# Criteria Selection Method in Design Evaluation for Product Development using Integrated Fuzzy-AHP

Design concept evaluation plays a critical role in the early phases of product development as it has significant impact on the downstream development processes as well as on the success of the product developed. In this paper, a novel methodology has been developed involving three stages. The preliminary stage is screening all the criteria from different viewpoints using TRIZ. The second stage uses Fuzzy-AHP to obtain the alternatives weight, and the final stage verifies the rank of alternatives by a Rough-Grey Analysis. This method will give the designers more effective, objective and relevant information in order to make the final decision. A case example from industry is presented to demonstrate efficacy of the proposed methodology. The result of the example shows that the integration of TRIZ, Fuzzy-AHP and Rough-Grey Analysis provided a novel alternative of existing methods to perform design concept evaluation.

Keywords: Design concept evaluation, product development, decision making

## 1. Introduction

In today’s industries, product design has become the main focus of competition in a highly competitive environment and fast-growing global market. Benchmarks used to determine competitive advantage of a manufacturing company are customer satisfaction, shorter product development time, higher quality and lower product cost (Wynne Hsu, 1998). It is widely recognized that up to 70% of the overall product development cost is committed at early design phases (Nevins, 1989). A good design process should take into account these criteria as early as possible in order to ensure the success of a product. Under such a circumstance, design concept evaluation in the early phase of product development plays a critical role as it has a significant impact on downstream processes (Lian-Yin Zhai, 2009). Design concept evaluation which is in the end of conceptual design is one of the most critical decision points in product development. It relates to the final success of product development, because a poor design concept can rarely be compensated at the later stages (Xiuli Geng, 2010).

The important step in designing new products is generating conceptual designs. Conceptual design process includes a set of technical activities, which are the refinement of customer requirements into design functions, new concept development, and embodiment engineering of a new product (Wenqiang Li, 2010). Design concept evaluation is a complex multi-criteria decision making process which involves many factors ranging from initial customer needs to resources and constraints of the manufacturing company. Concept design selection is the process of evaluation and selection from a range of competing design options with respect to customer needs and other criteria, comparing the relative strengths and weaknesses of the concept design, and selecting one or more concept designs for further investigation, testing, or development (Green, 2000). However, how to effectively and objectively evaluate design concepts at the early stage of product development has not been well addressed, as the information available is usually incomplete, imprecise, subjective or even inconsistent. Specifically, the evaluation process relies much on qualitative descriptions and subjective judgments in which design experts with adequate domain knowledge, experience and judgment are required to direct the evaluation (Rosenman, 1993). As such, the quest for more effective and objective approaches to systematically evaluate design concepts in the early stage of design process has invited much research interests.

The success of the complete design depends on selecting the right concept design alternative (Green, 1997). A mismatch between what the customers need, product and manufacturing process causes loss of quality, delay to market and increased cost (Millson, 2004). Changes made early in the design process are less costly than those made in detail design and later stages (Childs, 2004). Any design defect in the conceptual design is very difficult to correct in detail design and will incur further cost in the future (Francis E.H.

Tay, 2002). The process of choosing concept design is frequently iterative and may not produce a dominant concept design immediately (Liu, 2003). A large set of concept design alternatives should be initially screened down to a smaller set because some are clearly not feasible for obvious reasons, such as infeasibility for manufacturing or the cost of producing (Lovatt, 1998). Failing to choose the most appropriate concept design alternative may lead to rework or redesign and waste of resources.

Amongst the various tools developed for design concept evaluation, fuzzy set theory and Analytical Hierarchy Process (AHP) method have received the most attention due to their abilities in handling uncertainty and multi-criteria decision-making (Scott, 2002). The nature of vagueness in design concept evaluation has made this method a topic of considerable interest to many researchers. Although the Fuzzy-AHP method offers many advantages for design concept evaluation, it can be a time-consuming process with the increase in the number of design criteria and design concepts (Lian-Yin Zhai, 2009). This may result in a huge evaluation matrix, and the needs to conduct a large number of pairwise comparisons which may lead to low consistency (Ayag Z., 2007).

This paper aims to reduce the number of design criteria by introducing preliminary stage of design concept evaluation which is screening process using House of Quality (HOQ) method. The results from preliminary stage then will be evaluated using Fuzzy-AHP method with optimum number of pairwise comparisons.

## 2. Literature Review

### *2.1 Design concept evaluation*

Design concept evaluation can be classified into two categories, namely the non-numerical methods and the numerical methods. Generally, non-numerical methods are relatively simple and fast, and are more suitable for quick screening of design concepts for simple applications (Ayag Z., 2007). On the contrary, numerical methods are more systematic and can assist designers to achieve more accurate evaluations, especially for complex design concepts.

Design concept evaluation is a complex multi-criteria decision making (MCDM) problem which involves many factors ranging from task-related factors (e.g. product complexity, initial customer requirements impreciseness and information scarcity) to decision related factors (e.g. the expertise and diversity of DMs, and the method of aggregating judgments) (Zhang, 2009). It is always a group decision-making problem at the same time. Data and information involved in this problem come from design knowledge and experiences at the earlier design stages and subjective judgments of DMs. At the earlier design stages, design information is deficient and imprecise. DMs' judgments often lack precision and the confidence levels on them contribute to various degrees of uncertainty (Lo, 2006). Therefore, how to cope with uncertain and vague characteristics of information is critical to the effectiveness of decision-making. Furthermore, the aggregation method of individual judgments in group decision-making and the alternatives ranking method in the evaluation model are critical to the accuracy and effectiveness of design concept evaluation (Xiuli Geng, 2010).

## *2.2 TRIZ*

TRIZ, an acronym for the Theory of Inventive Problem Solving, began in 1946 when Altshuller, a mechanical engineer, began to study patents in the Russian Navy. This approach has widely been taught in Russia, but did not emerge in the West until the late 1980s. Several different solution systems have been derived by abstracting inventive principles from the ongoing analysis of patent data. Several of these solutions focus on contradictions or trade-offs in identifying innovative solutions (Te-Sheng Li, 2009).

The basic constituents of TRIZ are the contradictions, 40 inventive principles, the contradiction matrix (Domb, 1997; Zoyzen, 1997) and the laws of evolution (Petrov, 2002), the substance-field analysis modeling (Terninko, 2000), ideal final result (Domb, 1997), and substance field resources, and scientific effects (Frenklach, 1998). The core of TRIZ consists of 40 contradiction principles, and the matrix; other tools are auxiliary to assist design engineers in constructing the problem model and analyzing it.

Altshuller's early work on patents resulted in classifying inventive solutions into five levels, ranging from trivial to new scientific breakthroughs (Altshuller, 1999). Figure 1 illustrates this abstraction process, which classifies problems and solutions in seeking correlation that enables a set of generic problem solving operators or principles to be identified.

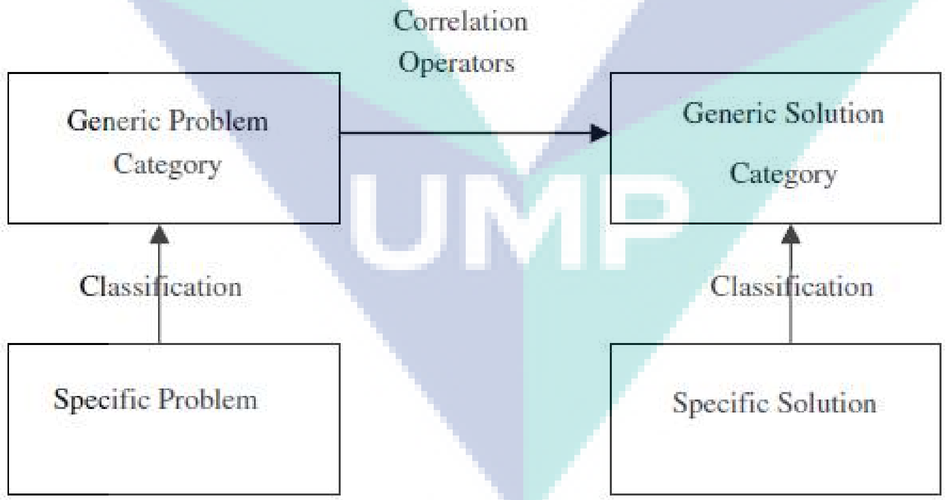


**Figure 1**. The general case for abstracting a solution system

Over a period of time Altshuller identified a further level of abstraction from the technical contradictions (Te-Sheng Li, 2009). He found that by defining the contradiction around one parameter with mutually exclusive states the correlation operators used to detect a solution could be more generic and there are four separation principles used to help resolve this type of contradiction. The separation principles can be summarized as separation of opposite requirements in space, separation of opposite requirements in time, separation within a whole and its parts, and separation upon condition. Figure 2 briefly illustrates the relationship between these two levels of abstraction.

