 22]. Process planning can be used to plan sustainable manufacturing, which makes a link between the design and manufacturing process with defining manufacturing plan outlines, sequence of processes, establishing machining data and standards, tooling inventories and stock availability [18, 22].

c) Sustainability for assembly and disassembly

The aim of sustainability for assembly/disassembly is reducing cost and time of the assembly and disassembly process [18]. Design for (ease of) assembly and disassembly is a strategy to improve assembly/disassembly cost and time for the reduction of the environmental footprint of a product during its life cycle [23]. Design for disassembly has a direct effect on the ease of service/maintenance, ease of recovery and re-manufacturing [23]. The following criteria should be considered during design for assembly and disassembly processes [24, 25] :

1- Minimising the number of parts and components' weight,

2- Declining handling and fastening time,

3- Designing parts that have end-to-end symmetry and rotational symmetry around the axis of insertion,
4- Avoiding parts which are slippery, delicate, very small, or very large, or that are toxic and hazardous,
5- Designing parts which are accessible and easy to position for assembly/disassembly processes,
6- Using standard parts,
7- Minimising non-recyclable materials and declining martial variability,
8- Minimising the need for special tools during assembly and disassembly procedures,

d) Sustainability for reuse/ recycling (the end of life cycle management)

One of the main goals in the sustainable product is to establish a close-loop system, which is called cradle to cradle [26]. Also, environmental rules and regulations are becoming more severe and stronger to control and reduce waste and disposal of products in the end of life cycle (EOL). Consequently, new strategies should be adapted to reuse, refurbish, remanufacture or recycle products [18, 27]. Disassembly should be taken into account for remanufacturing or recycling processes, when the component-level recovery is more worthwhile than product recovery [26]. End of life cycle management has witnessed significant changes from the 3R concept (reuse, recycle, reduce) to the 6R concept (reduce, reuse, recycle, recover, redesign and remanufacture) [28].

2.2 Sustainable product design

Among different scopes of sustainability, product design has the significant influence on the product development from materials selection, manufacturing, assembly and disassembly processes to product distribution, use, reuse, recycle or disposal. It is noticed that although product design constitutes only 5-7% cost of whole product development, it can determine around 75% of the entire product life cycle cost [29]. Sustainable design provides guidelines to mitigate the negative environmental impact in the product design stage. It is claimed that 80% of product's environmental footprint is established during design decisions [30, 31]. These decisions have a significant effect on material selection, manufacturing strategies, distribution, service, maintenance and the end of product life cycle, including reusing, recycling or disposal [30].

The challenge in sustainable design is to find a method to evaluate different aspects of sustainability for product design. Over the last decades, numerous methods and tools for environmental and sustainable metrics have been developed. They can be classified into three main groups as follows [18].

- **Sustainable design assessment with Eco-design tools**

Eco-design tools are used to evaluate environmental footprints of the product design. These tools are classified in three major groups: 1-tools based on checklists, 2-tools based on life cycle assessment, and 3- tools based on quality function deployment [18, 32].

Table 2-1. Sample of eco-checklist [33]

Items	Checklist criteria	Y	N	Comments
Material	Is there any material, contributing to chemical emissions (greenhouses, etc), physical emissions (noise, vibration, etc) or acidifications? Is there any toxic or hazardous material? Does the product contain CFC's or VOC's?			
Energy	List the sort of energy used in the product. The amount of primary energy (MJ / product) Electrical energy(MJ/Product) Water consumption (liter/product)			
Manufacturing	Minimum machining waste (RoHS and non-RoHS) Waste from poor quality control (RoHS and non-RoHS)			
End-of -life	Components can be easily separated? Product contains modular components? Product contains recyclable components? Product contains reusable components?			
Misc	Product benchmarking has been done?			

1- Checklists tools: These tools are classified as qualitative and subjective tools which are easy to use at the early stage of design, especially for small and medium industries [34]. As shown in Table 2-1, these tools use a list of many questions to check whether design satisfies sustainability criteria or not [33]. Checklist items provide questions such as, "Does the product contain renewable and recycled materials?", "Is the level of energy used in producing product high" or "Is it feasible and suitable for consumers?" [33]. These tools are very useful at the preliminary design stage to guide designers generating ideas for eco-design. However, they severely depend on the knowledge and experience of designers. In addition, like other qualitative tools, they are not accurate and designers cannot use them to validate their design quantitatively [33].

2- QFD-based tools: The objective of a traditional Quality Function Deployment (QFD) is to convert customers' needs into engineering characteristics and, at the same time, to improve the quality of the product [35]. By importing environmental criteria into QFD requirements, new set of eco-design tools are developed. QFD-based tools are semi-quantitative methods [35, 36]. They try to reconcile environmental concerns of design with consumer needs to achieve a balance between eco-design concept with the lowest environmental impact and economic aspects based on the voice of consumers [18]. The QFD method first collects both environmental strategies and social requirements, then tries to correlate and match these factors. The correlation of environmental-related design and consumer needs considerably depends on the knowledge and experience of designers when using QFD-based tools [37].

While QFD is a useful method to relate different attributes, it does not determine how different requirements can be collected and controlled to satisfy all of the customer needs without having contradictions. Two main problems are attributed to the QFD method [38]:

1- The excessive time and cost,
2- The possibility of losing customer needs.

The excessive development time and cost in conducting QFD happens when the customer needs are redundant and directly related to each other, which is called "coupled customer needs" [38]. The coupled customer needs causes the poor decision-making and forces designers to repeat and redefine the engineering parameters, which is costly and time-consuming. Also, designers may neglect or sacrifice some customers' needs when two or more requirements conflict each other. Hence, some of the customer needs may not be considered in the product design.

3- LCA-based tools: Generating a product has an impact on the environment and society through using materials, resources and energy. Life cycle assessment (LCA), as the most objective, holistic and quantitative tools, evaluates the entire environmental foot-prints of a product during its whole life cycle [18]. LCA has been standardized by ISO in 2006 [39], which can examine the product from close loop or "cradle to cradle" perspective [40]. LCA determines all environmental impacts (on air, water and soil) and energy consumption from extracting materials (cradle), manufacturing/production, transportation/ distribution, to the use phase, maintenance, recovery and reuse (cradle) or disposal (grave) [39, 40]. To accomplish the LCA method, following four phases should be defined [41, 42]:

1) Goal, scope and boundaries of LCA,

2) Life cycle inventory: determining all inputs (such as raw materials and initial energy consumption) and outputs (emissions, waste and other releases),

3) Life cycle impact assessment: monitoring and evaluating entire footprints of a product based on the LCA boundary,

4) Life cycle interpretation: the final step of LCA to determine the result and conclusions based on goals and scopes.

In order to conduct LCA, designers need detailed information and data related to the product life cycle which makes LCA costly, time-consuming and unsuitable for use at the early stage of design when detailed specifications are not available [43]. Some attempts have been done to make LCA efficient and compatible in the early stage of design which is known as streamlined life cycle assessment [39, 44]. Streamlined LCA identifies critical spots and provides efficient strategies of product design to improve environmental effects of a product. It is noticed that streamlined LCA is a semi-quantitative tool. Consequently, it cannot assess the environmental impact of certain life cycle stages, certain materials and energy flows, or certain impact categories [44].

2.3 Current related research

While there are various tools for sustainable design assessments, there is no unique solution to cover all aspects of the sustainable design. Although some methods, like Eco-checklist, are easy to use at the early stage of design, they cannot provide accurate results. On the other hand, some methods such as LCA-based tools need detailed information and data as inputs and outputs which are ambiguous at the early stage of design and make the sustainable assessment time-consuming and costly. Current research activities try to integrate eco-design tools together or with other traditional methods of product design in order to eliminate the above mentioned problems. Consequently, multi-criteria approach should be taken into account, which integrates all the traditional requirements of designing products with the relevant environmental aspects and impacts. The following paragraphs provide some recent research in sustainable design developments.

Bernstein et al [45] proposed a multi-criteria method to explore specific environmental impacts of each components in a product, which is called function impact matrix (FIM). The main goal of the FIM is to determine and re-examine functions of components based on the environmental criteria. FIM considers both environmental and functional aspects of products to determine the co-relationship between functions, behaviours and structures of products and their environmental impacts. In summary, FIM uses decomposition approaches to rate the contribution of each function in the entire system, and LCA to examine environmental footprints of each component [45]. In order to use FIM, LCA should be first conducted on benchmarks. As most of new designs are based on previous design concepts and knowledge, it would be reasonable to conduct LCA on similar products as a benchmark to establish the relationship between functions of product design and its environmental impact. In the next step, the function decomposition is used to rate the importance of each function. The environmental impact of each function is calculated by multiplying environmental footprints of each component by its related function rate. In the end, the designer can select the best components from different benchmarks based on the final score of environmental impact of each component and its function [45]. Although FIM considers environmental footprints of products with respect to their functions, it does not consider design parameters and consumer needs in the part selection procedure. In addition, the end of life cycle management (such as reuse, recycle, remanufacture) is not examined in FIM method.

Masui et al. [46] provided the quality function deployment for environment (QFDE) which combines the QFD method with environmental criteria and quality characteristics. At the first step, voices of customers (VoC), voices of the environment (VoE), and quality characteristics (QC) for traditional and environmental qualities are correlated [46]. Then QC and components are correlated. The outputs of steps I and II are used by the design team to establish re-design targets and determine the most effective parts to make improvement for the environmental effect of the product. QFDE is classified as a semi-qualitative method which can be used in the early stage of design.

However, it does not provide an accurate result to evaluate and calculate environmental footprints.

Life Cycle Quality Function Deployment (LC-QFD) is proposed by Ernzer et al. [47]. In this method, three different houses should be established individually: house of customer (HOC), house of environment (HOE), and house of regulation (HOR) [47]. In the next step, designers compare houses to decide important characteristics for sustainable product design [47]. LC-QFD is a semi-quantitative method and highly depends on the knowledge and experience of designer(s).

Rathod et al. [48] proposed a method called environmentally conscious quality function deployment (ECQFD). ECQFD combines customer's needs and environmental requirements to identify functions and components for both environmental and social requirements. In the next step, LCA is applied to assess and improve product's environmental impacts. While ECQFD considers environmental metric of the product, it does not consider cost aspects of design. Also, ECQFD only examines the possibility of reusing old parts of benchmarks without analysing other perspectives of the end of lifecycle management, such as recycling, remanufacturing, or disposal.

Gilchrist et al. [49] integrated the life cycle inventory (LCI) with LCA and FIM to compare the functional impact of innovative and common products based on material, energy and signals (EMS). The results reveal that there is an inverse relationship between innovation and sustainability. Based on their research, innovative products use more components and accessories than the common (traditional) products, which results in producing product with high level of environmental footprint, cost and weight. While integration of LCA with LCA and FIM can evaluate the environmental effect of products based on their solution of materials, energy flows and functions, it does not assess the social and economic impact of a product. In addition, the post life cycle management is not considered in the method. The assumption is to landfill products after their use phase.

In summary, the existing research solutions do not provide a holistic approach to evaluate different aspects of sustainability for design to analyse and map the customer needs, sustainable metrics and design parameters. While some current research uses QFD to link voice of customer to the voice of environment, they do not provide a solution to determine how different requirements of sustainable design can be identified and controlled with the lowest level of functional conflict. Also, they do not cover the end of life cycle management. Moreover, they just focus on the environmental aspect of sustainability. On the other hand, although some methods try to enhance the ability of a product for ease of maintenance, remanufacture, reuse and recycle, they do not provide a logical approach to determine the sustainable metrics. Consequently, there is a gap among identifying the sustainable needs, mapping the requirements, and managing the end of life cycle management.

This research will use the axiomatic design and QFD principles to identify and map both sustainable requirements and customer demands from qualitative criteria into the quantitative metrics to develop a sustainable product. Life cycle assessment (LCA) and benchmarking will be used to compare and select the best components of benchmarks based on the quantitative sustainable metrics. Following that, the new ideal product will be designed based on the selected components. Also, modularity will be adopted in the last step to enhance the ability of a product for ease of reusing, recycling and remanufacturing.

Following chapter will first introduce the research method. It then discusses details of the research process to generate the sustainable modular product based on the integration of axiomatic design, QFD and modular design principles.

CHAPTER 3

Research Method

In this chapter the research method is first introduced. The framework of the research process is already shown in Figure 1-1. It consists of three phases to establish the quantitative sustainable metrics for the sustainable product. The modular design is adopted to improve the product for ease of reusing, recycling and remanufacturing at the end of its life cycle. After discussing the steps of research process, the use of axiomatic design to map the sustainable requirements and customers' needs into design parameters will be discussed.

As shown in Figure 1-1, the sustainable design process starts with identifying and mapping the sustainable customer needs, functional requirements and physical properties based on the axiomatic design rules. The house of quality (HoQ) is used to make a link between the sustainable customer needs and functional requirements. It determines the top-level of functional requirements based on the sustainable requirements and customer demands. In the next step, the design matrix is formed to link the functional requirements and physical properties. Finally, the decision matrix is established to link the HoQ and design-matrices in order to determine the weight factors and priorities of the design.

An initial design is provided, based on the mapping process, to satisfy the customer needs and sustainable criteria. However, the further improvement of the initial design is impossible due to lack of knowledge, data and details at the beginning of design process. Consequently, some similar products are selected from the market as the benchmarks. The benchmarks are decomposed to their subassemblies and analyzed based on the priorities and weight factors derived from the decision matrix. The LCA is used to assess the environmental footprints of the benchmarks. The result of benchmarking reveals the details of product design to improve the initial design. In the last phase, the modularity is used as a crucial technique to improve the product for ease of reuse, recycle and remanufacture besides maintaining the functional requirements and physical interactions of the product.

In this research, the axiomatic design is used to determine the sustainable criteria and map customer needs into the functional requirements and design parameters. The principles and main rules of axiomatic design will be discussed in the next part. Following that, details of the research method including establishing the quantitative sustainable design metrics (with the usage of axiomatic design and QFD), benchmarking and modular design for the end of life cycle management will be explained.

3.1 Identification of CAs, FRs and DPs using axiomatic design

The first goal of this research is to identify and convert sustainable requirements and customer needs (CAs) from qualitative criteria into quantitative parameters. QFD is a good tool to develop product characteristics if the function requirements (FRs) and design parameters (DPs) are identified. However, as mentioned in the literature review (Section 2.2), QFD cannot determine details of functions and design parameters needed to meet customer requirements, or to determine the function requirements and design parameters without conflicts. Consequently, QFD requires the use of other tools, such as axiomatic design, to make the design solution. Axiomatic design can be integrated with the QFD to determine the minimum set of design characteristics to act without conflicts in the product.

Axiomatic design is a design tool to solve design problems systematically and effectively while converting customer needs into functional requirements, design parameters, and process variables [50]. As shown in Figure 3-1, the design process consists of three mappings among four domains. Customer mapping transforms the first domain which defines customer needs (CAs) into the function domain which represents functional requirements (FRs). Physical mapping converts FRs into design parameters (DPs) to determine design properties of a product. Finally, process variables (PVs) are defined by mapping the physical domain into the process domain. This mapping can be represented by matrices and process elements in order to translate DPs to PVs in the manufacturing and production procedure [50].

Conforming of CAs into FRs forms an important part of the axiomatic design. If the customer needs are not identified properly, the functional requirements will face many difficulties. There are two main rules (axioms) in the axiomatic design to govern the design process for an appropriate design. The two axioms are: a) independence axiom, and b) information axiom, which are described in the next step [50].

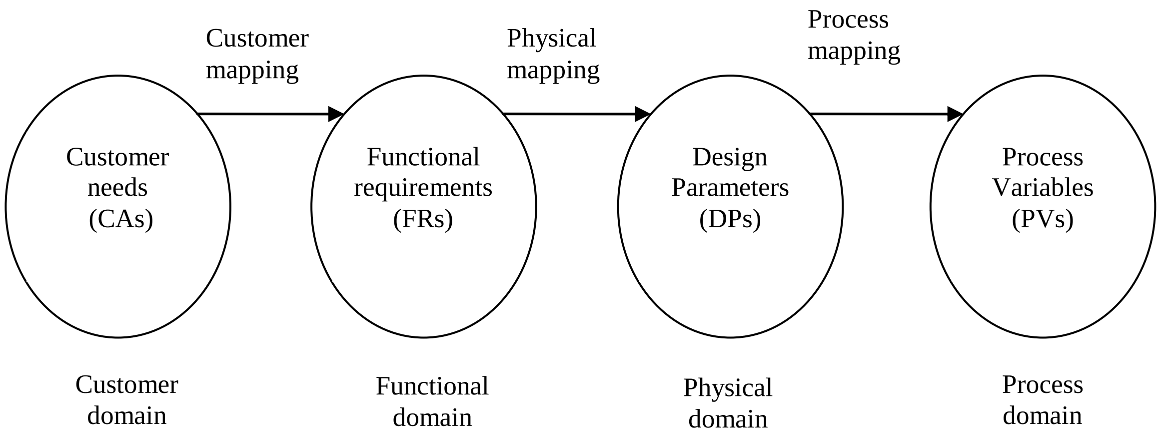


Figure 3-1. Mapping of the axiomatic design domains [50]

The independence axiom states that FRs should be independent from each other. Based on axiom one, FRs are defined as "a minimum set of independent requirements that completely characterize the functional needs of the product in the functional domain" [50]. When the independent functional requirements are completely defined, design parameters can be determined to satisfy all FRs. It should be considered that the functional domain represents "what is needed" and the physical domain states "how will the needs be achieved". Mapping of FRs and DPs is expressed by mathematical equation as shown in Equation 3-1 [50]:

$$\{\mathbf{FRs}\} = [\mathbf{A}]\{\mathbf{DPs}\} \qquad (3\text{-}1)$$

Where [A] is a design matrix, {FRs} and {DPs} are the vector formats of FRs and DPs, respectively. As shown in Figure 3-2, the design matrix exists in two cases: diagonal and triangular. Diagonal matrix leads to the uncoupled design and indicates that all requirements are independent. Consequently, each FR can be satisfied by one DP, the number of FRs and DPs are equal. Uncoupled design implies that the design is ideal.

If the design matrix is triangular, the design is decoupled which means there would be two or more DPs to satisfy one FR [50]. It should be considered that the number of DPs should be more than the number of FRs. If the number of DPs is less than the number of FRs, two FRS share one DP and the independence axiom is violated [50]. Consequently, it is important to establish an appropriate number of design parameters to meet FRs and keep their independencies.

$$[A] = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix}$$

Diagonal matrix (Uncoupled design)

$$[A] = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix}$$

Triangular matrix (Decoupled design)

Figure 3-2. Diagonal and triangular matrices [50]

Information axiom states that the best design is the one with the least information [50]. After defining FRs, designers should provide sufficient DPs based on the axiom one. However, for the same set of FRs, different DPs can be provided by different designers as the best solution. The amount of information to meet the intended requirements is called information content. The information content determines the probability of success in satisfying requirements. Hence, the axiom two implied that minimizing the information leads to maximising the probability of success. The following equation is used to determine the information content [50];

$$I = \log_2\left(\frac{1}{p_i}\right) \qquad (3\text{-}2)$$

Where I is defined in terms of the probability of satisfying a given FR, and P_i is the probability of DP_i in satisfying FR_i for a set of n FRs. P_i is defined by the following equation [50];

$$P_i = \frac{\text{common range}}{\text{System range}} \qquad (3\text{-}3)$$

The system range is the rage of values of the DP which can be made by a manufacturing process. Design range shows the change of the DP that will satisfy the FR. And the common range is the intersection of the system range and the design range.

In the axiomatic design, the axiom one should be first applied and then axiom two may be used. Axiom two can be used when the manufacturing process in defined. In order to provide a reasonable design, axiom one should be satisfied [50]. This research focuses on the design and most of the effort is to meet the axiom one.

Axiomatic design has the flexibility to adopt the new elements of design such as sustainable requirements. Sustainable requirements can be added to the common customer needs in the first domain, which should be mapped and satisfied by proper functions and design parameters. The following part will discuss details of phase one which is identifying and mapping of the customer needs and sustainable criteria, using axiomatic design method.

3.2 Mapping of sustainable CAs, FRs and DPs

The main goal of this stage is to identify and map customers' needs from the functional domain to the physical domain with respect to the sustainability criteria. As shown in Figure 3-3, in this research, the sustainable criteria are added to the traditional customer needs and they are mapped into the proper functional requirements and design parameters.

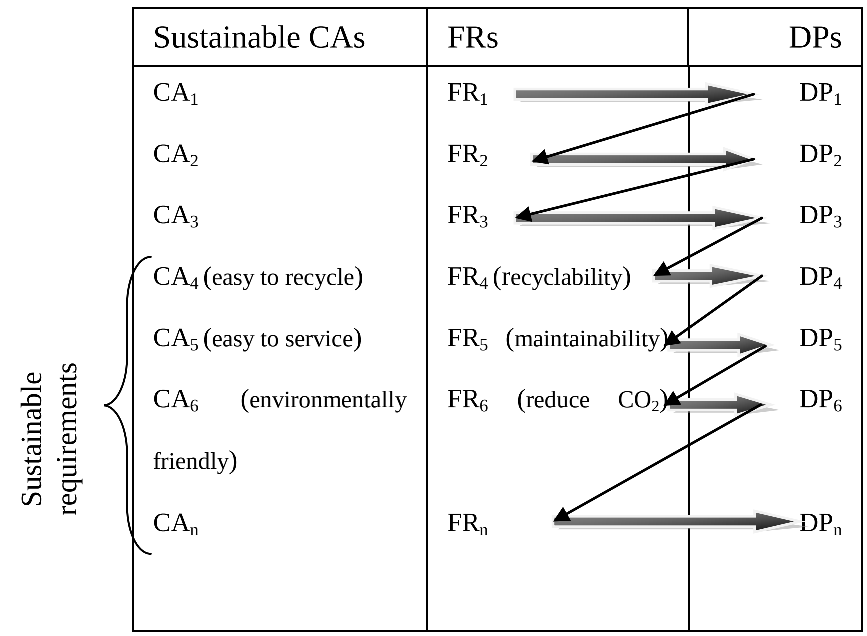


Figure 3-3. Mapping CAs, FRs and DPs based on the sustainability

The first step is to develop a list of the entire sustainable customers' needs (CAs). It should be considered that the customer domain contains both traditional and sustainable attributes of a product such as being durable, easy to use, inexpensive, safe, easy to maintain and environmentally friendly. In the next step, CAs should be converted into functional requirements (FRs). In accordance to the axiomatic design, FRs should be identified as the minimum set of independent requirements to meet all of the CAs. This process is important in the design process as it determines the engineering characteristics of a product to satisfy the entire CAs. Once all of the FRs are defined, the design parameters should be determined with respect to the FRs. DPs are the physical solutions of the FRs. The axiom one is followed in developing DPs and FRs. The correlation of

FRs and DPs is identified by drawing an arrow. It is important to maintain equal numbers of DPs and FRs, which results in an ideal design.

Once customer needs and sustainable criteria are identified and mapped into FRs and DPs, an initial design is formed. The initial design represents the general structure of an intended product. However, because of limited data and information of product at the early stage of design process, benchmarking is used to identify proper details of design.

3.3 Design process

The purpose of this section is to determine the sustainable design metrics with the integration of axiomatic design and QFD. This process consists of four steps:

1. Establishing House of Quality (HoQ) matrix between the sustainable CAs and FRs, and comparing benchmarks with respect to the sustainable CAs,
2. Establishing the design matrix between the sustainable FRs and DPs,
3. Forming of decision matrix for sustainable design metrics,
4. Identifying details of benchmarks and using these details to improve the initial design.

