Title:
Capturing Design Intent during concept evaluation using rough numbers and TODIM Method

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Introduction:
Design concept evaluation is one of the most important phases of the early design process which influences the success of new product development (NPD). The main objective of this work is to reduce the subjectivity involved in customers' preference evaluations and decision-makers' judgments, thus, improving the effectiveness of the concept evaluation process. This paper proposes an alternate way of performing design concept evaluations by capturing and incorporating the risk preferences of designers, instead of considering the cost and benefit characteristics of design criteria. All the decisions which the designer takes during decision-making are captured in the form of profit/advantage, loss/setback and no profit/no loss. This profit/loss depicts the design intent during the concept evaluation process. In this work, the advantage of rough numbers [5] in handling subjectivity and the merits of prospect theory [2] in considering risk preferences are combined to propose an integrated approach for the design concept evaluation. The work performs concept evaluations in two stages. In the first stage, the ranking of design criteria in terms of their relative importance is computed based on the importance assigned to each design criterion by the designers or the decision-makers (DM). In the second stage, customers' preferences for the generated user requirements are captured in the form of rough numbers [5]. The relative importance ranking computed in the first stage along with customers' preferences in the form of rough numbers are then used to develop rules for computing gain and loss to the designers during concept evaluation. In the second stage, these rules are incorporated in the framework of interval-valued fuzzy TODIM [3] (an acronym in Portuguese for iterative multi-criteria decision-making) using fuzzy numbers to select the best concept. Gomes and Lima [1] first proposed the TODIM method. The above framework is modified by using rough numbers instead of fuzzy numbers to propose a novel method known as Rough-TODIM.

The Rough TODIM method is primarily developed for capturing the design intent thus, resulting in effective concept evaluation. The previously developed concept evaluation methods consider only customer requirements as a major parameter during the selection of the best concept. They do not incorporate the intent of designers or decisions which designer needs to take to satisfy the ill-defined customer requirements. Also, customer requirements and preferences are dynamic in nature, the evaluated concept may not remain the best after some time. The designers' efforts to handle poor customer requirements as well as customer preferences are here captured in the form of gain or loss and rough numbers respectively. The proposed method thus incorporates both the intent of designers and customers to develop an effective concept evaluation method.

Methodology:

The Rough-TODIM method involves two stages namely, Evaluation of weights and importance ranking of design criteria and Computing the ranking of design alternatives. In Stage 1, the evaluation of weights and importance ranking of the design criteria are determined by the method proposed by Tiwari et al. [4] and Zhai et al. [6]. These weights and importance ranking are then introduced in the proposed rough-TODIM method to evaluate the ranking of design alternatives. The ranking obtained by the rough-TODIM method in terms of novelty captures both the judgments of designers and the preferences of customers in the risk environment. Taking the advantage of the rough numbers to capture the judgements of designers about the design criteria in terms of importance in Stage 1, Stage 2 uses this importance ranking of design criteria in interval-valued TODIM [3] with a few modifications to compute the ranking of design concepts.

Mathematical Model

The design criteria are determined by the designers based on user surveys and customer requirements. These design criteria have certain values which show the performance of the alternatives for that criteria.

Let design concepts/alternatives can be denoted by the layered vector set as $A = \{A_1, A_2, \ldots\ldots, A_k, \ldots\ldots, A_n\}$. Each A_k can be denoted by a layered vector set as $A_k = \{C_1, C_2, \ldots., C_k, \ldots.., C_m\}$ where C_k represents the design criteria. The performance of A_k for any C_k can be measured by the value of that design criteria.

The weights of design criteria and importance ranking are calculated by following steps:

1. Identify the design criteria and design alternatives based on customer requirements
2. Obtain the qualitative and quantitative judgements on each design criteria by potential designers
3. Aggregate the judgements of all designers for each design criterion and convert them into rough numbers as proposed by Tiwari et al. [4]. Normalize the rough numbers to compute the weight of the design criteria.
4. Based on the value of the weights the importance rating of the design criteria in terms of most important, important, average importance and low importance is calculated by the rules proposed by Zhai et al. [6].

In Stage 2, customer preferences for criteria values are captured in the form of rough numbers. These customers' preferences, criteria weights and importance ratings are used in the framework of Interval-Valued TODIM [3] along with developed rules of profit and loss to propose a novel model of concept evaluation namely Rough-TODIM. The important step of this stage is as follows