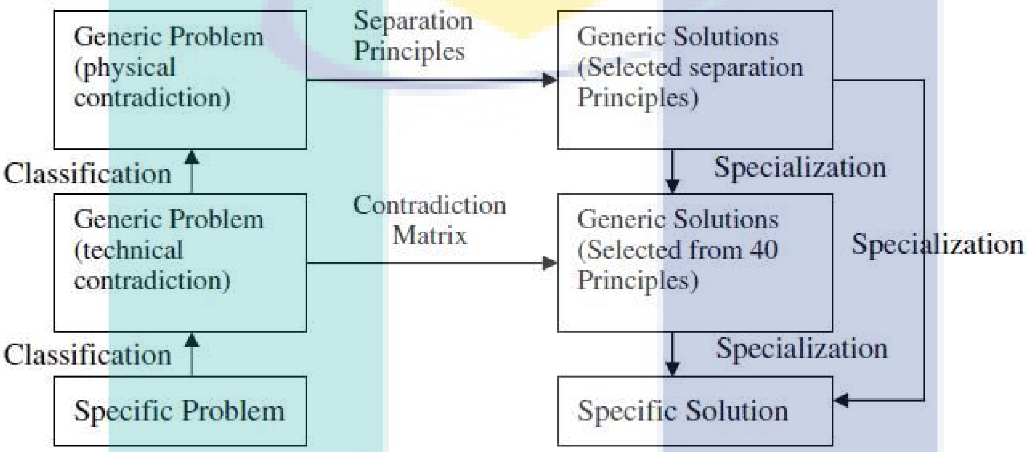


**Figure 2**. The first and second levels of abstraction

### *2.3 Fuzzy-AHP*

The basis of AHP method is the hierarchical representation that helps to solve a complex problem through successive simple processes (Hongre, 2006). It requires a problem to be decomposed into levels, each of which is comprised of elements or factors. The elements of the hierarchy in a given level are mutually independent, but comparable to the elements of the same level. Each element must connect to at least one element of the next higher level, which is considered as a criterion according to which we compare the elements of the next level below (Udo, 2000).

### *2.3.1 Pairwise comparison*

Table 1 shows the pairwise comparison scale developed for the traditional AHP (Saaty, 1977). It allows converting the subjective or qualitative judgments into numerical values. The pairwise comparisons are applied to every elements of a component at a given level in the hierarchy according to elements of the next higher level (Bimal Nepal, 2010).

**Table 1.** The traditional form of AHP pairwise comparison scale

| Numerical rating | Verbal scale | Description |
|---|---|---|
| 1 | Equal importance of both elements | Two elements contribute equally |
| 3 | Moderate importance of one element over another | Experience and judgement favour one over another |
| 5 | Strong importance of one element over another | An element in strongly favoured |
| 7 | Very strong importance of one element over another | An element is very strongly dominant |
| 9 | Extreme importance of one element over another | An element is favoured by at least an order of magnitude |
| 2,4,6,8 | Intermediate values | Used to compromise between two judgements |

For computing the priorities of elements, a judgmental matrix (also known as pairwise comparison matrix) is constructed as shown below.

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \dots & a_{2n} \\ \dots & \dots & 1 & \dots & \dots \\ 1/a_{n1} & \dots & \dots & \dots & 1 \end{bmatrix} \tag{1}$$

where, $a_{ij}$ represents a pairwise comparison if the element $e_i$ dominates $e_j$ (greater than or equal to one). On the other hand, $1/a_{ij}$ represents a similar comparison if the element

$e_i$ dominates $e_j$ (less than or equal to one). Likewise, '1' means if none of the elements dominate other, and '0' means a judgment is not available. The entries $a_{ij}$ are governed by the following rules:

$$a_{ij} > 0\,;\; a_{ij} = 1/a_{ji}\,;\; a_{ii} = 1 \quad \forall i \tag{2}$$

In the fuzzy-AHP model, instead of being discrete, the numbers 1 – 9 represent triangular fuzzy numbers, which are used to capture the subjectivity or vagueness of the pairwise preferences of CS attributes. Figure 3 shows the fuzzy set definition of five triangular fuzzy numbers with the corresponding membership function. The fuzzy set is defined as $F = \{x, \mu(x)), x \in U\}$, where $x$ takes it's values on the real line. $U$ is the universe of discourse, $\mu(x)$ is membership function whose values lie between [0, 1].

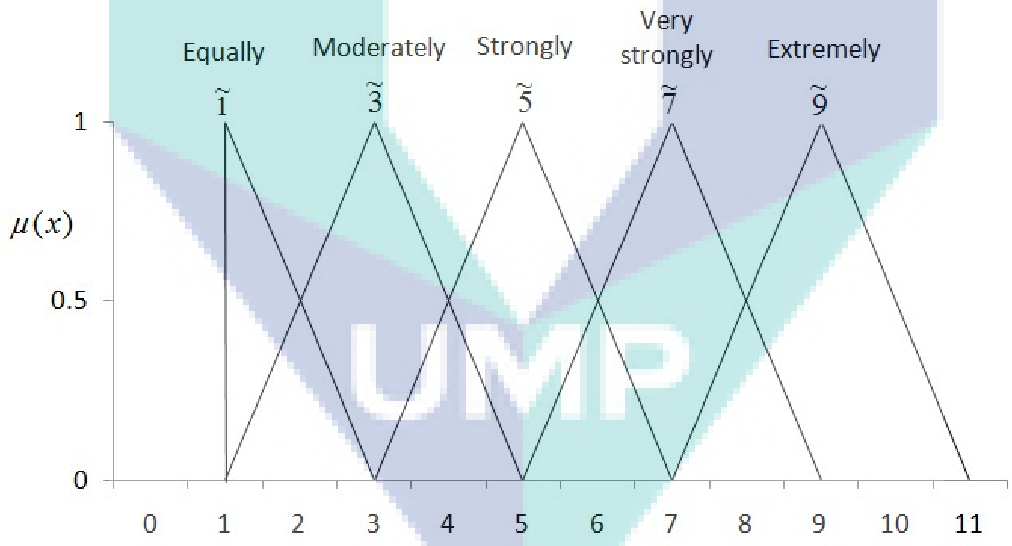


**Figure 3**. Fuzzy set definition with triangular membership function

Mathematically, the triangular type fuzzy membership function is defined as

$$\mu(x) = \begin{cases} 0 & x < l \\ \dfrac{x-1}{m-1} & l \le x \le m \\ \dfrac{u-x}{u-m} & m \le x \le u \\ 0 & x > u \end{cases} \tag{3}$$

### 2.3.2 *Determination of weights by computing fuzzy eigenvalues*

In case of crisp pairwise comparison matrix, weights of the attributes can be estimated by finding the principal eigenvector $w$ of the matrix $A$ (Saaty, 2000).

$$Ax = \lambda_{\max} x \tag{4}$$

where, $A$ is an $n \times n$ fuzzy matrix containing crisp numbers and x is non-zero $n \times 1$ crisp vector representing of crisp numbers $x_i$. When the vector $x$ is normalized, it becomes the vector of priorities of elements of one level with respect to the upper level. $\lambda_{\max}$ is the largest eigenvalue of the matrix $A$. This process is repeated at every level of the hierarchy. The aim is to determine the relative preferences (weights) of all elements on the same level according to each element on the next higher level.

