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Sensitivity Analysis of an Eco-design House of Quality Model

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Abstract This paper studies the sensitivity of an “eco-design” based House of Quality process using a case study related to the design of a medical forceps. The sensitivity analysis measures the effect of the three categorical scales used in the House of Quality to establish the relationship between stakeholder’s requirements and the engineering characteristics of products. The developed methodology for sensitivity analysis is applied to a case study to illustrate the influence that the selected levels have on the importance rating of the product engineering characteristics. A full factorial procedure is embedded within the process to enable an assessment of the stability of the ratings produced. The goal is to ensure that the designer is guided towards identifying the highest priorities including the eco-design parameters that should be adopted to produce a more sustainable product.

Keywords. Eco-design, House of Quality, Sensitivity analysis

1. Introduction

Customers are becoming more environmentally conscious. As society embraces higher levels of environmental awareness, new and developed products need to evolve to meet the needs aligned to this demand. From a product development process perspective, this current trend has resulted in much greater emphasis on environmental parameters. All phases in the product life cycle which typically include resource extraction, production, distribution, product use and disposal, are thus increasingly subjected to socio-ecological considerations to ensure sustainable product development [1,2]. The integration of environmental requirements into every stage of product development contributes to the establishment of a sustainable paradigm for manufacturing.

A number of methodologies have been developed in support of the new paradigm, ranging from simple methods, tools, and guidelines to more complex techniques such as life-cycle management frameworks [3, 4, 5]. The success of an eco-friendly design cannot however be judged merely from the environmental viewpoint. Product sustainability needs to be evaluated from both environmental and economic perspectives. In an ideal scenario, eco-design will be able to reduce both the environmental impact and production cost throughout product life cycles simultaneously. In reality, it is a challenge to strike an appropriate balance between environmental elements while keeping the production cost as low as possible. In meeting this challenge, knowledge of the various methodologies that align technologies and creativity within the implementation of eco-design concepts would help in product development stages.

Quality Function Deployment (QFD) was not specifically developed to enhance environmental awareness in product design. It was initially proposed to improve quality, reduce the time of the development process and increase organisational capabilities [6]. Its main objective is to map customer requirements to product characteristics allowing engineers to calculate their relative importance [7].

The methodology outlined in this paper uses the eco-design house of quality (Eco-HoQ) model that has been previously proposed [5] to ensure that product development embraces environmental considerations throughout the product life cycle. The aim of this study is to analyse the Eco-HoQ results by varying the numerical values assigned to the qualitative scales used in this process. This sensitivity analysis will help designers improve the quality of the product design and choose an optimal manufacturing and end-of-life strategy during the design stage.

The next section gives a brief overview of the related work on QFD. The experiment design is described in Section 3. The case study and evaluation of the experiment is presented in Section 4. The final section draws the conclusions.

2. Background of the study

In ISO 14040 standard [8], sensitivity analysis is described as a systematic procedure for estimating the effects of the choices made regarding methods and data on the outcome of a study. Sensitivity is analysed in this paper by the response of the Eco-HoQ model to variations in the rating scales used to weight and rank the eco-design quality characteristics (QC). Measurement is achieved by monitoring the impact of the variations on the conclusions to be drawn from the Eco-HoQ model.

QFD is a concurrent engineering tool for product development that helps translate the customer’s requirements into product design [9]. The house of quality (HoQ) matrix is the central construct of QFD and one of the most popular QFD tools [7]. It is described as “a conceptual map that provides the means for inter functional planning and communications” [10]. Its objective is to translate customer requirements into target values for the product engineering characteristics. It allows engineering characteristics that are the most promising for improving customer satisfaction and associated target values to be selected and set systematically and quantitatively [6]. This is achieved using a QFD relationship matrix in which degrees of correlations between customer requirements and product engineering characteristics are first assessed using symbols representing categorical scales. Typically the scales used are strong, medium and weak. A non-entry (or blank space) indicates that no relationship is determined. Later in the QFD procedure these categorical scales are converted to numerical rating values.

There are two types of numerical rating scales: linear and exponential. Examples of typical linear scales are 3-2-1 [11] and 5-3-1 [12]. The exponential scales that have been proposed include 4-2-1 [13] and 9-3-1 [10]. For all these scales, the biggest number represents a strong relationship, the smallest number represents a weak relationship and the other number represents a medium relationship. The most well-known rating scales used are the 5-3-1 (linear scale) and the 9-3-1 (exponential scale) [6]. A review of the application of these scales showed that linear scales were used in 41 out of 274 studies and exponential scales were used in 228 out of 274 studies [7]. However, none of the applications provided an explicit justification for the choice of rating scales.