3.3.1 Establishing HoQ between sustainable CAs and FRs

House of quality (HoQ) is a visualized tool of the QFD. It is used to establish the relationship matrix between CAs and FRs. It determines the importance level of each function based on customers' viewpoints.

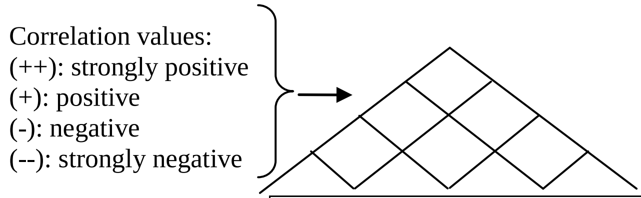
As shown in Figure 3-4, CAs are listed in the left column and the degree of importance is shown in front of each demand. FRs are then listed in the top row. In the next step, CAs are linked to the FRs in the relationship matrix. The relationship of CAs and FRs is defined as high with the score of 5, medium with the score of 3, or weak with the score of 1. If there is no interaction between a CA and a FR, their corresponding cell will be blank. Then, the roof of matrix, called the correlation matrix, is accomplished to determine the impact of functional requirements on each other. The correlation of functions can be strongly positive with the symbol of (++), positive with the symbol of (+), negative with the symbol of (-), or strongly negative with the symbol of (--). Based on the correlation matrix, the designer can eliminate physical contradictions between functional requirements. Once the relationship matrix is completed, the absolute and relative weights of each FR are calculated by following equations to determine priorities in the design [51] ;

$$\text{Absolute weight: } \quad W_j = \sum_{i=1}^{n} a_{ij} \, d_i \qquad (3\text{-}4)$$

$$\text{Relative weight: } \quad r_j = \frac{w_j}{\sum_{i=1}^{m} w_j} \qquad (3\text{-}5)$$

Where w_j is the absolute weight of each function, a_{ij} is the relationship value between CAs and FRs which can be 5, 3 or 1, d_i is the degree of importance for the i_{th} customer demand, and r_j is the relative weight of the each function.

As shown in Figure 3-4, the right columns of the HoQ represent the customer rating for different benchmarks. At this stage in completing HoQ, some similar products are selected as the benchmarks. Understanding how customers rate the benchmarks can be a tremendous competitive advantage. In this step of the QFD process, customers are asked for the products rating based on their expectations.



		Functional requirements				Customer rating for benchmarks		
Customer requirements	Importance degree	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}
	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		$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_j}$	$\mathbf{w_m}$			
Relative weight		$\mathbf{r_1}$	$\mathbf{r_2}$	$\mathbf{r_j}$	$\mathbf{r_m}$			

Figure 3-4. The general framework of HoQ

Benchmarking is a process to examine and compare the existing products for identifying of the best one [52]. The overall goal of benchmarking is to combine the best practiced solution for each sub-function in order to make an optimal product. There are three main advantages to use benchmarking [53]:

1- Eliminating the trial and error process,

2- Speeding up the improvements process,

3- Increasing the efficiency of the company in developing new ideas.

The benchmarking products selected should have similar functions and applications to be comparable; otherwise, results of benchmarking are not accurate.

While rating of the benchmarks brings a valuable data about the specifications of the product to meet customer needs, it does not provide details of design and components to satisfy FRs and sustainable criteria. Consequently, in order to compare details of benchmarks, design matrix and decision matrix should be established to determine the sustainable metrics. The details of benchmarks are then used to improve the initial design.

3.3.2 Establishing the design matrix between sustainable FRs and DPs

When mapping of FRs and DPs are completed in step one, the design matrix can be used 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 Figure 3-5, FRs are in the left column of the matrix, and DPs are listed in the top row. Values of 1 and 0 are used to determine the correlation of FRs and DPs. When DP satisfies FR the x is 1 and if there is no correlation between DP and FR x is equal to 0 [50]. The final score of each function is determined by adding values of its related row.

3.3.3 Forming of the decision matrix for sustainable engineering metrics

In the final step, HoQ matrix is used to develop the relationship of customer needs and functional requirements. It determines the importance of functional requirements based on the sustainable needs; then, the design matrix identifies how design parameters satisfy functional requirements.

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

Figure 3-5. General format of decision matrix

To make a link between HoQ matrix and design matrix, the decision matrix is used to distinguish the final weight factor for each FR based on the results of the HoQ and design matrices. The decision matrix is a quantitative method to systematically identify, analyze, and rank the importance of relationships between sets of data [54]. As shown in Figure 3-6, the relative weights of each function, derived from HoQ matrix, are listed in the second row. The total scores of each function, calculated from the design-matrix, are put in the third row. In the end, the final weight factor of each FR is calculated by Equation 3-6, which is in the last row [54].

$$\text{(The final weight factor)} \ F_i = R_i \times S_i \text{, (i =1, n)} \qquad (3\text{-}6)$$

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

Figure 3-6. Decision matrix framework

The final weight factors determine the priority of design based on the mapping of sustainable customer needs to the functional requirements and design parameters. The priorities are used in the next phase as the sustainable design metrics to compare and select the best sustainable product from different benchmarks.

3.3.4 Design improvements based on the details of benchmarks

In order to find the data and details of design, components benchmarks should be compared based on the results of decision matrix, which provides the quantitative sustainable metrics.

The benchmarks, selected for details of HoQ, are decomposed to their subassemblies and compared with each other based on priorities and weight factors for the best components of a sustainable product. LCA is conducted on all benchmarks to determine the environment footprints. SolidWorks 2013 is used in this research as it has ability to model and evaluate the design according to types of materials used in the product, manufacturing, energy usage, carbon footprint (CO_2), water toxicity, and soil acidification [55]. The benchmarking provides valuable data and details to improve the initial design. The material, accurate size, form of components, and type of mechanisms can be determined to improve the initial design. Based on the materials and details identified, the finite elements analysis can be conducted for the product. The modularity will be used in the next phase to enhance the product ability in ease of reusing, recycling and remanufacturing.

3.4 Using modularity to improve the end of life management

Modularity divides a product into the independent modules or clusters considered as the independent units [56]. A product life cycle includes design, manufacturing, assembly, distribution, operation (use), maintenance and services, reuse, re-manufacturing, recycling and disposal. The strategy of detaching products into modules has a direct effect on the ease of maintenance, assembly, disassembly, reuse, recycle and remanufacture.

3.4.1 Modularity for sustainable design

Modularity is used to improve a product for ease of maintenance, reuse, recycle and remanufacture [56]. The product is easily reused and recycled when its components in each functional module have the similar post-life cycle behaviour. There are many advantages of modularity for the end of life cycle managements as follows:

Modularity for the end of product life cycle management: when a product reaches its end of life cycle, there may be some usable components [56]. These components should be easily separable from the product for recycling. While the modularity is conducted for the end of life cycle management, it should not change the intended functions of the product. This requires the consideration of functional and physical interactions among components. The physical interactions contain spatial and geometrical relationships. It includes attachment, positioning and motion [57]. These physical and structural constraints must be considered when components are grouped into modules.

3.4.2 Modularity process

The modular design consists of three main steps: problem definition, interaction analysis, and modular formation [57].

a) Problem definition: the first step of modular design is to define the objective(s) of modularization. Modularity can be used for ease of manufacturing, assembly, disassembly, maintenance, and end life cycle management, such as various manufacturing cells formed by modularity in manufacturing systems.

b) Evaluation criteria and similarity analysis: based on objectives of modular design, a set of criteria can be defined to determine the correlation of components, such as the material type and life expectancy for the end life cycle management [57].

Table 3-1. Similarity values for the end of product life cycle

Similarity criteria for the end of product life cycle	**Score**
Components with the same end of life cycle (high)	10
Components have medium compatibility	8
Components with low compatibility	4
Components with total different end-of-life options	0

After determining the evaluation criteria, the similarity values are established for each objective [57]. As shown in Table 3-1, the similarity value can be high with the score of 10 (e.g. when the two components are reusable), medium with the score of 6 (e.g. when one is reusable and the other one is recyclable), low with the score of 2 (e.g. one component is recyclable and the other is mixture of recyclable and non-recyclable material) or none with the score of 0 (e.g. one component is reusable and the other one should be incinerated). When the criteria and similarity values are defined, the similarity matrix is formed to determine the correlation of components (Figure 3-7) [57]. Where A_i represents components of the product, and X is determined based on the similarity values. For example, if A_1 and A_2 are reusable components, x is assigned as 10.

c) Modular algorithm for clustering

When the objective, constraints and modular matrix are formed, a clustering algorithm can be applied to determine modules with the maximum interactions of components in each group. The unsupervised hierarchical clustering algorithm is used in this research to find the best solution for modularization. The unsupervised hierarchical clustering groups similar objects into "clusters". It is very useful when the data are set in the similarity matrix. Figure 3-8 shows the unsupervised hierarchical clustering process, which will be explained with an example later [58].

	A_1	**A_2**	**A_I**	**A_n**
A_1	10	x	x	x
A_2	x	10	x	x
A_i	x	x	10	x
A_n	x	x	x	10

Figure 3-7. Similarity matrix [57]

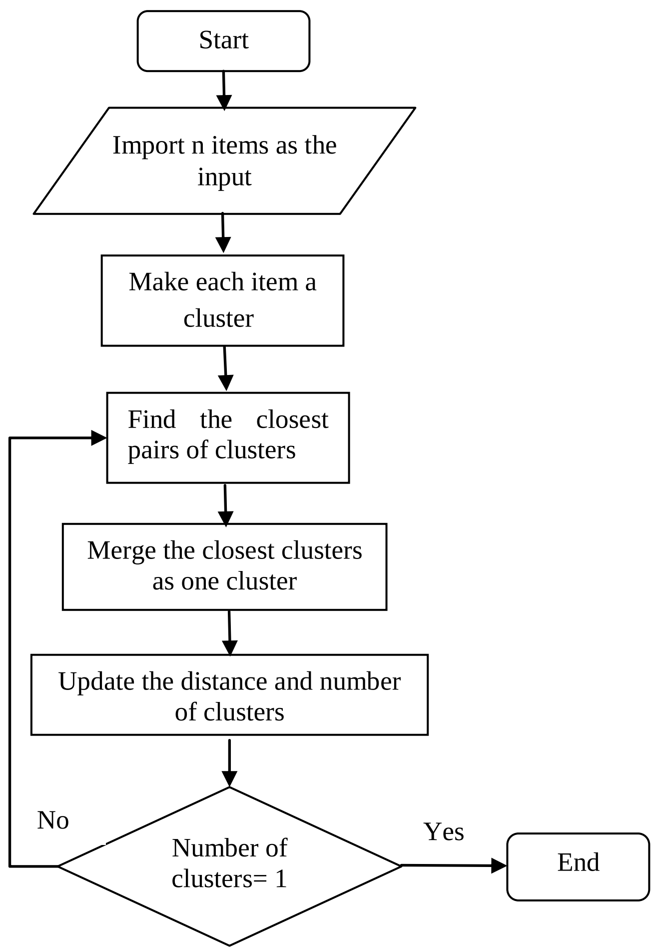


Figure 3-8. Hierarchical unsupervised clustering algorithm

Table 3-2. Two main objective functions

The objective function	Formulation
complete linkage clustering (maximum)	max $d\ (a, b\}: a \in A, b \in B$
single-linkage clustering (minimum)	min $d\ (a, b\}: a \in A, b \in B$

As shown in Table 3-2, the objective of clustering can be maximization, which is called complete clustering or minimization, which is called complete linkage clustering [58]. In this research, the objective function is the maximum interaction (or minimum of dissimilarity) of components for each cluster, which leads to the maximum similarity in each module.

Once the closest pair of clusters is defined, they should be merged into the single cluster and their relative row and column should be deleted in the similarity matrix; consequently, the number of clusters decreases to n-1. For example, in Figure 3-9, the product has 5 components (A, B, C, D, and E). As the minimum dis-similarity is between B and E, they are put in the same cluster. The row and column of the component with the bigger values is then deleted. In the next step, the closest interaction is determined among updated sets of clusters. This process is continued until the number of cluster reaches 1[58].

	A	B	C	D	E
A	10	3	4.6	2.7	4
B	3	10	7.5	5.6	1.4
C	4.6	7.5	10	2.2	8.5
D	2.7	5.6	2.2	10	6
E	4	1.4	8.5	6	10

	A	B,E	C	D
A	10	3	4.6	2.7
B,E	3	10	7.5	5.6
C	4.6	7.5	10	2.2
D	2.7	5.6	2.2	10

	A	B,E	C,D
A	10	3	2.7
B,E	3	10	5.6
C,D	2.7	5.6	10

	B,E	A,C,D
B,E	10	3
A,C,D	3	10

Figure 3-9. Example of unsupervised hierarchical clustering process

The final results of hierarchical clustering are illustrated in a tree diagram as shown in Figure 3-10 [58]. In this research, Matlab 2012 is used to search results of the hierarchical algorithm to deal with the complexity of similarity matrix. In the next chapter, four powered wheelchairs are selected as benchmarks to demonstrate the research method.

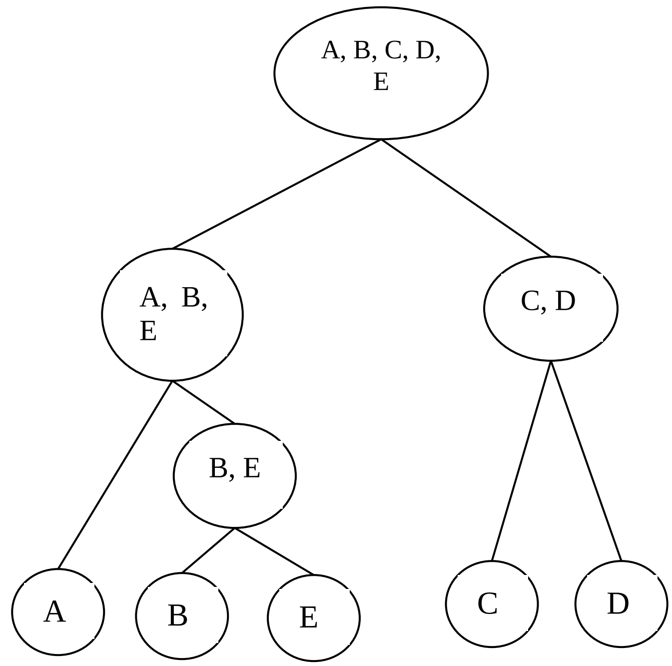


Figure 3-10. Tree diagrams of hierarchical clustering

CHAPTER 4

Case Study

In this Chapter, a novel wheelchair is designed based on the mapping of sustainable requirements and customer needs. As details of the design are not clear at the early stage of design process, four powered wheelchairs are selected as benchmarks to identify details of the design and improve the initial design using following steps.

1) Identifying and mapping of the sustainable criteria and customers' needs for the proper functional requirements and design properties based on the axiomatic design. An initial wheelchair is designed based on the preliminary concept from the mapping of customer needs and sustainable criteria,

2) Establishing the house of quality for a wheelchair to determine the correlation of the sustainable requirements and customers' needs with the functional requirements. Four wheelchair are selected as the benchmarks to be rated based on the CAs and sustainable criteria,

3) Establishing the design matrix to identify the relationship of functional requirements and design parameters of the wheelchair. The design solution is checked at this stage to meet the axiomatic design criteria based on the design matrix,

4) Forming the decision matrix to link house of quality and design matrix. At this stage the functional requirements are rated based on the customer needs, sustainable and functional requirements. The result of decision matrix identifies the priorities in a wheelchair design,

5) The details of the benchmarks are analyzed based on the priorities of design to select the best exchangeable components. The best components of the four wheelchairs are selected to design an ideal wheelchair. At this stage, the details of sustainable wheelchair design, such as material type, size and components characteristics to meet the sustainable and functional requirements are identified. These details are used to improve the initial design,

4.1 Mapping of sustainable criteria and customers' needs

Wheelchair is a chair with wheels to move people who have walking difficulties [59]. While there are vast varieties of wheelchairs in the market, they can be classified in three main groups: manual wheelchairs which are moved by turning the rear wheels using user's hands, powered (motorized) wheelchairs which are propelled with electric motors, and sport wheelchairs which are designed to be very light and small for disabled athletes [59].

The first step of designing a wheelchair is to provide a list of customer needs (CAs). The customer domain contains both structural and sustainable demands such as being stable, comfortable, light, inexpensive, durable and eco-friendly. Sustainability makes a balance between product cost, durability and low environmental footprints in design [8].

In order to balance different aspects of sustainable design requirement, the design metrics should be rated based on their weight factors.

Once the customer needs (CAs) is decided, the proper functional requirements should be identified to satisfy the CAs. Based on the axiomatic design, the functional requirements are defined as the minimum set of independent requirements that completely satisfy the intended demand of a wheelchair. By mapping CAs into FRs, the entire wheelchair's functions are identified. After determining all of the CAs and FRs, the next step is to determine design parameters of the wheelchair. The initial demand in the wheelchair is to carry the user (CA.1) which leads to the top level of customer needs (Figure 4-1). 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), the wheels should be operated with the electrical energy (FR.2), which needs electrical motors (DP.2). The mapping of structural and sustainable customer needs into the functional requirements and design parameters is illustrated in Figure 4-1. Based on the axiomatic design rules, the number of FRs and DPs are equal and FRs are independent from each other, resulting in the design solution.

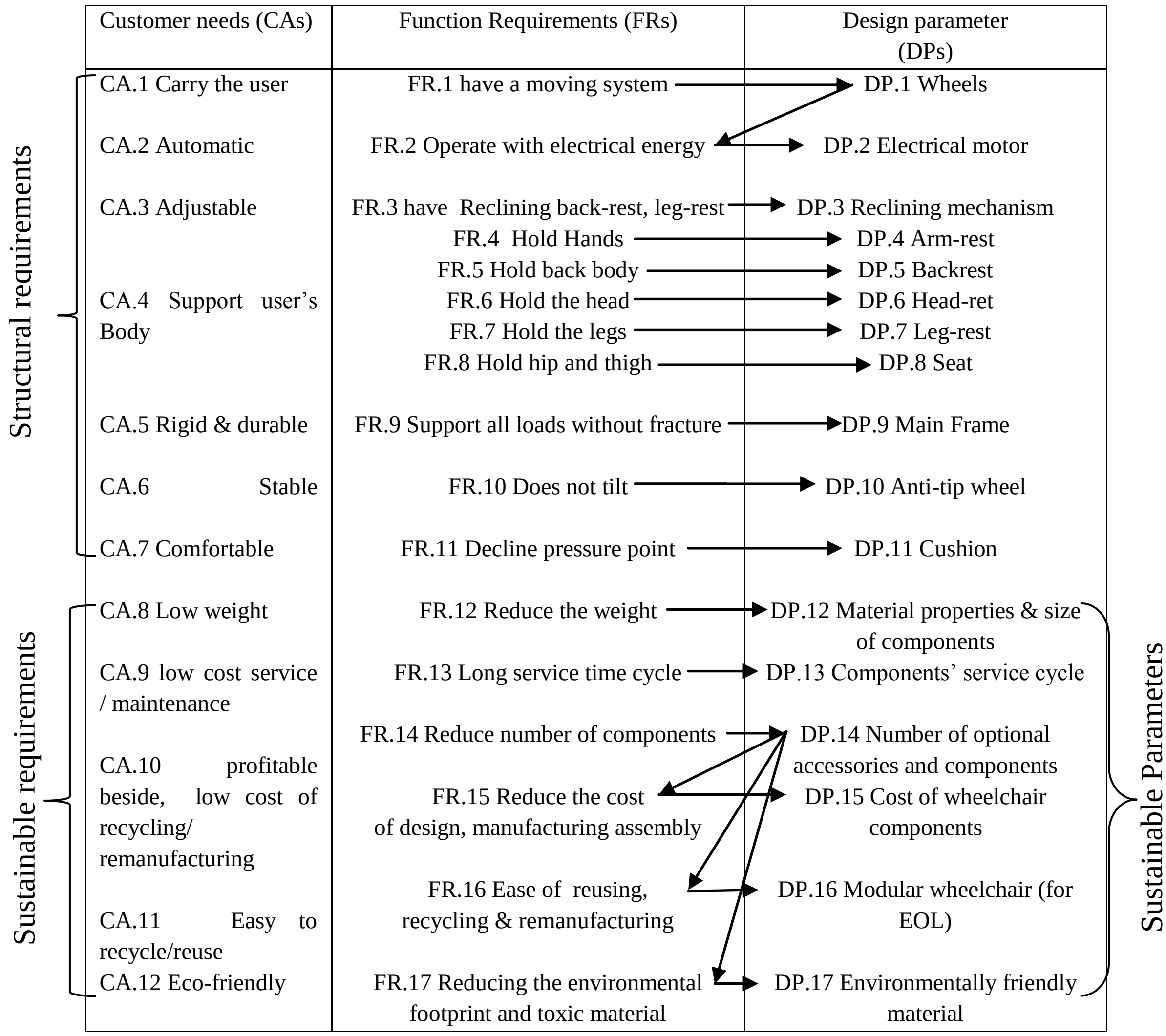


Figure 4-1. Sustainable design mapping of wheelchair

4.2 Initial wheelchair design based on mapping process

After completing the mapping process, an initial wheelchair is designed to meet the customer and sustainable needs as shown in Figure 4-2, the preliminary concept of the wheelchair design, such as holding the user's body, automatic moving system and adjustability, provides the general idea to design the frame, seat, back rest, leg rest, wheels and other components of wheelchair. As shown in Figure 4-2, the wheelchair can be propelled automatically with the electrical motors, mounted on the drive wheels. The back rest and leg rest have the flexibility to be folded or un-folded, providing the opportunity to use a wheelchair as a chair or bed. To fold and unfold components, the power-seat mechanism is used in the wheelchair [60, 62]. As shown in Figure 4-3, the rotational movement of the electric motor rotates the screw shaft. The screw shaft pushes/pulls the nut-block. Movement of nut-block provides the force and torque to rotate the U-joint levers and axis. U-joints are fixed (with welding or pin) to the axis and lever [61]. Consequently, the motion of the axis rotates head-rest, back rest, or leg-rest. The arm rests are adjustable to be set for different heights.

