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ESTMATING COST & IMPROVING TRADE-OFF BETWEEN PERFORMANCE AND COST AT THE EARLY DESIGN STAGES

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ABSTRACT
Typically 70% to 80% of a product's cost is said to have been committed by the end of the conceptual design stage [1]. Because of the importance of the conceptual stage, cost estimation should be carried out as accurately as possible to provide valuable information to product designers. Despite this level of built in costs at the conceptual stage of design, having useful cost estimates at this stage is very difficult, due to the limited availability of data, especially for new products when product specifications are expressed as a range of values. The main aim of the research presented in this paper is to use the Taguchi method of Design of Experiments in order to use the sparse and available conceptual information more effectively to estimate the cost of a product. A review of the literature about cost estimation techniques and the available information at the conceptual stage of design is presented. A case study is also presented and used to illustrate how the Taguchi method of Design of Experiments is applied in order to assist designers at the conceptual design stage to reduce uncertainty of cost estimates and to carry out a more informed trade-off between performance and cost.

Keywords: Cost estimation techniques, design process, concept development, design of experiments

1 INTRODUCTION
When designers start to design a new product, cost is a critical factor in determining whether the product will be produced or not. Estimating cost can play a significant part for designers in assessing the design and manufacture of a part in detail. The more accurate the cost estimate the better the results in design. Asiedu and Eu [2] state that; the greater the underestimate the greater the actual expenditure, the greater the overestimate the greater the actual expenditure and that the most realistic estimate results in the most economical project cost. Figure 1, the Freiman curve [3], shows the relationship between overestimation, underestimation and the product cost. The figure indicates the importance of accurate cost estimates in product design in terms of business outcomes.

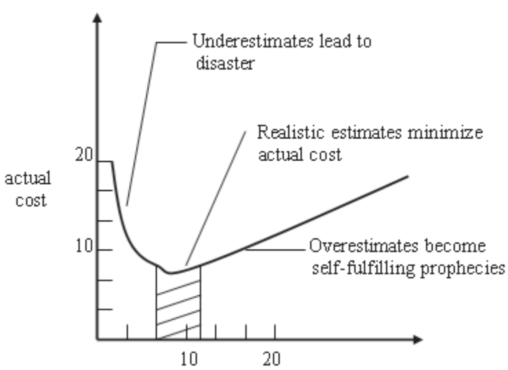

Figure 1. The Freiman curve [3].

In the design process, there are a number of design stages which vary from company to company although most accept that the conceptual and design process can be broken into the conceptual, embodiment and detail design stages [4]. Cost estimation accuracy differs from one stage to another. The accuracy of a cost estimate in the conceptual stage of design is lower than in the detail design stage. That is because, at this stage, available information is limited and also designers need to consider cost and uncertainty. As only basic information is available at the conceptual design stage, cost estimating tends to be inaccurate and of low priority. However, it is at this stage that the costs of a product become in-built [5]. Studies show that 70% to 80% of the product cost is in fact committed by the end of the conceptual design stage [1]. Mileham *et al*. [6], Dowlatshahi [7], Hundal [8] all agree that 70%-80% of a product cost is determined during the early design stage. Rehman and Guenov [9] and Ullman [10] both indicate that about 75% of the manufacturing cost of a typical product is committed by the end of the conceptual design stage. Although researchers understand the importance of cost estimation at the conceptual stage of design, in general cost estimation in industry is usually very limited or does not happen as the information is sparse and so designers wait until more detail and information is available [11]. The main aim of the research presented in this paper is to use the Taguchi method of design of experiments (DOE) in order to use the sparse and available information more effectively to estimate the cost and reduce the uncertainty of cost estimates. This can assist designers to consider cost as one of the factors at the conceptual stage of design in order to select the most appropriate concepts. Also it paves the way for designer to undertake trade-off analysis between performance and cost.

2 COST ESTIMATION TECHNIQUES AND THEIR APPLICARION

Life cycle costs (LCC) are the costs from inception to disposal for equipment, products, projects etc as typically determined by an analytical study and estimate of the total costs experienced in annual time increments during the products life with consideration for the time value of money [12]. A life cycle cost analysis calculates the cost of a system or product over its entire life span**.** These costs accumulate from the initial product concept or order, through product development, production, to its eventual disposal. Figure 2 indicates the composition of life cycle costs. Ehrlenspiel, *et al*. [13] explain that life cycle cost consists of two different sections including; manufacturer's costs and user's costs. Life cycle cost is the sum of these sections. According to them, user's costs consist of purchase price, one-time costs, operating costs and maintenance costs. Manufacturer's costs or total cost consists of manufacturing costs (production costs + material costs), environment and disposal costs and overhead costs. The research presented in this paper is based on using the Taguchi method of design of experiments to estimate the manufacturing cost. The same method will be used in the future to estimate life cycle cost.