## **2.4 Rough-Grey analysis**

### 2.4.1 *Rough sets and rough numbers*

Generally, a rough set is a formal approximation of a crisp set in terms of a pair of sets which give the lower and upper approximations of the target set (Pawlak, 1982, 1991). The lower approximation of a target set is a conservative approximation consisting of all the elements that can be definitely identified as the members of the set, whereas the upper approximation is a liberal approximation which collects all the elements that have the possibility to be identified as the members of the target set. The difference between the upper and lower approximations is the boundary region of a rough set, consisting of the elements that can neither be ruled in nor ruled out as members of the target set (Lian-Yin Zhai, 2009). The unique advantage of using rough set theory to handle vagueness and uncertainty is that it expresses vagueness by means of the boundary region of a set instead of membership function (Khoo, 1999).

The basic concept of rough number is to quantify vague perceptions of customers and designers in product development (Zhai, 2007). A rough number has the similar form as a fuzzy number, with its lower and upper limits indicating the two boundaries of an interval. Rough number enabled quantification of design information can better reflect the true perceptions of evaluators and thus respects the objectivity of the original data (Zhai, 2007).

### *2.4.2 Rough number enabled grey relation analysis*

Traditional grey relation analysis was designed for the analysis of discrete data sequences characterized by crisp values. Different from the crisp data used in the aforementioned grey relation analysis, rough numbers are presented in the form of intervals and thus the difference of rough numbers from the reference value needs to be defined (Lian-Yin Zhai, 2009). However, for two rough numbers in the form of intervals, their difference (or distance) cannot be similarly determined. Accordingly, a difference coefficient is proposed here to depict the distance between two rough numbers. Such a difference coefficient is then combined with the grey relation analysis to realize a Rough–Grey Analysis.

## 3. Proposed Method

The general framework of the approach has been depicted in Figure 4. The basic idea of this framework is to use problem decomposition to explicit value from different viewpoint to improve the understanding of complex problems (Chen, 2002). The framework allows each decision maker to focus on their own decomposed hierarchy with different criteria separately. The ranking outcome with their associated weights for each decision maker's viewpoint can be obtained by the evaluation methods (Ordoobadi, 2001). In Figure 4, decision maker can create a general hierarchy and then identify the relevant criteria or sub-criteria, and one can identify the criteria and sub-criteria and then put them into hierarchy. The output can be made using a screening process, followed by an evaluation and verification method from each hierarchy with its relevant criteria.

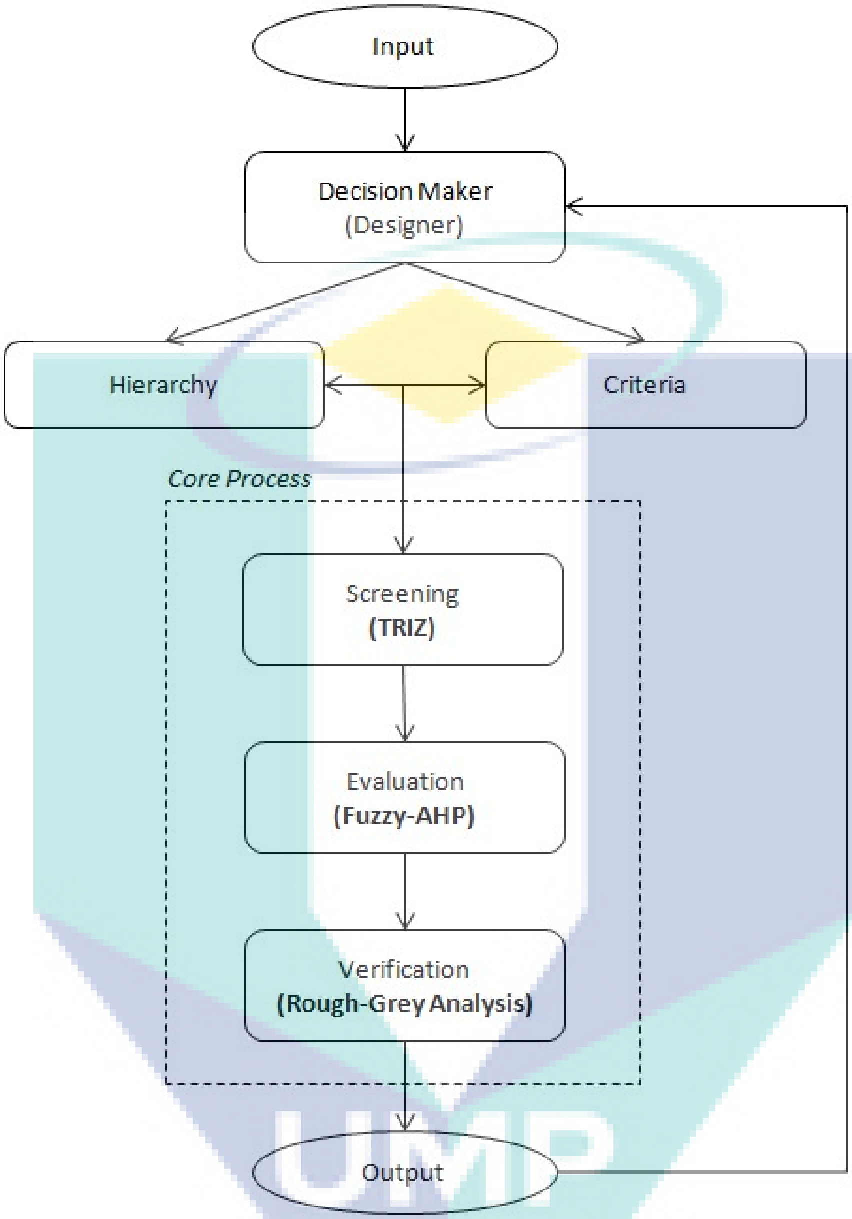


**Figure 4.** General Framework of proposed approach

In this paper, TRIZ method has been used for screening or pre-evaluating the alternatives suggested by the designer. Then the fuzzy-AHP method will be used for obtaining the weights of alternatives from the point of view of each decision maker. Finally, the rank of alternatives will be verified using Rough-Grey Analysis method.

### 3.1 *Development of Fuzzy-AHP model*

The proposed Fuzzy-AHP based methodology provides a framework for prioritization of alternatives at early stages of design process. The methodology can be divided into four steps as described in the following paragraphs.

### *3.1.1 Benchmarking and building of model hierarchical structure*

The proposed Fuzzy-AHP based methodology provides a framework for prioritization Figure 5 depicts the example of hierarchical structure of alternatives and criteria to prioritize alternatives for achieving the overall goal.

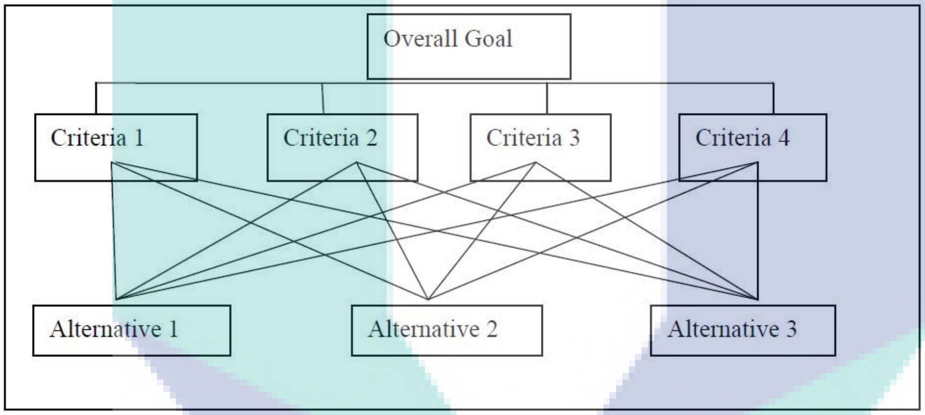


**Figure 5.** Analytic hierarchy structure

### *3.1.2 Construction of pairwise comparison matrices (PCM)*

The pairwise comparison process requires inputs from multiple layers of decision makers. Therefore, in order to get a good and reliable data, the subject matter experts should be chosen carefully.

### *3.1.3 Calculation of eigenvectors of elements by solving fuzzy PCM*

The objective of this step is to compute the relative importance (or principal eigenvector) of all the elements with respect to their next higher level element in the hierarchy.

