Advanced Engineering Informatics 30 (2016) 16–25

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

Product design concept evaluation using rough sets and VIKOR method

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ARTICLE INFO

Article history:
Received 7 May 2015
Received in revised form 16 September 2015
Accepted 19 November 2015

Keywords:
Design concept evaluation
Product design
VIKOR
Interval numbers
Rough numbers

ABSTRACT

Design concept evaluation is one of the most important phases in the early stages of the design process as it not only significantly affects the later stages of the design process but also influences the success of the final design solutions. The main objective of this work is to reduce the imprecise content of customer evaluation process and thus, improve the effectiveness and objectivity of the product design. This paper proposes a novel way of performing design concept evaluations where instead of considering cost and benefit characteristics of design criteria, the work identifies best concept which satisfy constraints imposed by the team of designers on design criteria's as well as fulfilling maximum customers' preferences. In this work, the rough number enabled modified Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method for design concept evaluation is developed by modifying the extended VIKOR method with interval numbers. The proposed technique is labeled as modified rough VIKOR (MR-VIKOR) analysis. The work primarily involves two phases of concept evaluation. In the first phase, relative importance ranking and initial weights of design criteria are computed through the importance assigned to each design criteria by the designers or the decision makers (DM); and in the second phase, customers' preferences to the generated user needs are captured in the form of rough numbers. The relative importance ranking computed in first phase along with customers' preferences is incorporated in the second phase to select the best concept.

1. Introduction

Concept evaluation is an important stage in the design process as it helps to assess the overall utility of design alternatives against the design objectives. Early concept evaluation can save both time and cost as 80% of overall product quality and 70–80% of product development cost is committed in the early stages of the design process [1–4]. The importance of design concept evaluation is obvious because the poor selection of a design concept can hardly ever be compensated at later stages of design process and may lead to large redesign costs [5]. Concept evaluation is a complex multi-criteria decision making problem inherent with a number of difficulties. Decision making during this process is hindered due to the complexity of problem solving, handling of conflicting decision-making criteria and assessment of product performance [6]. The need to incorporate highly subjective customer preferences in evaluation process, evaluation of trade-offs between conflicting design criteria, subjective judgments of experienced designers (or decision makers), calculating degree of satisfaction level of customers against the generated design alternatives and performance capabilities of design alternatives in terms of meeting the final technical specifications introduces various degree of uncertainty in the concept evaluation process.

The main design objectives that helps to determine the success of the final design concept (design solution) are customers' satisfaction, product development time and product cost. A designer should embrace these objectives in the design process to ensure competitive advantage in the fast growing market. Many previous concept evaluation frameworks consider customer satisfaction as most important objective, but most of the times, out of the real requirements specified by the customers, majority of the requirements are of poor quality. They are inconsistent, vague, infeasible to implement or manufacture, besides being not really mandatory, unverifiable and unobtainable. Poor quality requirements results in increase in product development time and cost besides leading to mistakes which have negative impact during the subsequent downstream design activities. Many a times, customer demands specification in a product without considering cost and benefit characteristics of design criteria and designer has to implement features in a product merely because user swore they

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http://dx.doi.org/10.1016/j.aei.2015.11.005
1474-0346/

needed badly, but after sometimes the user loses interest. Thus, considering only customer satisfaction during the concept evaluation phase of product design does not make the design process effective. It is required to give equal importance and incorporate customers' requirements as well as designers' limitation (or company constraints) for the success of the final design concept(s).

Earlier most of the concept evaluation frameworks consider cost and benefit characteristics of design criteria and select the best concept which performs the best based on these conflicting criteria. This paper considers importance level of design criteria (very high, high, medium and low) based on the judgments given by a team of designers, and thus proposes a different and novel way of concept evaluation. This method identifies the best concept that can fully satisfy designers or company specific constraints based on importance level of design criteria as well as maximize customer satisfaction. The proposed framework proves to be useful, during early stages of design when information about many attributes is not clear. With the help of proposed work, designers can easily find which concept is most preferable for certain important design attributes and least preferred for the uncertain design attributes. The work primarily involves two phases for concept evaluation. In the first phase, the rough numbers introduced by Zhai et al. [7] are used to calculate relative importance ranking and rating of conflicting design criteria from the team of designers' vague judgements. In the second phase, these computed ranking of design criteria in terms of importance level (designers' constraints) and highly subjective customer preferences for design specifications captured in the form of rough numbers is incorporated in the framework of extended VIKOR method with interval numbers [8] to evolve a new concept evaluation technique, labelled as, modified rough VIKOR (MR-VIKOR) analysis. The use of rough numbers would improve the overall effectiveness and help the designers to take good decisions in an uncertain environment.

2. Previous work

Two approaches, numerical and non-numerical, are developed by the designers to solve complex multi-criteria decision making (MCDM) problem of concept evaluation [9,10]. Non-numerical methods are graphical based methods, which are simple, effective and easier to use for quick selection of design concepts, but this approach have lower efficiency and accuracy as compared to the numerical approach. Some of the non-numerical methods are concept screening [11] and Pugh charts [12]. These approaches do not effectively deal with uncertain, vague and subjective judgement of the decision maker. Numerical approaches support both quantitative and qualitative judgement of design criteria by the decision makers. Utility function analysis [13,14] and goal programming [15,16] allows judgement of decision maker to be expressed in quantitative form only. The limitation of these approaches is that it is very difficult to represent some intangible design criteria and factors in quantitative form accurately during early design stages [13,14]. Other category of numerical approach for example, Fuzzy set theory and Analytical Hierarchy process (AHP) allows decision maker's judgement to represent in both quantitative and linguistic form.

King and Sivaloganathan [17] have classified concept selection into five categories i.e. utility theory, AHP, graphical tools, quality function deployment (QFD) and fuzzy logic method. Among these approaches developed so far, AHP and fuzzy set theory have been mostly used by the researchers due to their ability to handle uncertainty [18]. Integrated decision making method is preferred over single MCDM method to solve efficiently the problem of concept evaluation. Huang et al. [19] used fuzzy sets with neural network and genetic algorithm to propose an integrated approach to solve the concept evaluation problem. This approach has lengthy training process and unable to solve real world problems due to complex and difficult algorithm structure. Fuzzy set theory supports favouring evidence only, and does not allow the designer to express hesitancy degree. Geng et al. [10] have proposed integrated concept evaluation method based on vague set theory where linguistic judgements of decision makers are transformed into vague numbers. Modified weighted least square model (WSLM) is used to combine all the judgements and techniques for order preference by similarity to ideal solution (TOPSIS) are proposed to rank the design concepts. The advantage of using vague set theory is that it supports both favouring and opposing evidences in achieving subjective judgement of the designer. Zhai et al. [9] proposed an integrated approach to improve subjectivity in concept evaluation process by combining rough set theory [20] and grey relation analysis.

AHP and simulation analysis is combined by Ayag [21] and proposed an integrated approach to perform design concept evaluations. Song et al. [22] proposed a hybrid approach in which rough numbers and AHP are combined for evaluating criteria weights of alternatives; and rough numbers and TOPSIS are combined to select the best alternative. AHP can be time consuming process with increase in the number of design criteria and alternatives. Large number of criteria results in large pair wise comparisons and huge evaluation matrix [23,24]. There is strict requirement to control consistency in pair wise comparisons of criteria's at higher levels, as AHP at lower levels of consistency does not produce correct results [25]. Besides fuzzy set and AHP, some other theories have also been used by designers for design evaluations. Yang and Sen [26] developed evidence reasoning approach based on Dempster–Shafer theory of evidence to perform design concept evaluation. Evidence reasoning approach does not efficiently model vague subjective judgement during design evaluation [22].

