Application of Design for Six Sigma (DFSS) In Sustainable Product Design: A Case Study on an Electric Kettle

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Abstract: Sustainability is one the most crucial aspects currently focused by competitive companies who are coerced to consider their companies environmental, social and economic performance as requirements for product design. The intricate philosophy of designing physical objects, products, built environment and services to comply with the principles of social, economic and ecological sustainability is called sustainable product design. The main of this study is to improve product sustainability using Design for Six Sigma (DFSS) approach. This research primarily focuses on reviewing current sustainable product development approaches, developing a new framework to incorporate Design for Six Sigma into Sustainable Product Development and to conduct a case study on a product using this new framework. The chosen product is an electric kettle. An electric kettle is usually subjected to more extreme usage and physical damage than normal kettles. Most original internal components are very hard to come by in the replacement parts market making it a difficult product to repair and extend its life of use. The design tools used in this new framework are survey methodology, Quality Function Deployment (QFD), morphological chart and weighted rating method, SolidWorks 3D modelling and Sustainability Analysis besides DFM and DFA analysis software. Through applying the new framework under the DFSS approach a new electric kettle concept has been generated and it has been proven to be more sustainable than its predecessors proving that the new proposed framework is suitable for use in sustainable product development.

Keywords: Product design, sustainable development, design for six sigma, DFMA.

1. Introduction

Product design in engineering terms is a series of concurrent steps, from understanding customer needs to commercialization, used to create a product design [1]. Product designers often embody various possible design concepts, evaluating each unique idea to turn them into innovative products and inventions through a very systematic approach. Art, science and technology comes together when the product designer creates an innovative product that people can use. Global sustainability, a topic widely discussed in recent times, is heavily influenced by the product design sector as almost all products consumed by each individual are outputs of the product development process [2]. In brief, sustainability or sustainable development is that of which meets the needs of the present community without compromising the ability of future, advanced generations to meet their own personal needs [3]. However, one of the greatest challenges faced by the modern society of today is the issue of sustainability, encompassing all social, environmental and economic topics whereby it is overwhelming both in scale and the complexity [2, 4]. This problem is further complicated by the fact that the unprecedented global population growth and the desire to improve the quality of life drives the consumption rate of products and services to keep on going higher. To make this vision a successful
one, engineers and designers need to come up with radically creative solutions under the ever-present restraints of social, economic, and environmental sustainability considerations.

In general, to overcome this present issue, a generic problem-solving methodology called sustainable product design is used. Sustainable product design emphasizes on producing minimal amount of waste during the products entire cradle to grave life cycle from the onset of production, marketing, distribution, use and right up to the disposal of the product [5]. It is also important to note that design decisions have a very substantial impact on sustainability, in particular of those made in the early product design stages [6, 7]. Though there are many efforts worldwide being done to counter this worrying issue, analyzing the sustainability of each and every different product alternative is the toughest task since such comprehensive tools are either not yet available or not economically viable to producers. Sustainable product design clearly focuses on skilful, environmentally conscious design to reduce negative impacts of a product throughout its life. Sustainability is based on balancing three principal objectives which are environmental protection, economic growth and social equity [8]. Sustainable design on the other hand is about rethinking how to meet the need for growth while at the same time reducing negative environmental and social impacts [9]. It is also important to note that the most common approaches to achieving a sustainable product is by literally changing the design and the material composition of a product [10].

Therefore, it can be said that a design tool capable of evaluating a product with regards to sustainability considerations and selecting the most sustainability-oriented design alternative is still lacking thus further investigations are required to fill these gaps. Hence, this research will focus on creating a framework to promote sustainability in a manufacturing environment with the widely used problem solving tool, Design for Six Sigma (DFSS). Design for Manufacturing and Assembly (DFMA) approach is also integrated in the DFSS methodology to facilitate product improvement which can further support the economic sustainability of the product.

2. Methodology

In this paper, the main methodology used and referred to as a guideline is DFSS. This methodology is used to make a better improvement of an existing electric kettle towards sustainable product development.