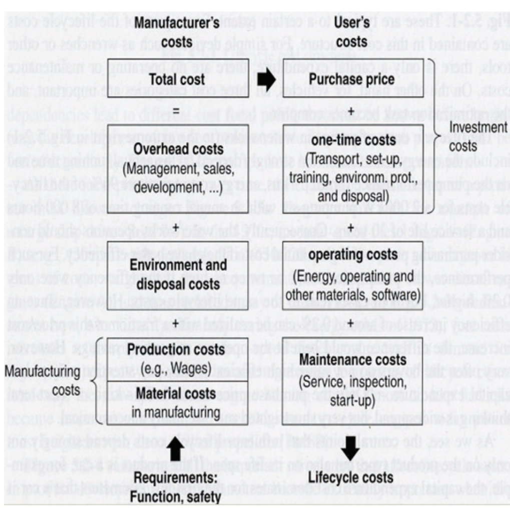

Figure 2. Composition of lifecycle costs [13].

There are several; different methods for evaluating future cost, but not all of these are suitable for the whole life cycle. Some methods are better than others depending on the context. Farineau *et al* [14] and Ben-Arieh [15] explain that cost estimation methods can be divided into four categories; intuitive, analogical, parametric and analytical. Roy [16] describes the cost estimation domain using five methods: traditional, parametric, feature based, case based reasoning and neural networks. Niazi and Dai [17] categorise cost estimation into qualitative and quantitative approaches. Qualitative cost estimation techniques are useful at the conceptual stages of product development. These techniques are based on identifying the similarities of new and manufactured products. On the other hand, quantitative techniques are based on detail analysis of a product. Most of these methods however are not applicable to the whole life cycle and some are better for some stages than others depending on the context. Farineau *et al* [14] suggest that the parametric method can be used in the early design stage or in other words, it can be useful at the conceptual stage of design. According to Farineau *et al* [10], the analytical approach can be applied from the detail design to after sales services stage. Xiachuan *et al*. [18] discuss the precision and uncertainty of cost estimation techniques at different stages of the design process. They suggest that the artificial neural networks (ANN) cost method can be used at the conceptual design stage; ANN and parametric cost methods in the early design stage; then parametric methods can be used at the general design stage and finally, engineering cost methods can be applied at the detail design stage.

3 DESIGN PROCESS AND AVAILABLE INFORMATION AT THE CONCEPTUAL DESIGN STAGE

Although there are different definitions of design, in the majority of cases, it is defined as a new solution to a problem. Various theories and methodologies have been developed in order to improve engineering design processes. Mistree *et al* [19] provide a comprehensive review of developments in the field of design theories and methodologies. Although models of the design processes vary, there are some models, which are widely acceptable to designers with the design process being broken into the three major stages [4]:

1. Conceptual design
2. Embodiment design
3. Detail design

The conceptual design stage defines the basic characteristic of a product. This involves the creation of the functions, which conform to the design specification, and leads to the development solution. At this stage, components generally exist in sketch form and the information describing them is limited. The concept of a product can include; material type, its main features and overall shape. In the embodiment and detail design stage, material specifications, dimensions, surface condition and tolerances are specified in the fullest possible detail for manufacturing.

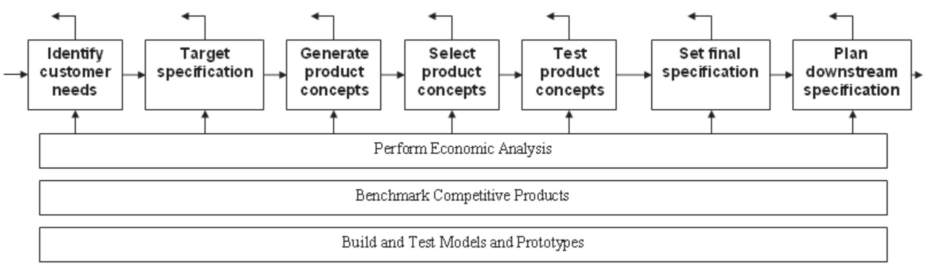

Figure 3. Concept development process [20].