It is clear from the above discussions, that many methods are developed so far to perform design concept evaluations but except a few methods which are effective in some cases, many methods fails or lacks the support to effectively represent designers' and decision makers' vague perception, and uncertain and subjective information.

3. Rough numbers

One of the challenges which are faced by researchers today in the field of fuzzy set theory is selection of membership function which is a necessary requirement for effective performance of the fuzzy system [27]. This work proposes the use of rough numbers based on rough set theory, to reduce the vague and subjective perception of designer in concept evaluation process. Rough set theory [20] is a mathematical tool which was proposed to take advantage of information inherent in a given data without requiring any auxiliary information or subjective judgement (e.g. membership functions in the case of fuzzy set theory) for analysis of data. It uses approximation operators like approximation space, lower and upper approximations of a set to deal with vagueness and uncertainty [28]. In general, rough set theory uses a set of objects comprising multi-valued attributes to analyse any data. This structure of objects is called an information table.

Zhai et al. [7] defined rough numbers and rough boundary interval through the use of upper and lower approximations which is extended from basic rough set theory. Mathematically, the rough numbers are defined in the following way:

All the objects described by multi-attributes in any information table are represented by universe U. A set of n classes, i.e., $R = \{C_1, C_2, \ldots, C_n\}$ ordered in the manner of $C_1 < C_2 < \cdots < C_n$

are used for analysing attributes of objects. For any class $C_i \in R$ and any object Y of U the lower approximation ($\underline{Apr}(C_i)$), and upper approximation ($\overline{Apr}(C_i)$) are defined as:

$$\underline{Apr}(C_i) = \cup\{Y \in U/R(Y) \leqslant C_i\} \tag{1}$$

$$\overline{Apr}(C_i) = \cup\left\{Y \in \frac{U}{R(Y)} \geqslant C_i\right\}; \tag{2}$$

In a set of ordered classes, all the objects in the information table, that have class values equal to or less than C forms lower approximation of C and those objects which have class values equal to or greater than C in same information table forms upper approximation of C. All the objects in information table which have different class values than C forms the boundary region of class C.

$$\text{Boundary region}: \; Bnd(C_i) = \cup\{Y \in U/R(Y) \neq C_i\} = \{Y \in U/R(Y) > C_i\} \cup \{Y \in U/R(Y) < C_i\} \tag{3}$$

The approximations of class defined above can be used to define lower limit ($\underline{Lim}(C_i)$) and upper limit ($\overline{Lim}(C_i)$) of rough number. Thus, any class can be efficiently represented by its rough number. Mathematically,

$$\underline{Lim}(C_i) = \frac{1}{M_L} \sum R(Y)|Y \in \underline{Apr}(C_i) \tag{4}$$

$$\overline{Lim}(C_i) = \frac{1}{M_U} \sum R(Y)|Y \in \overline{Apr}(C_i) \tag{5}$$

where M_L and M_U are number of objects contained in lower and upper approximation of C_i respectively.

Rough boundary interval ($RBnd(C_i)$) is the interval between lower limit and upper limit and can be defined as:

$$RBnd(C_i) = \overline{Lim}(C_i) - \underline{Lim}(C_i) \tag{6}$$

Any vague class can be effectively represented by rough number, which consist lower and upper limit. Rough number is expressed mathematically as:

$$RN(C_i) = \left[\underline{Lim}(C_i), \overline{Lim}(C_i)\right] \tag{7}$$

Rough numbers and rough boundary interval enables a designer to express vagueness of any class, as large rough boundary interval means class is less precise or vague.

Zhai et al. [7] adapted the operations of interval mathematics to manipulate rough numbers. If [A_1, B_1] and [A_2, B_2] are the lower and upper limit of rough numbers RN_1 and RN_2 respectively and k is a constant, then

$$RN_1 \times RN_2 = [A_1, B_1] \times [A_2, B_2] = [A_1 \times A_2, B_1 \times B_2] \tag{8}$$

$$RN_1 + RN_2 = [A_1, B_1] + [A_2, B_2] = [A_1 + A_2, B_1 + B_2] \tag{9}$$

$$RN_2 \times k = [A_2, B_2] \times k = [kA_2, kB_2] \tag{10}$$

Although, rough number is an effective tool to deal with subjectivity and vagueness in the early design stages, but it may be inefficient in dealing with other elements. This is due to the lack of effective evaluation framework for rough numbers in early design stages. There is need of effective methodology to systematically deal with subjectivity, uncertainty and vagueness in early design stages (e.g. concept evaluation). Traditionally MCDM approaches are integrated with fuzzy set theory to solve the issue described above. Torfi et al. [29] has proposed the integrated fuzzy set theory with AHP to determine criteria weights and with TOPSIS to rank the alternatives. This integrated method requires pre-setting membership function, which makes this method less efficient in subjective and vague environment of concept evaluation process. Also fixed fuzzy number interval is another limitation of this integrated method. The work developed here explores the possibility of using rough numbers with MCDM approach to propose modified rough VIKOR concept evaluation framework. This integrated method is expected to solve the problem of integrated fuzzy MCDM approach described above. Therefore in this respect, the proposed work presents a novel modified rough VIKOR methodology for design concept evaluation.

4. VIKOR method with interval numbers

Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method was proposed by Opricovic [30] for ranking of alternatives and generating compromise solution in the presence of conflicting and non-commensurable criteria. This method determines solution for multicriteria optimization of complex system. VIKOR method generates a multi-criteria ranking index, which is developed from an aggregating function representing "closeness" to "ideal" solution [30]. The ranking index is developed from $L_P - metric$, an aggregating function in compromise programming [31,32]. VIKOR method uses linear normalization method to eliminate the units of criteria and determines a compromise solution, which represents maximum "group utility" and a minimum individual regret for the "majority" and "opponent" respectively [33].

Let, there are m alternatives $A_1, A_2, \ldots, A_m$ generated for any complex problem of decision making. For an alternative A_i, f_{ij} is the performance value of jth criterion function. $L_P - metric$ which was used for starting the development of ranking measure of VIKOR method is as follows:

$$L_{pi} = \left\{\sum_{j=1}^{n} [(f_j^* - f_{ij})/(f_j^* - f_j^-)]^p\right\}^{1/p} \quad 1 \leqslant p \leqslant \infty; \quad i = 1, 2, \ldots, m.$$

$L_{1,i}$ and $L_{\infty,i}$ are used to formulate ranking measure S_i and R_i in VIKOR method respectively. The maximum group utility ("majority rule") and minimum individual regret of the "opponent" is calculated by min S_i and min R_i respectively.