The effect of the allocation of rating scales has been analysed by Park and Kim [14] who criticize the 9-3-1 rating scale and propose the use of a cardinal scale. This scale is proposed to equip the HoQ with a better way for assigning relationship ratings between customer requirements and design requirements. Other research [15] consider the use of five rating scales, which are 9-3-1, 7-3-1, 5-3-1, 9-3-0 and 4-2-1. The effect on the QFD process outputs arising from using the most common rating scales 9-3-1 and 5-3-1 has been examined [7] by using weighted sum and allocated sum to quantify the relative importance of QC. In all of these previous studies, it is clear that the rating scales are already set. This potentially produces a bias, which is one of aspects explored in this paper.

It is necessary to measure the sensitivity of processes in order to identify or grade parameter importance [16]. The research literature, however, indicates a very limited number of sensitivity studies applied to validate the robustness of the QFD process [15]. This paper reports a full factorial Eco-HoQ analysis, which measures the robustness and reliability of the approach by varying the scales used for numerical rating, and determining the level of importance of the QC considered. It is intended that this analytical tool can be applied to all subsequent QFD operations.

3. Experimental Design in Eco-HoQ Methodology

Figure 1 shows the Eco-HoQ model as a design tool supporting the assessment of the customers, recyclers, manufacturers requirements, including considerations of the environmental factors [5]. It consists of 6 sections.

Section (1) is used to define and prioritise stakeholders' demanded quality (DQ) requirements. These are essentially a list of customer needs which are developed in consultative forums during all stages of the project. They are focused on product and process sustainability considerations that need to be integrated into each phase of the concurrently executed "normal" QFD process [3]. In this way the development and application of the Eco-HoQ will be conducted in conjunction with determination and considerations relating to product planning, part deployment, process planning and production planning.

Section (2) is used to generate environmental parameters as defined within a set of demanded quality characteristics (QCs) that are based on the product specifications and identified sustainability parameters. These parameters are represented the technical specification of the product and manufacturing processes used in its production. The sustainability considerations are formed via the assessment of environmental impact using life cycle assessment (LCA) which enables the production of the environmental profile data.

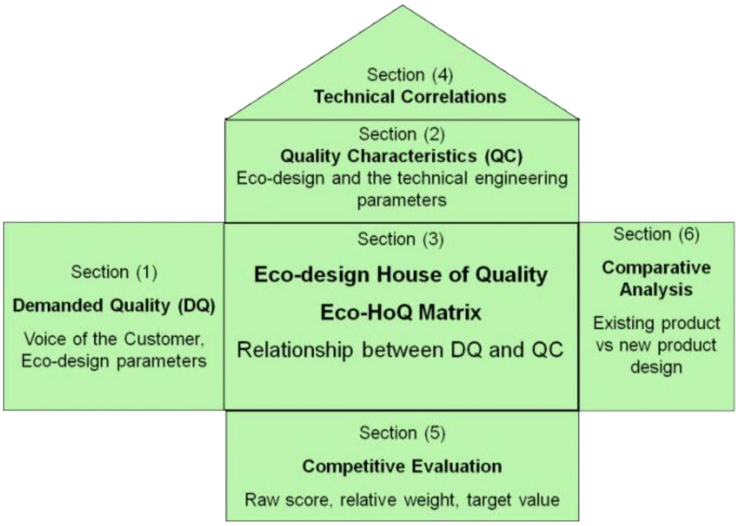

Figure 1: The Eco-HoQ model.

Section (3) represents the Eco-HoQ matrix which maps the degrees of correlation between DQs and QCs. These are assessed using various forums, consisting of all interested parties, normally using a qualitative three level rating scale to represent strong, medium or weak relationships. The absence of any entry is representative of the existence of no relationship. The next step is to multiply each cell’s value (represented by the chosen symbol) with the importance weights allocated to each DQ to provide the cell’s score.

Section (4) is used to identify interrelationships between QCs in the form of positive or negative correlations. These are recorded in order to ensure that all potential impacts arising from future changes to any QC are identified and raised as part of the process supporting such changes. Such changes are inevitable during the enactment of a product design and manufacturing process and this facility enables the appropriate considerations of impact upon sustainability issue that can arise.