2.1 Design for Six Sigma

Design for Six Sigma (DFSS) is a very innovative methodology for designing and redesigning products or services according to customer requirements and expectations. This DFSS methodology is a systematic and rigorous method within which tools, training and data are used to optimize the design process to achieve six sigma performances whereby it focuses on getting it right at the first time [11]. DFSS complements the six Sigma improvement methodology but takes it a step further by weeding out flaws of the product and process during the initial design stages itself. DFSS is simply not a rework of lessons learned in Six Sigma but a profoundly different approach [12]. The focus on early design phases in DFSS are primarily to account for customer needs and expectations besides proper production processes. DFSS incorporates its own roadmap as to what DMAIC is to Six Sigma. DFSS also uses another roadmap called DMADV. This roadmap is abbreviated into the following phases: Define, Measure, Analyze, Design and Verify [13, 14]. The DMADV roadmap focus is on redesigning an existing product or process so that the shortcomings of the product or process are corrected immediately.

2.2 Integrating DFSS Approach for Sustainable Product Design

Methods of sustainable product design can be the core principle in all the traditional design methodologies in which the desired outcome is a sustainable product. With major criteria’s that needs to be considered in sustainable product design includes a very wide range of topics like environmental, economic and societal phases, it is important that new tools and approaches are found to assess the selected sustainability criterions. Numerous sustainable product design tools have been proposed and developed over the years. Current tools vary significantly in the data presentation methodology and
design process implementation. Based on the literature review on existing sustainable product development, a new approach for investigating an existing electric kettle towards sustainable product development using DFSS is outlined in Figure 1. There are five different phases in the DFSS methodology and each of the phases are attached to a design tool. The DFM and DFA analysis was done in the verify part of the DFSS methodology. This is to ensure that the designed part is economically sustainable and can improve the products sustainability with regards to its manufacturing and assembly.

![Figure 1. Proposed methods chosen for each DFSS Stage.](image)

3. Case Study

In this section, a case study is conducted to illustrate the proposed approach. An existing electric kettle that is readily available in the market nowadays in the market was used as the case study and as a benchmark for the new proposed electric kettle design. The new conceptual design of the electric kettle must achieve key sustainability characteristics based on the three key elements of sustainability for example like customer satisfaction, life cycle orientation and significant design improvements. Design for Six Sigma (DFSS) is primary focused on designing products and service capable of meeting customer requirements or reaching Six Sigma quality methods.

3.1 Defining User Experience and Requirements for an Electric Kettle

In this DMADV approach, the first phase is known as the Define phase. The most suitable tool that can used in this to collect data is through a survey. Hence, an online survey form was created as a tool to help define the user experience and requirements on an electric kettle. It is of utmost importance that information and feedback from respondents are collected as their opinions on usage patterns can ultimately be the deciding factor in choosing or upgrading certain parts of the design. The respondents were 100 students who own an electric kettle where 45 of them were female and the rest were male students. Table 1 shows the sum of features fraction from feedback of respondents, there are total of the scores from respondents for each feature in this survey. Based on the data obtained from the survey, the respondents clearly want the conceptual design to be adjustable to use of temperature controls, energy efficient, safe enough to prevent hot water scalding and use non-toxic materials in the design of the new electric kettle.
Table 1. Sum of Features Fraction from Feedback of Respondents

|                      | Social (Users) | Economic | Environment |
|----------------------|----------------|----------|-------------|
| 100 Respondents      |                |          |             |
| Human Design: Ergonomics | 402            | 370      | 431         |
| Durability: Long lasting | 412            | 391      | 340         |
| Controls: Adjusts to Use | 340            | 371      | 427         |
| Safety: Scald Prevention | 389            | 409      | 406         |
| Maintenance: Easy to Clean | 0.092         | 0.085    | 0.100       |
| Maintenance: Wide accessory and replacement hardware support | 0.095          | 0.090    | 0.079       |
| Maintenance: Common Components | 0.090         | 0.085    | 0.089       |
| Maintenance: Low Impact Materials | 0.089         | 0.094    | 0.093       |
| Material: Non Toxic | 0.079          | 0.085    | 0.374       |
| Material: Design for Recycling | 0.462         | 0.164    |             |
| Total Rating               | 0.462          | 0.164    | 0.374       |