In this work, Extension of VIKOR method for decision making problem with interval numbers proposed by Sayadi et al. [8] is modified to include importance ranking of design criteria. The compromise ranking algorithm proposed by Sayadi et al. [8] is as follows:

Suppose $A_1, A_2, \ldots, A_m$ are alternatives considered and $C_1, C_2, \ldots, C_n$ are criteria available to evaluate performance of an alternative. The rating of alternative A_i with respect to criteria C_j is f_{ij} and w_j is weight of criterion. The decision matrix representing the performance of each alternative in the form of interval numbers is:

	C_1	C_2	…	C_n
A_1	$[f_{11}^L, \; f_{11}^U]$	$[f_{12}^L, \; f_{12}^U]$	…	$[f_{1n}^L, \; f_{1n}^U]$
A_2	$[f_{21}^L, \; f_{21}^U]$	$[f_{22}^L, \; f_{22}^U]$	…	$[f_{2n}^L, \; f_{2n}^U]$
…	…	…	…	…
A_m	$[f_{m1}^L, \; f_{m1}^U]$	$[f_{m2}^L, \; f_{m2}^U]$	…	$[f_{mn}^L, \; f_{mn}^U]$

a. Determine Positive ideal solution (PIS) and Negative ideal solution (NIS).

$$PIS = f_j^* = \left(\max_i f_{ij}^U | j \in I\right) \text{ or } \left(\min_i f_{ij}^L | j \in J\right) \quad j = 1, 2, \ldots, n \tag{11a}$$

$$NIS = f_j^- = \left(\min_i f_{ij}^L | j \in I\right) \text{ or } \left(\max_i f_{ij}^U | j \in J\right) \quad j = 1,2,\ldots,n \tag{11b}$$

where I is associated with benefit criteria and J is associated with cost criteria.

b. Compute $[S_i^L, \ S_i^U]$ and $[R_i^L, \ R_i^U]$ intervals as below:

$$S_i^L = \sum_{j \in I} w_j \left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right) + \sum_{j \in K} w_j \left(\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right) \quad i = 1,2,\ldots,m \tag{12a}$$

$$S_i^U = \sum_{j \in I} w_j \left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right) + \sum_{j \in K} w_j \left(\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right) \quad i = 1,2,\ldots,m \tag{12b}$$

$$R_i^L = \max\left\{\left(w_j\left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right)\bigg| j \in I\right), \quad \left(w_j\left(\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right)\bigg| j \in J\right)\right\}$$
$$i = 1,2,\ldots,m \tag{13a}$$

$$R_i^U = max\left\{\left(w_j\left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right)\bigg| j \in I\right), \quad \left(w_j\left(\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right)\bigg| j \in J\right)\right\}$$
$$i = 1,2,\ldots,m \tag{13b}$$

c. Compute the aggregating function interval $Q_i = [Q_i^L, \ Q_i^U]$

$$Q_i^L = v * \left(\frac{S_i^L - S^*}{S^- - S^*}\right) + (1 - v) * \left(\frac{R_i^L - R^*}{R^- - R^*}\right) \tag{14a}$$

$$Q_i^U = v * \left(\frac{S_i^U - S^*}{S^- - S^*}\right) + (1 - v) * \left(\frac{R_i^U - R^*}{R^- - R^*}\right) \tag{14b}$$

where

$$S^* = \min_i(S_i^L), \quad S^- = \max_i(S_i^U) \tag{15}$$

$$R^* = \min_i(R_i^L), \quad R^- = \max_i(R_i^U) \tag{16}$$

v = Weight of the strategy of "the majority criteria" (*or* "the maximum group utility")

d. According to VIKOR method, the alternative that has minimum Q_i is the best alternative. However, for interval numbers, Sayadi et al. [8] introduced a new method of comparison which was as follows:
Suppose $[a_1^L, \ a_1^U]$ and $[a_2^L, \ a_2^U]$ are two interval numbers. For choosing minimum interval numbers four cases are:
   1. If the interval number has no intersection, then minimum interval is one that has lower values i.e. if $a_1^U \leqslant a_2^L$ then, we choose $[a_1^L, \ a_1^U]$ as minimum interval number.
   2. If two interval numbers are same then both are of same priority.
   3. If interval numbers have intersection, then for situation – If $a_1^L \leqslant a_2^L$ and $a_2^U \leqslant a_1^U$ and $\propto *(a_2^L - a_1^L) \geqslant (1-\alpha)(a_1^U - a_2^U)$ then $[a_1^L, \ a_1^U]$ is minimum else $[a_2^L, \ a_2^U]$ is minimum
   4. If $a_1^L \leqslant a_2^L$ and $a_1^U \leqslant a_2^U$ and $\propto *(a_2^L - a_1^L) \geqslant (1-\alpha)(a_2^U - a_1^U)$ then $[a_1^L, \ a_1^U]$ is minimum else $[a_2^L, \ a_2^U]$ is minimum

Here $\propto$ is optimism level of decision maker $0 \leqslant \alpha \leqslant 1$. The optimist decision maker has higher $\propto$ values than pessimist decision maker. For rational decision maker value of $\propto$ is 0.5.

5. Proposed methodology

The two important steps in design concept evaluation are (i) determination of design criteria and their relative importance rating (criteria weights) and (ii) development of an evaluation model. The design criteria are predetermined and developed based on customer needs [10]. The proposed method of concept evaluation is divided into two phases. In phase I, relative importance ranking and relative importance rating of each design criteria's is determined by the rough set enhanced fuzzy approach proposed by Zhai et al. [7] based on rough numbers. In phase II, these ranking and rating of design criteria are introduced in extended VIKOR method with interval numbers proposed by Sayadi et al. [8] along with captured customers' preferences for design specifications in the form of rough numbers to propose a novel method, named here as, modified rough VIKOR (MR-VIKOR) analysis. This method in terms of novelty captures the designers' perception of design attributes (in the terms of their importance level) along with the customers' perception of design attributes values by rough numbers, and tries to propose the best concept(s) which satisfies the designers' constraints on design criteria as well as fulfilling maximum customer requirements. As designers can give actual judgement about the design criteria and customers preferences may be poor in terms of quality, so taking this into account, the method, in the phase I, classifies the design criteria in terms of their importance, and in phase II uses this classification along with customers' preferences in extended VIKOR with interval numbers [8] framework by some modifications to identify the best concept.

5.1. Computing relative importance ranking and rating of design criteria (phase I)

As already mentioned design criteria are pre-determined and are generated based on customer requirements. Here, design attributes (DAs) serve as design criteria, which are developed by a team of designers working on the project. Each DA has its own values which are called here as design attribute values (AVs). These AVs are developed based on customer requirements so can act as customer needs. Design Alternatives (As) are generated by a team of different designers based on a combination of different attribute values for each design criteria.

Generation of design alternatives;

Suppose there are m design alternatives $A_1, A_2, \ldots, A_m$ and n design attributes $DA_1, DA_2, \ldots, DA_n$ generated by team of designers and experts.

Design attributes are denoted by layered vector set as $DA = \{DA_1, DA_2, \ldots, DA_n\}$. Further each DA_j has values which are denoted here as:

For example, $DA_1 = \{AV_{11}, AV_{12}, \ldots, AV_{1k}\}$ have k attribute values. AV_{11} , here denote as first value of the first design attribute. Design alternatives are generated based on combination of attribute values and denoted here as $A_i = \{AV_{jp}\}$ where $j \to 1$ to n; and p indicate index of attribute value from design attributes.

The basic steps of this phase are as follows:

1. Generation of design attributes, customer needs and design alternatives.
2. Obtain linguistic and subjective judgement (importance assignment) on each design attribute by different designers.
3. Aggregate designers' judgement on each design attributes and transforms them into rough numbers by using Eqs. (1)–(10).
4. Normalize the rough number importance rating for comparison and compute the relative importance ranking of design attributes based on rules proposed by Zhai et al. [7] as the most important, important, medium important and low important

design attribute. Zhai et al. [7] have used these ranking rules for customer needs but in this paper it is used for ranking of design attributes.