The concept development stage varies from industry to industry and product to product. Ullman [10] introduces three major steps for conceptual design including; generating concepts, evaluating concepts and selecting concepts. Ulrich and Eppinger [20] created a generic diagram (Figure 3), which shows the activities that must be considered for all projects. These activities are: identify customer needs, set target specification, generate product concepts, select product concepts, test product concepts and set final specification. Pahl *et al* [21] explain that conceptual design can be broken into four major steps:

1. Abstracting to identify the essential problems.
2. Establishing Function Structures.
3. Developing working structures.
4. Developing concepts.

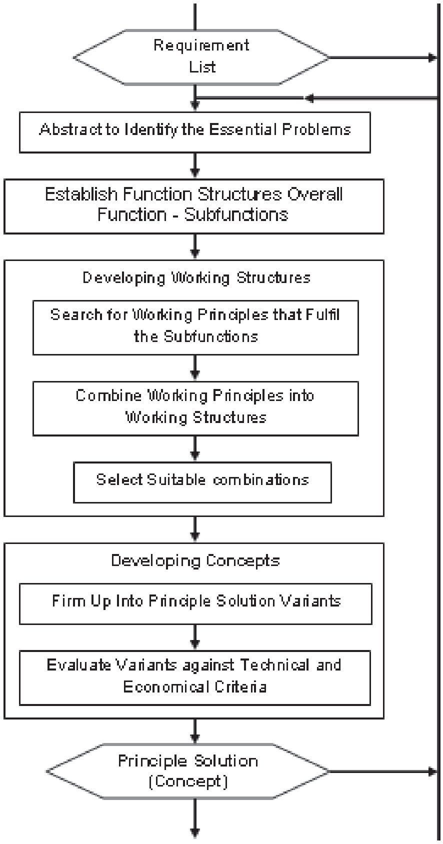

Figure 4. Steps of conceptual design [21].

Figure 3 illustrates that the first step in the conceptual design process is identifying customer needs. Normally designers do not consider this stage part of the concept development process. Ulrich however emphasises the importance of this stage before the concept development process. The next stage is setting the target specification. This stage is normally considered as the first stage in the concept development process. At the target specification stage agreement on the general design functions is achieved. The target specifications are set to meet the design requirements. However, they are established before the designers know what constraints the product technology will place on the design and what can be achieved [20]. Hence, targets are expressed as a range of values. For the target specification the values are wide and are reduced in the final specification list. Since these values are the only available information at the beginning of the concept process development, the aim of this research is to use these values to estimate the cost and reduce the uncertainty of cost estimates. The Taguchi orthogonal array approach is used in this research to evaluate the cost of each concept by combining the product specification values and assess how changing these values influenced the cost. Also the results show how changing these values and selecting an appropriate set of parameters can help designers to reduce the uncertainty of the cost estimate (variance of cost estimated) for each concept at the conceptual stage of design. Table 1 illustrates the target specification for a fluid dispenser used as a case study in this research.

Table 1. The target specification for fluid dispenser [24].

No.	Metric	Unit	Value	Important rating
A	Total mass when full	kg	< 3.5	5
B	Capacity	ml	> 500	5
C	Width	mm	<150	2
D	Depth	mm	<150	2
E	Number of actions to obtain fluid		< 2	5
F	Time to clean and sterilise	minutes	<2	3
G	Number of different drinks		>= 2	3
H	Time to disassemble/ reassemble for maintenance	seconds	20-60	3
I	Number of parts		1-10	3
J	Force required to operate with hands when sitting	N	<2.32	3
K	Time to get a drink	s	<25	2

After estimating the cost and variance for each concept using the values in the target specification, this information can be added to the concept-screening matrix used by designers in order to reduce the number of concepts and to select the final concept. Since the available information is limited at this stage, designers normally do not consider cost as a factor in selecting the final concept. The method presented in this research can assist designers to consider cost as a factor in selecting the most appropriate concepts by adding cost and the confidence level of the cost estimates to the concept screening matrix, shown in table 2 in bold.

Table 2. Adding cost to the screening matrix.