1. Obtain the qualitative and quantitative judgements on each design criterion value by customers.
2. Aggregate the judgements of all the customers for each design criterion value and convert them into rough numbers and normalize them as proposed by Tiwari et al. [4]. This will form the rough normalized decision matrix. The decision matrix is in the form of Tab. 1.
3. Calculate the dominance of each alternative A_i over A_j using the Eqn. (2.1):

$$\delta(A_i, A_j) = \sum_{c=1}^{n} \phi_c\,(A_i, A_j)\ \vee (i, j) \tag{2.1}$$

where the value of $\phi_c(A_i, A_j)$ as proposed by Krohling et al. [3] for the profit, loss and neutral condition for the designer is mentioned respectively as $\sqrt{\frac{W_{rc}}{\sum_{c=1}^{m} W_{rc}}}\left(d(A_i, A_j)\right), \frac{-1}{\theta}\sqrt{\frac{W_{rc}}{\sum_{c=1}^{m} W_{rc}}}\left(d(A_i, A_j)\right)$ and 0. The term $\phi_c(A_i, A_j)$ represents the dominance contribution factor of criterion to the term $\delta(A_i, A_j)$. The term $\left(d(A_i, A_j)\right)$ stands for the distance between the performance values of alternatives (P_{ic}^-, P_{ic}^+) and (P_{jc}^-, P_{jc}^+). The term (P_{ic}^-, P_{ic}^+) denotes lower and upper limit performance value of alternative A_i. It is calculated by the Eqn. (2.2):

$$|P_{jc}^- - P_{ic}^-| + |P_{jc}^+ - P_{ic}^+|. \tag{2.2}$$

Alternatives	*Criteria*			
	C_1	C_2	C_3	C_4
A_1	(P_{11}^-, P_{11}^+)	(P_{12}^-, P_{12}^+)	(P_{12}^-, P_{12}^+)	(P_{12}^-, P_{12}^+)
A_2	(P_{21}^-, P_{21}^+)	(P_{22}^-, P_{22}^+)	(P_{23}^-, P_{23}^+)	(P_{24}^-, P_{24}^+)
A_3	(P_{31}^-, P_{31}^+)	(P_{32}^-, P_{32}^+)	(P_{33}^-, P_{33}^+)	(P_{34}^-, P_{34}^+)
A_4	(P_{41}^-, P_{41}^+)	(P_{42}^-, P_{42}^+)	(P_{43}^-, P_{43}^+)	(P_{44}^-, P_{44}^+)

Tab. 1: Rough Normalized Decision Matrix.

The term θ represents the attenuation factor of the losses. Here, the risk preferences of the designers are incorporated in the framework of rough TODIM by proposing the condition for profit, loss, partial gain and partial loss to the designer during decision-making. The rules for calculating risk preferences for the designer are

A. If the criterion is important or most important as well as customer preference is more for that alternative in comparison to the other alternatives then it is a gain/advantage for the designer, otherwise loss/setback to the designer.

B. If the criterion is averagely important, as well as customer preference is more for that alternative when compared with the other alternative then it is partial profit to the designer, otherwise a partial loss to the designer. In such cases, a factor of 0.5 should be multiplied to both the terms $\sqrt{\frac{W_{rc}}{\sum_{c=1}^{m} W_{rc}}}\left(d\left(A_i, A_j\right)\right)$, $\frac{-1}{\theta}\sqrt{\frac{W_{rc}}{\sum_{c=1}^{m} W_{rc}}}\left(d\left(A_i, A_j\right)\right)$ to compensate for the average important criteria.

C. If the criterion is less important as well as customer preference is low for that alternative in comparison to the other alternatives, then it is a loss to the designer, otherwise a profit.

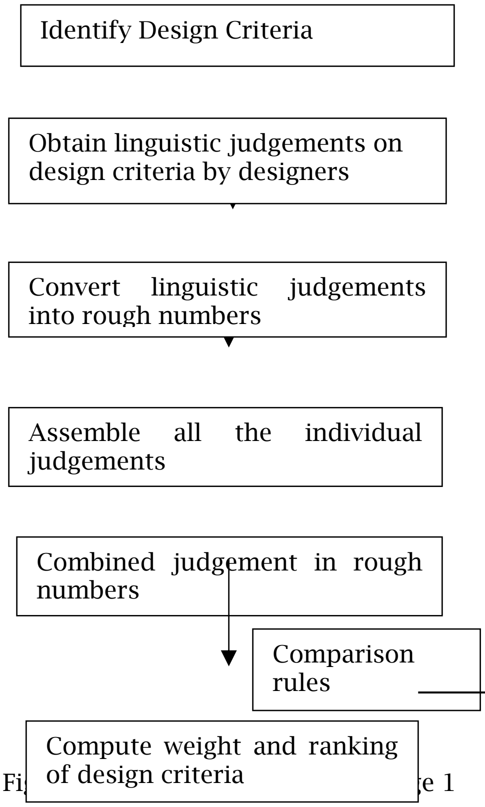
4. The final dominance matrix is the sum of all dominance matrices of dominance for each criterion.
5. Normalize the final dominance matrix. The Eqn. (2.3) represents the global value of any alternative A_i. The best alternative is to have the highest value of ε_i

$$\varepsilon_i = \frac{\sum \delta(i,j) - min \sum \delta(i,j)}{max \sum \delta(i,j) - min \sum \delta(i,j)} \qquad (2.3)$$

The implementation process for both stages is shown in Fig. 1 and Fig. 2.