The eigenvector or relative importance of elements can be computed in multiple ways (Saaty, 1980). First method is by solving the characteristic equation of matrix **A**, det(**A** – λ **I**) = **0**, and then substituting the largest eigenvalue into the equation, **AX** = $\lambda_{max}$ **X**. Finally upon normalization of $X_i$-values will get the relative importance of the element *i*. A relatively simple approach to determine the prioritization weight (relative importance) is by using the following formula:

$$w_i = \frac{\sum_{i=1}^{I} \left( \frac{aij}{\sum_{j=1}^{J} aij} \right)}{J} \tag{5}$$

where, wi is the relative importance for criterion *i*. *J* is the index number of columns in the pairwise matrix, *I* is the Index number of rows in the pairwise matrix, *aij* is the Value of pair wise comparison between elements *i* and *j*.

One of the key advantages of AHP over other multi-objective decision models is being able to check the consistency in the judgments of decision makers. In order to check the consistency of our pairwise comparisons, we calculate $\lambda_{max}$ and CI for all the PCMs as follows. $\lambda_{max}$ is determined by solving the equation

$$Aw = \lambda_{\max} w \tag{6}$$

where, *A* is the pairwise matrix and *w* is a column matrix of principal eigenvectors (relative importance of elements) (Saaty, 2000). Similarly, CI and CR were determined using the following formulas:

$$CI = \frac{\lambda_{\max} - n}{n-1}$$
$$CR = \frac{CI}{RI} \tag{7}$$

Depending upon the size of the matrix, n, an appropriate value of random consistency index (RI) was chosen to calculate CR. See Table 2 for RI values (Saaty, 1980). Saaty suggests that CR should be less than 0.1 in order for pairwise comparisons to be consistent and acceptable.

**Table 2.** Average consistencies indexes of random matrices

| Size | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0.00 | 0.00 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.40 | 1.45 | 1.49 |

### *3.1.4 Calculating of overall prioritization weights for each alternatives*

The overall or total prioritization weight (TW) of a alternative was calculated by considering the individual weights of all the relevant secondary criteria. Mathematically, it can be represented as follows (Bimal Nepal, 2010):

$$TW_{Ak} = \sum_{k} W_{\substack{Ui \\ i\in Uij}} \times W_{\substack{Uij \\ Uij\in Ak*}} W_{Ak} \quad \forall k \tag{8}$$

where, $W_{\substack{Ui \\ i\in Uij}}$ is the relative importance of general criterion $U_i$ that is relevant to the secondary criteria $U_{ij}$. $W_{\substack{Uij \\ Uij\in Ak}}$ is the Relative importance of secondary criteria $U_{ij}$ that are relevant to the alternatives $A_k$. $W_{Ak}$ is the Relative importance of an alternative $A_k$ with regard to its next higher level secondary criterion. $A_K$ is the alternatives, $k = 1, 2, 3$.

## 3.2 *Procedure of the rough–grey analysis*

Rough-Grey Analysis approach is very suitable for solving the group decision-making problem under uncertainty environment. The attribute ratings $\otimes v$ for benefit attributes is shown in Table 3. The selection procedures are summarized as follows (Chunguang Bai, 2010, 2011; Guo-Dong Li, 2008):

**Table 3.** The scale of attribute ratings ⊗v for benefit attributes

| Scale | $\otimes v$ |
|---|---|
| Very poor (VP) | [0,1] |
| Poor (P) | [1,3] |
| Medium poor (MP) | [3,4] |
| Fair (F) | [4,5] |
| Medium good (MG) | [5,6] |
| Good (G) | [6,9] |
| Very good (VG) | [9,10] |

### 3.2.1 *Establishment of grey decision table*

Form a committee of decision makers (DMs) and determine attribute values of alternatives. Assume that a decision group has *K* persons, and then the grey number value of attribute $\otimes v_{ij} = \left[\underline{v}_{ij}, \bar{v}_{ij}\right]$ can be calculated as

$$\otimes v_{ij} = \frac{1}{K}\left[\otimes v_{ij}^{1} + \otimes v_{ij}^{2} + \cdots + \otimes v_{ij}^{K}\right] \tag{9}$$

where $i$ refers to alternatives, while $j$ refers different attributes; $\otimes v_{ij}^{K} = \left[\underline{v}_{ij}^{K}, \bar{v}_{ij}^{K}\right]$, $(i = 1,2,\cdots,m; j = 1,2,\cdots,n)$ is the attribute rating value of *K*th DM that is expressed by grey number. The decision values $d_i$, $i$=1,2,$\cdots$,$m$ from DMs are given by [yes, yes or no, no] three types. The final values are determined by most of DMs' judgments according to the attributes rating values. The real numbers for [yes, yes or no, no] are given as [2, 1, 0] by the important degree of alternatives.

### 3.2.2 *Normalization of grey decision table*

Form a committee of decision makers (DMs) and determine attribute values of

$$\otimes v_{ij}^{*} = \left[ \frac{\underline{v}_{ij}}{v_j^{\max}}, \frac{\bar{v}_{ij}}{v_j^{\max}} \right] \tag{10}$$

where $v_j^{\max} = \max_{1 \le i \le m} \{\bar{v}_{ij}\}$.

For cost attributes, its normalized grey number value $\otimes v_{ij}^{*}$ is expressed as

$$\otimes v_{ij}^{*} = \left[ \frac{v_j^{\min}}{\bar{v}_{ij}}, \frac{v_j^{\min}}{\underline{v}_{ij}} \right] \tag{11}$$

where $v_j^{\min} = \min_{1 \le i \le m} \{\underline{v}_{ij}\}$.

The normalization method mentioned above is to preserve the attribute that the ranges of normalized grey number belong to [0, 1].

### 3.2.3 *Determination of the suitable alternatives*

In order to decrease unnecessary information and keep the determining rules, we determinate the suitable alternatives by grey-based rough set with lower approximation. The lower approximation of suitable alternatives $S^*$ are determined by

$$\underline{R}S^* = \{S_i \in U \mid [S_i]_R \subseteq S^*\} \tag{12}$$

where $S^* = \{S_i \mid d_i = yes\}$.

### 3.2.4 *Making the ideal alternative for reference*

According to $\underline{R}S^*$ obtained from equation (12), we determinate the ideal alternative $S^{\max}$ for reference by

$$S^{\max} = S_0 = \left\{ \left[ \max_{\forall i} \underline{v}_{i1}^{*}, \max_{\forall i} \overline{v}_{i1}^{*} \right], \left[ \max_{\forall i} \underline{v}_{i2}^{*}, \max_{\forall i} \overline{v}_{i2}^{*} \right], \cdots, \left[ \max_{\forall i} \underline{v}_{im}^{*}, \max_{\forall i} \overline{v}_{im}^{*} \right] \right\} \quad (13)$$

### 3.2.5 *Selection the most suitable alternative*

The grey relational coefficient (GRC) of $\otimes x_i$ with respect to $\otimes x_0$ at the *k*th attribute is calculated as (Dang YG, 2005)

$$\gamma\left(\otimes x_0(k), \otimes x_i(k)\right) = \frac{\Delta \min + \rho \Delta \max}{\Delta_{0i}(k) + \rho \Delta \max} \quad (14)$$

where

$$\Delta \max = \max \max_{\forall i, \forall k} L\left(\otimes x_0(k), \otimes x_i(k)\right) \quad (15)$$

$$\Delta \min = \min \min_{\forall i, \forall k} L\left(\otimes x_0(k), \otimes x_i(k)\right) \quad (16)$$

$$\Delta_{0i}(k) = L\left(\otimes x_0(k), \otimes x_i(k)\right) \quad (17)$$

$L\left(\otimes x_0(k), \otimes x_i(k)\right)$ is the Euclidean space distance of $\otimes x_0(k)$ and $\otimes x_i(k)$ which is calculated by equation below:

$$L(\otimes x_1, \otimes x_2) = \sqrt{\left(\underline{x}_1 - \underline{x}_2\right)^2 + \left(\overline{x}_1 - \overline{x}_2\right)^2} \quad (18)$$

ρ is the distinguishing coefficient, ρ=[0, 1]. The GRG between each comparative sequence $\otimes x_i$ and the reference sequence $\otimes x_0$ can be derived from the average of GRC, which is denoted as

$$\Gamma_{0i} = \sum_{k-1}^{n} \frac{1}{n} \gamma\left(\otimes x_0(k), \otimes x_i(k)\right) \tag{19}$$

where $\Gamma_{0i}$ represents the degree of relation between each comparative sequence and the reference sequence. Through the calculation of GRG between comparative sequences $\underline{R}S*$ with reference sequence $S^{\max}$, the alternative corresponding to the maximum value of GRG can be considered as the most suitable alternative.