Selection Criteria	**Plunger** (Reference)	**Armband**	**Disposable Cup**	**Camelback**
Ease of handling	0	-	+	0
Ease of use	0	-	-	0
Readability of setting	0	+	+	+
Dose metering accuracy	0	0	0	+
Durability	0	0	+	-
Ease of manufacture	0	-	0	0
Portability	0	0	0	0
COST	**0**	-	-	+
VARIANCE OF COST ESTIMATE	**0**	-	+	-
Sum +'s	0	1	4	3
Sum 0's	9	0	0	4
Sum –'s	0	5	2	2
Net Score	0	-4	2	1
Rank	3	4	1	2
Continue?	Combine	No	Yes	Combine

Designers normally use Quality Function Deployment (QFD) (which can be found in detail in [22]) to transfer customer requirements into engineering functions. This technique is used by designers to rate the metrics (A-K in table 1) of the product specification in terms of performance. The last advantage of using the Taguchi orthogonal array approach in this research is to assess how changing the metrics (A-K in table 1) values influences the cost of a product. In other words, by using the Taguchi approach designers are able to identify metrics or factors which have the greatest impact on cost of a product. This can assist designers to rate the metrics of the product specification in terms of cost and make the trade-off between performance and cost much easier. This will be discussed in detail in the following sections.

4 TAGUCHI METHOD OF DESIGN OF EXPERIMENTS

The principle of robustization attempts to reduce the deviation by considering control and signal factors against noise factors in order to identify product specifications that make the quality characteristics insensitive to noise. Robust Design utilizes the Taguchi method of experimental design and has been used by designers to minimize the deviation of a quality characteristic from its target value in order to improve the quality of products. Taguchi's orthogonal array approach used by designers reduces the number of experiments necessary to determine results for a number of parameter combinations and parameter values. This technique is used in this research to improve the quality of cost estimates (in this case, improving quality is reducing the uncertainty of the cost estimate). As mentioned, target specifications for new products are expressed as a range of values, shown in table1. Because of this uncertainty at the beginning of the conceptual stage of design, cost estimation is very difficult since designers need to combine these values in different levels for different metrics (A-K in table 1). Taguchi's orthogonal array approach allows designers to reduce the number of experiments necessary to determine cost and the confidence level of the cost estimates. To conclude this, Taguchi's orthogonal array approach is used in this research to find input parameters (expressed as a range in product specification) for a new product in order to estimate cost and its deviation. The technique can assist designers to reduce cost deviation (uncertainty of cost estimate) by selecting a set of appropriate input parameters in order to provide designers with more accurate cost estimates. Therefore, the necessary information needed in this research to apply the Taguchi method are the product specification table (table 1) and design alternatives (in any form, preferably in CAD form) for a product. The Taguchi method will be discussed in detail later in the following sections [23].

5 RESEARCH APPROACHES

Figure 5 shows the three phases being applied to validate the proposed DOE approach and its applicability at the concept design stage of a product. The three phases required to validate this research are analyzing the product specification, applying the Taguchi method (estimating manufacturing cost) and selecting the most appropriate concept designs. Each of these phases is described in the next sections via an applied case study.

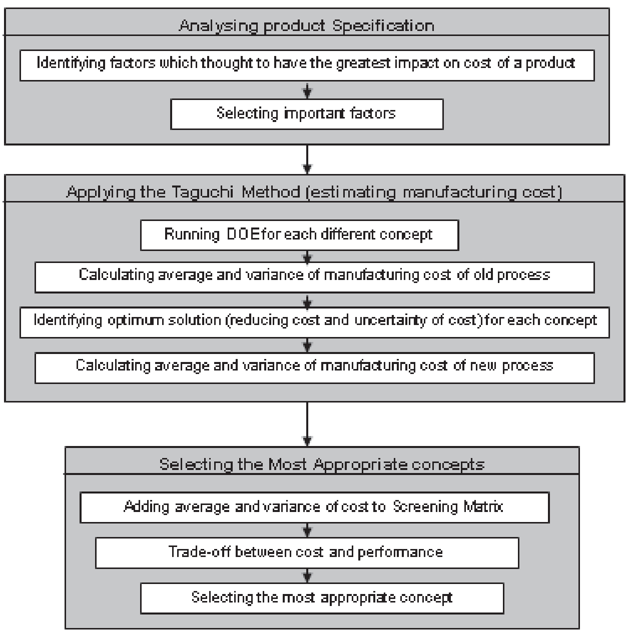

Figure 5. Research methodology.