These scores are used in two analyses; the competitive evaluation of QCs in Section (5) and the comparative analysis of DQs in Section (6). In both analyses the total scores for each parameter are calculated as sums; vertically in section (5), horizontally for section (6). The interactive computer based solution provided by the deployed Eco-HoQ allows users to explore the impact on sustainability of developments and design decisions. This is undertaken in this specific location, with feed into and back from the four stages of the QFD process.

The scores entered in section (5) are used as the basis of ranking the relative importance of the QC attributes. These are usually normalized to a percentage, which enables a simple ranking to be applied. In the Eco-HoQ, the QCs include inputs focusing design attention upon environmental considerations. The last step in the Eco-HoQ process is to establish the importance of the eco-design parameters in this case. This is achieved using the analysis conducted within section (5) by identifying the highest total scores, which are associated with design elements needed to satisfy the stakeholders' requirements. This score is an indication of the importance eco-design parameters in meeting the customer's satisfaction.

The process of establishing the actual numerical scores for each cell and thereby for each QC is obviously reliant upon the numerical values allocated to each of the three scale symbols. The assessment of the robustness of such a process, and the dependence that the solutions have upon the specific values used to convert the qualitative representation of relationships provided by the use of the three symbols into these numerical value allocations is the purpose of this research. It is clearly very important that a value be set for each symbol that represents the intention of those determining the level of such a relationship. Thus, there is a need to determine if, for example, changing from a 9-3-1 to a 5-3-1 allocation for the strong-medium-weak has an effect on subsequent decisions.

Figure 2 shows a design experiment to conduct sensitivity analysis to assess the effect of the values selected on the relationships between DQs and QCs in the Eco-HoQ model.

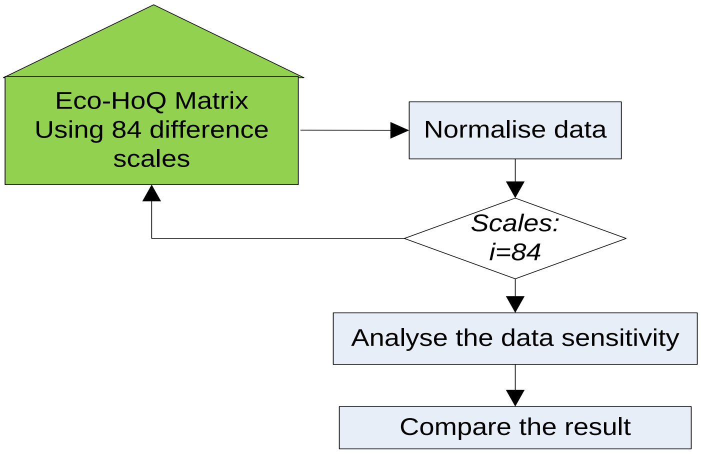

Figure 2: Design experiment

There are 84 possible scales that may be used in the Eco-HoQ matrix based upon the starting point of using a maximum value of 9 and a minimum value of 1. Each of these scales, shown in Table 1, were employed within the Eco-HoQ analysis tool to examine the impact that their relative values have upon the ranking achieved for the QC parameters.

Table 1: Tested combinations of strong-medium-weak values

9-8-7	9-8-6	9-8-5	9-8-4	9-8-3	9-8-2	9-8-1	7-6-1	7-6-2	7-6-3	7-6-4	7-6-5
	9-7-6	9-7-5	9-7-4	9-7-3	**9-7-2**	**9-7-1**	**7-5-1**	**7-5-2**	7-5-3	7-5-4	
	8-7-6	9-6-5	9-6-4	9-6-3	**9-6-2**	**9-6-1**	**7-4-1**	**7-4-2**	7-4-3	6-5-4	
		8-7-5	9-5-4	**9-5-3**	**9-5-2**	**9-5-1**	7-3-1	7-3-2	6-5-3		
		8-6-5	8-7-4	9-4-3	9-4-2	9-4-1	7-2-1	6-5-2	6-4-3		
			8-6-4	8-7-3	9-3-2	9-3-1	6-5-1	6-4-2	5-4-3		
			8-5-4	8-6-3	8-7-2	9-2-1	**6-4-1**	6-3-2			
				8-5-3	**8-6-2**	8-7-1	6-3-1	5-4-2			
				8-4-3	**8-5-2**	**8-6-1**	6-2-1	5-3-2			
					8-4-2	**8-5-1**	5-4-1	4-3-2			
					8-3-2	8-4-1	**5-3-1**				
						8-3-1	5-2-1				
						8-2-1	**4-3-1**				
							4-2-1				
							3-2-1				

The aim of this process is to investigate the robustness of the Eco-HoQ process by conducting a sensitivity analysis. This analysis is based upon observing changes to QC prioritisation and the effect it may have on the final output. This experiment can be best presented in terms of the implementation of the approach to a case study.