Case Study: Design Concept Evaluation of Weightlifting Bench

In this manuscript, to demonstrate the application of the proposed method the design example of a Weightlifting Bench is taken as a case study. The objective of the proposed concept evaluation method is to identify the best alternative in the uncertain (risk) environment by identifying the gain or losses to the designer during the decision-making. The best concept also satisfies the maximum preferences of customers as well. A total of four design concepts, namely, A_1, A_2, A_3, and A_4 were evaluated based on four design criteria, namely C_1 = Size of the Bench, C_2 = Safety and Stability features, C_3 = Overall cost, C_4 = Weight of the bench. Customer requirements are represented with the help of the design criteria values, i.e., C_1= small, medium, large, very large; C_2 = very less, less, Average, high; C_3 = low, medium, high, very high; C_4 = low, medium, high, very high. Each design alternatives have one value from each design criterion which represents the performance of that concept. Tab. 2 represents the performance of each alternative.



Fi e 1

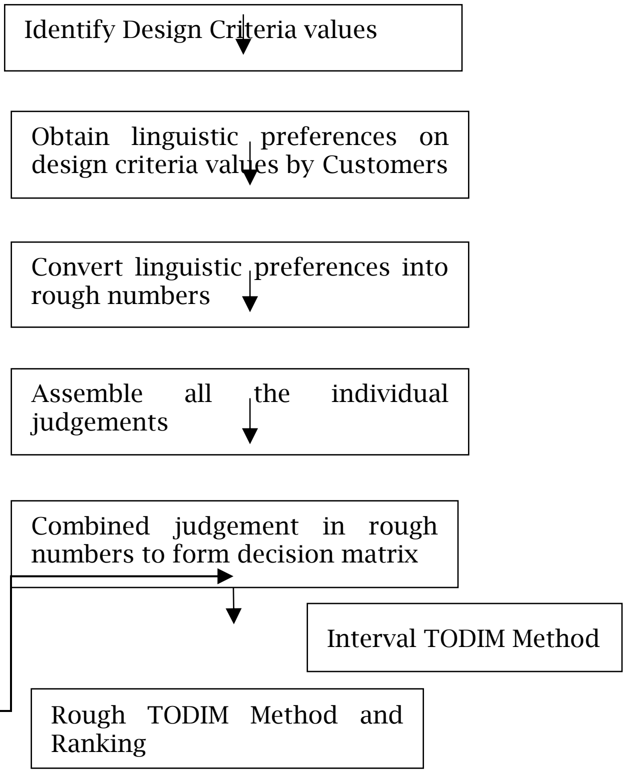


Fig. 2: Implementation Steps of Stage 2

Design Criteria	*Alternatives*			
	A_1	A_2	A_3	A_4
C_1	large	small	Very large	Medium
C_2	Very Less	Less	Average	High
C_3	Very High	Medium	High	Low
C_4	High	Medium	Very High	Low

Tab. 2: Performance of each alternative.

After applying all the steps of Stage 1, the weights of design criteria in rough number form and their importance ranking are shown in Tab. 3. After applying the steps of Stage 2, the global measurements and ranking of the alternatives are shown below in Tab. 4

Design Criteria	*Weights*	*Importance Ranking*
C_1	[0.69, 0.99]	Important
C_2	[0.84, 1]	Most Important
C_3	[0.61, 0.92]	Medium
C_4	[0.48, 0.59]	Low Important

Tab. 3: Weights of Design Criteria in Rough Numbers.

Design Criteria	*Global Measurement*	*Ranking*
A_1	0.5122	Second
A_2	1	First
A_3	0	Fourth
A_4	0.0249	Third

Tab. 4: The global measurements and ranking of the alternatives.

Comparison with other methods

The proposed concept evaluation method is compared with other methods namely, the TODIM method developed by Gomes et al. [1] and interval-valued intuitionistic fuzzy TODIM developed by Krohling et al.[3] to demonstrate the effectiveness of the method. The ranking of the alternatives is calculated for θ values of 1 and 2.5 and are shown in Tab.5. The proposed method captures both the subjective judgements of designers and linguistic preferences of customers in the form of rough numbers, whereas the method proposed by Gomes considers crisp values and Krohling uses interval-valued intuitionistic fuzzy numbers.

θ Value	**Ranking computed by Proposed Rough-TODIM**	**Ranking computed by TODIM**	**Ranking computed by Fuzzy TODIM**
θ = 1	$A_2 > A_1 > A_4 > A_3$	$A_3 > A_1 > A_2 > A_4$	$A_3 > A_1 > A_2 > A_4$
θ = 2.5	$A_2 > A_1 > A_4 > A_3$	$A_3 > A_1 > A_2 > A_4$	$A_3 > A_1 > A_2 > A_4$

Tab. 5: Ranking of Alternatives compared with other methods.

Conclusion

In this manuscript, the concept evaluation process is made effective by capturing the risk in terms of profit and gain for the designers during the decision-making. This helps in capturing the design intent effectively during the early design stage of the product development process. Also, the rough numbers help to reduce uncertainty as well as help in capturing the true perception of customers and handling the subjective judgements of the designers. The alternative ordering achieved by the rough-TODIM method seems to be satisfactory as it considers the opinion of both the designers and customers during the design concept evaluation.

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