5 CASE STUDY – FLUID DISPENSER

5.1 Analysing product specification

To illustrate the proposed methodology, a case study was undertaken of the design of a novel fluid dispenser for people who are not able to use conventional cups. A product designer undertook this activity and the user requirements were identified. These requirements were translated into the engineering terms and a target specification created, table 1.

Four concept designs were created based on; a plunger, disposable cup, armband, and camelback, using the defined target specification. The metrics in the target specification were rated in terms of their functionality using Quality Function Deployment (QFD) techniques [24].

By using the proposed DOE technique, the designer was able to evaluate the cost of each concept and assess how changing the values of the product specification influenced the cost. An example where this was relevant in the particular design was the capacity (volume of liquid) the device was to hold. For example, in Table 1, if the value of capacity was increased to 1000 ml the new cost and its accuracy needed to be determined. Similarly if it was changed to 1400 ml the costs again needed determining this could also show how changing these values would influence the confidence level of the cost estimate or in which estimate the company had the highest cost confidence level.

The first stage was to identify the factors which where considered to have the greatest impact on product cost. To identify the factors the Delphi method [25] was used for which more than 15 experts in engineering design and cost estimation were interviewed. This resulted in seven factors (A, B, E, F, G, H and I) being identified as cost sensitive together with five interactions (AxG, GxH, IxG, GxB and AxB) between these factors (see table 3 for the factors and interactions identified).

5.2 Applying Taguchi method

The next step was to select an appropriate Taguchi orthogonal array and as seven factors and five interactions were identified an $L16(2^{15})$ array (16 is the number of experiments, 2 is the number of levels and 15 is the number of factors) was selected. Table 3 shows the orthogonal array for the fluid dispenser case study. After selecting the standard $L16(2^{15})$ orthogonal array, the next step was to assign the factors to the orthogonal array and run the experiments to estimate cost and its deviation for each concept.

To illustrate how this is applied, the plunger-based concept is presented to demonstrate the cost outputs. The 7 factors and 5 interactions were examined in 2 levels (more than 2 levels can be examined if greater accuracy is required), which is illustrated in figure 6. For example for factor A (total mass when full), 3 kg was selected for level 1 and 3.5 for level 2. Appropriate levels were similarly selected for all other factors. Sixteen experiments were carried out and the manufacturing cost of the product for each experiment was estimated (SEER-DFM software was used to estimate the manufacturing cost) and placed in the last column of table 3. For example for experiment 1, the cost of the product was 19.91 cost units for the combination of the factors. The cost of the other experiments was similarly calculated. It is important to notice that the standard orthogonal array ($L16(2^{15})$) and levels of factors should be the same for all the concepts but cost of each was different since their designs are different.

After estimating the product cost for each experiment, the next step was to create a response table of factor effects for unit cost. As shown in table 4, the difference between level 1 and level 2 of each factor was calculated and factors with the highest difference ranked as factors that had the greatest impact on product cost. Figure 6 shows the sensitivity of cost to each factor. As it is shown, factor G had the greatest impact and factor H had the smallest impact on product cost. In order to reduce the uncertainty of cost estimates five factors (G, I, E, F and GxI) which has the greatest impact on the product cost were selected. Because designers are typically looking for minimum product cost, the quality characteristic the "smaller-the-better" was used as the output. Therefore, G1, I1, E2 and F1 were selected as the optimum solution. GxI was not selected since there is no interaction between factor G and I, shown in figure 6 (when there is no interaction then the interaction breakdown is parallel).

Table. 3 Orthogonal array for fluid dispenser.