4. Case study

A case study is conducted for a company engaged in the provision of single-use surgical instruments. A key product range is selected based on the development of sterile single-use medical forceps used primarily for Ear Nose and Throat (ENT) surgery. A representation of the current product that is used in this case study is shown in Figure 3. The assessment of the environmental impact of the material selection, manufacturing process, use of the product and end-of-life considerations associated with this product is performed in this case study using the Eco-HoQ.

Table 2 shows the parameters and allocated weightings used in the DQ section; they consist of two categories: customer and environmental requirements. This section describes the consideration of sustainability within all phases of product design, development and manufacture. Each DQ is weighted using a scale between 1 and 5 to register identified priorities.

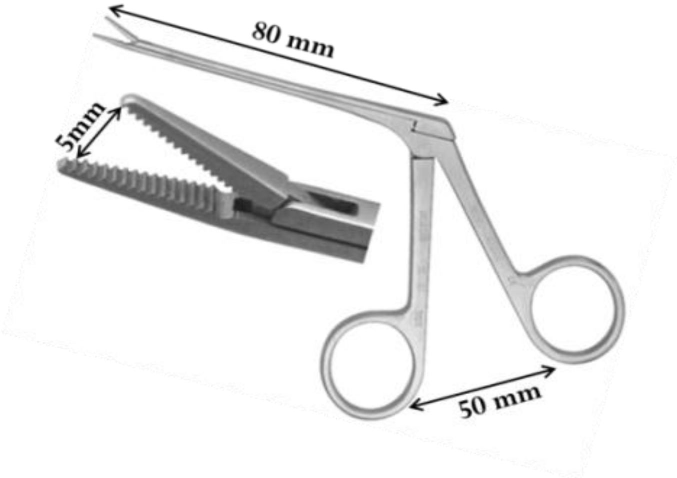

Figure 3: The medical forceps used in this case study.

Table 2: List of demanded qualities (and their weights)

Customer and environmental requirements	
Lightweight (1) Easy to process and assemble (3) Easy to transport and retain (3) Less energy consumption (5) Material Durability (5) Low cost (5) Easy to reuse (5) Easy to disassemble (3)	Easy to clean (3) Easy to smash (1) Easy to sort (1) Safe to incinerate (3) Safe to landfill (3) Harmless to the living environment (5) Safe emission (3) Possible to dispose of easily (5)

Table 3 shows the QC inputs including those acquired from the design specification of the product and eco-design parameters. These represent the technical specification of the product and manufacturing processes used in its production.

Using a programme embedded within the Eco-HoQ procedure the results of the analysis were transformed into numerical values for each of the 84 possible scale combinations shown in Table 1. This resulted in a series of scores for each QC. In each case, these are normalised to a percentage and ranked in order of their relative importance in meeting the required medical forceps attributes. The rankings produced for every test are analysed to provide a count of the position of each parameter. The result of this analysis is shown in Figure 4.

Table 3: Quality characteristics and eco-design parameters

Quality Characteristics	**Eco-design Parameters**
Weight	Carbon footprint
Volume of parts	Water eutrophication
Number of parts	Air acidification
Number of materials	Manufacturing region
Hardness	Rate of recycled materials/ parts
Product life span	Biodegradability
Per-use cleaning cost	Toxicity of materials
Cost per unit	Total energy consumed