### *3.3 Case example*

This paper presents an example from industry to demonstrate the efficacy of the proposed methodology. The application is to select the best potentiometer design among six developed concept designs which have been designed by design engineers. These alternatives are depicted in Figure 6. From point of view of design engineers, all six alternatives can be potentially manufactured. There are five decision makers whose views are deemed important and they should be taken into account for making a decision. They are the OEM customers, distributors, sales department, top management group, and the manufacturing department.

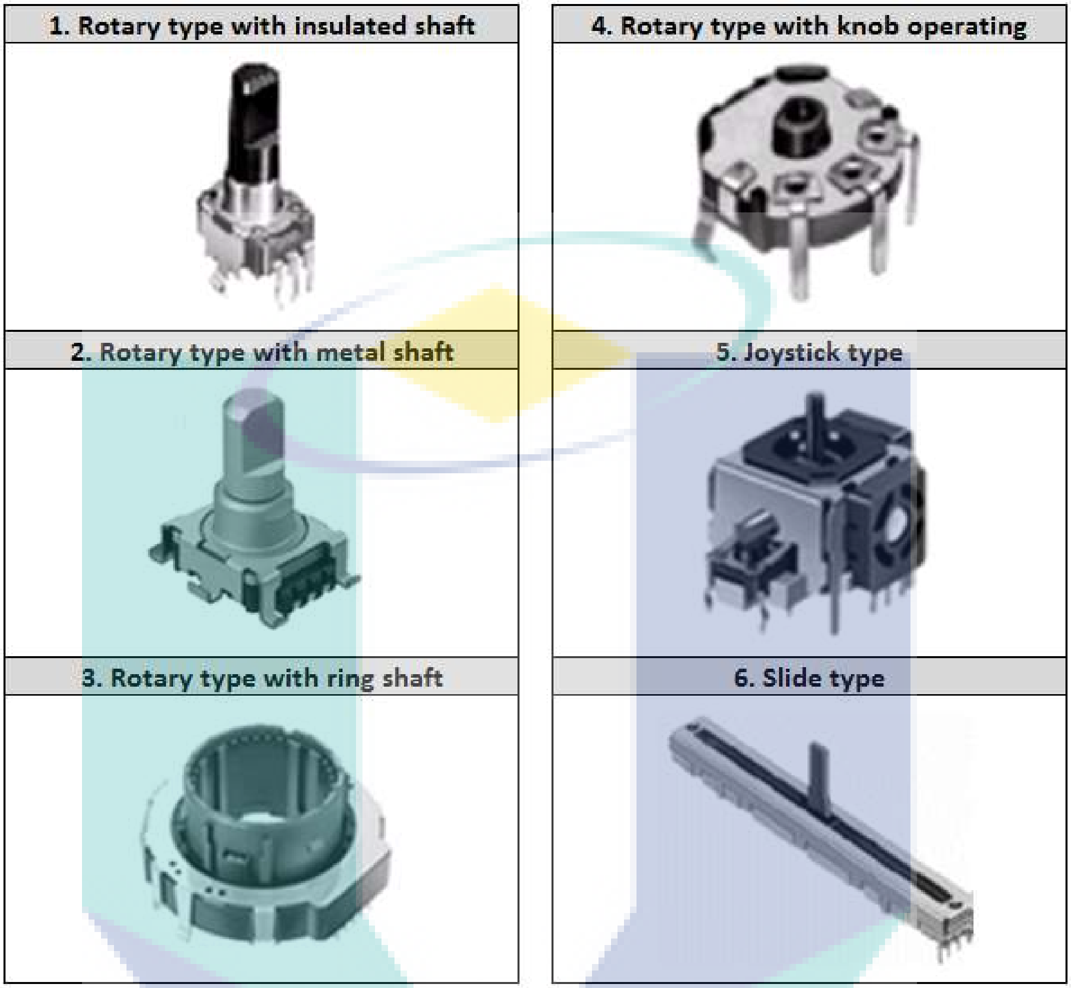


**Figure 6.** Six new design proposals of potentiometer

To choose a design, a set of criteria should be identified at first based on the characteristics of requirements. The selected evaluation criteria are depicted in Table 4.

**Table 4.** Evaluation criteria

| Specifications |
|---|
| Weight |
| Cost |
| Time-scales |
| Materials |
| Disposal |
| Product life span |
| Maintenance |
| Environmental |

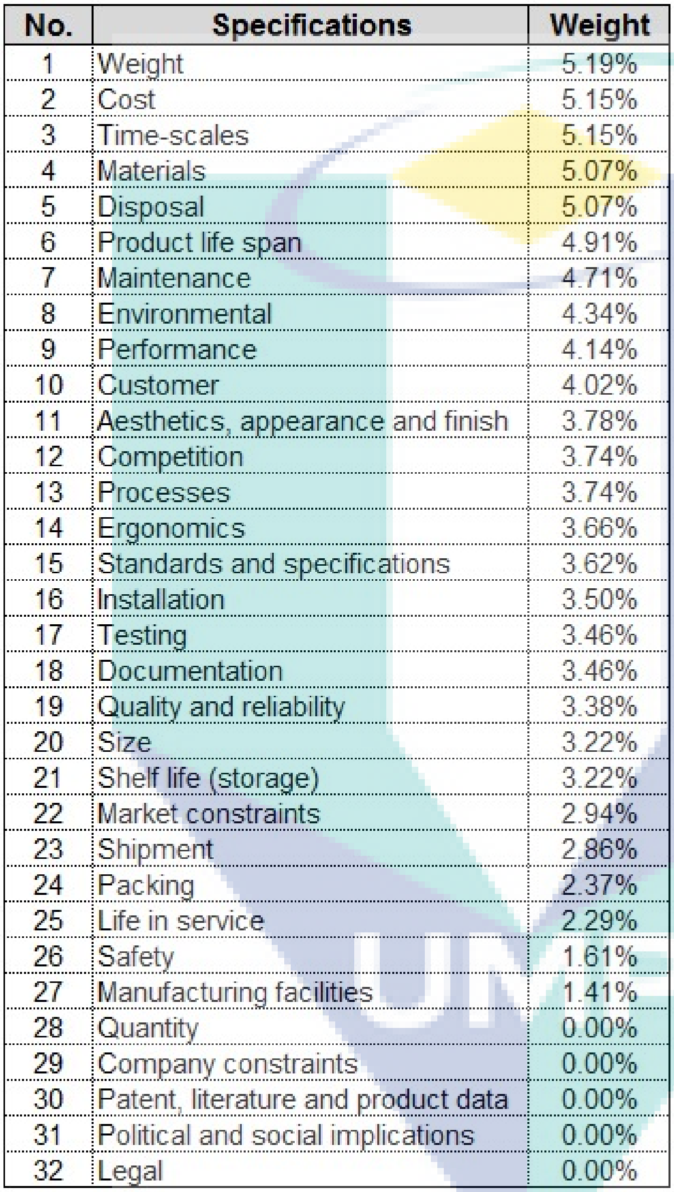
| |
|---|
| Installation |
| Customer |
| Aesthetics, appearance and finish |
| Competition |
| Processes |
| Ergonomics |
| Standards and specifications |
| Testing |
| Documentation |
| Size |
| Shelf life (storage) |
| Market constraints |
| Performance |
| Shipment |
| Packing |
| Life in service |
| Safety |
| Quality and reliability |
| Manufacturing facilities |
| Quantity |
| Company constraints |
| Patent, literature and product data |
| Political and social implications |
| Legal |

## 4. Results and Discussion

### *4.1 Screening process using TRIZ method*

In utilizing the TRIZ for screening process of this case example, the process explained in previous section was followed. Based on TRIZ contradiction principle, undesired effect (UDE) shall be eliminated at first. Then, experts in the multidisciplinary team identified the parameter to be improved and parameters that worsen for each criterion, and finally determine recommended inventive principles using TRIZ contradiction matrix. Table 5 presents the summary of TRIZ including relative weight or relative importance of each characteristic. The weight obtained will be ranked and filtered, and used as a reference for the next process. Table 6 is the modified TRIZ summary after eliminated the criteria which are less than 4.0% of weight.