	I	G	GxI	A	e	GxA	F	B	e	GxB	e	AxB	GxH	E	H	Unit Cost
1	8 parts	1 drink	1	3.0 kg	1	1	1.5 min	1 litre	1	1	1	1	1	1 Action	20 sec	19.91
2	8 parts	1 drink	1	3.0 kg	1	1	1.5 min	1.5 litre	2	2	2	2	2	2 Action	60 sec	19.09
3	8 parts	1 drink	1	3.5 kg	2	2	2 min	1 litre	1	1	1	2	2	2 Action	60 sec	22.02
4	8 parts	1 drinks	1	3.5 kg	2	2	2 min	1.5 litre	2	2	2	1	1	1 Action	20 sec	22.75
5	8 parts	2 drinks	2	3.0 kg	1	2	2 min	1 litre	1	2	2	1	1	2 Action	60 sec	21.52
6	8 parts	2 drinks	2	3.0 kg	1	2	2 min	1.5 litre	2	1	1	2	2	1 Action	20 sec	22.06
7	8 parts	2 drinks	2	3.5 kg	2	1	1.5 min	1 litre	1	2	2	2	2	1 Action	20 sec	24.87
8	8 parts	2 drinks	2	3.5 kg	2	1	1.5 min	1.5 litre	2	1	1	1	1	2 Action	60 sec	22.17
9	10 parts	1 drink	2	3.0 kg	2	1	2 min	1 litre	2	1	2	1	2	1 Action	60 sec	24.1
10	10 parts	1 drink	2	3.0 kg	2	1	2 min	1.5 litre	1	2	1	2	1	2 Action	20 sec	23.27
11	10 parts	1 drink	2	3.5 kg	1	2	1.5 min	1 litre	2	1	2	2	1	2 Action	20 sec	20.56
12	10 parts	1 drinks	2	3.5 kg	1	2	1.5 min	1.5 litre	1	2	1	1	2	1 Action	60 sec	21.29
13	10 parts	2 drinks	1	3.0 kg	2	2	1.5 min	1 litre	2	2	1	1	2	2 Action	20 sec	24.92
14	10 parts	2 drinks	1	3.0 kg	2	2	1.5 min	1.5 litre	1	1	2	2	1	1 Action	60 sec	25.47
15	10 parts	2 drinks	1	3.5 kg	1	1	2 min	1 litre	2	2	1	2	1	1 Action	60 sec	24.93
16	10 parts	2 drinks	1	3.5 kg	1	1	2 min	1.5 litre	1	1	2	1	2	2 Action	20 sec	24.32

Table 4. Response table for factor effects for unit cost.

	I	G	GxI	A	GxA	F	B	GxB	AxB	GxH	E	H
Leve1 1	21.79	21.62	22.92	22.54	22.83	22.28	22.85	22.57	22.62	22.57	23.17	22.83
Level 2	23.60	23.78	22.48	22.86	22.57	23.12	22.55	33.83	22.78	22.83	22.23	22.57
Difference	1.81	2.16	0.44	0.32	0.26	0.84	0.30	0.26	0.16	0.26	0.94	0.26
Rank	2	1	5	6	8	4	7	8	12	8	3	8

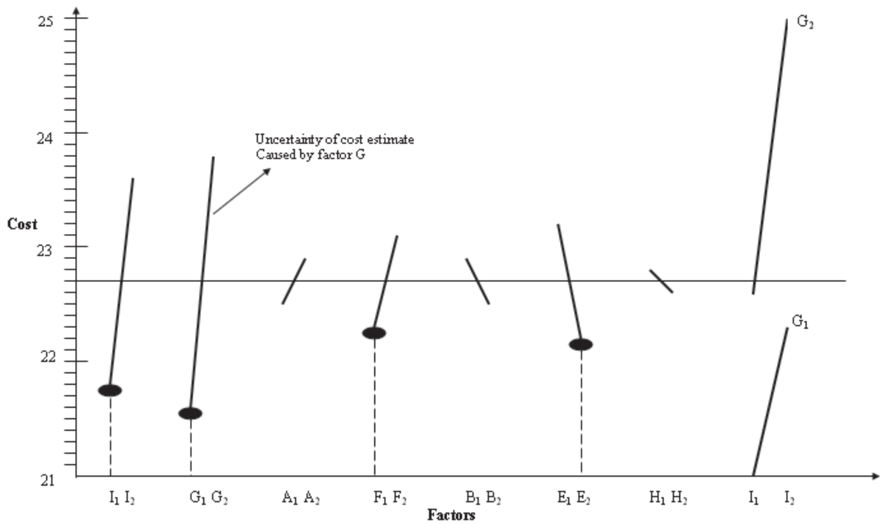

Figure 6. Factors/levels.

5.3 Selecting the most appropriate concepts

After selecting the appropriate factor levels, the next step was to calculate the average cost and uncertainty of the cost estimate (variance) before and after optimization. To calculate the average cost and uncertainty of the cost estimate after optimisation a new orthogonal array was used. Since four factors were selected for optimisation, four experiments were run for the three remaining factors (A, B and H). It is important to notice that since there is no interaction between factors, these interactions were eliminated and were not considered in the new experiment. The standard $L4(2^3)$ orthogonal array was selected and the cost of the product for each experiment was calculated, shown in table 5.

Table 5. $L4(2^3)$ orthogonal array for fluid dispenser.