5.2. Development of evaluation model (phase II)

In this phase, linguistic judgements on preferences of AVs assigned by customers are captured by using rough numbers. The relative importance rating and ranking of DAs computed in phase I along with preferences of customers are introduced in the framework of extended VIKOR method with interval numbers to develop evaluation model for concept selection process. The basic steps of this phase are as follows:

1. Obtain linguistic and subjective judgement (preference assignment) on each design attributes values by different customers.
2. Aggregate all customers' preference judgement on each AV and transforms them into rough numbers by using Eqs. (1)–(10). This will form rough group preference decision matrix which shows diversity of customers' perceptions for each AV.
3. Construct the framework of modified VIKOR with interval numbers: identify the PIS and NIS from rough group preference decision matrix according to relative importance ranking of DAs. The rules to select the PIS and NIS for the proposed work are as follows:
   a. Alternative whose attribute value is most preferred by the customers for the case of important and most important design attribute is PIS and least preferred attribute value is NIS
   b. Alternative whose attribute value least preferred by the customers for the case of the low importance design attribute is PIS and most preferred attribute value is NIS
4. Calculate the aggregating function (ranking measure), and then rank the alternatives according to relative closeness to the "ideal" solution.
   The process of implementing the proposed approach is shown with the help of Figs. 1 and 2.

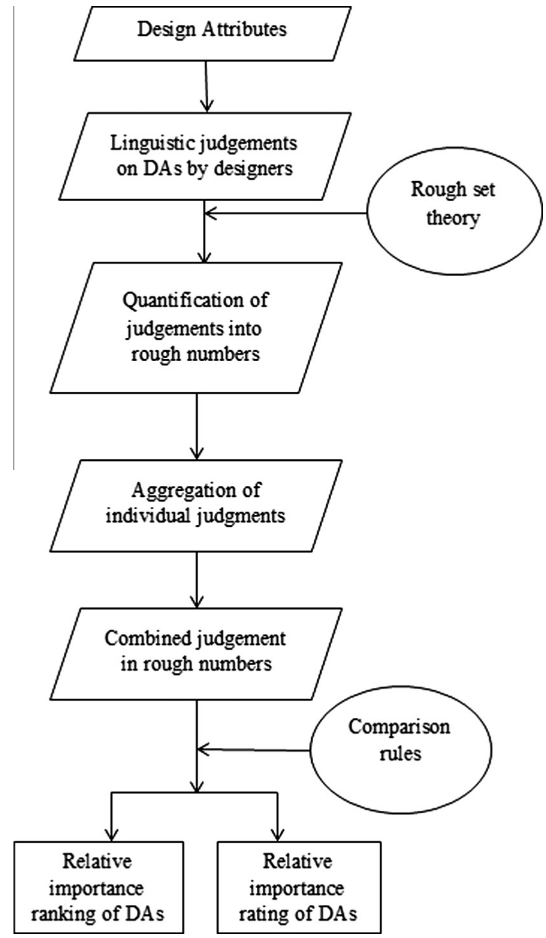

Fig. 1. Implementing process of the phase I (computing relative importance ranking and rating of DAs).

5.3. Procedure of modified rough VIKOR method with interval numbers

After computing relative importance ranking of DAs in phase I, they are classified into categories like the most important DA, important DA, medium importance DA and low importance DA. The steps of modified rough VIKOR method with interval numbers are as follows:

1. Suppose rough group preference decision matrix computed through Step 2 of phase II has the following form:

$$X = \begin{bmatrix} [x_{11}^-, x_{11}^+] & [x_{12}^-, x_{12}^+] & \ldots & [x_{1n}^-, x_{1n}^+] \\ [x_{21}^-, x_{21}^+] & [x_{22}^-, x_{22}^+] & \ldots & [x_{2n}^-, x_{2n}^+] \\ \ldots & \ldots & \ldots & \ldots \\ [x_{m1}^-, x_{m1}^+] & [x_{m2}^-, x_{m2}^+] & \ldots & [x_{mn}^-, x_{mn}^+] \end{bmatrix} \quad (17)$$

   where $\left[x_{ij}^-, x_{ij}^+\right]$ is the combined preference rating of alternative A_i with respect to design attribute DA_j assigned by customers in the form of rough numbers. x_{ij}^- and x_{ij}^+ are the lower and upper limits, respectively.
2. Generate the PIS and NIS based on importance category of DA unlike on the basis of benefit and cost as proposed by many concept evaluation frameworks. For the most important and the important DAs, the PIS would be the largest preference value it may take. Thus, in this work, the largest upper limit of all the rough numbers that these DAs takes is selected as PIS. For NIS, smallest lower limit of all rough numbers is chosen. Similar analysis can be done for the low importance DA. As for medium importance DA, average value of upper limits of all rough numbers is chosen as PIS and average value of lower limits is chosen as NIS. Mathematically,
   For, most important and important DAs:

$$\text{PIS}, \ x_j^* = \left(\max_i (x_{ij}^+) | j \in I\right) \quad j = 1, 2, \ldots, n; \ i = 1, 2, \ldots, m \quad (18a)$$

$$\text{NIS}, \ x_j^- = \left(\min_i (x_{ij}^-) | j \in I\right) \quad j = 1, 2, \ldots, n; \ i = 1, 2, \ldots, m \quad (18b)$$

For, medium importance DAs

$$\text{PIS}, \ x_j^* = \left(\underset{i}{avg} (x_{ij}^+) | j \in J\right) \quad j = 1, 2, \ldots, n; \ i = 1, 2, \ldots, m \quad (19a)$$

$$\text{NIS}, \ x_j^- = \left(\underset{i}{avg} (x_{ij}^-) | j \in J\right) \quad j = 1, 2, \ldots, n; \ i = 1, 2, \ldots, m \quad (19b)$$

For, low importance DAs

$$\text{PIS}, \ x_j^* = \left(\min_i (x_{ij}^+) | j \in K\right) \quad j = 1, 2, \ldots, n; \ i = 1, 2, \ldots, m \quad (20a)$$