Figure 4-2. The initial wheeelchair design

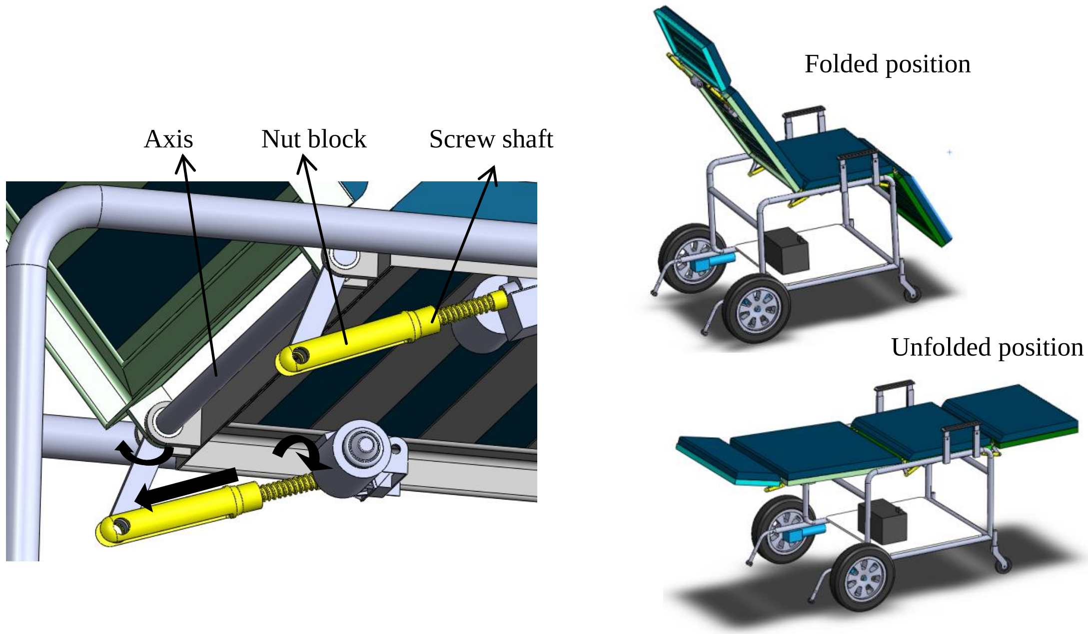


Figure 4-3. Reclining mechanism for power (electric) seat

Although the mapping of the customer and sustainability needs provides the preliminary concept for wheelchair design, the further design improvements and evaluations are required for following design details to improve the preliminary design:

1- Material type: it is difficult to set the exact type of materials for each component at the early stage of design as details of the design are not clear.

2- Accurate size and geometry: as materials and design parameters of components are unclear. Conducting a finite element analysis is impossible as the material and details of design are not set.

3- Forms of subassemblies and mechanisms to meet sustainable and functional requirements are unclear at the early stage of design, such as the mechanism to be used for folding and unfolding motions.

4- Modular design cannot be conducted to satisfy the ease of reusing, recycling and remanufacturing.

In order to find the detail of accurate parameters to improve the initial design, four wheelchairs are selected as benchmarks in the next step to determine further details of the design.

4.3 HoQ-matrix

In this section house of quality (HoQ) is established to link the customer needs and sustainable considerations into the functional requirements. Four power wheelchairs are selected as the benchmarks from the Quickie manufacturer company [62]. These wheelchairs are used to be rated and compared in the HoQ. The four wheelchairs are entitled as Quickie S-525, Groove, P-220, and Z-Bop, they are classified as powered (motorized) wheelchairs [62]. The four wheelchairs are similar in function and application. Table 4-1 shows the general specifications of each the wheelchairs, which are provided by the Quickie manufacturer [62].

Table 4-1. The general specifications of the four benchmarks [62]

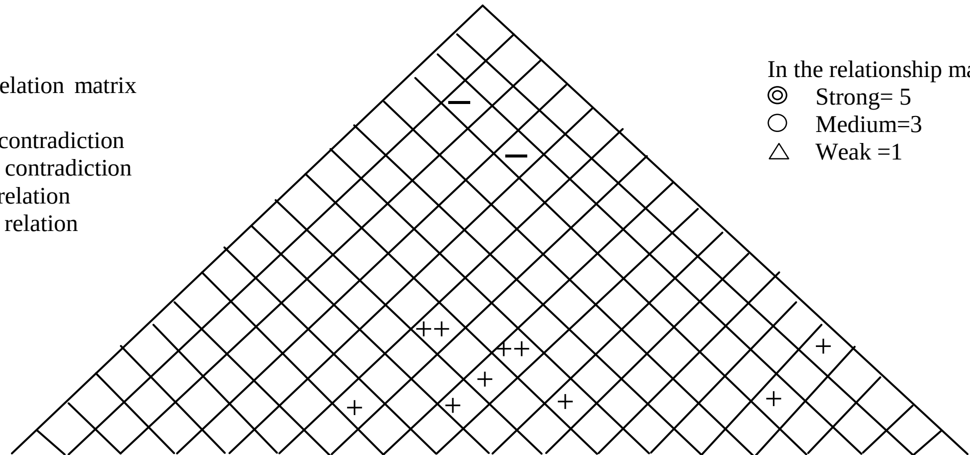
	Wheelchair A: Q- S525	Wheelchair B: Q- Groove	Wheelchair C: Q- P220	Wheelchair D: Q- Zippie Zbop
Cost (CAD)	5298	6440.7	6923.7	7003.7
Weight (Kg)	35.5	45.3	41.6	51.2
Speed (Km/h)	8	9.2	10	8
Battery	Armstron 12V / 34Ah	12V, 55Ah	12V, 42Ah	12V, 65Ah
Reclining back rest	N/A	Manual recliner	N/A	Power recliner
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

When CAs, FRs and DPs of the wheelchair are identified, the HoQ is formed to link the customer needs and functional requirements. As shown in Figure 4-4, CAs are listed on the left and FRs are set on the top in the HoQ. Next step is to accomplish the relationship matrix, where the correlation of customer needs and FRs is determined. The relationship can be weak (with value $\Delta = 1$), medium (with value $\circ = 3$), or strong (with value $\Theta = 5$). To determine the absolute score of each FR, the customer importance score is multiplied by the value of related cell. Then, numbers are added up in their respective columns to determine the absolute score of each FR. For example, reducing the number of components (FR.13) makes the wheelchair light (CA.8) and the product cost change (CA.9). Hence, the absolute weight of reducing the "number of components" (FR.13) is $3\times5 + 5\times3 = 30$. The roof of HoQ, called the correlation matrix, is formed to determine how functional requirements will impact on each other. Finally, the relative weight factor of the wheelchair is calculated by dividing each absolute weight on the total score. For example, the relative weight factor for reducing the number of components (FR.13) is $(30 / 371) \times 100 = 8\%$.

As shown in Figure 4-5, in the last step of completing the HoQ, four benchmarks are rated based on the customer needs and sustainable criteria. For instance, regarding the item of being automatic, all wheelchairs have an electrical engine for movement; however, wheelchair D is equipped with electrical reclining back-rest mechanism, wheelchair B has manual reclining mechanism and wheelchairs A and C has fixed one [62]. Consequently, the rate of wheelchair D is 5, wheelchair B is 4, and wheelchairs A and C are 3.

In the correlation matrix roof
- - : strong contradiction
- : Medium contradiction
++: strong relation
+: Medium relation

In the relationship matrix
◎ Strong= 5
○ Medium=3
△ Weak =1



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. Reusing,/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	371
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 4-4. House of quality for wheelchairs

	Importance score	Rating of the four Benchmarks in HoQ A: Quickie S-525 Score:= 1: lowest, 5: highest B: Quickie Groove C: Quickie P-220 D: Quickie Z-Bop				
CAs		1	2	3	4	5
1- Carry user	5					A, B , C ,D
2- Automatic	2			A, C	B	D
3- Adjustable	3		A	C	B	D
4- Support user's Body	5			A	D	B, C
5- Rigid & durable	5			A,B	C	D
6-Stable	4	Unknown, (Needs more details)	Unknown	Unknown	Unknown	Unknown
7-Comfortable	4			A, C	D	B
8- Low weight	3	D	B	C	A	
9- low cost service / maintenance	5	Unknown	Unknown	Unknown	Unknown	Unknown
10- profitable	5	D	C	B	A	
11- Easy to recycle/reuse	4	Unknown	Unknown	Unknown	Unknown	Unknown
12- Eco-friendly	5	Unknown	Unknown	Unknown	Unknown	Unknown

Figure 4-5.The right column of HoQ to rate the benchmarks

HoQ identifies the relationship between customer needs, sustainable criteria and functional requirements. Also, general specifications of the benchmarks can be compared based on the CAs. However, HoQ is not enough to analyze and compare the details of benchmarks. For instance, in order to compare the environmental footprints, recyclability and maintainability of the benchmarks, their components should be evaluated, which is unknown at this stage of research. Hence, the design and decision matrices are formed in the next sections, to identify the quantitative sustainable metrics and analyzing the details of benchmarks' components.

4.4 Design matrix

The HoQ is used to transfer Customer needs into the proper functional requirements. The design matrix is formed to display the relationship between the DPs and FRs [50].

Figure 4-6 shows the design matrix of a wheelchair to identify the relationship between FRs and DPs. In order to accomplish the relationship of FRs and DPs, 1 and 0 are used, where 1 indicates that the design parameter satisfies the function and 0 means there is no link between FRs and DPs. For example, as shown in Figure 4-6, in order to rotate wheels automatically (DP.1), electrical energy is needed (FR.2). This rotational movement is provided by electrical motors (DP.2). The relationship of FR.2, DP.1 and DP.2 is determined by assigning value 1 in the related cells. Consequently, the score of FR.2 is 2. The final score for each function is determined by adding the values of each row. The last column of matrix determines the score of each FR.

Figure 4-6 indicates that the design matrix for wheelchairs is triangular. Based on the axiomatic design rules, the dependency axiom is not violated; consequently, the design is decoupled which means the design solution is achieved [50].

DPs / FRs	DP- 1	DP. 2	DP. 3	DP. 4	DP. 5	DP. 6	DP. 7	DP. 8	DP. 9	DP. 10	DP. 11	DP. 12	DP. 13	DP. 14	DP. 15	DP. 16	DP.17	SCORE
FR. 1	**1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
FR. 2	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**
FR. 3	**0**	**0**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
FR. 4	**0**	**0**	**0**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
FR. 5	**0**	**0**	**0**	**0**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	**1**
FR. 6	**0**	**0**	**0**	**0**	**0**	**1**	0	0	0	0	0	0	0	0	0	0	0	**1**
FR. 7	**0**	**0**	**0**	**0**	**0**	**0**	**1**	0	0	0	0	0	0	0	0	0	0	**1**
FR .8	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	0	0	0	0	0	0	0	0	0	**1**
FR. 9	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	0	0	0	0	0	0	0	0	**1**
FR.10	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	0	0	0	0	0	0	0	**1**
FR.11	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	0	0	0	0	0	0	**1**
FR.12	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	0	0	0	0	0	**2**
FR.13	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	0	0	0	0	**2**
FR.14	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	0	0	0	**2**
FR.15	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**1**	0	0	**3**
FR.16	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	0	**2**
FR.17	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**2**

Figure 4-6.Triangle design matrix for wheelchairs

4.5 Sustainable design priorities

FRs / score	1. Moving system	2. Operate electricity	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. Decline the pressure point	12. Reduce the weight	13. Long service time cycle	14. number of components	15. Reduce the cost	16. Ease of reusing, recycling	17.environmental
Relative weight based on HoQ (Figure 4-4)	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
Score based on design matrix (Figure 4-5)	1	2	1	1	1	1	1	1	1	1	1	2	2	2	3	2	2
Final weight factor	7.2	5.4	4	4	6.7	1.3	4	6.7	5.4	5.4	5.4	8	13	16	27	19	16
Importance rank	6	8	9	9	7	10	9	7	8	8	8	5	4	3	1	2	3

Figure 4-7. Decision matrix for wheelchair based on HoQ (Figure 4-4) and design matrix (Figure 4-5)

Design matrix shows how engineers can fulfill the required functions based on design elements. As shown in Figure 4-7, to make a link between house of quality and design matrix, the decision matrix is formed. In order to calculate the final weight factor of each functional requirement, the score of the design matrix is multiplied by a corresponded relative weight factor in the HoQ. For example, the relative weight factor of reducing cost in the HoQ is 9.1. This item adopts the value 3 from the design matrix. Consequently, the final weight factor of reducing cost is 9.9× 3= 27.3.

Results of the decision matrix with the final weight factor determine the most important sustainable metrics of a wheelchair. As shown in Figure 4-7, the design metrics are ranked based on their weight factors. Cost, environmental footprints, number of components, weight, service time, and ease of reusing, recycling, and remanufacturing are the most important parameters or sustainable design priorities in designing wheelchairs. These priorities are used in the next phase to compare the benchmarks and select the best components of the wheelchair.

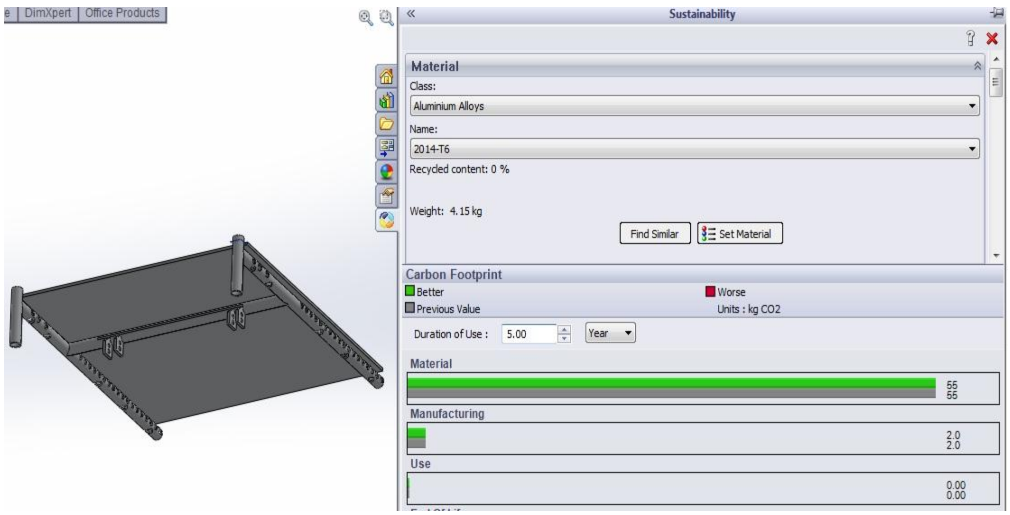
4.6 Details for design improvements

In this section, components and details of the four wheelchairs are analyzed and compared to find the best exchangeable components for sustainable design of wheelchairs. These data and details are used in the next step to improve the initial design.

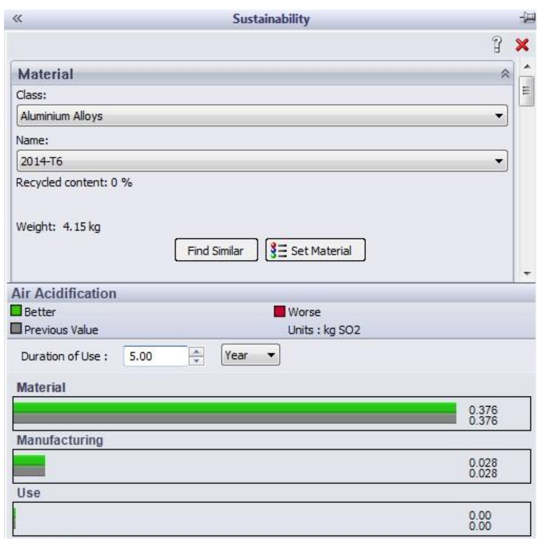
4.6.1 The sustainable metrics of four wheelchairs

The four wheelchairs are ranked in the HoQ in Section 4.3. However, the details of wheelchairs, such as environmental footprints, number of components, recyclability, maintainability, are not analyzed in the HoQ. As shown in Figures 4-13 to 4-16, in order to evaluate and compare the details of benchmarks, they are decomposed into their components. The specifications of each wheelchair, including the material, size, cost, number of components and service time, are obtained from the reference manuals [62, 63]. The selected wheelchairs are redesigned in SolidWorks 2013 to evaluate their weight and environmental footprints (Figures 4-13 to 4-16). The main materials used in the wheelchairs are steel, aluminum, Abs, composite, and rubber [62]. The Quickie S-525 and P-220 have fix back-rest; however, the Quickie Groove and Z Bop are equipped by reclining (tilt-able) back-rest. The Quickie Groove has manual reclining back rest and the Quickie Z Bop has the powered (automatic) reclining seat. While S-525 uses the solid tire in the front wheels, the other three wheelchairs have the pneumatic tire. The height of the arm rests and the position of leg-rests in S-525 and p-220 are adjustable while these components are fixed in the other two wheelchairs [62].

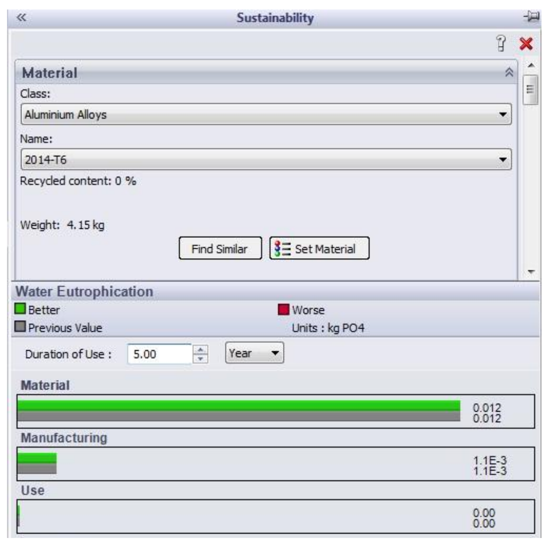
In order to calculate the weight and environmental footprints of each component, the selected wheelchairs are evaluated in SolidWorks2013. The SolidWorks Sustainability package enables designers to assess a wide range of environmental factors during the design procedure to reduce the environmental impacts of a product [64]. SolidWorks Sustainability package provides a tool to evaluate the life cycle assessment (LCA) of a product from cradle to grave [64]. The environmental footprints can be classified as a) air acidification, which is typically measured in unit of kg sulphur dioxide equivalent (SO_2), b) Carbon footprint, which is measured in unit of kg carbon dioxide equivalent (CO_2), c) Water emission, which is measured in unit of kg phosphate equivalent (PO_4) [14, 64]. SolidWorks2013 Sustainability can determine the air acidification, carbon footprint, and water emission of a product based on the extracting and processing of the material, manufacturing process, transportation and the end of life cycle. In order to evaluate the environmental footprint of components, the material type and duration of use (life cycle time) should be set. There is an option for the manufacturing process to evaluate the environmental footprint of manufacturing of the product. Also, the duration of using the component should be set [64]. As this research focuses on the design stage, the environmental foot print is calculated based on the material, product geometry, and life cycle time.



a) Carbon footprints



b) Air acidification



c) Water emission

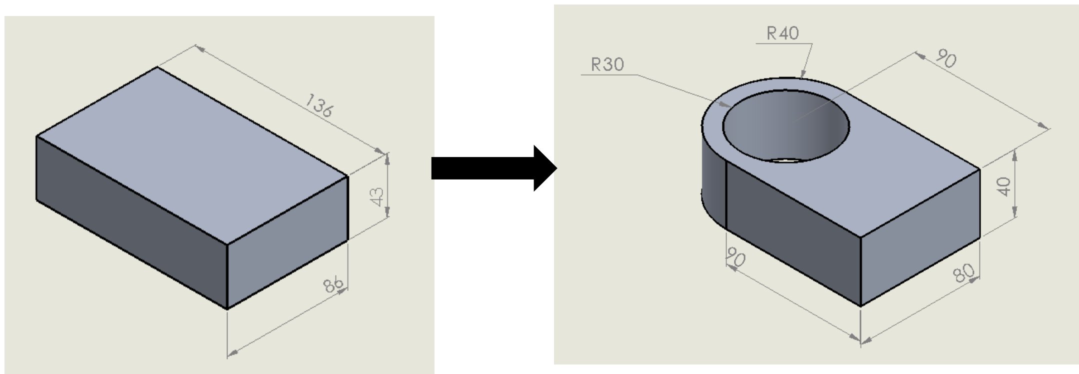
Figure 4-8. Environmental footprints of the seat frame

For example, as shown in Figure 4-8, the seat frame of Quickie S-525 is evaluated in SolidWorks 2013 to find the weight and environmental footprints. Aluminum T6 is used as the material [63], and the duration of use is set for 5 years [65]. As shown in Figure 4-8, 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, derived from the SolidWorks sustainability assessment (Figure 4-8):

Total environmental footprint of 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 calculation shows the main environmental footprint belongs to the carbon footprint, which is the main factor in the global warming. The same evaluation is done for all components of the four wheelchairs.

The sale price of each component of the four wheelchairs is provided by the Quickie manufacturer. Sale price contains many factors such as price of raw materials, manufacturing processes, labour cost, assembly, packing, distribution and profit of the manufacturer. This research just focuses on the design stage. Cost of raw materials and manufacturing process are evaluated in this research and other expenses are considered as the rest cost of making the product. It is assumed that all components are provided and manufactured by the same manufacturer. The parameters and standards of manufacturing processes are considered consistently for all components. The price of raw materials is evaluated based on the webpage of Online Metal Company [66]. Also, SolidWorks2013 has a useful tool to evaluate manufacturing cost [67]. The head rest gripper of wheelchair Q-S525 is considered as an example to evaluate the costs of raw materials and manufacturing processes.



a) Raw material (stock body)

b) Final product

Figure 4-9. 3D view of the raw material and final shape of the head rest gripper

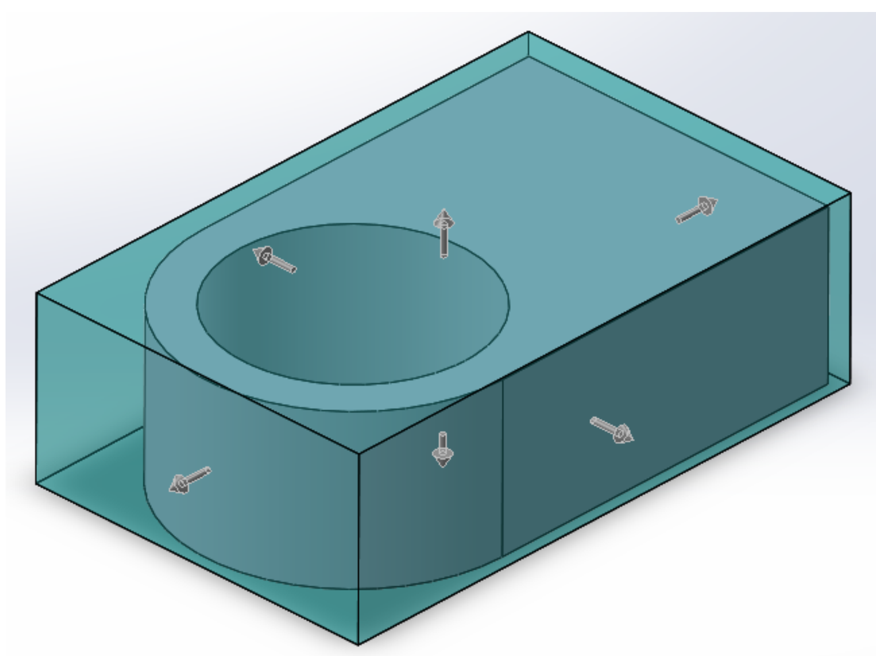
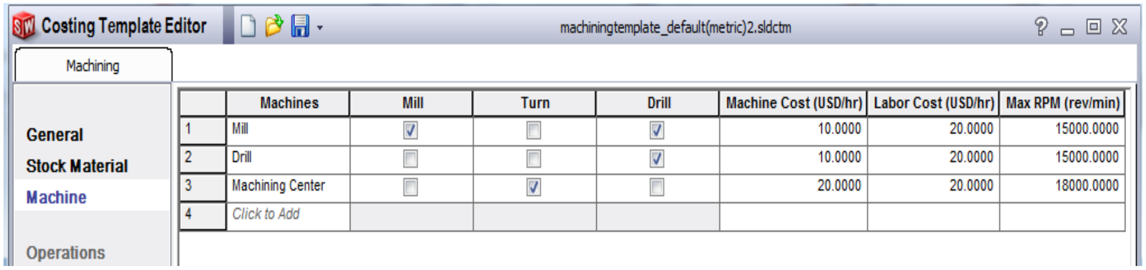