**Table 5.** TRIZ summary



| No. | Specifications | Weight |
|---|---|---|
| 1 | Weight | 5.19% |
| 2 | Cost | 5.15% |
| 3 | Time-scales | 5.15% |
| 4 | Materials | 5.07% |
| 5 | Disposal | 5.07% |
| 6 | Product life span | 4.91% |
| 7 | Maintenance | 4.71% |
| 8 | Environmental | 4.34% |
| 9 | Performance | 4.14% |
| 10 | Customer | 4.02% |
| 11 | Aesthetics, appearance and finish | 3.78% |
| 12 | Competition | 3.74% |
| 13 | Processes | 3.74% |
| 14 | Ergonomics | 3.66% |
| 15 | Standards and specifications | 3.62% |
| 16 | Installation | 3.50% |
| 17 | Testing | 3.46% |
| 18 | Documentation | 3.46% |
| 19 | Quality and reliability | 3.38% |
| 20 | Size | 3.22% |
| 21 | Shelf life (storage) | 3.22% |
| 22 | Market constraints | 2.94% |
| 23 | Shipment | 2.86% |
| 24 | Packing | 2.37% |
| 25 | Life in service | 2.29% |
| 26 | Safety | 1.61% |
| 27 | Manufacturing facilities | 1.41% |
| 28 | Quantity | 0.00% |
| 29 | Company constraints | 0.00% |
| 30 | Patent, literature and product data | 0.00% |
| 31 | Political and social implications | 0.00% |
| 32 | Legal | 0.00% |

**Table 6.** Modified TRIZ summary

| No. | Specifications | Weight |
|---|---|---|
| 1 | Weight | 14.73% |
| 2 | Cost | 14.61% |
| 3 | Time-scales | 14.61% |
| 4 | Materials | 14.38% |
| 5 | Disposal | 14.38% |
| 6 | Product life span | 13.93% |
| 7 | Maintenance | 13.36% |

### *4.2 Evaluating process using Fuzzy-AHP method*

Figure 7 depicts the hierarchical structure of alternatives and general criteria to prioritize alternatives for selecting the best material in order to optimize the cost and performance of the product. The criteria ($U_i$) represent a combination of strategic index and key factors in design selection based on screening results obtained from previous process. At the next level, six alternatives that significantly influence the criteria were considered.

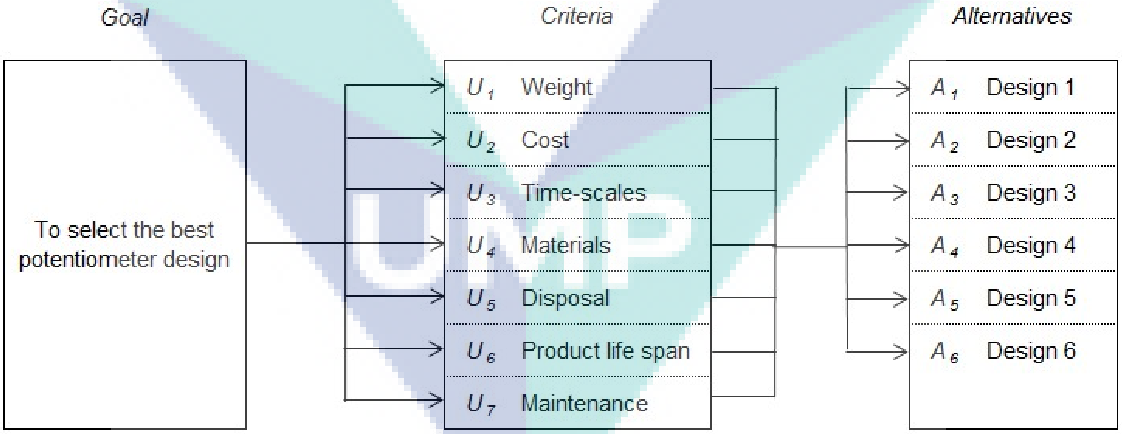


**Figure 7.** Hierarchy tree

Figure 8 represents the subset of alternative PCMs. Table 7 presents the results of prioritization weights calculations for the alternatives with respect to the criteria. In this study, the CR values for all of the pairwise comparison matrices have been found to be less than 0.1 which is consistent and acceptable. It also shows the largest eigenvalue, *CI* and *CR* validating the pairwise comparison. The final results of overall prioritization weight for each alternative are presented below in Table 8.

**$U_1$ Weight**

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ |
|---|---|---|---|---|---|---|
| $A_1$ | 1.00 | 1.06 | 1.75 | 1.40 | 1.75 | 1.17 |
| $A_2$ | 0.94 | 1.00 | 0.61 | 0.76 | 0.61 | 0.91 |
| $A_3$ | 0.57 | 1.65 | 1.00 | 0.80 | 1.00 | 0.67 |
| $A_4$ | 0.71 | 1.32 | 1.25 | 1.00 | 0.80 | 1.20 |
| $A_5$ | 0.57 | 1.65 | 1.00 | 1.25 | 1.00 | 0.67 |
| $A_6$ | 0.86 | 1.10 | 1.50 | 0.83 | 1.50 | 1.00 |

**$U_2$ Cost**

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ |
|---|---|---|---|---|---|---|
| $A_1$ | 1.00 | 1.00 | 1.67 | 1.40 | 1.75 | 1.40 |
| $A_2$ | 1.00 | 1.00 | 0.60 | 0.71 | 0.57 | 0.71 |
| $A_3$ | 0.60 | 1.67 | 1.00 | 0.84 | 1.05 | 0.84 |
| $A_4$ | 0.71 | 1.40 | 1.19 | 1.00 | 0.80 | 1.00 |
| $A_5$ | 0.57 | 1.75 | 0.95 | 1.25 | 1.00 | 0.80 |
| $A_6$ | 0.71 | 1.40 | 1.19 | 1.00 | 1.25 | 1.00 |

**$U_3$ Time-scales**

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ |
|---|---|---|---|---|---|---|
| $A_1$ | 1.00 | 1.00 | 1.00 | 0.96 | 1.47 | 1.00 |
| $A_2$ | 1.00 | 1.00 | 1.00 | 1.04 | 0.68 | 1.00 |
| $A_3$ | 1.00 | 1.00 | 1.00 | 0.96 | 1.47 | 1.00 |
| $A_4$ | 1.04 | 0.96 | 1.04 | 1.00 | 0.65 | 0.96 |
| $A_5$ | 0.68 | 1.47 | 0.68 | 1.53 | 1.00 | 0.68 |
| $A_6$ | 1.00 | 1.00 | 1.00 | 1.04 | 1.47 | 1.00 |

**$U_4$ Materials**

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ |
|---|---|---|---|---|---|---|
| $A_1$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.44 | 1.00 |
| $A_2$ | 1.00 | 1.00 | 1.00 | 1.00 | 0.70 | 1.00 |
| $A_3$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.44 | 1.00 |
| $A_4$ | 1.00 | 1.00 | 1.00 | 1.00 | 0.70 | 1.00 |
| $A_5$ | 0.70 | 1.44 | 0.70 | 1.44 | 1.00 | 0.70 |
| $A_6$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.44 | 1.00 |

**$U_5$ Disposal**

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ |
|---|---|---|---|---|---|---|
| $A_1$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.44 | 1.00 |
| $A_2$ | 1.00 | 1.00 | 1.00 | 1.00 | 0.70 | 1.00 |
| $A_3$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.44 | 1.00 |
| $A_4$ | 1.00 | 1.00 | 1.00 | 1.00 | 0.70 | 1.00 |
| $A_5$ | 0.70 | 1.44 | 0.70 | 1.44 | 1.00 | 0.70 |
| $A_6$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.44 | 1.00 |

**$U_6$ Product life span**

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ |
|---|---|---|---|---|---|---|
| $A_1$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.31 | 1.00 |
| $A_2$ | 1.00 | 1.00 | 1.00 | 1.00 | 0.76 | 1.00 |
| $A_3$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.31 | 1.00 |
| $A_4$ | 1.00 | 1.00 | 1.00 | 1.00 | 0.76 | 1.00 |
| $A_5$ | 0.76 | 1.31 | 0.76 | 1.31 | 1.00 | 0.76 |
| $A_6$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.31 | 1.00 |