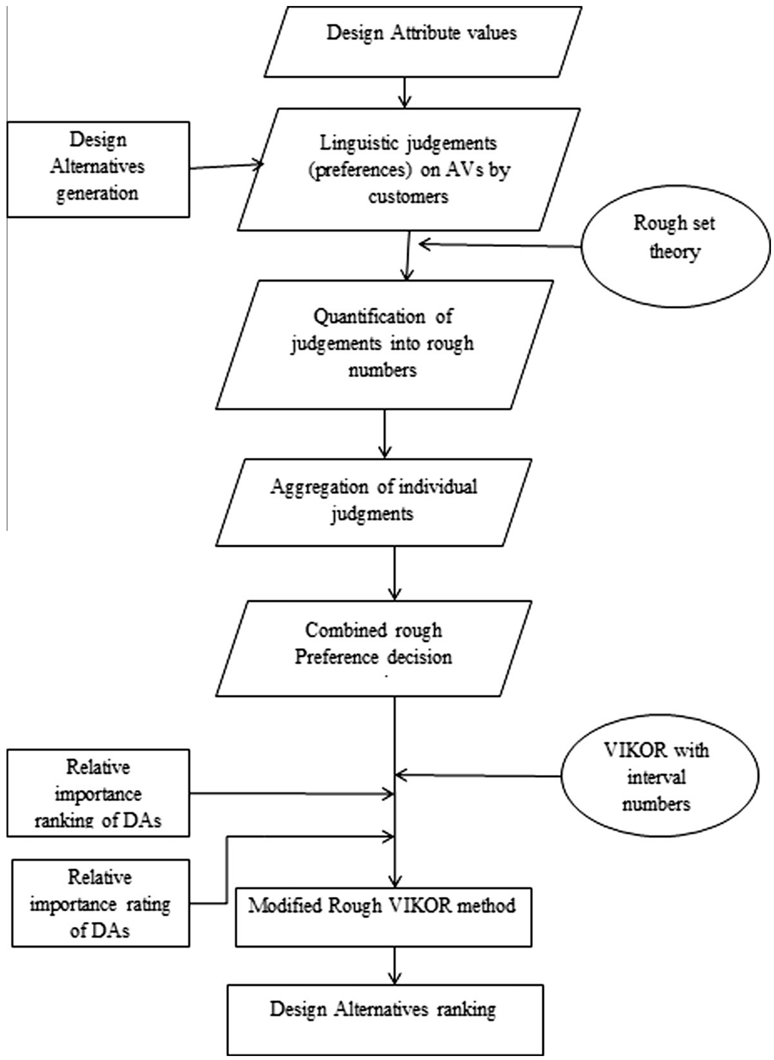

Fig. 2. Implementing process of the phase II (development of evaluation model for concept selection.

$$\text{NIS, } x_j^- = \left(\max_i (x_{ij}^-) | j \in K\right) \quad j = 1,2,\ldots,n;\ i = 1,2,\ldots,m \tag{20b}$$

where I is associated with the most important and important DAs, and J is associated with medium importance DAs, K is associated with low importance DAs. Alternative whose attribute value is most preferred by the maximum customers for the most important and important design attribute and least preferred by the customers for low importance design attribute is the ideal solution for the case proposed. For medium important design attribute, alternative whose attribute value is neither most preferred nor least preferred is the ideal solution.

3. The values of $[S_i^-,\ S_i^+]$ and $[R_i^-,\ R_i^+]$ are computed here according to the importance level of design attribute. So modified formulas according to the case proposed is shown as below:

$$S_i^- = \sum_{j\in I} w_j^- \left(\frac{x_j^* - x_{ij}^+}{x_j^* - x_j^-}\right) + \sum_{j\in J} w_j^- \left(\frac{\min(A,B)}{x_j^* - x_j^-}\right) + \sum_{j\in K} w_j^- \left(\frac{x_{ij}^- - x_j^*}{x_j^- - x_j^*}\right) \tag{21a}$$

$$S_i^+ = \sum_{j\in I} w_j^+ \left(\frac{x_j^* - x_{ij}^-}{x_j^* - x_j^-}\right) + \sum_{j\in J} w_j^+ \left(\frac{\max(A,B)}{x_j^* - x_j^-}\right) + \sum_{j\in K} w_j^+ \left(\frac{x_{ij}^+ - x_j^*}{x_j^- - x_j^*}\right) \tag{21b}$$

$$R_i^- = \max\left\{ \left(w_j^- \left(\frac{x_j^* - x_{ij}^+}{x_j^* - x_j^-}\right) \middle| j \in I\right), \left(w_j^- \left(\frac{\min(A,B)}{x_j^* - x_j^-}\right) \middle| j \in J\right), \left(w_j^- \left(\frac{x_{ij}^- - x_j^*}{x_j^- - x_j^*}\right) \middle| j \in K\right) \right\} \tag{22a}$$

$$R_i^+ = \max\left\{ \left(w_j^+ \left(\frac{x_j^* - x_{ij}^-}{x_j^* - x_j^-}\right) \middle| j \in I\right), \left(w_j^+ \left(\frac{\max(A,B)}{x_j^* - x_j^-}\right) \middle| j \in J\right), \left(w_j^+ \left(\frac{x_{ij}^+ - x_j^*}{x_j^- - x_j^*}\right) \middle| j \in K\right) \right\} \tag{22b}$$

where $w_j = [w_j^-,\ w_j^+]$ are DA's relative importance rating (weights) calculated from phase I. The values of A and B depend on following rules:

(a) If $x_j^* > x_{ij}^+$ then $A = x_j^* - x_{ij}^+$ and $B = x_j^* - x_{ij}^-$
(b) If $x_j^* < x_{ij}^+$ but $x_j^* > x_{ij}^-$ then $A = -(x_j^* - x_{ij}^+)$ and $B = x_j^* - x_{ij}^-$
(c) If $x_j^* < x_{ij}^-$ then $A = -(x_j^* - x_{ij}^+)$ and $B = -(x_j^* - x_{ij}^-)$

4. Compute the aggregating function interval $Q_i = [Q_i^-,\ \ Q_i^+]$

$$Q_i^- = v * \left(\frac{S_i^- - S^*}{S^- - S^*}\right) + (1 - v) * \left(\frac{R_i^- - R^*}{R^- - R^*}\right) \tag{23a}$$

$$Q_i^+ = v * \left(\frac{S_i^+ - S^*}{S^- - S^*}\right) + (1 - v) * \left(\frac{R_i^+ - R^*}{R^- - R^*}\right) \tag{23b}$$

where

$$S^* = \min_i(S_i^-), \quad S^- = \max_i(S_i^+) \tag{24}$$

$$R^* = \min_i(R_i^-), \quad R^- = \max_i(R_i^+) \tag{25}$$

v = Weight of the strategy of "the majority criteria"
The best concept is chosen by the comparison rules as mentioned in Step 'd' of VIKOR method with interval numbers.

6. Case study: product concept evaluation of a testing rig machine

In this section, design concept evaluation of a testing rig (used for carrying out load tests) machine is taken as a case study to demonstrate the application of the proposed method. Further, comparison among the proposed method, the extended VIKOR method with interval numbers [8] and integrated method based on rough number, AHP and TOPSIS [22] are carried out to analyse the performance of the proposed Modified rough VIKOR method (MR-VIKOR). Suppose, a company 'Y' is a design and manufacturing firm of testing rig. A total of four design alternatives (A_1, A_2, A_3, A_4) of testing rig have been generated by a team of designers during the conceptual design phase. The objective of this evaluation is to identify the best concept which satisfies all, the constraints imposed by the team of the designers on design attributes as well as satisfy the needs of group of maximum customers.

Customer survey reveals that, small-sized customers are mainly interested in reliable, safe, simple and cost effective performance of the testing rig machine. Therefore, in order to meet customers basic requirements, team of experts and designers have identified some core functional requirements of testing rig which are namely, safe and reliable operation, cost effective and simple design, easy to manufacture and good operating characteristics. Design team and experts chooses four DAs (i.e. design criteria).