Weight/Importance		Quality Characrecristics (QC) (Environmental Engineering Matrix (EM)) / Demanded Quality (DQ) (Stakeholder's requirements)	Weight	Volume	Number of parts	Number of materials	Hardness	Product life span	Per use cleaning cost : auto clave	Cost per unit	Carbon footprint	Water eutrophication	Air acidification	Manufacturing region	Rate of recycled materials	Biodegradability	Toxicity of materials	Total energy consumed
1	Environmental requirements	Lightweight	●	●	●	●	△				●	●	●		●	●	●	●
3		Easy to process and assemble	●	●	●	●		△			●	△	△	●	△	△	△	△
3		Easy to transport and retain	●	●	●	●					●	△	△	●	△			●
5		Less energy consumption	●	△	●	●	●	●			●	●	●	●				●
5		Material durability	◆	◆	△	◆	●	●			△	△	△					△
5		Low cost	●	●		△	●	●		●				●	●			
3		Easy to reuse	△	△	△	△		●			●	●	●				△	●
3		Easy to disassemble	△	△	●	●											△	
3		Easy to clean	△	△	●	●	△							△			△	
1		Easy to smash					△										△	
1		Easy to sort	●	●	●	●	△											
3		Safe to incinerate	△	△	●	●	◆										△	
3		Safe to landfill	◆	◆	△	●										●	●	
5		Safe to living environment	◆	◆	◆	●					●	●	●	●			●	●
3		Safe emission	◆	◆	△	●					●	●	●	●			●	●
5		Possible to dispose at ease	●	●	●	●	△								●	●	●	
		Weight / Importance	415.0	410.0	385.0	441.0	244.0	186.0	0.0	45.0	247.0	241.0	241.0	240.0	147.0	105.0	281.0	244.0
		Relative Weight	10.7	10.6	9.9	11.4	6.3	4.8	0.0	1.2	6.4	6.2	6.2	6.2	3.8	2.7	7.3	6.3

Key: ● Strong relationship △ Medium relationship ◆ Weak relationship

Figure 4: Relationship strength between DQs and QCs using scale 9-8-7

5. Discussion

Figure 5 shows the results of this analysis, with the basic count for the ranking of each parameter given. Thus, for the QC “Number of parts” the analysis shows three possible rankings and occurrences of each; it is ranked number 2 in 47 tests, number 3 in 18 and number 4 in 19. Figure 5 has been shaded to indicate the occurrences of the maximum frequency ranking for each of the 16 parameters. It also indicates the maximum number of occurrences for each parameter, mean rank and modal positions. These results are used to complete Table 4, which shows the final ranking of the QC eco-design priorities identified. The table also shows the overall percentages of this ranking position and the alternative rankings produced.

Ranking		Weight	Volume of parts	Number of parts	Number of materials	Hardness	Product life span	Per use cleaning cost : auto clave	Cost per unit	Carbon footprint	Water eutrophication	Air acidification	Manufacturing region	Rate of recycled materials	Biodegradability	Toxicity of materials	Total energy consumed
Frequency Max	1	0	0	0	84	0	0	0	0	0	0	0	0	0	0	0	0
	2	41	0	47	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	43	21	18	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	61	19	0	0	0	0	0	0	0	0	2	0	0	0	0
	5	0	1	0	0	0	0	0	0	8	0	0	18	0	0	64	0
	6	0	1	0	0	0	0	0	0	76	0	0	0	0	0	0	0
	7	0	0	0	0	1	0	0	0	0	0	0	42	0	0	14	33
	8	0	0	0	0	3	0	0	0	0	11	11	14	0	0	6	51
	9	0	0	0	0	2	0	0	0	0	72	72	1	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	1	1	5	0	0	0	0
	11	0	0	0	0	75	4	0	0	0	0	0	2	0	0	0	0
	12	0	0	0	0	3	80	0	0	0	0	0	0	0	0	0	0
	13	0	0	0	0	0	0	0	0	0	0	0	0	84	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0	0	84	0	0
	15	0	0	0	0	0	0	0	84	0	0	0	0	0	0	0	0
	16	0	0	0	0	0	0	84	0	0	0	0	0	0	0	0	0
Max num		43	61	47	84	75	80	84	84	76	72	72	42	84	84	64	51
Mean Rank		2.5	3.8	2.7	1.0	10.8	12.0	16.0	15.0	5.9	8.9	8.9	7.0	13.0	14.0	5.5	7.6
Mode		3	4	2	1	11	12	16	15	6	9	9	7	13	14	5	8

Figure 5: The frequency of ranking for 84 sets of scales.

The importance of the eco-design parameters are then classified. Here the ranks of 1 to 6 are considered being “very important”, 7 to 11 are “important” and 12 to 16 are “less important”. The use of this classification allows attention to be centred where it can be most effective. It also serves as a purpose in creating categories which can be used to examine the effect of changing the scale values. The eco-design parameters which are included in the “very important” classification are (in descending order): the number of materials, number of parts, weight, volume of parts, toxicity of materials, and the carbon footprint. Although nearly all of these parameters show at least one alternative ranking, they are usually maintained within the category; only ‘’toxicity of materials’’ has an alternative ranking which falls outside of this, being alternatively ranked at 7 and 8. This result is relevant as it suggests that the Eco-QFD process is robust and can provide a good indication of the main criteria that should be applied in the design process.