**$U_7$ Maintenance**

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ |
|---|---|---|---|---|---|---|
| $A_1$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.31 | 1.00 |
| $A_2$ | 1.00 | 1.00 | 1.00 | 1.00 | 0.76 | 1.00 |
| $A_3$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.31 | 1.00 |
| $A_4$ | 1.00 | 1.00 | 1.00 | 1.00 | 0.76 | 1.00 |
| $A_5$ | 0.76 | 1.31 | 0.76 | 1.31 | 1.00 | 0.76 |
| $A_6$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.31 | 1.00 |

**Figure 8.** Pairwise comparison matrice

**Table 7.** Summary of relative importance

| Criteria | | $\lambda_{max}$ | C.I. | C.R. |
|---|---|---|---|---|
| $U_1$ | Weight | 6.478 | 0.096 | 0.077 |
| $U_2$ | Cost | 6.612 | 0.122 | 0.098 |
| $U_3$ | Time-scales | 6.234 | 0.047 | 0.037 |
| $U_4$ | Materials | 6.183 | 0.037 | 0.029 |
| $U_5$ | Disposal | 6.183 | 0.037 | 0.029 |
| $U_6$ | Product life span | 6.101 | 0.020 | 0.016 |
| $U_7$ | Maintenance | 6.101 | 0.020 | 0.016 |

**Table 8.** Overall prioritization weight

| Total alternative weight $TW_{Ak}$ | | Ranking |
|---|---|---|
| $A_1 =$ | 0.1868 | 1 |
| $A_2 =$ | 0.1850 | 2 |
| $A_3 =$ | 0.1605 | 5 |
| $A_4 =$ | 0.1697 | 4 |
| $A_5 =$ | 0.1248 | 6 |
| $A_6 =$ | 0.1732 | 3 |

### *4.3 Verifying process using Rough-Grey Analysis method*

There is a grey information system $T = (U, A, V, f_{\otimes})$ for selection of alternatives. The grey decision table is expressed by $T = (U, A \cup D, f_{\otimes})$. $U = \{S_i, i = 1,2,...,6\}$ are six potential alternatives for ten attributes $A = \{a_j, j = 1,2,...,10\}$. The ten attributes include qualitative attributes and quantitative attributes. $a_6$, $a_8$, $a_9$ and $a_{10}$ are benefit attributes, the larger values are better. $a_1$, $a_2$, $a_3$, $a_4$, $a_5$, and $a_7$ are cost attributes, the smaller values are better. The selection structure is shown in Figure 9.

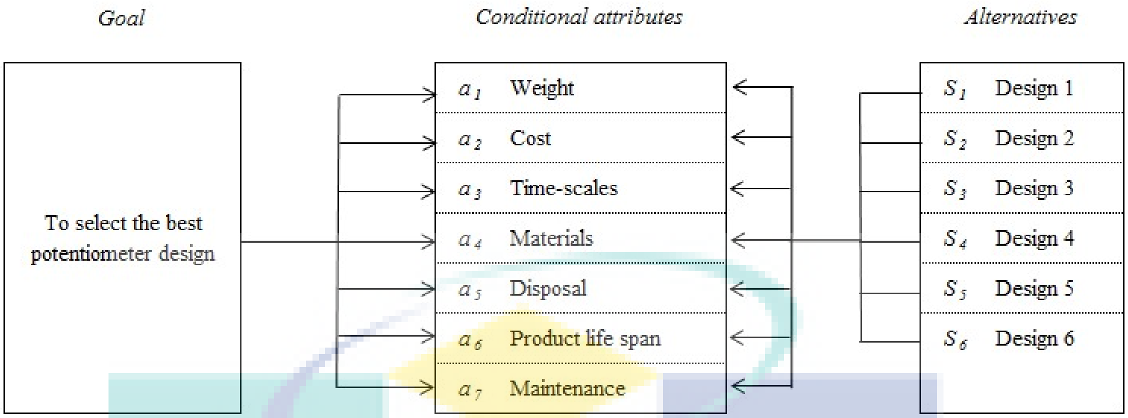


**Figure 9.** Selection structure

Survey results from five groups of decision maker are formed to express their preferences on attributes and decision. Then grey decision table is formed as shown in Table 9.

**Table 9.** Grey decision table

| Alternatives | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ |
|---|---|---|---|---|---|---|
| $a_1$ | [6.5,7.5] | [6.1,7.1] | [3.5,4.5] | [4.5,5.5] | [3.5,4.5] | [5.5,6.5] |
| $a_2$ | [6.5,7.5] | [6.5,7.5] | [3.7,4.7] | [4.5,5.5] | [3.5,4.5] | [4.5,5.5] |
| $a_3$ | [4.5,5.5] | [4.5,5.5] | [4.5,5.5] | [4.7,5.7] | [2.9,3.9] | [4.5,5.5] |
| $a_4$ | [4.1,5.1] | [4.1,5.1] | [4.1,5.1] | [4.1,5.1] | [2.7,3.7] | [4.1,5.1] |
| $a_5$ | [4.1,5.1] | [4.1,5.1] | [4.1,5.1] | [4.1,5.1] | [2.7,3.7] | [4.1,5.1] |
| $a_6$ | [3.7,4.7] | [3.7,4.7] | [3.7,4.7] | [3.7,4.7] | [2.7,3.7] | [3.7,4.7] |
| $a_7$ | [3.7,4.7] | [3.7,4.7] | [3.7,4.7] | [3.7,4.7] | [2.7,3.7] | [3.7,4.7] |
| Decision | 2 | 2 | 1 | 1 | 1 | 2 |

Next step is to normalize the grey decision table. As a result, the grey normalized decision table is shown in Table 10.

**Table 10.** Grey normalized

| Alternatives | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ |
|---|---|---|---|---|---|---|
| $a_1^*$ | [0.867,1] | [0.813,0.947] | [0.467,0.6] | [0.6,0.733] | [0.467,0.6] | [0.733,0.867] |
| $a_2^*$ | [0.867,1] | [0.867,1] | [0.493,0.627] | [0.6,0.733] | [0.467,0.6] | [0.6,0.733] |
| $a_3^*$ | [0.789,0.965] | [0.789,0.965] | [0.789,0.965] | [0.825,1] | [0.509,0.684] | [0.789,0.965] |
| $a_4^*$ | [0.804,1] | [0.804,1] | [0.804,1] | [0.804,1] | [0.529,0.725] | [0.804,1] |
| $a_5^*$ | [0.804,1] | [0.804,1] | [0.804,1] | [0.804,1] | [0.529,0.725] | [0.804,1] |
| $a_6^*$ | [0.787,1] | [0.787,1] | [0.787,1] | [0.787,1] | [0.574,0.787] | [0.787,1] |
| $a_7^*$ | [0.787,1] | [0.787,1] | [0.787,1] | [0.787,1] | [0.574,0.787] | [0.787,1] |
| Decision | 2 | 2 | 1 | 1 | 1 | 2 |

The GRA is a numerical measure of the relationship between comparative values and objective values, and the numeric values are among 0 and 1. By the rule that the design corresponding to the maximum value of GRG is the most suitable design, and calculating using Eq. (14) – (19), the grade is $S_1 > S_2 > S_6 > S_4 > S_3 > S_5$ as shown in Table 11.

**Table 11.** Grey relational grade

| GRG | Total | Ranking |
|---|---|---|
| $\Gamma_{01}$ | 1.148 | 1 |
| $\Gamma_{02}$ | 1.126 | 2 |
| $\Gamma_{03}$ | 0.826 | 5 |
| $\Gamma_{04}$ | 0.944 | 4 |
| $\Gamma_{05}$ | 0.000 | 6 |
| $\Gamma_{06}$ | 0.981 | 3 |

### *4.4 Results*

The Fuzzy-AHP analysis suggests that Design 1 with weight of 0.1864 should be given the highest priority. Among the six alternatives selected in this study, the second most important alternative is Design 2 with a weight of 0.1805 followed by Design 6 (0.1748). The rest are Design 4 (0.1656), Design 3 (0.1597) and Design 5 (0.1329). The result is being verified using Rough-Grey analysis method. Similarly, from the GRG results, Design 1 is the most suitable design 1 $(\Gamma_{01} = 1.481)$, followed by Design 2 $(\Gamma_{02} = 1.376)$, Design 6 $(\Gamma_{06} = 1.231)$, Design 4 $(\Gamma_{04} = 1.111)$, Design 3 $(\Gamma_{03} = 0.992)$, and Design 5 $(\Gamma_{05} = 0.000)$. All of this result is consistent with the results of evaluation using Fuzzy- AHP method.