Figure 4-10. Milling process for top and side surfaces, drilling for hole of the gripper

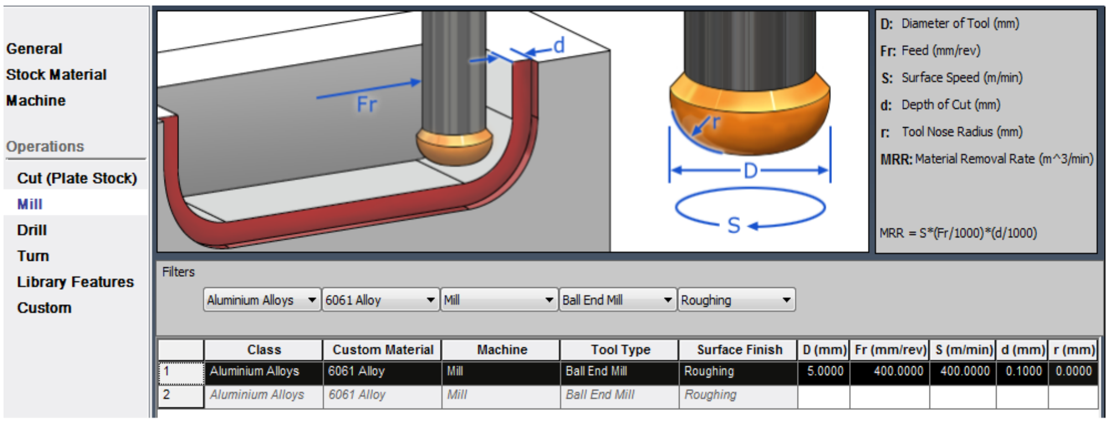
Figure 4-9 shows 3D views of the raw material and final shape of the head rest gripper. As shown in Figure 4-10, two manufacturing operations are needed to make the head rest gripper: a) milling process for top and side surfaces, and b) drilling for hole of the gripper. The material removal rate (MRR) for each manufacturing process is calculated from the following equation [67, 68]:

$$MRR = S \times (Fr/1000) \times (d/1000)$$

Where S is surface speed (m/min), Fr is feed rate (mm/rev) and d is depth of the cut (mm). As shown in Figure 4-11, manufacturing parameters are selected in SolidWorks2013 for milling and drilling processes based on ISO metric standard [67]. Figure 4-11 shows the labour cost and (set up) machine cost, which are 10 USD/hr and 20 USD/hr, respectively [67]. The material of the gripper is Al 6061 T6. As shown in Figure 4-12, the price of the raw material is evaluated as 13.71 USD by SolidWorks. As shown in Figure 4-12, the milling cost of top and lateral surfaces is 4.47 USD, and cost of drilling operation is 7.54 USD based on the selected parameters of milling and drilling processes. The set up cost (time that is spent by the labour to set up the fixture, calculating tool offsets, and performing all the necessary tasks to produce the part) for all milling and drilling operations is 15 USD [67]. The total cost of 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. The sale price of this component is 116.87 [62]. The rest cost is 116.87 - 40.72 = 76.15 USD. The rest cost represents the cost of assembling, packing, distributing and profit of the company. The same evaluation is conducted for all components of the four wheelchairs.



a) The setup cost and labour cost of different manufacturing processes



b) Milling parameters based on the raw material and milling tool selection

Figure 4-11. Manufacturing parameters selection based on ISO metric standard in SolisWorks2013 [67]

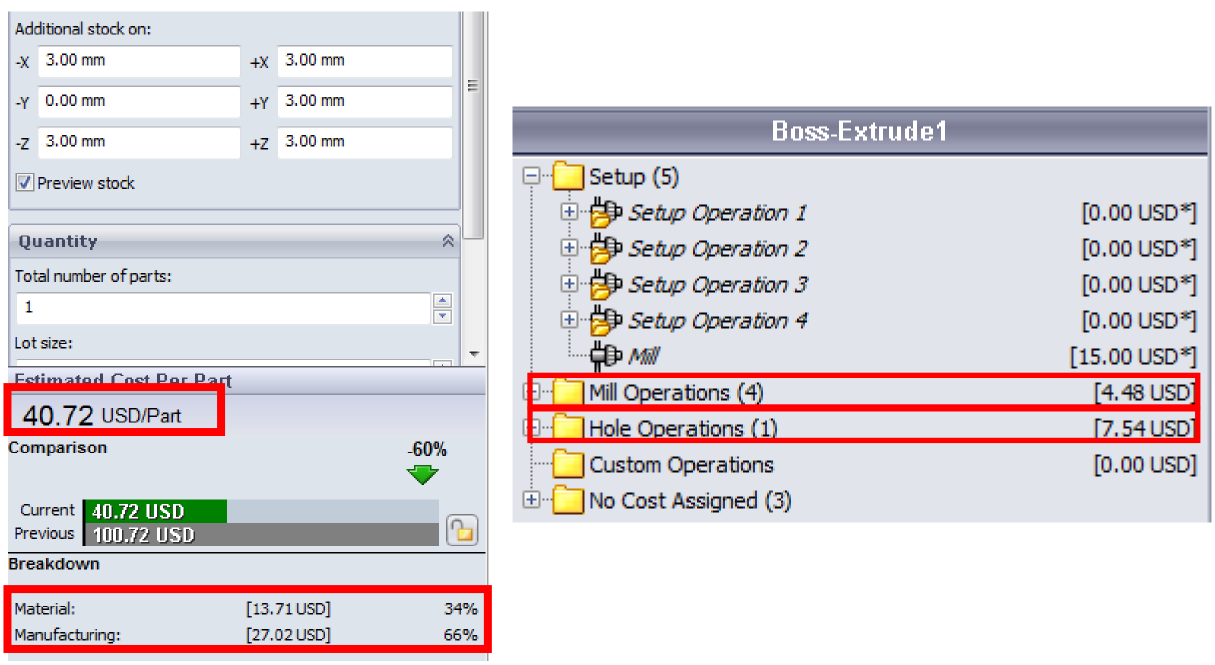


Figure 4-12. Evaluation of the raw material, milling and drilling costs in SolidWorks2013

The exploded views and specifications of each wheelchair, including the sale price, cost of making component (raw material and manufacturing costs), material, number of components, service time, weight, and total environmental footprint, are represented in Figures 4-13 to 4-16 and Table 4-2 to 4-5.

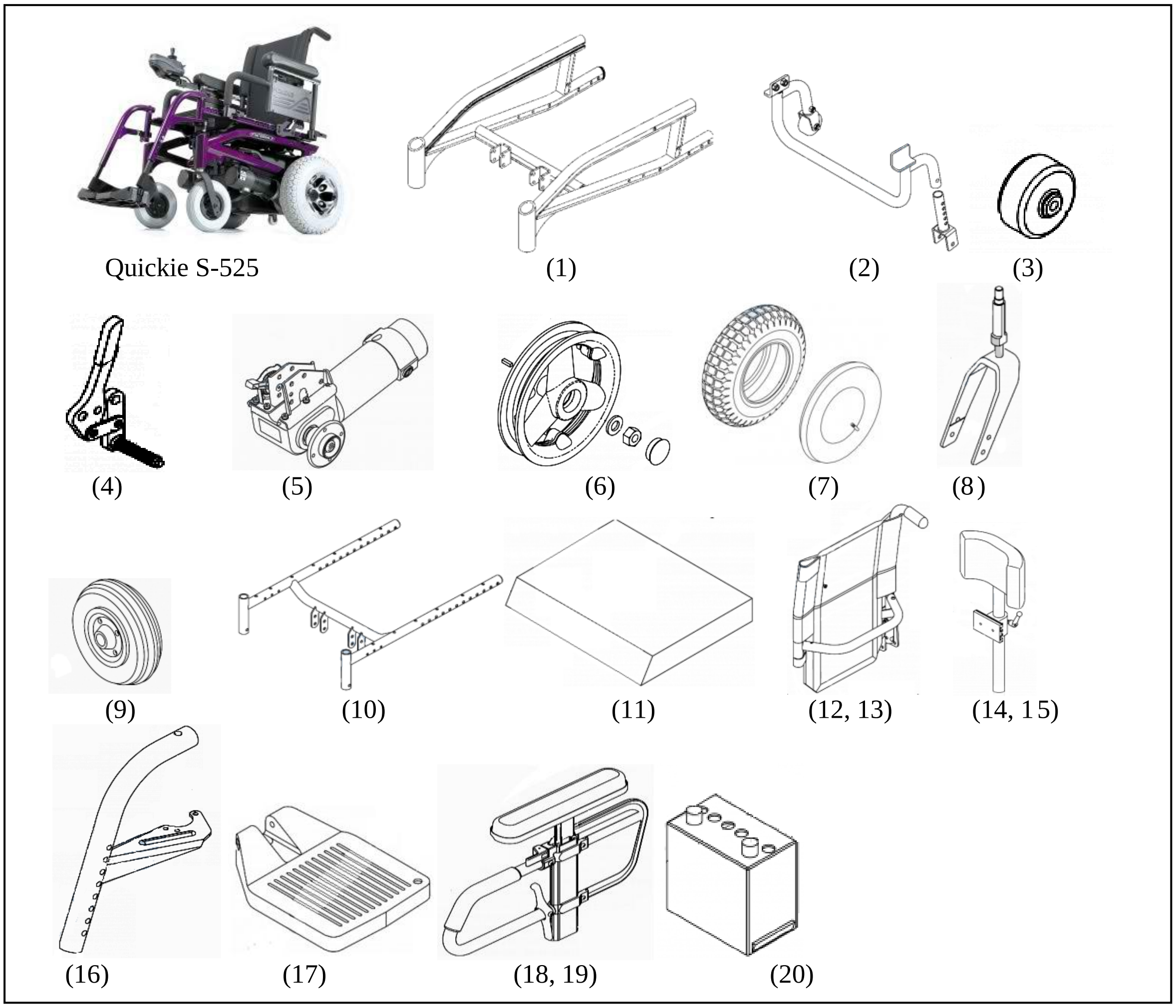


Figure 4-13.Exploded view of the Quickie S- 525

Table 4-2. The specifications of the Quickie S-525 wheelchair

#	A: Quickie S-525	Sale price (USD)	Making Cost (USD)			Material	Number of component	Service time (year)	Weight (Kg)	Environmental footprint (Kg)
			Raw material	Manufacturing	Rest					
1	Base Frame	1179	168.51	222.26	788	Al T6 6061	18	1	5.2	57.2
2	Anti-tip structure	85	13.2	21.6	50.2	Chromoly	12	1/4	2.3	5.2
3	Anti-tip wheel	12	2.16	4.02	5.82	ABS	1	1/12	1.15	3
4	Manual Wheel lock	44.13	4.8	11.28	28	St4031	9	1/4	0.1	0.17
5	Motor package	983	178	381.3	423	Al, Cu, St	9	1/4	6.8	1.36
6	Drive wheel rim	84	39.2	24.52	20.3	Al T6 6061	4	1/12	4.3	45.15
7	Drive wheel pneumatic tire & tube	54.8	14.47	20.55	19.7	rubber	4	1/12	6.47	2.11
8	Front fork& caster	95	14.57	23.25	57.2	Al T6 6061, ABS	9	1/4	0.56	5.88
9	Tire	40	13.02	15.1	11.8	Fo, Ru, Kevlar	3	1/12	5.82	11.04
10	Fixed seat frame	1088	145.4	214.6	728	Al	17	1	4.27	44.83
11	Seat cushion	101	12.62	16.83	71.5	Foam, Fabric	2	1	0.14	0.67
12	Non folding back rest frame	231	35	46.2	149	Al, St, ABS	18	1	0.9	10.35
13	Back rest cushion	98	12.2	16.3	69.5	Foam, fabric	1	1	0.14	0.19
14	Head rest-structure	320	20.7	61.37	238	St 4031	15	1/4	0.8	2
15	Headrest-pad	45	5.6	7.64	31.7	Foam, fabric	1	1	0.05	0.065
16	Swing away hanger	266	33.25	53.2	179	Al T6 6061	20	1/4	0.4	4.4
17	footrest	77	17.4	12.7	47	Composite	12	1/4	0.75	8.7
18	Adjustable Armrest structure	197	28.14	38.82	130	Al T6 6061	13	1/4	0.74	8.14
19	Armrest pad	22.5	2.8	3.82	16	Foam, Fabric	1	1	0.025	0.035
20	Battery	75	9.47	15.98	50	Lead, sulfuric acid, ABS	12	1	10.48	13.3
	Total	5097	770.51	1211.34	3115	N/A	181	N/A	35.84	156.86
			1981.85							

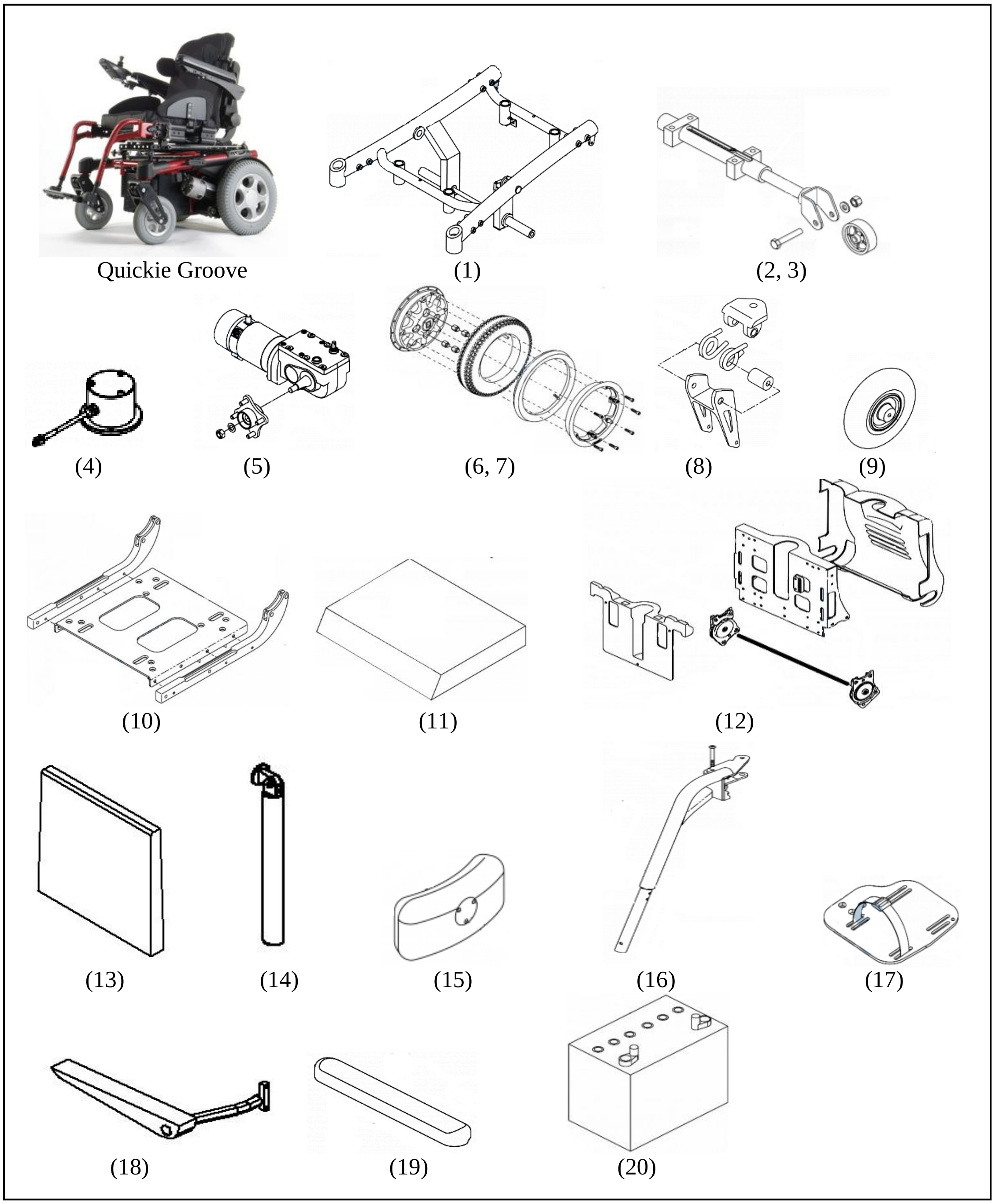


Figure 4-14. Exploded view of the Groove wheelchair

Table 4-3. The specifications of the Quickie Groove wheelchair

#	Quickie Groove	Sale price (USD)	Making cost (USD)			Material	Number of component	Service time (year)	Weight (Kg)	Environmental footprint (Kg)
			Raw material	Manufacturing	Rest					
1	Base Frame	1378	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	1174	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	Caster & tire	50	13.25	18.7	18.	Rubber & 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	St chromoly	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 (Q-Groove)		6304	1014.18	1511.69	3768		188		54.91	204.418
			2525.87							

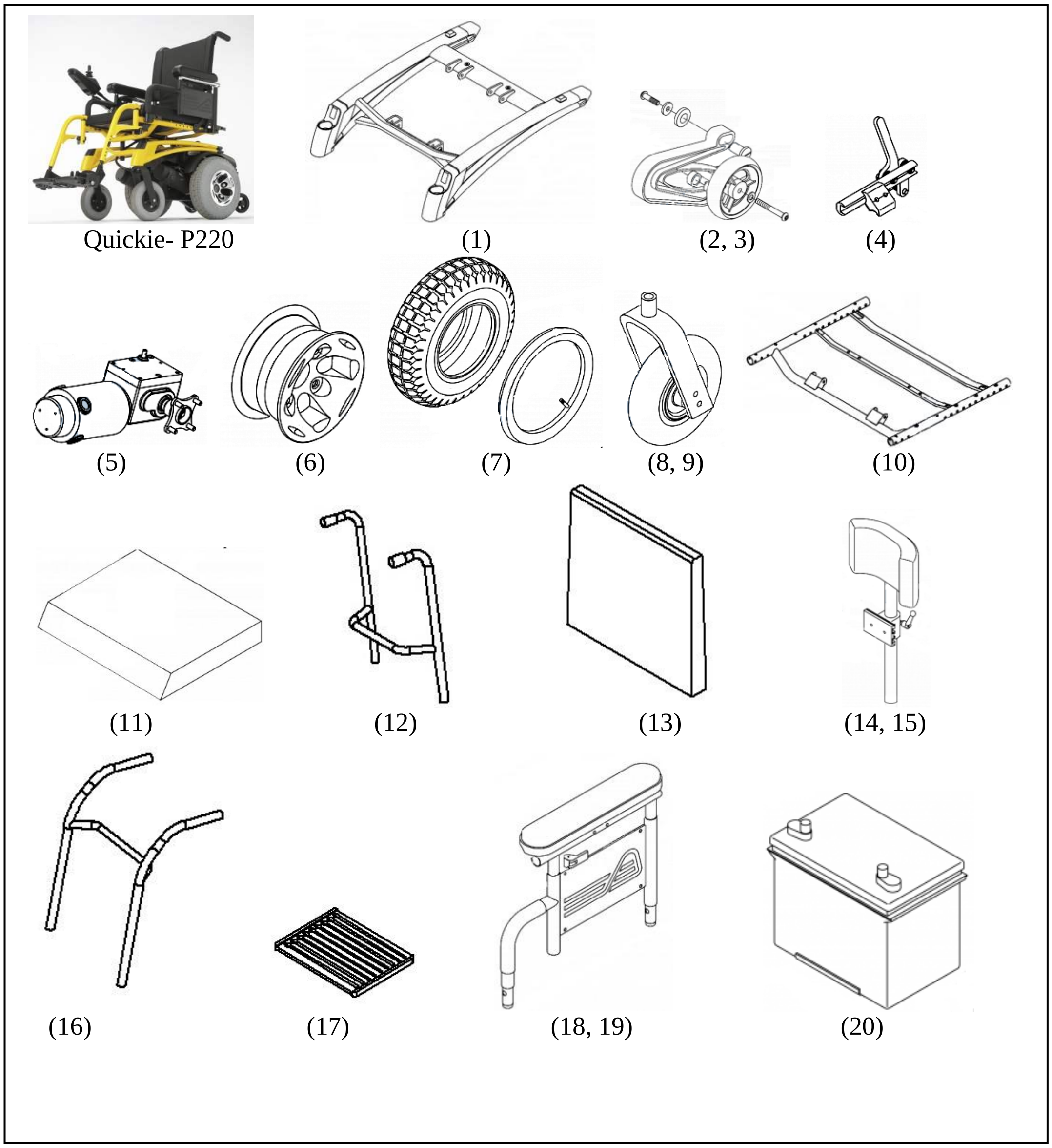


Figure 4-15. The exploded view of Quickie- P220 wheelchair

Table 4-4. The specifications of Quickie- P220 Wheelchair

#	Quickie P220	Sale price (USD)	Making cost (USD)			Material	Number of component	Service time (year)	Weight (Kg)	Environmental footprint(Kg)
			Raw material	Manufacturing	Rest					
1	Base Frame	1673	281.43	244.54	1147	Aluminum, ABS	13	1	8.86	96.8
2	Anti-tip structure	62.2	3.93	16.62	41.65	St	9	1/4	0.57	6.3
3	Anti-tip wheel	23	4.93	7.89	10.18	Plastic PUR	1	1/4	3.45	7.2
4	Manual Wheel lock	65	6.23	16.62	42.15	Steel choromoly	15	1/4	0.14	0.28
5	Motor package	1180	183.23	460.11	536.6	Al, Cu, St	23	1/4	7	1.54
6	Drive wheel - rim	108.45	47.95	30.98	29.52	Al T6 6061	6	1/12	5.26	60.49
7	Drive wheel tire & tube	46.95	12.4	17.62	16.93	Rubber	2	1/12	6.45	2.02
8	Front fork structure	76.11	8.94	16.03	51.14	Al T6 6061	13	1/4	0.3	3.45
9	Caster & tire	95	14.7	35.62	44.68	Rubber & plastic	1	1/12	6.58	11.4
10	Seat frame	1306	185.71	261.2	859.1	St 4031	32	1	3.6	41.4
11	Cushion	100.98	12.6	16.8	71.58	Foam, fabric	2	1	0.15	0.72
12	back rest	622	77.85	124.4	419.7	Al T6, ABS	9	1	3.97	20.77
13	Back rest cushion	150	18.7	25	106.3	Foam, fabric	1	1	0.17	0.336
14	Head rest-structure	405	66.08	76.41	262.5	St 4031	15	1/4	0.4	5.1
15	Headrest-pad	45	5.6	7.64	31.76	Foam, fabric	1	1	0.05	0.065
16	Swing – away fixed	420	51.5	84.08	284.4	Al T6 6061	11	1	1.96	6.44
17	Footrest	49	6.1	10.1	32.8	Plastic ABS, St	8	1/4	1.38	1.3
18	Dual post height adjustable Armrest	211.5	35.14	52.2	139.1	Al T6 6061	6	1/4	0.97	11.15
19	Armrest pad	22.5	2.8	3.82	15.88	Foam, fabric	1	1	0.025	0.035
20	Battery	135	16.8	28.68	89.52	Lead, sulfuric acid	12	3	14.3	14.01
Total (Q-P220)		6796.7	1042.6	1536.36	4232		181		45.56	178.68
			2578.98							