Similar behaviour is also observed in the other two classifications. For example, in the "important" classification (rankings 7 to 11) the included parameters are seen to be ranked alternatively, but normally remain within the specified classification. There are however some exceptions. The QC parameter ''manufacturing region'' has five alternative ranks, including 4 and 5; thus, it was deemed to be "very important" in these two cases. Similarly ''hardness'' was alternatively ranked at 12, moving it outside of this category. Finally, for the "less important" classification, only the ''product life span'' parameter has an alternative ranking outside its category (in this case 11) while all the other parameters are ranked accordingly within the category from 12 to 16.

Table 4: QC ranking information.

QC parameters	Ranking for 18 scales	% at ranking for 18 scales	Alternative rankings for all scales	Benchmark ranking for scale 9-3-1	Importance
Number of materials	1	100			Very important
Number of parts	2	56	3,4		
Weight	3	51	2		
Volume of parts	4	73	3,5,6		
Toxicity of materials	5	77	7,8	8	
Carbon footprint	6	90	5		
Manufacturing region	7	50	4,5,8,9,10,11	5	Important
Total energy consumed	8	61	7	7	
Water eutrophication	9	86	8,10		
Air acidification	9	86	8,10		
Hardness	11	89	7,8,9,12		
Product life span	12	95	11	11	Less important
Rate of recycled materials	13	100			
Bio-degradability	14	100			
Cost per unit	15	100			
Per-use cleaning cost	16	100			

The analysis shown in Table 4 indicates that 18 of the set of scales produce identical ranking priorities of the QC. These scales are shown in bold type in Table 1. It is interesting to note that the commonly deployed "5-3-1" ranking is one of these, but the widely deployed alternative "9-3-1" is not. For this reason, the differences arising between the 9-3-1 and the analysis for the 18 scales are indicated in Table 4. This would suggest that some care should be taken when determining the actions to be undertaken following such an analysis, particularly in regard to the middle ranked parameters, where the scale values have the most obvious influence. The positions identified for the lowest ranked parameters are very stable. This can be credited to the influence that having a number of "no entries" in the Eco-QFD shown in Figure 4 has; clearly the value of such an entry remains as zero irrespective of any other changes.

The results provide confidence in the robustness of the deployed Eco-QFD process. The sensitivity analysis procedure embedded within the methodology can inform designers of potential differences associated with the selection and application of suitable scale weightings. To date this has been confined to the completion of the competitive evaluation (section 5 in Figure 1) of the Eco-QFD process. It will also be important to apply the approach to the comparative analysis (section 6 in Figure 1) of the demanded quality parameters. This will enable a greater level of confidence with regards to the understanding of customer priorities. Where this may be most relevant is in the incorporation of eco-design and sustainable considerations into customer thinking. This is a relatively straightforward process that requires the application of the scale weighting procedure to the analysis of the results provided in the comparative analysis section. It is hoped that the outcome of the process may be beneficial to customers as to their requirements in a way that may be reflected across their organisation rather than be confined to a single product.

6. Conclusions

The application of an Eco-HoQ process using a case study relating to the design of a medical forceps has been presented. A sensitivity analysis is used to assess the effect of varying the numerical values allocated to the scales underpinning the procedure used to form the ratings within the Eco-HoQ matrix. The performed sensitivity analysis is intended to support an increased understanding of the relationships between stakeholder requirements and product engineering characteristics in the decision process. It allows greater confidence to be placed in the results of the Eco-QFD procedure being a representation of the required relationships rather than an arbitrary effect of scale value selection.

The operation of the sensitivity analysis can be integrated within the procedure used to generate and populate the Eco-HoQ matrix. Running the model developed then assures that users can take into account any level of uncertainty arising from the different set of scales. This study has shown that, although different sets of scales are used, they generally produced only small differences to the result. This means that the results of the Eco-HoQ method are normally robust and stable. However, it is also clear that some significant differences may arise and it is important to know when and where these happen to avoid committing resources incorrectly. This will help the designer to identify the highest priorities of product requirements and eco-design parameters that should be adopted to produce a more sustainable product.

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