DA_1: Expected mechanical safety, DA_2: Amount of wear, DA_3: Operating and maintenance cost and DA_4: Overload reserve of a machine. Each DA has values which represents customer requirement. AVs for each DA are DA_1: low, average, high, very high; DA_2: very low, low, medium, high; DA_3: low, medium, high, very high and DA_4: low, medium, high, very high. Design alternatives are generated based on different combinations of attribute values from each DA. Table 1 shows design attribute values of each design alternatives i.e. specifications of each design alternative. The evolved alternatives with their specification values are presented in Table 1 and are:

Design Alternative (or Concept) A_1 includes high mechanical safety, very low amount of wear, very high operating and maintenance cost and high overload reserve of machine; Alternative A_2 includes low mechanical safety, low amount of wear, medium operating and maintenance cost and medium overload reserve of the machine; A_3 includes very high mechanical safety, medium amount of wear, high maintenance and operating cost and very high overload reserve of the machine; A_4 includes average mechanical safety, high amount of wear, low operating and maintenance cost and low overload reserve of the machine.

6.1. Computing relative importance ranking and rating of design criteria

During this phase, team of four designers have been asked to assign judgment (importance rating) on each DA. Symmetrical triangular fuzzy numbers (STFNs) are used to capture the vagueness of designer's perception towards DAs. These STFNs are used by many researchers [34–36] to analyse voice of customers. To capture "Voice of designer", 9-Point scale, as proposed by [36] is used. This scale can be represented by crisp numbers or STFNs and have values represented by Table 2.

Four designers D_1, D_2, D_3 and D_4 have assigned importance from 9-Point scale to each DA which is shown in Table 3. Although STFNs can be used to capture vague perception of designers' mind, but, it is very difficult to determine appropriate fuzzy membership function in case of STFNs [7]. From Table 2, STFNs has fixed boundary interval of "2". This may not correctly represent degree of vagueness of different importance ratings assigned by designers. Therefore, rough number (RN) may be good alternative to capture more effectively the diversity of designers' opinion. Thus, each designer's importance assignment in the form of STFNs is converted into rough numbers as shown in Table 4 using Eqs. (1)–(10). Combined importance assignment as shown in Table 5 is obtained by taking average sum of importance assignment of each DA by every designer. Relative importance rating (Attribute weight) is obtained by normalizing value of RN for every DA as shown in fourth column of Table 5. These values are then analysed by the comparison rules proposed by [7] to obtain relative importance ranking of DA. Based on comparison rules, importance ranking of DA and their classification is as follows:

$$DA_2 > DA_1 > DA_3 > DA_4 \tag{26}$$

DA_2 = Most important criteria; DA_1 = Important criteria; DA_3 = Medium important criteria; DA_4 = Low importance criteria.

6.2. Development of evaluation model

Table 1 is rearranged to achieve decision matrix which has the form shown below.

Table 2
Scale for measuring relative importance of design attributes.

Scale (importance)	Crisp value and STFN
Very low (VL)	1 [0, 2]
Very low	2 [1, 3]
Low (L)	3 [2, 4]
Low	4 [3, 5]
Moderate (M)	5 [4, 6]
Moderate	6 [5, 7]
High (H)	7 [6, 8]
High	8 [7, 9]
Very high (VH)	9 [8, 10]

Table 1
Attribute values of each design alternatives developed by the designers.

Design attributes	Design alternatives			
DA_i	A_1	A_2	A_3	A_4
DA_1 (Expected mechanical safety)	High	Low	Very high	Average
DA_2 (Amount of wear)	Very low	Low	Medium	High
DA_3 (Operating and maintenance cost)	Very high	Medium	High	Low
DA_4 (Overload reserve of a machine)	High	Medium	Very high	Low

Table 3
Importance assigned to design attributes by team of designers.

Design attributes	Designers			
DA_i	D_1	D_2	D_3	D_4
Expected mechanical safety	H (7) [6, 8]	M (5) [4, 6]	H (7) [6, 8]	L (3) [2, 4]
Amount of wear	M (5) [4, 6]	M (5) [4, 6]	H (7) [6, 8]	H (7) [6, 8]
Operating and maintenance cost	H (7) [6, 8]	L (3) [2, 4]	L (3) [2, 4]	H (7) [6, 8]
Overload reserve of a machine	L (3) [2, 4]	L (3) [2, 4]	L (3) [2, 4]	M (5) [4, 6]

Table 4
Importance assigned to design attributes in the form of rough numbers.

Design attributes	Designers			
DA_i	D_1	D_2	D_3	D_4
Expected mechanical safety	[5.5, 7]	[4, 6.33]	[5.5, 7]	[3, 5.55]
Amount of wear	[5, 6]	[5, 6]	[6, 7]	[6, 7]
Operating and maintenance cost	[5, 7]	[3, 5]	[3, 5]	[5, 7]
Overload Reserve of a machine	[3, 3.5]	[3, 3.5]	[3, 3.5]	[3.5, 5]

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{array}{c} \begin{array}{cccc} DA_1 & DA_2 & DA_3 & DA_4 \end{array} \\ \begin{bmatrix} \text{High} & \text{Very Low} & \text{Very High} & \text{High} \\ \text{Low} & \text{Low} & \text{Medium} & \text{Medium} \\ \text{Veryhigh} & \text{medium} & \text{High} & \text{veryhigh} \\ \text{Average} & \text{High} & \text{Low} & \text{Low} \end{bmatrix} \end{array}$$

In order to obtain customers' perception for each attribute values, a customer survey is conducted, during which four customers are asked to assign their preferences as shown below in D_1, D_2, D_3, D_4 for design attribute values in the form of crisp values through following assumption:

7 = high preference; 5 = medium preference; 3 = low preference; 1 = very low preference

$$D_1 = \begin{bmatrix} 7 & 5 & 1 & 7 \\ 5 & 7 & 7 & 1 \\ 3 & 3 & 5 & 5 \\ 1 & 1 & 3 & 3 \end{bmatrix} \quad D_2 = \begin{bmatrix} 5 & 7 & 3 & 1 \\ 7 & 5 & 1 & 5 \\ 3 & 3 & 5 & 7 \\ 1 & 1 & 7 & 3 \end{bmatrix}$$

$$D_3 = \begin{bmatrix} 5 & 7 & 1 & 3 \\ 7 & 5 & 3 & 1 \\ 3 & 3 & 5 & 7 \\ 1 & 1 & 7 & 5 \end{bmatrix} \quad D_4 = \begin{bmatrix} 3 & 5 & 1 & 7 \\ 1 & 7 & 3 & 3 \\ 7 & 1 & 7 & 5 \\ 5 & 3 & 5 & 1 \end{bmatrix}$$

These four matrices are then assembled to form combined decision matrix as shown below

$$D_{combined} = \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{bmatrix} 7,5,5,3 & 5,7,7,5 & 1,3,1,1 & 7,1,3,7 \\ 5,7,7,1 & 7,5,5,7 & 7,1,3,3 & 1,5,1,3 \\ 3,3,3,7 & 3,3,3,1 & 5,5,5,7 & 5,7,7,5 \\ 1,1,1,5 & 1,1,1,3 & 3,7,7,5 & 3,3,5,1 \end{bmatrix}$$

Rough group preference decision matrix is obtained by converting these preferences into rough numbers form using Eqs. (1)–(10) is shown below:

$$D_{Rcombined} = \begin{bmatrix} [4.5, 5.83] & [5.5, 6.5] & [1.125, 1.875] & [3, 6.04] \\ [3.5, 6.33] & [5.5, 6.5] & [2.29, 4.79] & [1.54, 3.5] \\ [3.22, 4.75] & [2.125, 5.75] & [5.125, 5.875] & [5.5, 6.5] \\ [1.25, 2.75] & [1.125, 1.875] & [4.5, 4.70] & [2.165, 3.83] \end{bmatrix}$$