3.2 Measuring Respondents Satisfaction and Identifying Design Specifications for New Electric Kettle Design

In DFSS’s DMADV approach, the second phase is called the Measure phase. The most desirable tool for this phase is Quality Function Deployment (QFD). The primary focus of QFD is to transform qualitative respondents’ requirements on sustainable product development into quantitative parameters besides helping to deploy the function forming quality and methods of achieving the design quality into subsystems and component parts. QFD is designed to assist designer focus on characteristics of new or existing product from the viewpoints of market segment or technical development needs. QFD will transform respondents’ needs or voice of customer into engineering characteristics for a product, prioritizing each product characteristic while setting the targets for product development at the same time. In the beginning a competitive benchmarking was done. Competitive benchmarking is the strategy of comparing the products of competitors. In this study, three existing electric kettle models from different brands in the market were chosen as competitive benchmarking. The three chosen kettle models were named as EK A, EK B and EK C. The analysis of the QFD was continued when the house of quality chart for the new electric kettle design was constructed. From this a target for the new product to achieve is obtained. Based on the analysis through the QFD, the highest total importance goes to product material which has a relative weight of 14.6%. Hence, the products material must be chosen properly according to customer needs and it must have a lesser impact on the environment. In second place is number of parts with a relative weight of 13.04%. This is related to the assembly and disassembly of the electric kettle. With lesser amount of parts, it is easier to assemble and disassemble. In third place is material life cycle with a relative weight of 11.75%. A much more sustainable material must be used in order to make the product at its end of life more recyclable.

3.3 Analyze and Selecting the Material to be Used in New Electric Kettle Design

The third phase of DMADV approach of Design for Six Sigma (DFSS) is the analyze part. In this specific phase of this research, a morphological chart and weighted rating method is used to generate new alternative concepts primary focusing on material choice and key functions. This analysis will aid tremendously with integrating key features into the conceptual design of the new electric kettle. With part material, reduction in number of parts and the material used life cycle key concerns of respondents in the survey hence it is of utmost importance of using materials which have a low impact on the environment throughout its entire use.
To ensure the new concept design is environmentally friendly throughout its entire lifecycle, selection of materials and other key components of the product is done by using a morphologic chart and weighted rating method. Hence, through the application of these methods a greater emphasis to sustainability can be incorporated into the product design and its entire lifecycle. Table 2 shows the alternative combinations and list of parameters of new conceptual electric kettle design.

### Table 2. Weighted Rating Method Scores of New Electric Kettle Design

| NO | Criteria                                      | Importance | Weight | Concept Alternative | Rating | Weighted Rating | Rating | Weighted Rating | Rating | Weighted Rating | Rating | Weighted Rating | Rating | Weighted Rating |
|----|-----------------------------------------------|------------|--------|---------------------|--------|-----------------|--------|-----------------|--------|-----------------|--------|-----------------|--------|----------------|
| 1  | Human Design: Ergonomics                     | 0.092      | 3      | 3                   | 0.276  | 3               | 0.276  | 3               | 0.276  | 3               | 0.276  | 3               | 0.276  | 3               |
| 2  | Durability: Long lasting                      | 0.085      | 4      | 4                   | 0.340  | 5               | 0.425  | 3               | 0.255  | 4               | 0.340  | 5               | 0.425  | 3               |
| 3  | Controls: Adjusts to Use                      | 0.100      | 4      | 4                   | 0.400  | 4               | 0.400  | 4               | 0.400  | 4               | 0.400  | 4               | 0.400  | 4               |
| 4  | Safety: Scald Prevention                      | 0.095      | 3      | 3                   | 0.285  | 5               | 0.475  | 5               | 0.285  | 5               | 0.475  | 5               | 0.475  | 5               |
| 5  | Maintenance: Easy to Clean                   | 0.090      | 4      | 4                   | 0.360  | 5               | 0.450  | 3               | 0.270  | 4               | 0.360  | 5               | 0.450  | 3               |
| 6  | Maintenance: Common Components Maintenance    | 0.079      | 3      | 3                   | 0.237  | 3               | 0.237  | 3               | 0.237  | 3               | 0.237  | 3               | 0.237  | 3               |
| 7  | Wide accessory and replacement hardware support| 0.085      | 3      | 3                   | 0.255  | 3               | 0.255  | 3               | 0.255  | 3               | 0.255  | 3               | 0.255  | 3               |
| 8  | Energy: Efficiency                            | 0.098      | 4      | 4                   | 0.392  | 5               | 0.490  | 3               | 0.294  | 4               | 0.392  | 5               | 0.490  | 3               |
| 9  | Material: Low Impact Materials                | 0.089      | 4      | 4                   | 0.365  | 5               | 0.445  | 3               | 0.267  | 3               | 0.267  | 5               | 0.445  | 3               |
| 10 | Material: Non Toxic                           | 0.094      | 4      | 4                   | 0.376  | 5               | 0.470  | 3               | 0.282  | 3               | 0.282  | 5               | 0.470  | 3               |
| 11 | Material: Design for Recycling                | 0.093      | 4      | 4                   | 0.372  | 4               | 0.327  | 3               | 0.279  | 3               | 0.279  | 5               | 0.465  | 3               |
|    | Total                                         | 1          | 3.658  | 4.295               | 3.29   | 3.373           | 4.488  | 4               |