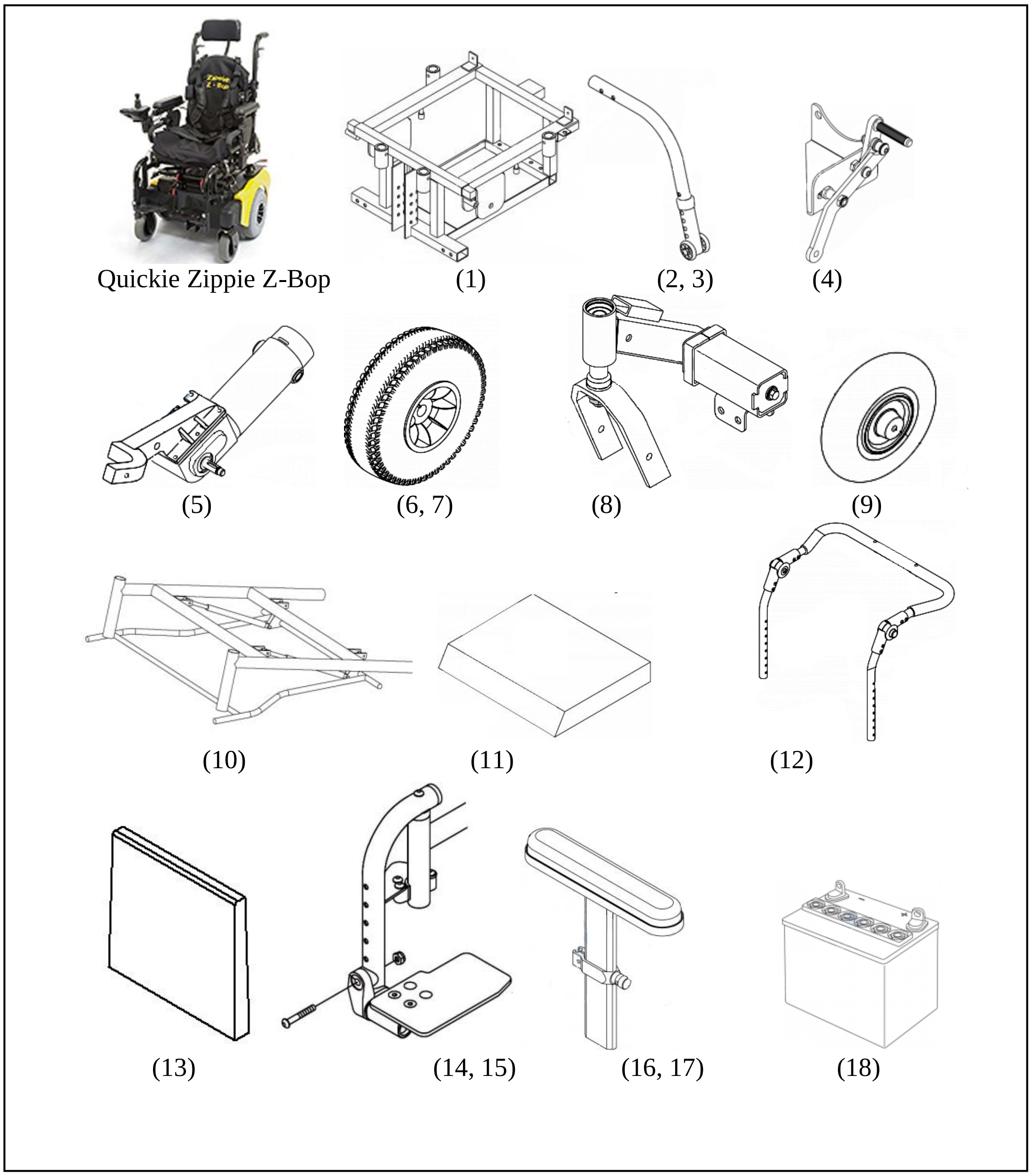


Figure 4-16. The Exploded view of Quickie Zippie Z Bop

Table 4-5. The specifications of Quickie Zippie Z Bop wheelchair

#	Quickie Zippie Z Bop	Cost (USD)	Making cost (USD)			Material	Number of component	Service time (year)	Weight (Kg)	Environmental footprint(Kg)
			Raw Material	Manufacturing	Rest					
1	Base frame	1667	318.6	240.93	1107	Al T6 6061	16	1	8.27	90.97
2	Anti-tip structure	46	3.07	12.56	30.37	St 4031	4	1/4	0.51	5.5
3	Anti-tip wheel	10	2.14	3.42	4.44	ABS	1	1/4	0.014	0.05
4	Manual Wheel lock	95	10.56	24.29	60.15	St-chromoly	3	1/4	0.19	0.38
5	Motor package	1350	209.41	524.72	615.8	Al, Cu, St	21	1/4	8	1.85
6	Drive wheel-rim	64	30.08	18.36	15.56	Al T6 6061	4	1/12	3.3	34.65
7	Drive wheel tire & tube	44.8	11.88	16.87	16.05	Rubber	4	1/12	6.47	2.11
8	Front fork structure	298	42.56	61.6	193.8	Al, PUR	9	1/4	1.62	18
9	Caster & tire solid tire	50	13.25	18.7	18.05	Rubber & Abs	1	1/12	0.88	10.2
10	Power seat frame	1820.25	227.8	364.05	1228	Al, St	63	1	9.32	107.18
11	Seat cushion	213	24.6	35.4	153	Foam, Fabric	2	1	0.16	0.76
12	Back rest	373	49.23	74.6	249.2	Al	26	1	2.71	31.16
13	Back rest cushion	213	24.6	35.4	153	Foam, fabric	1	1	0.16	0.38
14	Swing–away	410	47.26	80.94	281.8	Al T6 6061	17	1/4	1.7	8
15	Footrest	77	17.4	12.7	46.9	Composite	12	1/4	0.75	8.7
16	Arm rest	107.5	15.27	21.73	70.5	Al T6 6061	12	1	0.3	3.35
17	Armrest pad 10”	22.5	2.8	3.82	15.88	Foam	1	1	0.025	0.035
18	Battery	162.7	20.33	34.57	107.8	Lead, sulfuric acid, ABS	12	3	20	29.77
Total (Q-ZBop)		7003.7	1070.8	1584.66	4368		206		51.28	279.08
			2655.5							

After identifying the specifications of these wheelchairs, their components are compared based on the metrics and weight factors, derived from the decision matrix shown in Figure 4-7. For example, as shown in Table 4-6, the amount of cost, the number of components, weight, service time, and environmental footprints of the four frames are multiplied by their relative weight factors. The result shows that frame A-1 has the lowest price, the number of components, weight, and environmental footprint and the highest service time. The same evaluation is conducted for the rest components to find the lowest price, number of components, weight and environmental footprint, and the longest service time. The last column of Table 4-6 shows the selected component based on the sustainable metrics derived from the decision matrix.

Table 4-6. The comparison of wheelchairs components to select the best sustainable parts

Metrics		Cost (USD)	Number of components	Weight (Kg)	service time (year)	Environmental footprint (kg)	Sum	result
Weight factor / Component		29.7	17.4	13.2	1/ 14.4	26		
A- Frame	A-1 (S 525)	1179 × 29.7	18× 17.4	1.2 × 13.2	1/ (1× 14.4)	13.8 × 26	35691	A-1
	A-2 (Groove)	1378.25 × 29.7	14× 17.4	2.09 × 13.2	1/ (1× 14.4)	21.45 × 26	41742	
	A-3 (P220)	1673 × 29.7	13× 17.4	1.86 × 13.2	1/ (1× 14.4)	15.7 × 26	50346	
	A-4 (Z Bop)	1667 × 29.7	16× 17.4	2.27 × 13.2	1/ (1× 14.4)	17.02 × 26	50260	
B- Anti-tip	B-1 (S 525)	197 × 29.7	13 × 17.4	2.45 × 13.2	1/ (1/12 × 14.4)	8.2 × 26	6249	B-4
	B-2 (Groove)	115 × 29.7	7× 17.4	0.84 × 13.2	1/ (¼ × 14.4)	9.5 × 26	3797	
	B-3 (P220)	112.2 × 29.7	10× 17.4	0.67 × 13.2	1/ (¼ × 14.4)	7.5 × 26	3711	
	B-4 (Z Bop)	56 × 29.7	5 × 17.4	0.52 × 13.2	1/ (¼ × 14.4)	5.5 × 26	1901	
C-Wheel lock	C-1 (S 525)	44.13 × 29.7	9 × 17.4	0.08 × 13.2	1/ (¼ × 14.4)	0.17 × 26	1474	C-1
	C-2 (Groove)	502 × 29.7	4 × 17.4	0.63 × 13.2	1 (1/12 × 14.4)	1 × 26	15014	
	C-3 (P220)	65 × 29.7	15 × 17.4	0.14 × 13.2	1/ (¼ × 14.4)	0.28 × 26	2202	
	C-4 (Z Bop)	95 × 29.7	3 × 17.4	0.19 × 13.2	1/ (¼ × 14.4)	0.38 × 26	2887	

D-Motor	D-1 (S 525)	983 × 29.7	9 × 17.4	6.8 × 13.2	1/ (¼ × 14.4	1.36 × 26	29477	D-1
	D-2 (Groove)	1204 × 29.7	14 × 17.4	7.5 × 13.2	1/ (¼ × 14.4	1.77 × 26	36148	
	D-3 (P220)	1180 × 29.7	23 × 17.4	7 × 13.2	1/ (¼ × 14.4	1.54 × 26	35579	
	D-4 (Z Bop)	1350 × 29.7	21 × 17.4	8 × 13.2	1/ (¼ × 14.4	1.85 × 26	40615	
E-Drive wheel	E-1 (S 525)	138.8 × 29.7	8 × 17.4	4.77 × 13.2	1 (1/12 × 14.4	47.26 × 26	5554	E-4
	E-2 (Groove)	150 × 29.7	7 × 17.4	5.11 × 13.2	1 (1/12 × 14.4	55.47 × 26	6087	
	E-3 (P220)	155.4 × 29.7	8 × 17.4	5.71 × 13.2	1 (1/12 × 14.4	62.51 × 26	6456	
	E-4 (Z Bop)	108.8 × 29.7	8 × 17.4	3.77 × 13.2	1 (1/12 × 14.4	36.76 × 26	4376	
F-caster & front wheel	F-1 (S 525)	135 × 29.7	12 × 17.4	1.38 × 13.2	1 (1/12 × 14.4	16.92 × 26	4676	F-1
	F-2 (Groove)	336 × 29.7	16 × 17.4	1.62 × 13.2	1 (1/12 × 14.4	18.71 × 26	10766	
	F-3 (P220)	171.11 × 29.7	14 × 17.4	1.88 × 13.2	1 (1/12 × 14.4	14.85 × 26	5737	
	F-4 (Z Bop)	348 × 29.7	10 × 17.4	2.5 × 13.2	1 (1/12 × 14.4	28.2 × 26	11276	
G- Seat	G-1 (S 525)	1188.98× 29.7	19 × 17.4	4.41 × 13.2	1/ (1× 14.4)	45.5 × 26	36884	G-2
	G-2 (Groove)	845.98 × 29.7	29 × 17.4	3.78 × 13.2	1/ (1× 14.4)	38.12 × 26	26671	
	G-3 (P220)	1406.9 × 29.78	34 × 17.4	3.75 × 13.2	1/ (1× 14.4)	42.12 × 26	43633	
	G-4 (Z Bop)	2033.25 × 29.7	65 × 17.4	9.46 × 13.2	1/ (1× 14.4)	107.94 × 26	64450	
H-Back-rest	H-1 (S 525)	329 × 29.7	19 × 17.4	0.94 × 13.2	1/ (1× 14.4)	10.54 × 26	10388	H-1
	H-2 (Groove)	532 × 29.7	16 × 17.4	4.19 × 13.2	1/ (1/4 × 14.4)	43.59 × 26	17267	
	H-3 (P220)	772 × 29.7	10 × 17.4	4 × 13.2	1/ (1× 14.4)	21.1 × 26	23703	
	H-4 (Z Bop)	586 × 29.7	27 × 17.4	2.8 × 13.2	1/ (1× 14.4)	31.54 × 26	18731	
I-Headrest	I-1 (S 525)	465 × 29.7	16 × 17.4	0.8 × 13.2	1/ (1/4 × 14.4)	2.04 × 26	14152	I-2
	I-2 (Groove)	345 × 29.7	15 × 17.4	0.24 × 13.2	1/ (1/4 × 14.4)	0.32 × 26	10518	
	I-3 (P220)	425 × 29.7	16 × 17.4	0.4 × 13.2	1/ (1/4 × 14.4)	5.14 × 26	13040	
	I-4 (Z Bop)	N/A	N/A	N/A	N/A	N/A	N/A	
J-Swing-away	J-1 (S 525)	266 × 29.7	20 × 17.4	0.4 × 13.2	1/ (1/4 × 14.4)	4.48 × 26	8370	J-1
	J-2 (Groove)	314 × 29.7	13 × 17.4	0.46 × 13.2	1/ (1/4 × 14.4)	5.29 × 26	9695	
	J-3 (P220)	410 × 29.7	11 × 17.4	0.56 × 13.2	1/ (1 × 14.4)	6.44 × 26	12543	
	J-4 (Z Bop)	420 × 29.7	17 × 17.4	0.7 × 13.2	1/ (1/4 × 14.4)	8 × 26	12987	

K-Foot-rest	K-1 (S 525)	77 × 29.7	12 × 17.4	0.75 × 13.2	1/ (1/4 × 14.4)	8.7 × 26	2731	K-3
	K-2 (Groove)	121.97 × 29.7	15 × 17.4	1.35 × 13.2	1/ (1/4 × 14.4)	15.5 × 26	4304	
	K-3 (P220)	49 × 29.7	8 × 17.4	0.38 × 13.2	1/ (1/4 × 14.4)	1.3 × 26	1633	
	K-4 (Z Bop)	57 × 29.7	9 × 17.4	0.75 × 13.2	1/ (1/4 × 14.4)	8.7 × 26	2085	
L-Armrest	K-1 (S 525)	219.83 × 29.7	14 × 17.4	0.74 × 13.2	1/ (1/4 × 14.4)	8.17 × 26	6994	L-4
	K-2 (Groove)	487.5 × 29.7	26 × 17.4	0.97 × 13.2	1/ (1/4 × 14.4)	11.17 × 26	15234	
	K-3 (P220)	234 × 29.7	7 × 17.4	0.6 × 13.2	1/ (1/4 × 14.4)	6.8 × 26	7256	
	K-4 (Z Bop)	130 × 29.7	13 × 17.4	0.3 × 13.2	1/ (1 × 14.4)	3.37 × 26	4178	
M- Battery	M-1 (S 525)	175 × 29.7	12 × 17.4	10.5 × 13.2	1/ (1× 14.4)	13.3 × 26	5647	M-3
	M-2 (Groove)	139 × 29.7	12 × 17.4	17.01 × 13.2	1/ (4 × 14.4)	18.41 × 26	4892	
	M-3 (P220)	135 × 29.7	12 × 17.4	14.3 × 13.2	1/ (3 × 14.4)	14 × 26	4660	
	M-4 (Z Bop)	162.7 × 29.7	12 × 17.4	20 × 13.2	1/ (3 × 14.4)	29.7 × 26	5914	

In the next section, an ideal sustainable wheelchair is designed based on the results of comparing of the benchmarks. Its specifications (cost, weight, number of components and environmental footprints) are compared to the benchmark products.

4.6.2 An ideal wheelchair based on the benchmarking

An ideal wheelchair is designed based on the selected parts from the benchmarking analysis of the four wheelchairs. Figure 4-17 shows the 3D drawing of the improved sustainable wheelchair. Specifications of the ideal wheelchair (based on the results of Table 4-6) are presented in Table 4-7.

Figure 4–17. The ideal sustainable wheelchair

Table 4-7. Specifications of the ideal wheelchair based on results of Table 4-6

Ideal wheelchair	Cost (USD)	Making cost (USD)			Material	Number of component	Service time (year)	Weight (kg)	Environmental footprint (kg)
		Raw material	Manufacturing	Rest					
1- Base Frame	1179	168.51	222.26	788	Al T6 6061	18	1	5.2	57.2
2-Anti-tip structure	46	3.07	12.56	30.37	St 4031	4	1/4	0.51	5.5
3-Anti-tip solid wheel	10	2.14	3.42	4.44	ABS	1	1/4	0.014	0.05
4- Wheel lock	44.13	4.8	11.28	28	St 4031	9	1/4	0.1	0.17
5-Motor package	983	178	381.3	423	Al, Cu, St	9	1/4	6.8	1.36
6- Drive wheel rim	64	30.08	18.36	15.56	Al T6 6061	4	1/12	3.3	34.65
7- Drive wheel tire & tube	44.8	11.88	16.87	16.05	Rubber	4	1/12	6.47	2.11
8- Front fork & caster	95	14.57	23.25	57.2	Al, ABS	9	1/4	0.56	5.88
9- solid tire	40	13.02	15.1	11.8	Fo, Ru, Kevlar	3	1/12	5.82	11.04
10-Seat frame	745	106.42	151	487	Al T6 6061	27	1	3.63	37.7
11- Seat cushion	100.9	12.6	16.8	71.5	Foam, FABRIC	2	1	0.15	0.72
12-Non folding back rest frame	231	35	46.2	149	Al, St, ABS	18	1	0.9	10.35
13-Back rest cushion	98	12.2	16.3	69.5	Foam, Fabric	1	1	0.14	0.19
14-Head rest-structure	200	27.5	43.1	129	St 4031	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 hanger	266	33.25	53.2	179	Al T6 6061	20	1/4	0.4	4.4
17- Footrest	49	6.1	10.1	32.8	Plastic ABS, St	8	1/4	1.38	1.3
18- Non-adjustable arm rest	107.5	15.27	21.73	70.5	Al T6 6061	12	1	0.3	3.35
19- Armrest pad	22.5	2.8	3.82	15.88	Foam, FABRIC	1	1	0.025	0.035
20- Battery	135	16.8	28.68	89.52	Lead, sulfuric acid,	12	3	14.3	14.01
Total	4370.83	699.61	1102.97	2568		177		37.5	126.07
		1802.58							

The total cost, number of components, total weight, and total environmental footprints of the four benchmarks and the ideal wheelchair are summarized in Table 4-8. Figures 4-18 to 4-21 show the specification of the wheelchairs using bar charts.

As shown in Figures 4-18 to 4-21, the wheelchair S-525 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 ideal wheelchair is 13.08 percent lower than that of S-525. The second sustainable factor is the environmental footprint where there is 18.55 percent reduction. Also, the weight and number of components of the new wheelchair decrease by 4.5 and 2.2 percentages, respectively.

Table 4-8. Specifications of the benchmarks and ideal wheelchair based on Tables 4-2 to 4-7

Metrics / Item	Sale price (USD)	Making Cost (USD)			Number of components	Weight (Kg)	Environmental footprint (Kg)
		Raw material	Manufacturing	Rest			
Wheelchair A: Q- S525	5097	770.51	1211.34	3115	179	35.84	156.86
		1981.85					
Wheelchair B: Q- Groove	6440.7	1014.18	1511.69	3914	188	54.91	204.41
		2525.87					
Wheelchair C: Q- P220	6923.7	1042.6	1536.36	4232	178	45.56	1778
		2578.98					
Wheelchair D: Q- Zippie Zbop	7003.7	1070.8	1584.66	4368	206	51.28	279.08
		2655.5					
Ideal sustainable wheelchair	4370.8	699.61	1102.97	2568	177	37.55	126.07
		1802.58					