6.3. Modified rough VIKOR method with interval numbers (MR-VIKOR)

1. Rough group preference decision matrix depicts the customers' perception towards AVs and is shown below

$$D_{Rcombined} = \begin{bmatrix} [4.5, 5.83] & [5.5, 6.5] & [1.125, 1.875] & [3, 6.04] \\ [3.5, 6.33] & [5.5, 6.5] & [2.29, 4.79] & [1.54, 3.5] \\ [3.22, 4.75] & [2.125, 5.75] & [5.125, 5.875] & [5.5, 6.5] \\ [1.25, 2.75] & [1.125, 1.875] & [4.5, 4.70] & [2.165, 3.83] \end{bmatrix} \tag{27}$$

   where for example $[4.5, 5.83]$ is the combined preference rating of attribute value AV_{13}, assigned by customers, for alternative A_1 with respect to design attribute DA_1 .
2. Generate the PIS and NIS based on importance classification of DA from Eqs. (18)–(20), unlike on the basis of benefit and cost according to the rules proposed in phase II.
   For, most important and important DAs:

   PIS, $x_1^* = 6.33$; $x_2^* = 6.5$
   NIS, $x_1^- = 1.25$; $x_2^- = 1.125$

   For, medium importance DAs

   PIS, $x_3^* = 4.31$
   NIS, $x_3^- = 3.26$

   For, low importance DAs

   PIS, $x_4^* = 1.54$
   NIS, $x_4^- = 6.5$
3. Compute $[S_i^-, \; S_i^+]$ and $[R_i^-, \; R_i^+]$ intervals from Eqs. (21) and (22) respectively. Values of $[S_i^-, \; S_i^+]$ and $[R_i^-, \; R_i^+]$ are shown in Table 6.
4. The aggregating function $Q_i = [Q_i^-, \; Q_i^+]$ is computed from Eq. (23) and its values for each alternative is shown in Table 7.

The best design alternative (s) based on constraints imposed by the team of the designers on design attributes and preferences of customers is chosen by the comparison rules as mentioned in Step 'd' of VIKOR method with interval numbers. For different values of optimism level of decision maker (α), alternative ranking is computed as shown in Table 8.

Table 5
Relative importance rating of DAs and their normalized and STFN form.

Design attribute	Relative importance rating (RN)	Relative importance rating (STFNs)	Normalized rating (RN)
DA_1 (Expected mechanical safety)	[4.5, 6.47]	[4.5, 6.5]	[0.69, 0.99]
DA_2 (Amount of wear)	[5.5, 6.5]	[5, 7]	[0.84, 1]
DA_3 (Operating and maintenance cost)	[4, 6]	[4, 6]	[0.61, 0.92]
DA_4 (Overload reserve of a machine)	[3.125, 3.875]	[2.5, 4.5]	[0.48, 0.59]

Table 6
Values of $[S_i^-, \ S_i^+]$ and $[R_i^-, \ R_i^+]$.

S_i^-	S_i^+	R_i^-	R_i^+
1.4423711	3.8794332	1.414619048	2.790666667
0.3514378	2.7514161	0.278857143	1.769904762
1.1522273	3.4285412	0.47347619	1.371238095
1.6058831	2.6621843	0.722790698	1.058070866

Table 7
Values of aggregating function $[Q_i^-, \ Q_i^+]$.

Q_i^-	Q_i^+
0.3806953	1
0	0.6369409
0.1522315	0.653547
0.2661537	0.4825972

Table 8
Ranking of design alternatives based on optimism level of decision maker.

Optimism level of decision maker (α)	Design alternative ranking
0.3	$A_1 > A_4 > A_3 > A_2$
0.4	$A_1 > A_4 > A_3 > A_2$
0.5	$A_2 > A_1 > A_4 > A_3$
0.6	$A_2 > A_1 > A_4 > A_3$
0.7	$A_2 > A_3 > A_1 > A_4$
0.9	$A_2 > A_3 > A_4 > A_1$

For $\alpha = 0.5$, design alternative ranking is as $A_2 > A_1 > A_4 > A_3$. As seen in Table 8 for values of $\alpha \geqslant 0.5$, A_2 is the best concept based on both customers' preferences for AVs and designers' importance assignment for DAs. But, for $\alpha < 0.5$, A_1 is the best concept followed by A_4.

As this paper proposes novel way of incorporating designers' constraints along with customers' preferences in concept evaluation framework, the best concept i.e. A_2 is correct choice based on assumed rules because alternative A_2's attribute values is most preferred by the customers for most important and important design attribute (Amount of wear and expected mechanical safety) and least preferred for low importance design attribute (overload reserve of a machine). Also for medium importance design attribute, its values are close to averagely preferred ideal attribute values.

7. Comparison with other methods

To reveal the advantages of the proposed method, comparison has been done with other methods namely, the extended VIKOR method with interval numbers [8] and integrated method based on rough number, AHP and TOPSIS [22]. The ranking of design alternatives are calculated for different values of optimism level of decision makers for the same case study of a testing rig. The results are depicted in Table 9. The proposed method captures both subjective and vague perceptions of designers' as well as preferences of customers' and select best design concept based on satisfaction of both designers and customers. The other two methods considers cost and benefit characteristics of design criteria (DAs, here) for performing concept evaluations; but, the proposed method uses importance ranking of DAs for computing design alternatives ranking. Thus, ranking computed by proposed method is different from other two methods. As in the proposed case study, A_2 comes out to be the correct choice based on assumed rules of selection as alternative A_2's attribute values are most preferred by the customers for the most important, and important design attributes i.e. Amount of wear and expected mechanical safety; and the least preferred for the low importance design attribute i.e. overload reserve of a machine. Further, for medium importance design attribute, its values are close to averagely preferred ideal attribute values. The other method integrated method based on rough number, AHP and TOPSIS [22] concludes A_1 and A_3 as the best concept based on only cost and benefit characteristics of design criteria.

The proposed concept evaluation framework allows designers to consider the importance of design criteria in concept evaluations instead of cost and benefit characteristics of criteria, thus developing alternative way of concept selection process which might be useful to the industries in some cases. The proposed framework proves to be useful, when the team of designers are confident about values of certain design attribute while uncertain about the rest of attribute values, which is the common case during early stages of design when information about many attributes are not clear. Based on the proposed work, designers can easily find which concept is most preferable for certain important design attributes and least preferred for the uncertain design attributes. The solution obtained by integrated method based on rough numbers, AHP and TOPSIS [22] is different than the extended VIKOR method with interval numbers [8] due to difference in normalization methods and difference in calculating aggregating functions. Moreover, in integrated method based on rough numbers, AHP and TOPSIS [22], the rough numbers are converted to crisp values which may lead to miss some information due to approximations.

8. Conclusions

This work proposes a rough number enabled VIKOR method with the objective of developing a systematic framework for concept evaluation process and to reduce subjectivity associated with this process. In the proposed method, the vague, raw and subjective perceptions of designers' and continuously changing preferences of customers are captured and represented in the form of rough numbers. The new concept of incorporating importance ranking of design criteria in the framework of concept evaluation process along with customers' preferences provides a novel alternative for this critical task during early stages of product development. The proposed method selects the best concept, which satisfies both the constraints imposed by the designers

Table 9
Ranking of design alternatives computed with the other two methods.