Based on the weighted sum ranking determined, the Combination 5 gained the highest total score of weights where it obtained a value of 4.488. The result of the weighted ranking method further supports the fact that the Combination 5 is the best design alternative from the five different combinations that was put up. Table 3 shows the final concept selection for the newly designed electric kettle.

3.4 Design and Modelling the New Electric Kettle’s Conceptual Design using SolidWorks Software

The next phase in DFSS methodology is Design. Results from the survey which was thoroughly analyzed showed a desire from the respondents to have the product be more sustainable in terms of material used is non-toxic and has a complete life cycle whereby it can be recycled besides energy efficiency and reduction in the number of parts of the kettle. The new conceptual design has incorporated almost all of these desired characteristics with a special attention to detail. The 3D modelled detail drawings of the new electric kettle’s conceptual design are modelled using SolidWorks 2015 software as shown in Figure 2. Table 4 shows the comparison of new electric kettle design and the existing electric kettle.
### Table 3. Conceptual Selection of New Electric Kettle Design

| NO | FUNCTION                  | SPECIFICATION |
|----|---------------------------|---------------|
| 1  | Kettle Body Material      | Stainless Steel |
| 2  | Kettle Lid Material       | Stainless Steel |
| 3  | Kettle Handle Material    | Plastic       |
| 4  | Kettle Base Material      | Plastic       |
| 5  | Heating Element Type      | Flat          |
| 6  | Temperature Control       | Electronic    |
| 7  | Joining Methods           | Screws        |
| 8  | Screw Material            | Stainless Steel |
| 9  | Screw Head Types          | Flat          |
| 10 | Power Button Type         | Toggle        |
| 11 | Power Button Shape        | Round         |

*Figure 2. A 3D Drawing of New Electric Kettle Design in SolidWorks Interface*
Table 4. Comparison of new electric kettle design and existing electric kettle

| Existing Electric Kettle | Newly Designed Electric Kettle |
|--------------------------|--------------------------------|
| Plastic Walls of the electric kettle body are not really heat resistant and can cause severe scalding issues. | New double walled design makes the hot water only come in contact with the inner layer making the outer layer less hot to touch. |
| Plastic material is not really environmentally friendly and has end of life issues of sustainability as because it cannot be fully recycled and ends up as plastic waste material. The plastic material also starts to leech chemicals into the water after some long usage. This effects indirectly the health of the person using the kettle. | The new stainless-steel design is focused at helping with the end of life recyclability issue of the electric kettle. Stainless steel is one of the most recycled material in the world and thus this reduced its environmental effect. This stainless steel also does not leech chemicals into the water thus making it a more socially concerned product. |
| The old electric kettle is set to a default temperature and sometimes over boils the water due to its thermostat sensitivity. | Water used need not be boiling hot to make a simple drink. The new electric kettle contains better electronic temperature control system which can boil water to a certain temperature as needed by the user. |
| The old electric kettle is not very ergonomically designed, and this can lead to people touching the wrong parts of the kettle and getting their selves a burn. | The new electric kettle design has an ergonomic handle so that the user comes in contact with the kettle at proper places. The lid is also designed flat with a small hole in between so that if ever the user touches the kettle that small hole will be where his hand will touch the lid. |
| The old electric kettle has a heating element that comes in contact with the water. This provides a means for the heating coils to get coated with a layer of scale that reduces the efficiency of the heating element as a whole which in turn translates to a higher electric power consumption. This scale slowly corrodes the heating element. | The new electric kettle has a flat heating element located at the bottom of the kettle. This new design does not make the heating element come in contact directly with the water making it more efficient for a longer time and reduces the chances of scale deposits on the heating elements corroding. |