	A	B	H	Cost
1	3.0 kg	1 litre	20 sec	19.20
2	3.0 kg	1.5 litre	60 sec	19.09
3	3.5 kg	1 litre	60 sec	19.20
4	3.5 kg	1.5 litre	20sec	19.22

The average cost before optimization (ACBO) for the plunger was calculated using table 4 and the equation below:

$$\text{ACBO} = \frac{19.91 + 19.09 + \ldots + 24.32}{16} = 22.70 \text{ (unit cost)}$$

The average cost after optimisation or predicted average cost (PAC) was calculated using table 5 and the equation below:

$$\text{PCA} = \frac{19.20 + 19.09 + 19.20 + 19.22}{4} = 19.17 \text{ (unit cost)}$$

To calculate the uncertainty of the cost estimate the variance before and after optimisation was calculated using; the variance of the cost estimate before optimisation was calculated using table 3 and equation below:

$$\sigma^2_{n-1} = \frac{\Sigma y^2 - nY^2}{n-1} \rightarrow \sigma^2_{16-1} = \frac{8303.97 - 16 \text{ x } 515.29}{15} = \boxed{3.95}$$

The variance of the cost estimate after optimisation was calculated using table 5 and equation below:

$$\sigma^2_{4-1} = \frac{1471.1 - 4 \text{ x } 367.48}{3} = \boxed{0.39}$$

As shown, the average cost before optimization was 22.70 cost units and after optimization the average cost (new average cost) had reduced to 19.17. Also the uncertainty of the cost estimate (variance) for the plunger was reduced from 3.95 to 0.39. The optimum solution was the lowest possible cost and highest possible accuracy of the cost estimates that the designer could achieve by changing the control factors in the design (whilst meeting the specifications). These estimates were added to the Screening matrix (as it is shown in bold in table 2) to help designers to consider cost as a factor in selecting the most appropriate concept at the conceptual stage of design. For example, as is shown in table 2, both the average cost and variance of cost estimates for the armband is higher than the plunger but although the average cost of the disposable cup is higher then the plunger, the variance of the cost estimates for the disposable cup is lower than the plunger. By comparing these the designer was able to consider cost as a factor to select the most appropriate factor.

5.4 Trade-off between performance and cost

As described, designers create a product target specification (table 1) before starting to generate concepts. They rate factors (in this research A – K in table 1) in terms of their functionality or performance using Quality Function Deployment (QFD) techniques [24], the last column in table 1. The aim of this research was to present a method in order to rate these factors also in terms of cost and by putting the performance and cost rating together, designers can carry out a more informed trade-off between performance and cost. Figure 6 shows the sensitivity of cost to each factor. As it is shown in figure 6, factor G had the greatest impact on the product cost but in table 1, the performance rating for factor G was 3. This means that trade-off between performance and cost for factor G was much easier than factors were cost sensitivity and performance rating were both high.

This can be done for each concept and it can pave the way for designers to reduce the number of concepts and select the most appropriate one. For example, in the case of the fluid dispenser, if factor E (number of actions to obtain fluid) is very important for the product (rated 5 in table 1), a concept which has less cost sensitivity to factor E can be selected.

Rating factors in terms of cost also can be used by designers after selecting the final concept. Ulrich and Eppinger [20] indicate that when designers select the final concept, they start to make the specifications more accurate by reducing ranges. By putting the cost and performance rating together, designers should be able to make the specifications more accurate in a more informed manner. For example factor E is important both in terms of cost and performance, therefore designers should be carful when they make the specifications more accurate, but for factor G they should consider cost more important than performance.

6 CONCLUSION

Cost estimation is a critical factor for companies to determine whether their products will be produced or not and since it is known that 70% to 80% of products cost are determined at the conceptual design stage, cost estimation should be accurate and happen as soon as possible. Although researchers understand the importance of cost estimation at the conceptual stage of design, in general cost estimation is usually very limited or does not happen as the information is sparse and so designers wait until more detail and information is available. The new method presented in this paper uses available information at the conceptual stage to estimate the product cost and variance of cost estimates. This can assist designers in considering cost as one of the factors in order to select the most appropriate concept. The Taguchi method of design of experiments has been used to estimate the product cost at the early design stage using the impact of the specification on the manufacturing cost. The manufacturing cost of the product has been estimated and the lowest possible cost and variance for each concept has been calculated. Also how this information can be used by designers to carry out a more informed trade-off between performance and cost has been presented.

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