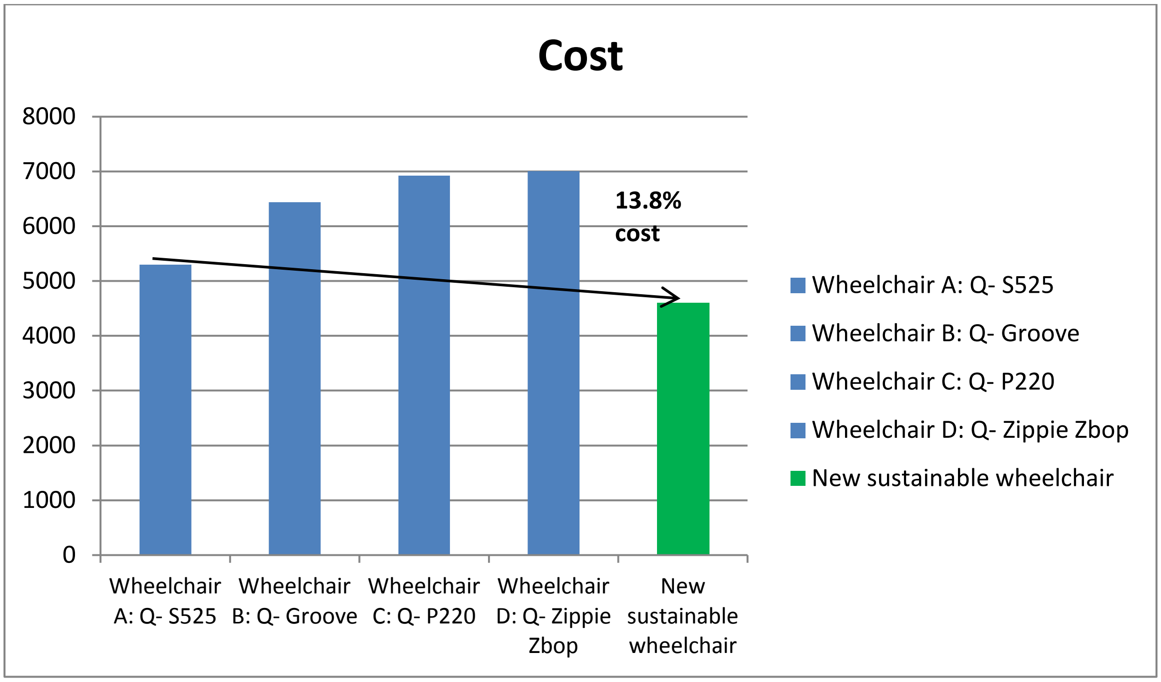


Figure 4-18. Cost comparison

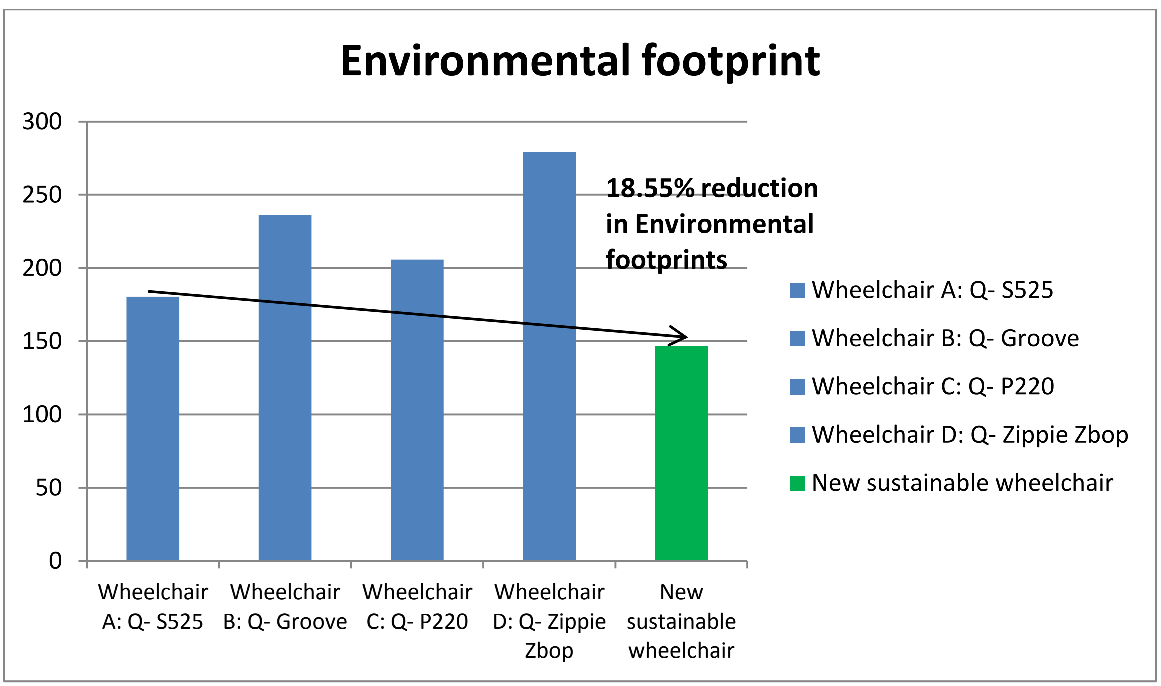


Figure 4-19. Environmental footprints

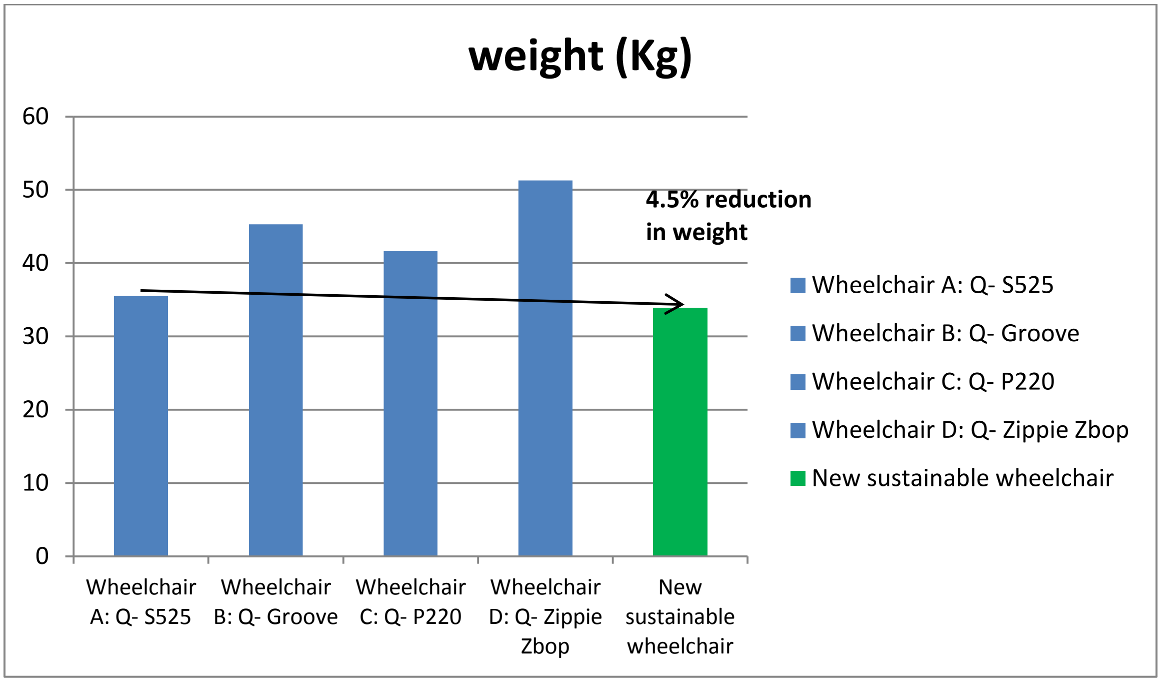


Figure 4-20. Weight comparison

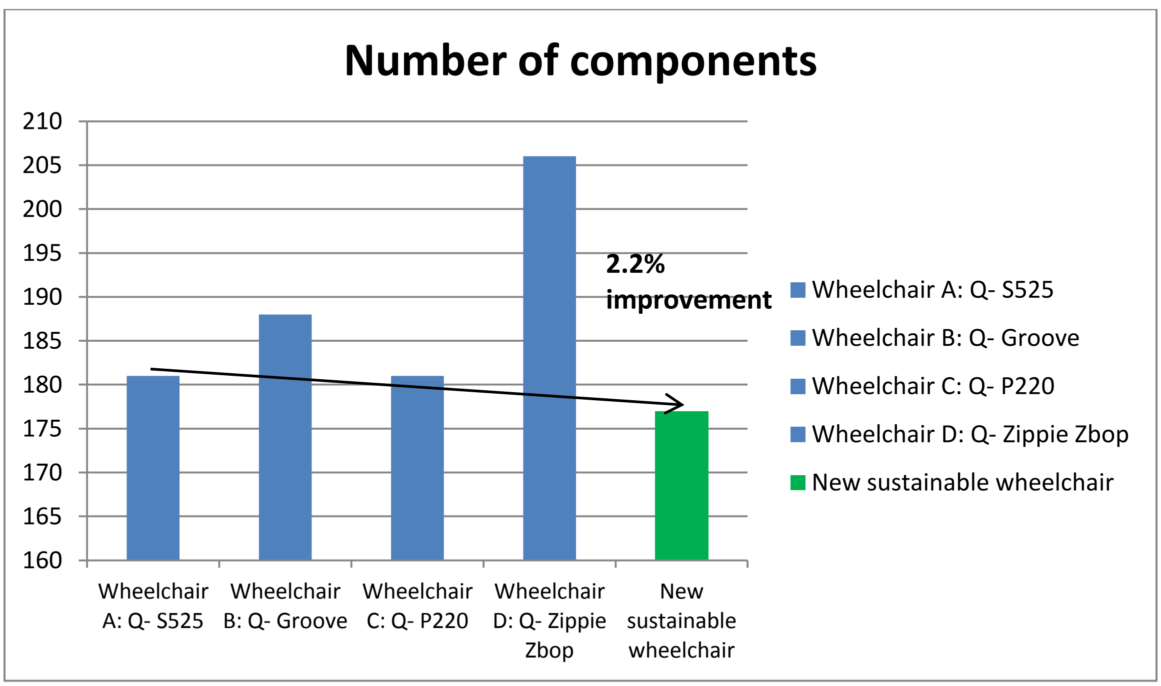


Figure 4-21. Number of components

The comparing result of the four wheelchairs and the ideal wheelchair reveals that there is a link between cost, number of components, environmental footprint, and weight for a sustainable design. As weight, material, and number of components decrease, the environmental footprints and cost of the final product improve. In addition, the result of this research is in accordance with the research done by Gilchrist et al. [49]. Gilchrist et al. reveal that "the complexity and more functions can raise more number of components and materials, resulting in a larger environmental impact". The design complexity and the number of components to satisfy each desired function have direct effects on the cost and environmental footprint. For example, the main function of back-rest in wheelchairs is to support the weight of the back body. As mentioned in Section 4.6.1, all wheelchairs except Q-Groove and Z Bop have a fixed back rest. Quickie Z-bop wheelchair is equipped with the automatic (electrical) reclining back-rest, which allows the user to set the back rest for different angle. However, electric reclining back-rest needs more material and components than a fix one, resulting in more cost, weight and environmental impact. In addition, based on the axiomatic design "the simplest solution is the best one" and the minimum set of functions should be determined to satisfy intended requirements of an ideal product [50]. Consequently, the minimum set of functions, components, and materials should be identified to obtain the sustainable design. The other parameter in the sustainable design is the material selection. Material selection has a direct effect on the cost, weight, and environmental footprints. For instance, as shown in Tables 4-2 to 4-5, 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. Consequently, using ABS, as the solid tire of an anti-tip wheel, generates less environmental footprints with the lower cost and less weight than PUR and rubber.

In the next chapter, details of benchmarking are used to improve the initial design of the wheelchair to set the proper materials, forms and sizes of components.

CHAPTER 5

Design Improvements

Benchmarking provides specifications and details of wheelchairs' characteristics to meet both customer needs and sustainable requirements such as the material type, shape, size and mechanisms used in wheelchairs. These details are considered to improve the initial wheelchair design as follows.

5.1 Materials

The structure of wheelchairs can be made of steel, aluminum or titanium. However, based on the results of benchmarking, Aluminum (Al T6) is mostly used for the frame and main structure of the wheelchair. Al T6 has a reasonable price, density, strength and environmental footprint in comparison with stainless steel and titanium [39, 55]. Based on the results of benchmarking, ABS plastic is selected for back rest and leg-rest cover plates. ABS has low density, price and environmental footprints and it can be reused or recycled at the end of life cycle. Finite Element Analysis is conducted in next part to determine the proper thickness of cover plates. Also, ABS is used for the anti-tip wheels.

5.2 Subassemblies and mechanisms for functional and sustainable requirements

Functional requirements of wheelchairs are identified in Section 4.1 to meet the sustainable criteria and customer needs. Different forms of designs and mechanisms can be used in a wheelchair to satisfy the intended functional requirements. The initial wheelchair design is generated based on the knowledge and experience of the designer. However, further improvements of the design are difficult and time-consuming due to the lack of information about the detail of the design. Benchmarking provides valuable details about the wheelchair design. Improvements of the components' design are discussed as follows.

5.2.1 Seat, reclining back-rest and leg-rest

As shown in Figure 4-2, the back-rest and leg-rest of the initial wheelchair are adjustable. The electric reclining back-rest and leg-rest provide the automatic adjustment for different positions. The question is how the back-rest and leg-rest of a wheelchair can be designed to be comfortable as well as producing low environmental footprint and being profitable. As discussed in the benchmarking section, Quickie Groove and Z-Bop are both equipped by the reclining mechanism. As shown in Figures 4-9 and 4-11, Quickie Groove has a manual reclining back-rest, and Quickie Z-Bop is equipped by the electric power back-rest. Based on the results of comparing benchmarks in Table 4-6, although the automatic (electric) backrest provides more conformance than manual, it generates more environmental footprints and needs more service and maintenance. Also, it is more expensive than the manual one. Consequently, as shown in Figure 5-1, the “manual reclining mechanism” is adopted from the benchmarking results to improve the design of back-rest and leg-rest.

As shown in Figure 5-2, four main components involve in actuating of the reclining mechanism, including adjusting member, locking member, spur gear and actuating member [63, 67]. The locking member consists of the internal spur gear and is fixed to the seat frame while the actuating member is connected to the backrest and can rotate around the axis [69]. As shown in Figure 5-3, once the user pushes the adjusting member, the spur gear relives from the locking member and the reclining mechanism can rotate around the axis. The reclining mechanism can be set in the locking position, when the locking member, spur gear and actuating member are connected together. The springs are designed to pull out the spur gear and put it in the locking position [69]. The manual reclining mechanism is designed for back-rest and leg-rest to bring conformance for users as well as balancing the cost, environmental footprints, weight and number of components.

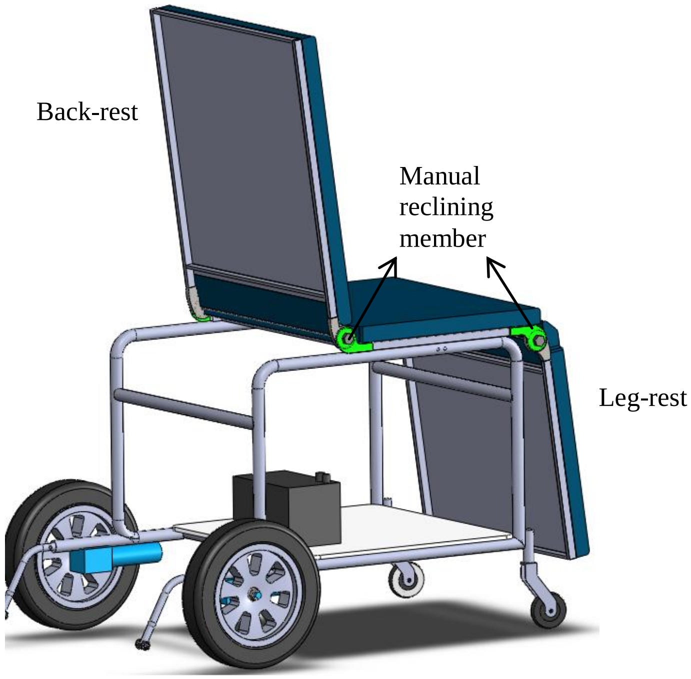


Figure 5-1. Adopting the manual reclining design concept based on the benchmarking

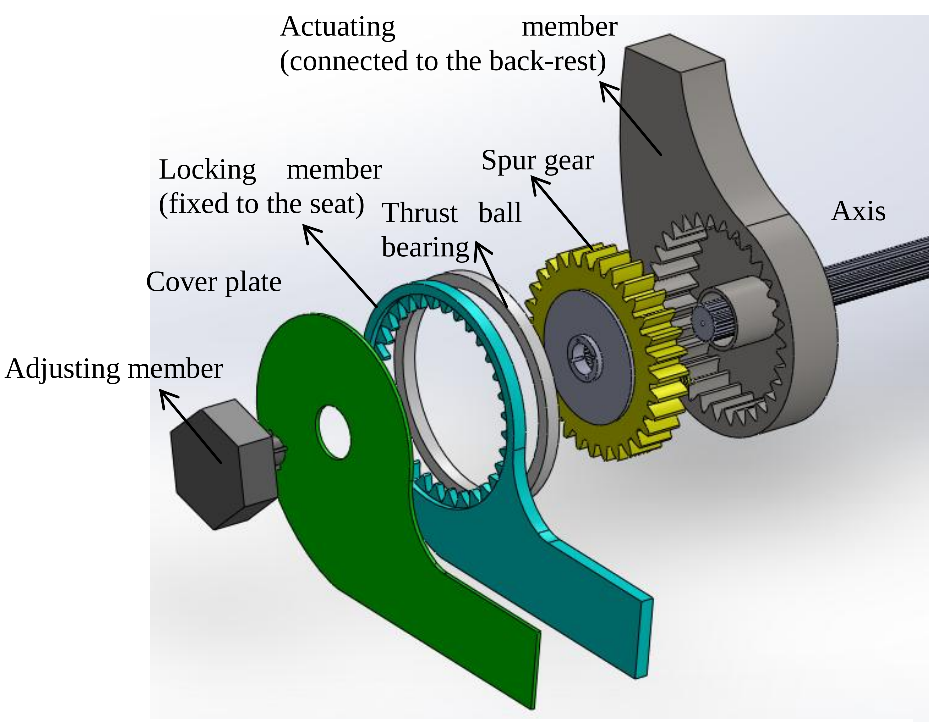
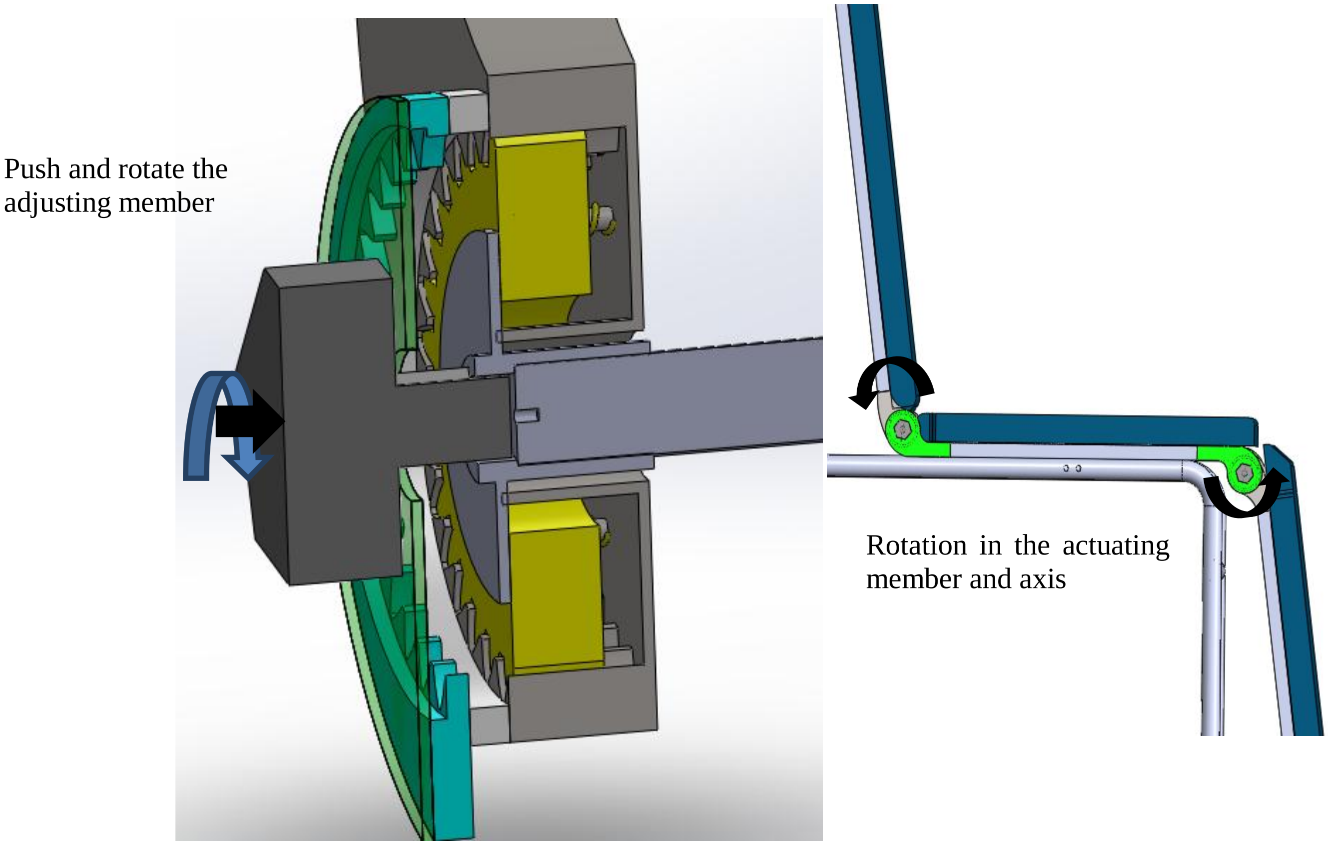
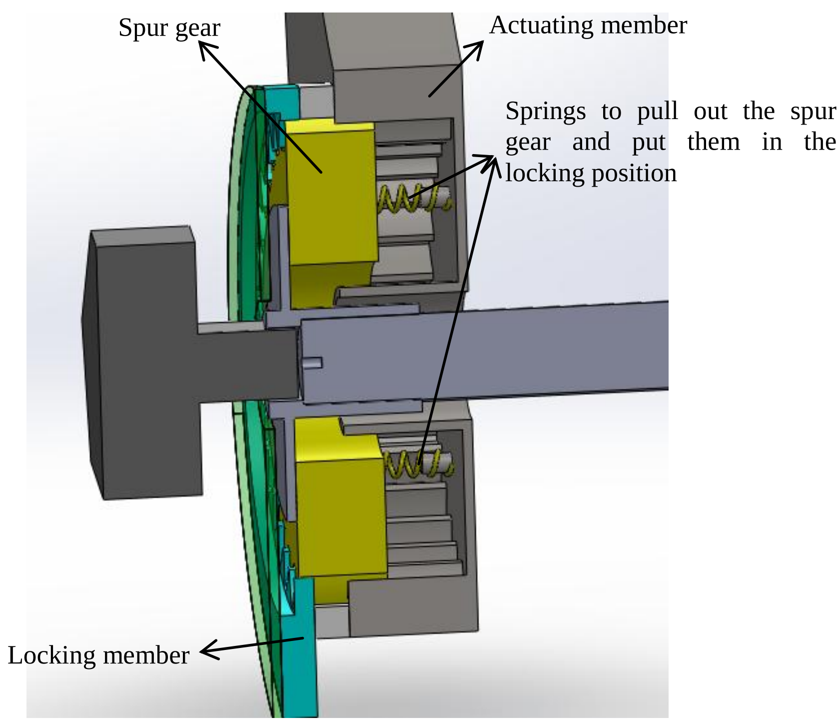


Figure 5-2.Exploded view of manual reclining mechanism



a) Actuating position of spur gear for reclining motion



b) Locking position of reclining mechanism

Figure 5-3. Locking and actuating positions of manual reclining mechanism [67]

5.2.2 Arm-rest design

As shown in Figure 4-2, the arm-rest of initial design is adjustable dual post, which allows the user to set the arm-rest for different heights. The results of benchmarking (Table 4-6) reveals that the nonadjustable single-post arm-rest has the lower environmental footprints, price and number of components than the adjustable one, as well as providing the comfort for users to put their hand on it. In addition it needs less service and maintenance than the adjustable one as it exposes to the erosion less than adjustable one. Consequently, as shown in Figure 5-4, the design of nonadjustable single-post arm-rest is adopted from benchmarking to improve the proficiency and environmental footprints of the wheelchair. The height of arm-rest is 9 inches above the seat based on the standard and benchmarks [59, 63].

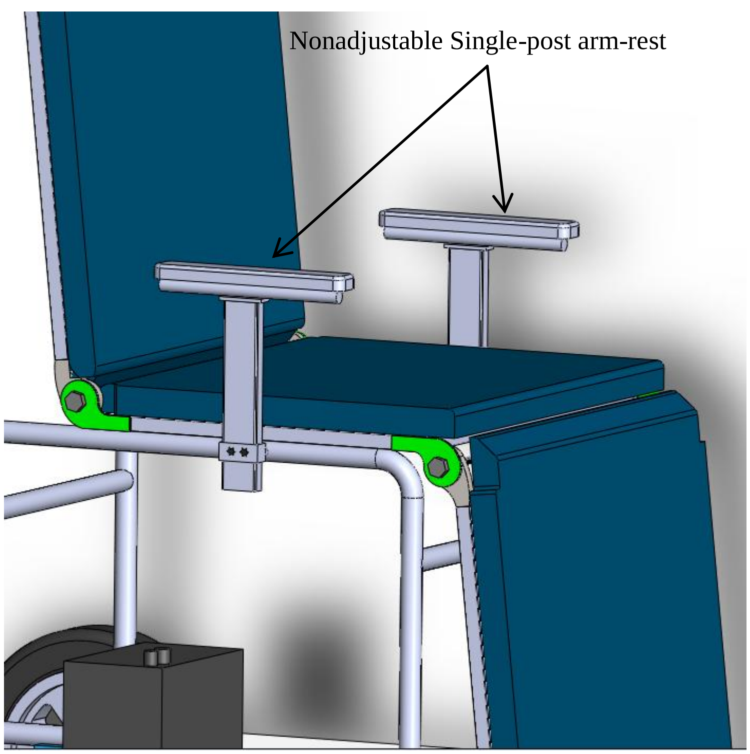


Figure 5-4. Nonadjustable single-post arm-rest design based on the benchmarking results

5.2.3 Head rest design

The main function of the head rest is to provide comfort for users to lean their head on it. It is considered as an optional part of wheelchairs [59]. As shown in Figure 4-5, the head-rest of the initial design is attached to the backrest and it can automatically rotate around the axis with the power of two electrical engines. As discussed in Section 4.4, the four benchmarks are equipped by a head rest except Quickie Z-Bop. The Head-rest is designed as a detachable component, which can be removed easily from the wheelchairs. As shown in Figures 4-9 and 4-11, the ideal head-rest can be adjusted manually for different height and variable angles, as well as it can be easily removed from the wheelchair at the end of life cycle. As mentioned above, the initial design of head-rest is rotated automatically with the power of two engines and it is connected firmly to axis, making it expensive. In addition, it is difficult to be detached from the wheelchair for service, maintenance and end of life cycle management. Hence as shown in Figure 5-5, the head-rest design of the ideal wheelchair (which is designed based on the benchmarking) is adopted to improve the initial design.