Even though it is a simple case example, the results obtained from this analysis provide an in-depth insight of the real problem being faced by the industry. The distribution of weights assigned to various criteria, secondary criteria, and alternatives provide hands-on information to formulate an order winning strategy for design engineers.

## 5. Conclusion

Since, design concept evaluation is a critical task in the early phases of product development as it has significant impact on the quality and the cost of a product to be developed, this research is expected can proposed systematic design concept evaluation methods. The task is to model and analyze the design concept evaluation under uncertainty.

This paper is concentrated on prescriptive models of engineering design using Fuzzy-AHP framework to facilitate the design concept evaluation process. In contrast to the previous work of design concept evaluation, the advantage of Fuzzy-AHP allows the design community to have better condition with sufficient data before making. Prospective impacts of the proposed design evaluation method may reduce the development time of development stage in product life cycle. Furthermore, it can help designers to reduce the risk of late corrections.

In the proposed rough–grey analysis for design concept evaluation, the raw design information in the early phases of product development is characterized by rough numbers in the form of intervals, which can be solicited through a collective analysis about the perceptions of design experts. The result of the example presented in this work shows that the proposed rough–grey analysis as provided a novel alternative of existing methods to perform design concept evaluations in the early stages of product development, with the capability in accommodating uncertainties and vagueness. Prospective applications of the proposed method may facilitate the establishment of expert systems for systematic evaluation of design concepts during product development process.

In overall, the proposed framework will provide design engineers with a hands-on analytical tool to formulate an order winning strategy while considering any undertaking for products improvement. Furthermore, the proposed framework provides a structured decision making process, which may useful in design concept evaluation process.

## References

Altshuller, G. (1999). *The innovation algorithm*. USA: Technical Innovation Centre Inc.

Ayag Z., O. (2007). An Analytic Network Process-Based Approach to Concept Evaluation in a New Product Development Environment. *Journal of Engineering Design, 18(3)*, 209-226.

Bimal Nepal, O. P. Y., Alper Murat. (2010). A fuzzy-AHP approach to prioritization of CS attributes in target planning for automotive product development. *Expert Systems with Applications, 37*, 6775-6786.

Chen, L. C., and Lin, L. (2002). Optimisation of product configuration design using functional requirements and constraints. *Research in engineering design, 13*, 167-182.

Childs, P. R. (2004). *Mechanical design*. Oxford: Elsevier Butterworth-Heinemann.

Chunguang Bai, J. S. (2010). Integrating sustainability into supplier selection with grey system and rough set methodologies. *Int. J.ProductionEconomics, 124*, 252-264.

Chunguang Bai, J. S. (2011). Evaluating supplier development programs with a grey based rough set methodology. *Expert Systems with Applications, 38*, 13505-13517.

Dang YG, L. S., Liu B. (2005). *On the multiple-attribute incidence decision model for interval numbers.* Paper presented at the Proceedings on Networking, Sensing and Control IEEE.

Domb, E. (1997). 40 inventive principles with examples. *TRIZ Journal of 1997*(July).

Francis E.H. Tay, J. G. (2002). Product Modeling for Conceptual Design Support. *Computer in Industry, 48*(2), 143-155.

Frenklach, G. (1998). Classifying the technical effects. *TRIZ Journal of 1998*(March).

Green, G. (1997). Modeling concept design evaluation. *Artificial intelligence for engineering design, analysis and manufacturing, 11*, 211-217.

Green, G. (2000). Towards integrated evaluation: validation of models. *Journal of engineering design, 11*(2), 121-132.

Guo-Dong Li, D. Y., Masatake Nagai. (2008). A grey-based rough decision-making approach to supplier selection. *International Journal of Advanced Manufacturing Technology, 36*, 1032-1040.

Hongre, L. (2006). *Identifying the Most Promising Business Model by using the Analytic Hierarchy Process Approach.* Paper presented at the 23rd World Gas Conference, Amsterdam, Netherlands.

Khoo, L. P., Tor, S. B., Zhai, L. Y. (1999). A rough-set based approach for classification and rule induction. *International Journal of Advanced Manufacturing Technology, 15*, 438-444.

Lian-Yin Zhai, L.-P. K., Zhao-Wei Zhong. (2009). Design Concept Evaluation in Product Development using Rough Sets and Grey Relation Analysis. *Expert Systems with Applications, 36*, 7072-7079.

Liu, Y. C., Bligh, T., and Chakrabarti, A. (2003). Towards an 'ideal' approach for concept generation. *Journal of design studies, 24*, 341-355.

Lo, C., Wang, P., Chao, K. (2006). A fuzzy group-preferences analysis method for new-product development. *Expert Systems with Applications, 31*(4), 826-834.

Lovatt, A. M., and Shercliff, H.R. . (1998). Manufacturing process selection in engineering design. Part 2: an approach for creating task-based process selection procedures. *Journal of material and design, 19*, 217-230.

Millson, M., Miles, B., and Tennant. C. (2004). *Effective new product introduction in SMEs.* Paper presented at the Paper presented at the Proceeding of 2nd international conference on manufacturing technology, Sheffield Hallam University, United Kingdom.

Nevins, J. L., & Whitney, D. (1989). *Concurrent design of products and processes - A strategy for the next generation in manufacturing*. New York: McGraw-Hill.

Ordoobadi, S. M., and Mulvaney, N.J. (2001). Development of a justification tool for advanced manufacturing technologies: system-wide benefits value analysis. *Journal of engineering and technology management, 18*, 157-184.

Pawlak, Z. (1982). Rough sets. *International Journal of Computer Information Science, 11*(5), 341-356.

Pawlak, Z. (1991). *Rough sets: Theoretical aspects of reasoning about data*. Dordrecht: Kluwer Academic Publishing.

Petrov, V. (2002). The laws of system evolution. *TRIZ Journal of 2002*(March).

Rosenman, M. A. (1993). Qualitative evaluation for topological specification in conceptual design. *Applications and Techniques of Artificial Intelligence in Engineering, 2*, 311-326.

Saaty, T. L. (1977). A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology, 15*, 234-281.

Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting and Resources Allocation*. New York: McGraw-Hill.

Saaty, T. L. (2000). *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*. Pittsburg: RWS Publications.

Scott, M. J. (2002). *Quantifying Certainty in Design Decisions: Examining AHP.* Paper presented at the ASME Design Engineering Technical Conferences (DETC2002).

Te-Sheng Li, H.-H. H. (2009). Applying TRIZ and Fuzzy AHP to develop innovative design for automated manufacturing systems. *Expert Systems with Applications, 36*, 8302-8312.

Terninko, J. (2000). Su-field analysis. *TRIZ Journal of 2000*(February).

Udo, G. G. (2000). Using Analytic Hierarchy Process to Analyze the Information Technology Outsourcing Decision. *Industrial Management & Data Systems, 100(9)*, 421-429.

Wenqiang Li, Y. L., Jian Wang, Xiaoying Liu. (2010). The Process Model to Aid Innovation of Products Conceptual Design. *Expert Systems with Applications, 37*, 3574-3587.

Wynne Hsu, I. M. Y. W. (1998). Current Research in the Conceptual Design of Mechanical Products. *Computer-Aided Design, 30*(No. 5), 377-389.

Xiuli Geng, X. C., Zaifang Zhang. (2010). A new integrated design concept evaluation approach based on vague sets. *Expert Systems with Applications, 37*, 6629-6638.

Zhai, L. Y., Khoo, L. P., Zhong, Z. W. (2007). A rough set enhanced fuzzy approach to quality function deployment. *International Journal of Advanced Manufacturing Technology, 37*(5-6), 613-624.

Zhang, Z., Chu, X. (2009). A new integrated decision-making approach for design alternative selection for supporting complex product development. *International Journal of Computer Integrated Manufacturing, 22*(3), 179-198.

Zoyzen, Z. (1997). Solving contradictions in development of new generation products using TRIZ. *TRIZ Journal of 1997*(February).