3.5 Verifying the Sustainability of Newly Designed Electric Kettle through a Sustainability Analysis in SolidWorks Software and DFMA Software

The main purpose of this analysis is to determine the environmental impact of a specifically designed product in terms of carbon footprint, air acidification, water eutrophication and total energy consumed throughout the lifetime of the product. The result of the environmental effects this product has is based on four major aspects of considerations which are material production, product manufacturing region, region for product use, end of life and transportation.

The sustainability analysis will be applied to evaluate sustainability of the new electric kettle design and compare its performance with the existing electric kettle design. By referring to the results of sustainability analysis component of the SolidWorks software, it can be clearly seen that there are differences on environmental impact level among the new and existing electric kettle design. Table 5 shows an in-depth comparison of the values obtained from the Sustainability Analysis Report. From Table 5, it can be seen based on the results each electric kettle is ranked by their environmental impact. Based on the result the new design has a lower impact on the environment when compared to the existing electric kettles design. Therefore, the new conceptual design of the electric kettle is able to bring benefits to the environment and can reduce the negative impacts on the environment. The main components of the electric kettle which is mainly using low impact materials like stainless steel helped this new design concept fare much better in this analysis.
### Table 5. Sustainability Report of New and Existing Electric Kettle Design

| Sustainability Analysis                  | New Design | Existing Design |
|------------------------------------------|------------|-----------------|
| Carbon footprint (kg CO2e)               | 25         | 46              |
| Total Energy Consumed (MJ)               | 340        | 960             |
| Air Acidification (kg SO2e)              | 0.142      | 0.364           |
| Water Eutrophication (KgPo4e)           | 0.066      | 0.021           |
| The least impact on Environment          | 1          | 2               |

Besides, Table 6 shows that, through the DFMA analysis it can be seen that the new electric kettle assembly is much cheaper to manufacture and assemble than the existing electric kettle. This reduction in time is mainly due to the fact that the setup of the machines in injection molding takes a longer time and the initial tooling investment in these injection molding is very high causing the parts to cost more although plastic is cheaper material. Plastic injection molding also has a high rate of rejects and other heat related forming issues like warping further adding to the waste of material thus reducing the sustainability of the product and increasing its production cost.

### Table 6. Simplified Version of DFMA Report

|                             | Existing Product | New Product |
|-----------------------------|------------------|-------------|
| Total Cost per Product (RM) | 56.14            | 37.56       |
| Total Assembly Time (s)     | 253.46           | 63          |

### 4. Conclusion and Recommendation

In conclusion, it can be deduced that the main research objective of the study which is to improve product sustainability using Design for Six Sigma (DFSS) approach has been successfully achieved. The DFSS approach is used in this study to redesign an existing electric kettle that incorporates more sustainability related considerations in its build based on the customer requirements. Throughout each of the 5 phases of DFSS, from Define to Verify phase, the DFSS approach has provided means to incorporate rigorous design tools and processes to generate a better product design that has sustainability considerations in its core design process.

DFSS methodology serves as a very good approach to develop new products or redesign an existing product because this approach employs specialized tools as a guidance to ensure the outcome of design will achieve customer needs. For this study, a new electric kettle design was generated using the DFSS approach where this approach was proposed to reduce negative environmental impact and minimize products waste and also promote the use of low environmental impact materials. Replacing plastic parts with stainless steel makes more sense because it is recyclable and sustainable while being tough and have a better surface finish. The conceptual design of the new electric kettle has been verified to be much more sustainable that its predecessor, the existing electric kettle by using SolidWorks software.

In this study, the new conceptual design was only based on the materials used in the kettle and its impact on the environment. The other main elements in the electric kettle like the wiring and the efficiency of the heating coils was not really focused in this study. This field has a possibility to be further explored and if it is successful, it can further improve the sustainability of the electric kettle.
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