The material type of the wheelchair's component is determined in Section 5.2.1 and improvements of the initial design are accomplished based on the sustainable requirements and details of the benchmarks' design. In the next section, finite element analysis is conducted to determine the accurate size of the component for the safety and durability of the wheelchair.

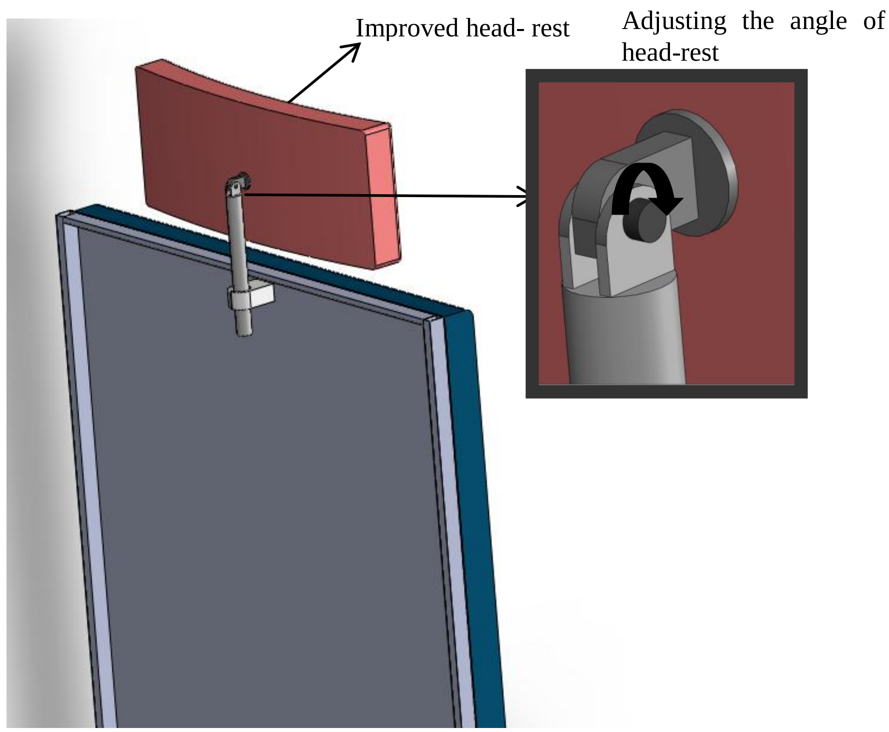


Figure 5-5. The final design of head-rest after comparing the initial design and benchmarks

5.3 Finite element analysis

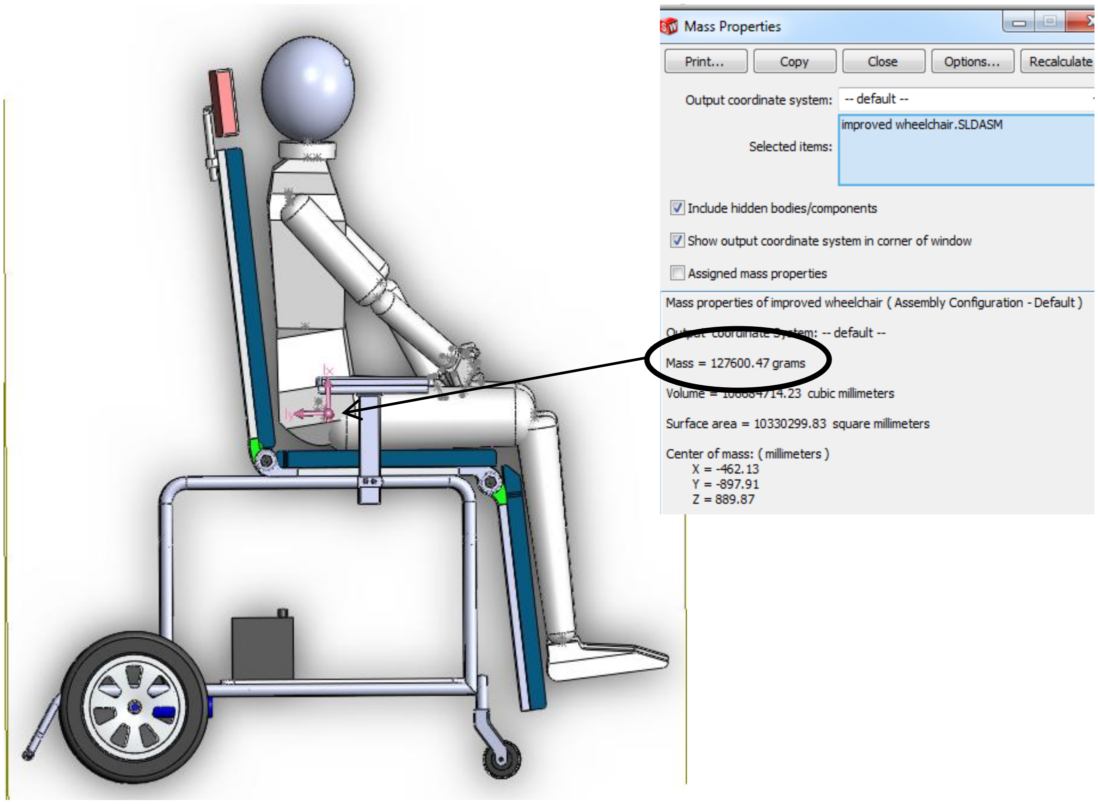
At this section, finite element analysis is conducted to determine the accurate thickness and size of the components to make the wheelchair safe and secure for users. The main function of the wheelchair is to hold and move the user. As shown in Figure 5-6, the wheelchair should sustain the weight of users in different positions. The human body is designed based on the ergonomics data to evaluate the load and centre of gravity [68, 69]. The weight of the adult body is distributed as follows: head is 5Kg, trunk is 40Kg, hip to knee is 26Kg, and the weight of leg (from knee to foot) is 14Kg [68, 69]. As shown in Figure 5-6 weight of the wheelchair and user is 126.7 Kg. This load sustains with the seat frame, main frame and finally distributes between front and rear wheels.

Figure 5-6 shows the changes of the centre of gravity in seat and bed positions of the wheelchair.

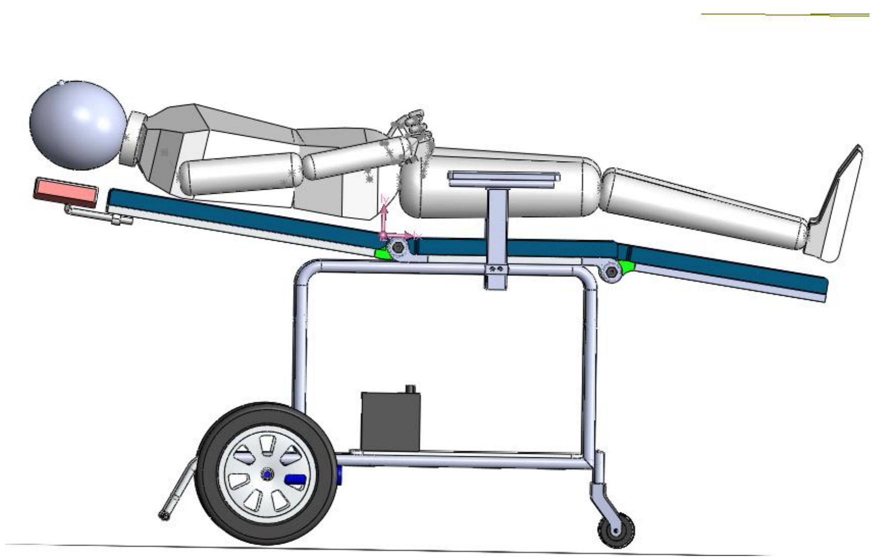
The first part, which is considered for the finite element analysis, is the seat. This component should sustain a weight of the whole body and transfer it to the main frame. The weight of the body is considered as 85kg which provides a load of 834N [68, 69]. As shown in Figure 5-6, this load is distributed on the seat cover plate. Based on the benchmarking, the material of seat cover is Aluminum. The width and length of the seat frame is designed as 17 and 16 inches, respectively [59, 63]. However, in order to determine the thickness of the cover sheet, the finite element analysis is needed to find the proper value. The initial thickness of the aluminum sheet is set as 0.5 millimetre to start the finite element analysis. The mechanical properties of Aluminum 1060 are shown in Table 5-1.

Table 5-1. The mechanical properties of Al-6061 T6 [69]

Item	**property**
E **(**Elastic modulus)	69G.Pa
Poisson's ratio	0.33
Yield strength	27.5 MPa
Ultimate Tensile Strength	68.9MPa
Material Model	Linear, Isotropic, plain stress



a) seat position



b) bed position

Figure 5-6. Different positions of the wheelchair and center of gravity

The finite element analysis is conducted in CosmosWorks Simulation to determine the maximum stress, deformation and factor of safety. As shown in Figure 5-7, the maximum stress is 123 Mpa which is more than the yield strength of the Aluminum. The safety factor is 0.22, which is less than 1. However the safety factor should be more than 1. Consequently, the thickness of the cover sheet should be increased to reach the acceptable stress and factor of safety. Different thicknesses are analysed to get the best result. Finally, as shown in Figure 5-8, the 3mm thickness is selected for the cover sheet of the seat. Figure 5-8 shows that the maximum stress is 13.1 MPa which is lower than the yield stress of Al-T6 (27.5) and the minimum safety factor is 2.1. As shown in Figure 5-8, once the accurate size of the seat sheet is determined, the final weight and environmental footprints are evaluated. The same evaluations are conducted for all components to set the accurate size of the wheelchair's components, which are shown in Appendix-A.

Name	Type	Min	Max
Aluminum sheet	**0.5mm**	**N/A**	**N/A**
Stress	VON: von Mises Stress	5.16984e+006 N/m^2 Node: 3141	1.23007e+008 N/m^2 Node: 4472
Displacement	URES: Resultant Displacement	0 mm Node: 1	6.02586 mm Node: 86
Factor of safety	Von Mises	0.224167 Node: 4472	5.33367 Node: 3141

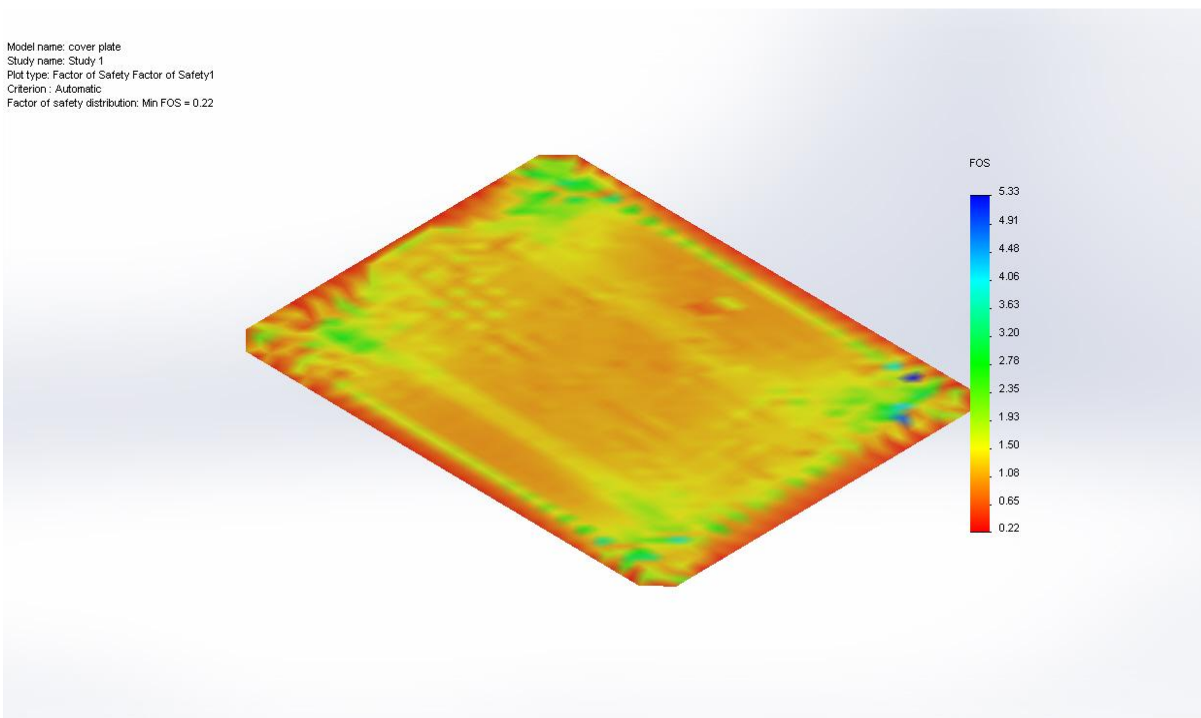


Figure 5-7. Results of FEA for 0.3 mm of cover sheet. The minimum safety factor is less than 1 for the initial thickness, which is improved in the next design

Name	Type	Min	Max
Aluminum sheet	**3mm**	**N/A**	**N/A**
Stress	VON: von Mises Stress	169558 N/m^2 Node: 5305	1.31168e+007 N/m^2 Node: 4716
Displacement	URES: Resultant Displacement	0 mm Node: 20	1.31194 mm Node: 4401
Factor of safety	Von Mises	2.10221 Node: 4716	162.624 Node: 5305
Weight	Kg	2.5	N/A
Environmental footprints	Kg	28.4	N/A

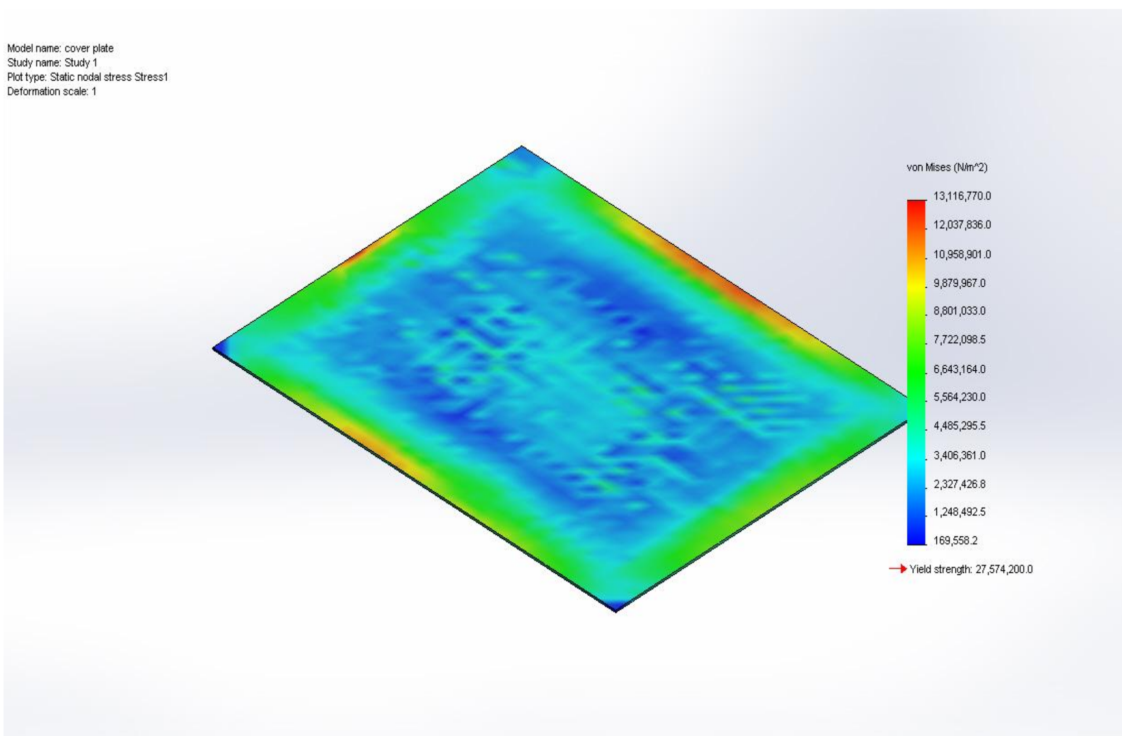


Figure 5-8. Results of FEA for 3mm of cover sheet

Figure 5-9 shows the final design of the improved wheelchair based on design details. The specifications of the final design, including size, weight, environmental footprints, and quantity, are shown in Table 5-2.

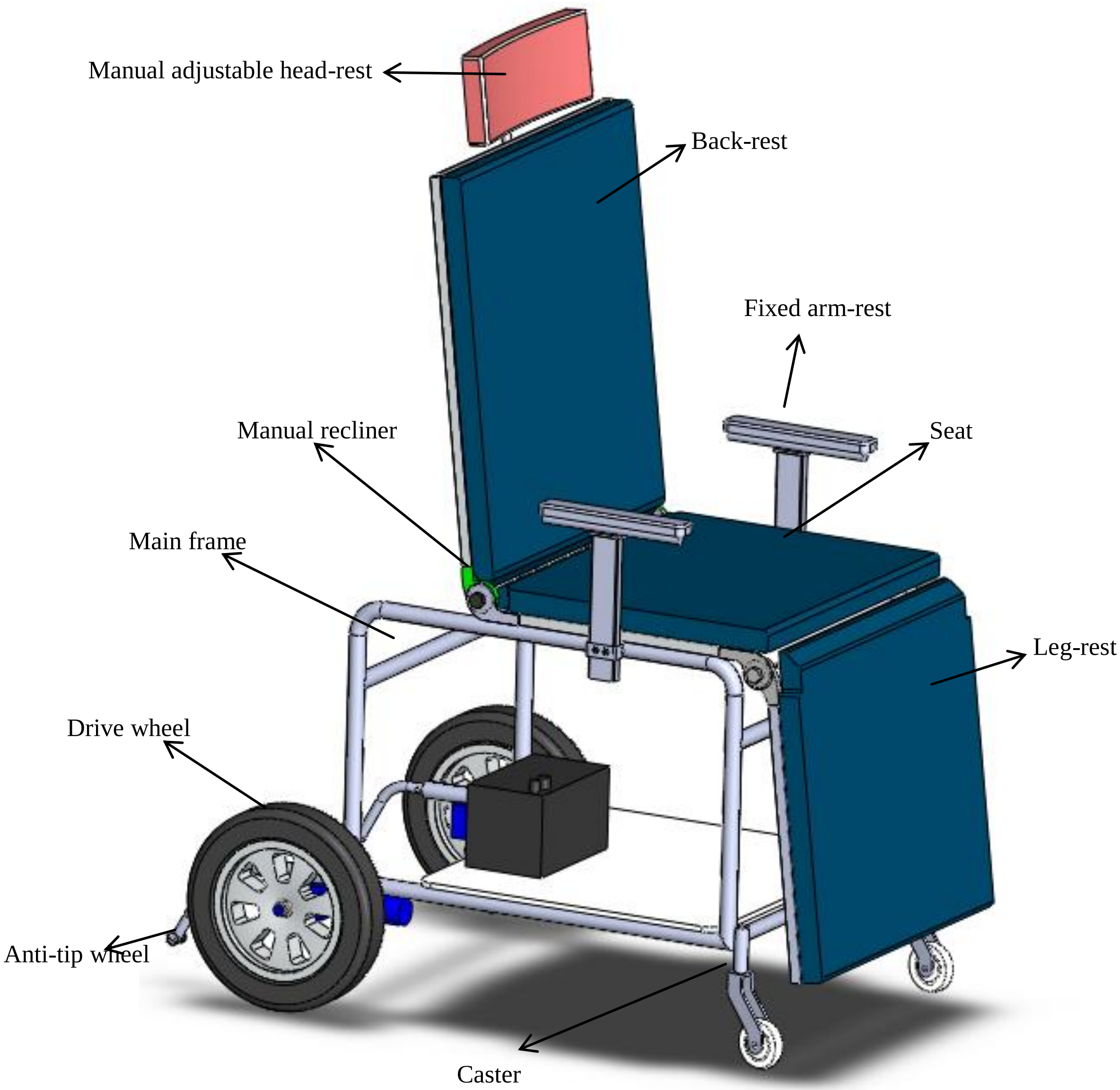


Figure 5-9. The final design of the wheelchair after improvements

Table 5-2. The specifications of the improved wheelchair based on data of benchmarking and finite element analysis

Item	Part name	Descriptions	material	QTY	weight(Kg)	Environmental footprint(Kg)
1	Base Frame	Tubular bar cross section: 20×1(mm)	Al-T6	1	2.3	25.4
2	Anti-tip structure	Tubular bar length: 440mm	Al-T6	2	0.51	5.5
3	Anti-tip solid wheel	D×W: 50×20 (mm)	ABS	2	0.014	0.05
4	Motor package	250LB, 4.5 MPH, 12” ×4”	Metal & Plastic	2	6.8	1.36
5	Drive wheel –rim	8” ×3”	Al	2	2.1	23.73
6	Drive wheel-tire & tube	10” ×3.5”	Rubber	2	0.47	2.11
7	Caster & Fork	Length× thickness: 110×3 mm	Al	2	0.72	8.13
8	Solid tire	8×2	Rubber	2	0.82	11.04
9	Seat frame	L×W×T: 400×650×23	Al T6	1	5.4	61.2
10	Seat cushion	L×W: 500×640	Foam	1	0.23	1.1
11	back rest frame	L×W×T: 400×650×23	Al	1	6	67.8
12	Back rest cushion	L×W: 500×640	Foam	1	0.26	1.2
13	Recliner	Manual	Al	2	3.4	39
14	Head rest-structure	Manual	Al	1	0.13	0.27
15	Headrest-pad	L×W: 300×110	Foam	1	0.01	0.05
16	Leg-rest	L×W×T: 400×650×23	Al	1	5.4	61.2
17	Leg-rest cushion	L×W: 500×640	Foam	1	0.23	1.1
18	Arm rest	Fix-Single post	AL	2	0.3	3.35
19	Armrest pad	Length: 250mm	Foam	2	0.005	0.025
20	Battery	12v,65Ah	Lead, sulphuric acid, ABS	1	14.3	14.01

5.4 Modularized wheelchair

In this section, modularization is used for the end of life cycle management, leading to ease of reusing, recycling and remanufacturing. As mentioned in Section 3.5, three steps are required for modularization: problem definition (modularized objective), similarity criteria, and modular algorithm for clustering. The objective of modular design in this research is to improve the wheelchair for ease of reusing, recycling or remanufacturing with respect to the functional compatibility and physical connections of the wheelchair's components. Components list of the improved wheelchair is shown in Table 5-3 the 3D CAD view and all specifications of the wheelchair are shown in Figure 5-9 and Table 5-2.

The second step is to establish the similarity matrix for the end of life cycle management for the modular design based on the function and material of the wheelchair's components. In order to form the similarity matrix, the similarity and dependency between the components for the end of life cycle are determined first. As shown in Table 5-4, three main factors are considered to establish the end of life cycle compatibility between components based on the functional and physical relationship.