Optimism level of decision maker (α)	Design alternative ranking by proposed MR-VIKOR	Design alternative ranking by extended VIKOR method with interval numbers	Design alternative ranking by integrated method based on rough number, AHP and TOPSIS
0.3	$A_1 > A_4 > A_3 > A_2$	$A_4 > A_3 > A_2 > A_1$	$A_1 > A_3 > A_4 > A_2$
0.4	$A_1 > A_4 > A_3 > A_2$	$A_2 > A_4 > A_3 > A_1$	$A_1 > A_3 > A_4 > A_2$
0.5	$A_2 > A_1 > A_4 > A_3$	$A_2 > A_4 > A_3 > A_1$	$A_3 > A_1 > A_4 > A_2$
0.6	$A_2 > A_1 > A_4 > A_3$	$A_4 > A_2 > A_1 > A_3$	$A_3 > A_1 > A_4 > A_2$
0.7	$A_2 > A_3 > A_1 > A_4$	$A_4 > A_1 > A_2 > A_3$	$A_3 > A_1 > A_4 > A_2$
0.9	$A_2 > A_3 > A_4 > A_1$	$A_1 > A_4 > A_3 > A_2$	$A_1 > A_3 > A_4 > A_2$

and satisfies the preferences of customers. The results of the case study presented in this work, shows that proposed method provides novel and more effective design alternative ranking framework, while considering both designers' and customers' conflicting thoughts. One of the limitation of the proposed best concept might be that selected concept might be more close to designers' expectation than the customers' expectations.

References

[1] J.L. Nevins, D. Whitney, Concurrent Design of Products and Processes – A Strategy for the Next Generation in Manufacturing, McGraw-Hill, New York, 1989.
[2] B. Nepal, L. Monplaisir, N. Singh, Integrated fuzzy logic-based model for product modularization during concept development phase, Int. J. Prod. Econ. 96 (2) (2005) 157–174.
[3] A. Niazi et al., Product cost estimation: technique classification and methodology review, J. Manuf. Sci. Eng. Trans. ASME 128 (2) (2006) 563–575.
[4] Y.L. Tu, S.Q. Xie, R.Y.K. Fung, Product development cost estimation in mass customization, IEEE Trans. Eng. Manage. 54 (1) (2007) 29–40.
[5] G. Pahl, W. Beitz, Engineering Design: A Systematic Approach, Springer, London, and Hong Kong, 1996.
[6] J. Jiao, M.M. Tseng, Fuzzy ranking for concept evaluation in configuration design for mass customization, Concurrent Eng.: Res. Appl. 6 (3) (1998) 189–206.
[7] L. Zhai, L. Khoo, Z. Zhong, A rough set enhanced fuzzy approach to quality function deployment, Int. J. Adv. Manuf. Technol. 37 (5–6) (2008) 613–624.
[8] M.K. Sayadi, M. Heydari, K. Shahanaghi, Extension of VIKOR method for decision making problem with interval numbers, Appl. Math. Model. 33 (5) (2009) 2257–2262.
[9] L. Zhai, L. Khoo, Z. Zhong, Design concept evaluation in product development using rough sets and grey relation analysis, Expert Syst. Appl. 36 (3) (2009) 7072–7079.
[10] X. Geng, X. Chu, Z. Zhang, A new integrated design concept evaluation approach based on vague sets, Expert Syst. Appl. 37 (9) (2010) 6629–6638.
[11] K. Ulrich, S. Eppinger, Product Design and Development, McGraw-Hill Inc, 2000.
[12] S. Pugh, Total Design, Addison-Wesley, New York, 1991.
[13] D. Thurston, A formal method for subjective design evaluation with multiple attributes, Res. Eng. Design 3 (2) (1991) 105–122.
[14] D. Thurston, J. Carnahan, Fuzzy ratings and utility analysis in preliminary design evaluation of multiple attributes, J. Mech. Des. 114 (1992) 648.
[15] A. Alonso-Ayuso, L. Escudero, A. Garin, M. Ortuno, G. Perez, On the product selection and plant dimensioning problem under uncertainty, Omega 33 (4) (2005) 307–318.
[16] F. Mistree, B. Bras, W. Smith, J. Allen, Modelling design processes: a conceptual, decision-based perspective, Int. J. Eng. Des. Automat. 1 (4) (1996) 209–221.
[17] A.M. King, S. Sivaloganathan, Development of a methodology for concept selection in flexible design strategies, J. Eng. Des. 10 (4) (1999) 329–349.
[18] M. Scott, Quantifying certainty in design decisions: examining AHP, in: Proceedings of the 2002 ASME Design Engineering Technical Conferences (DETC2002), 2002.
[19] H.Z. Huang, R.F. Bo, W. Chen, An integrated computational intelligence approach to product concept generation and evaluation, Mech. Mach. Theory 41 (2006) 567–583.
[20] Z. Pawlak, Rough sets, Int. J. Comput. Inform. Sci. 11 (5) (1982) 341–356.
[21] Z. Ayag, An integrated approach to evaluating conceptual design alternatives in a new product development environment, Int. J. Prod. Res. 43 (4) (2005) 687–713.
[22] W. Song, X. Ming, Z. Wu, An integrated rough number-based approach to design concept evaluation under subjective environments, J. Eng. Des. 24 (5) (2013) 320–341.
[23] Z. Ayag, R.G. Ozdemr, An analytic network process-based approach to concept evaluation in a new product development environment, J. Eng. Des. 18 (3) (2007) 209–226.
[24] F.J. Carmone, A. Kara, S.H. Zanakis, A Monte Carlo investigation of incomplete pair wise comparison matrices in AHP, Eur. J. Oper. Res. 102 (3) (1997) 538–553.
[25] T.L. Saaty, The Analytic Hierarchy Process, McGraw-Hill, New York, 1980.
[26] J.B. Yang, P. Sen, Multiple attribute design evaluation of complex engineering products using the evidential reasoning approach, J. Eng. Des. 8 (3) (1997) 211–230.
[27] Y.C. Jin, Advanced Fuzzy Systems Design and Applications, Springer, 2003.
[28] L.-P. Khoo, S.-B. Tor, L.-Y. Zhai, A rough-set based approach for classification and rule induction, Int. J. Adv. Manuf. Technol. 15 (1999) 438–444.
[29] F. Torfi, Z.R. Farahani, S. Rezapour, Fuzzy AHP to determine the relative weights of evaluation criteria and fuzzy TOPSIS to rank the alternatives, Appl. Soft Comput. 10 (2) (2009) 520–528.
[30] S. Opricovic, Multicriteria Optimization of Civil Engineering Systems, Faculty of Civil Engineering, Belgrade, 1998.
[31] P.L. Yu, A class of solutions for group decision problems, Manage. Sci. 19 (8) (1973) 936–946.
[32] M. Zeleny, Multiple Criteria Decision Making, Mc-Graw-Hill, New York, 1982.
[33] S. Opricovic, G.H. Tzeng, Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS, Euro, J. Oper. Res. 156 (2) (2004) 445–455.
[34] L.-P. Khoo, N.C. Ho, Framework of a fuzzy quality function deployment system, Int. J. Prod. Res. 34 (2) (1996) 299–311.
[35] L.-H. Chen, M.-C. Weng, A fuzzy model for exploiting quality function deployment, Math. Comput. Model. 38 (2003) 559–570.
[36] L.-K. Chan, M.-L. Wu, A systematic approach to quality function deployment with a full illustrative example, Omega 33 (2005) 119–139.