Table 5-3. Components for the improved wheelchair

Part number	Part name	Part number	Part name
1	Base Frame	11	back rest frame
2	Anti-tip structure	12	Back rest cushion
3	Anti-tip solid wheel	13	Recliner
4	Motor package	14	Head rest-structure
5	Drive wheel –rim	15	Headrest-pad
6	Drive wheel- tire & tube	16	Leg-rest
7	Caster & Fork	17	Leg-rest cushion
8	Solid tire	18	Arm rest
9	Seat frame	19	Armrest pad
10	Seat cushion	20	Battery

1) As shown in Table 5-4, in the first case, two components have the same end of life cycle behaviour. In this case, if they have a strong functional and physical compatibility, the similarity score will be 10. In the second option, the similarity score is 8 where the two components have some functional and physical compatibility. For example, the seat frame and back-rest frame are both recyclable. The seat frame hold the weight of upper body and some thighs while the back rest just hold the weight of back body. Also, they are connected with threaded fasteners. Hence, their similarity value is 8. If the two components have limited functional and physical similarity, such as main frame and anti-tip structure, the similarity score is assigned 4. When the two components have no functional and physical relationships the similarity score will be 0.

2) The second case happens when two components have some end of life cycle compatibility. For example, the two components are recyclable, but they have different materials or, they should be disassembled into components to be remanufactured or reused, such as the electrical motor or battery. In this case, if the two components have

the same function, the similarity score is 6. If there is a limited functional and physical compatibility, the score is 2. When there is no functional and physical relationship, the score is 0. 3). If the components have totally different end of life cycle strategy, the similarity score is 0. For example, one component is recyclable (the aluminum head rest frame) and the other one is land filled or incinerated (the tires).

After determining the similarity criteria, the similarity matrix is established as shown in Figure 5-10. Each cell of the similarity matrix is decided based on the relationship of the two intended components. For example, the related cell to component 9 (seat frame) and component 11 (back rest frame) has a score 8, as they are both recyclable with some functional compatibility and physical connection.

Table 5-4. Similarity criteria for the end of life cycle and functional compatibility

Similarity factor	**Score**
1- **Two components with the same end of life cycle (both can be reused/recycled/ incinerated):**	
And they have strong functional compatibility and physical connections	10
And they have some functional compatibility and physical connection	8
And they have little functional compatibility and weak physical connection	4
No functional compatibility and connection	0
2- Components with some end of life cycle compatibility:	
And they are participating in same function and have some physical connections	6
And they have limited similarity in function and physical connection	2
And they have no functional compatibility and connection	0
3- Components with totally different end of life cycle (one reused and the other one incinerated)	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	10	4	0	2	0	0	6	0	10	0	2	0	0	0	0	2	0	10	0	0
2	4	10	6	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	6	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	2	0	0	10	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
5	0	2	0	2	10	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	10	0	8	0	0	0	0	0	0	0	0	0	0	0	0
7	6	0	0	0	2	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	8	0	10	0	0	0	0	0	0	0	0	0	0	0	0
9	10	0	0	0	0	0	0	0	10	0	8	0	8	0	0	8	0	0	0	0
10	0	0	0	0	0	0	0	0	0	10	0	8	0	0	8	0	8	0	8	0
11	2	0	0	0	0	0	0	0	8	0	10	0	8	8	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	8	0	10	0	0	8	0	8	0	8	0
13	0	0	0	0	0	0	0	0	8	0	8	0	10	0	0	8	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	8	0	0	10	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	8	0	8	0	0	10	0	8	0	8	0
16	2	0	0	0	0	0	0	0	8	0	0	0	8	0	0	10	0	0	0	0
17	0	0	0	0	0	0	0	0	0	8	0	8	8	0	8	0	10	0	8	0
18	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
19	0	0	0	0	0	0	0	0	0	8	0	8	0	0	8	0	8	0	10	0
20	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10

Figure 5-10. Similarity matrix for modular design for 20 components of the wheelchair

The final step of modular design is conducting the clustering algorithm to group the components in the proper modules based on the similarity matrix. As mentioned in Section 3.5.2, the unsupervised hierarchical clustering algorithm is used to cluster the modules. Matlab 2012 is used to search results of the hierarchical algorithm to deal with the complexity of similarity matrix.

Table 5-5.The composition of modules

Module no.	Part number
1	{11, 14}
2	{9,13,16}
3	{1, 18}
4	{5, 7}
5	{10, 12, 15, 17, 19}
6	{6, 8}
7	{4, 20}
8	{2, 3}

Table 5-5 shows the output of Matlab for clustering of the new wheelchair. This result is shown in Figure 5-11, to identify the modules graphically. As shown in Figure 5-11, there are 8 different modules. Components 11 and 14 (back rest and head rest) are set in the same module, as they are recyclable and they should be attached to each other. Also, both of them should support the weight of upper body. The next module consists of components 9 (seat frame), 13 (reclining member) and 16 (leg-rest). All of them are made of aluminum and they can be recyclable. Also, they should be fixed to each other and they support the weight of lower body. The link between modules 1 and 2 is component 13 (reclining member). The third module contains components 1 (main frame) and 18 (arm-rest frame), which are firmly fixed to each other. Arm-rest frame (component 18) supports the weight of arm and hand. The force transfers to the main frame with the threaded attachments between components 1 and 18. Also, they can be reused by disassembling at the end of life cycle. The next module consists of components 5 (drive wheel-rim) and 7 (Caster and fork) as they are designed for orientation and movement of the wheelchair. The fifth module contains components 10, 12, 15, 17 and 19 as they are all made from foam and they are considered as the waste (land filled or incinerated). Also, they have the same function to reduce the pressure and provide conformance for the user. Components 6 (rear tire) and 8 (front tire) are in module 6. They have same material and usually they are land filled or incinerated at the end of life cycle. In addition, they have the same function in the moving system. Components 4 (electrical engine) and 20 (battery) are in the same module because both of them are made of different materials (plastics and metals). They should be disassembled first, and then they need some recovery activities before remanufacturing and reusing. Also, they provide the electrical power for the wheelchair. The last module includes components 2 and 3 (the anti-tip structure and its wheel) as they are recyclable and have the same function, providing movement and balance for the rear body. In conclusion, modularization improves the wheelchair for ease of reusing, recycling and remanufacturing.

Next Chapter will describe the conclusion and contribution remarks of this research.

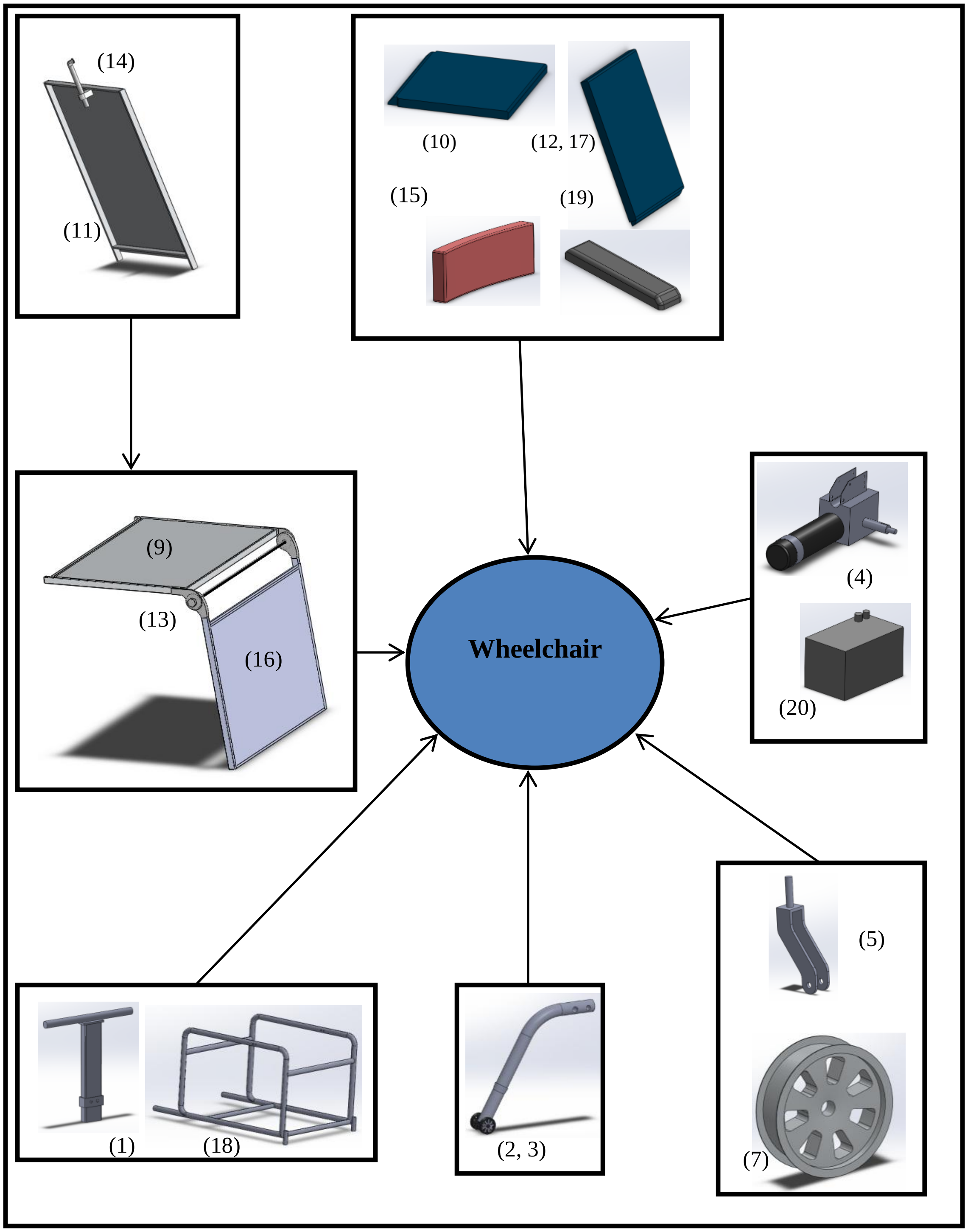


Figure 5-11. Wheelchair's modules

CHAPTER 6

Conclusions and contribution remarks

6.1 Conclusions

This research discusses the sustainable product design. The axiomatic design and Quality function Deployment (QFD) methods are integrated with the Eco-design tools to develop a new multi-criteria sustainable method. The main challenge is to meet different requirements of design including cost, comfort, strength, environmental footprints, maintainability, and recyclability. In order to find a satisfied solution, the priority and weight factors of sustainable design parameters are determined. The customer needs and sustainable considerations are mapped into the functional requirements and design parameters based on the axiomatic rules to identify the minimum set of independent functional requirements. A house of quality (HoQ) is formed to link the customer needs, sustainable considerations, and functional requirements. The design matrix is then established to find correlations between functional requirements and design parameters. In order to determine the priorities of the sustainable design, the decision matrix is formed to link the HoQ and design matrix analysis.

In this research, a wheelchair is designed as a case study. The result of decision matrix for the wheelchair design reveals that cost, environmental footprints, recyclability weight, number of components, and maintainability are the most important parameters to satisfy the customer needs and sustainable considerations. The initial wheelchair is designed based on the concept derived from the decision matrix to meet customer needs and sustainable requirements. The design has the flexibility to be used as a bed or wheelchair. The electric power seat mechanism is adopted to design a reclining backrest, headrest and leg-rest. Also, the drive wheels are propelled by two electrical motors, and the arm-rest of the initial wheelchair is designed as the adjustable one. While the general scheme of designing a wheelchair is attained from mapping of the customer needs and sustainable consideration into the functional requirements and design parameters, the further details of design is required for improvement of the initial detail to meet sustainable measurements. Benchmarking is used to examine and compare the existing wheelchairs. The four powered wheelchairs are selected from the market [62] and they are compared based on the cost, environmental footprints, maintainability, weight and number of components. The best components of the wheelchairs are selected to meet the sustainable metrics. The results of the benchmarking reveal that the material type, complexity and number of components for each function have a direct effect on cost, weight, maintainability, and environmental footprints. As the number of components and complexity decrease, the cost, weight and environmental footprints of the wheelchair decrease. The results and data of benchmarking are used to improve the initial wheelchair design. In addition, the finite elements analysis is conducted to make the wheelchair safe and secure for use. The modular design is conducted to improve the wheelchair design for ease of reusing, recycling and remanufacturing. The function, material and end of life cycle strategy are considered as the similarity and dependency criteria to put the components in different clusters.

6.2 Contributions

The contributions of this research are as follows:

1- Establishing the quantitative method for the sustainable design evaluation: Most of the current research does not provide a quantitative multi-criteria method considering both traditional and sustainable aspects of design. This research provides a quantitative multi-criteria method with adding the sustainable consideration to the integration of axiomatic design and QFD. The axiomatic design assures that the number of functional requirements, to meet the sustainable criteria and customer needs, are minimized and there is no conflict between them. Also, the qualitative criteria are mapped into quantitative measures with the usage of Design Matrix and House of Quality.

2- The wheelchair design is improved based on the data derived from the benchmarking. Most of the existing research, discussed in the literature review, uses the benchmarking just for comparing the existing components. In this research, while the existing power wheelchairs are compared and examined to select the ideal components, an initial design is improved with respect to the results of benchmarking. LCA is conducted for all benchmarks to evaluate their environmental footprints. This research assesses the air pollution, water contamination and solid emission of components.

3- In this research, the similarity criteria of modular design are applied based on both the end of life cycle management and functional similarity to group components in the proper clusters. Most of the current research form the similarity matrix just based on functional similarity and physical connections of the components without considering the end of life cycle option.

6.3 Suggestions

In this research, the main focus is to establish the quantitative sustainable metrics through mapping of customer needs and sustainable criteria into the functional requirements and design parameters. The benchmarking is conducted to provide details of the design. The modularity is conducted at the end of research process to enhance the wheelchair for ease of reusing, recycling and remanufacturing. For the future research, in order to provide a sustainable modular design solution, the modularity should be used before establishing details of the design. Stages of a suggested method are described as follows:

1- Mapping sustainable requirements and customer needs into design parameters to identify the initial design,

2- Selecting the benchmarks,

3- Establishing house of quality (HoQ) and rating the benchmarks,

4- Conducting the modular design for ease of reusing, recycling, maintainability, assembly and disassemble,

5- Identifying details of the design based on the benchmarks,

6- Evaluating details of the design and modularization.

6.4 Future work

Further research should consider the entire product life cycle to achieve the complete product sustainability. This research focuses on only the design area. The sustainability for manufacturing, for assembly and disassembly are not discussed in this research. In addition, the environmental footprint is evaluated just based on the material and size of the components. In order to find the accurate cost and environmental footprints of a product, other aspects of product design, such as manufacturing, assembly, disassembly and distribution, should be studied. In this research making cost is evaluated based on the raw material and manufacturing process. It is assumed that all raw materials are provided by the same producer and all components are manufactured in the same factory. However, in order to find the accurate price of raw materials, real data of raw materials (which may provide by different producers) should be considered in future studies. In addition, process planning should be conducted to determine manufacturing plan, sequence of processes, establishing machining data and standards, tooling inventories and stock availability in future work. The cost of assembly, packing, distribution and profit of the company are not considered in this research which should be evaluated in the future work.

This research uses wheelchair with limited components as a case study. Four powered wheelchairs are considered as benchmarks to improve the initial design. Different products with more components and complexity should be used as case studies to evaluate the design based on the sustainable metrics.

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Following papers are published related to this research:

[1] Hosseinpour, A. and Peng, Q., "Sustainable design using integrated TRIZ and eco-checklist with function impact matrix", Proceedings of ASME IDETC/CIE 2012, DETC2012-70431.

[2] Peng, Q., Hosseinpour, A., and Gu, P., "Tools for sustainable product design: review and expectation", Proceedings of ASME DETC/CIE 2013, DETC2013-13350.

Appendix-A

In this appendix, results of the finite element analysis to determine the accurate size of components of the wheelchair are described.

1- The sitting reaction of front and rear wheels, based on the data in Section 5.2, is evaluated in SolidWorks.

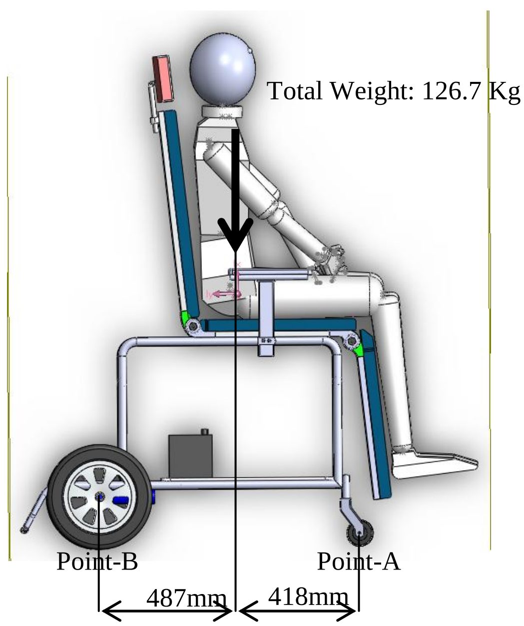

Figure A-1. The position of centre of gravity (based on Figure 5-6)

The reaction of each wheel based on the equivalent equations [72]:

$\sum M_A$= - (126.7)×(9.81)×487 + R_A×905=0 ⇒ R_A= 668.8 N: The reaction force at Front wheels

$\sum F$ = 0 ⇒ - + R_A+ R_B =0 ⇒ R_B= 1242.9 – 668.8 = 574.1 N The reaction Force at Rear wheels

Based on the electric engine, used for the wheelchair in Section 5.2, the maximum speed of a wheelchair can be 10Km/h [62]. The stress analysis of the front fork (caster) is conducted when there is a collision of the wheelchair to the solid block at the speed of 10 km/h.

Name	Type	Min	Max
Aluminum 6061T6	**5mm thickness**	**Yield point: 2.75e+008 N/m^2**	**Tensile strength: 3.1e+008 N/m^2**
Stress	VON: von Mises Stress	112266 N/m^2 Node: 4162	5.90961e+007 N/m^2 Node: 15271
Displacement	URES: Resultant Displacement	0.00854137 mm Node: 13109	0.144176 mm Node: 189
Safety Factor	von Mises Stress	4.6 Node: 15271	245 Node: 4162
Weight	Kg	0.167	N/A
Environmental footprints	Kg	2.3	N/A

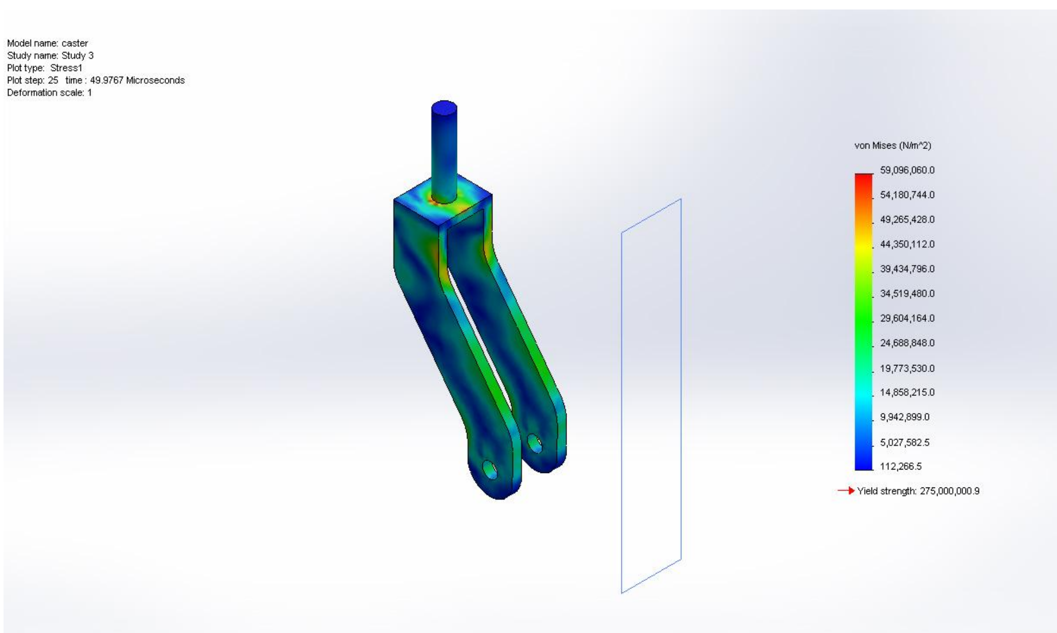

Figure A-2. FEA of the Front Fork due to the collision to the solid block at the speed of 10 km/s

The stress analysis of the back-rest cover is done when the wheelchair is set in the bed position based on the data in Section 5.2 for the human body weight distribution.

Name	Type	Min	Max
ABS Plastic	**3mm thickness**	**Yield point: 35e+007 N/m^2**	**Tensile strength: 3e+007 N/m^2**
Stress	VON: von Mises Stress	7.79962 N/m^2 Node: 72	5.31801e+006 N/m^2 Node: 16016
Displacement	URES: Resultant Displacement	0 mm Node: 1	4.27578 mm Node: 15111
Weight	Kg	1.3 Kg	N/A
Environmental footprints	Kg	4.7	N/A

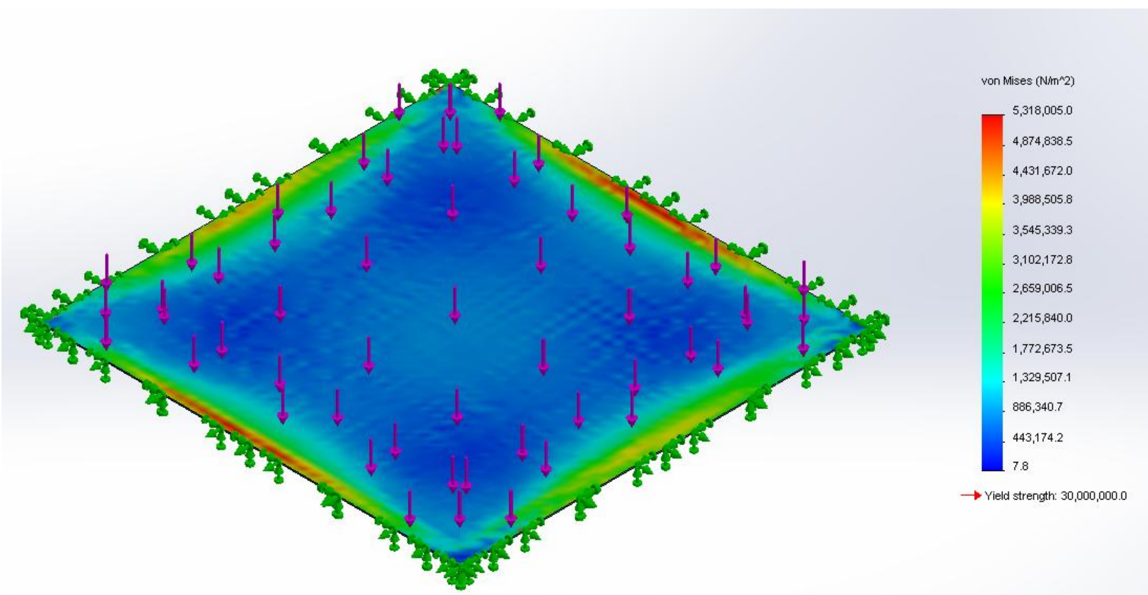

Figure A-3. FEA of the back rest sheet to sustain the load of user's upper body