Arabian Journal for Science and Engineering (2022) 47:3751–3762
https://doi.org/10.1007/s13369-021-06049-w

RESEARCH ARTICLE-SYSTEMS ENGINEERING

Design Decision in the Manufacturing Environment Using an Improved Multiple-Criteria Performance Evaluation Method

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Received: 10 March 2021 / Accepted: 30 July 2021 / Published online: 25 August 2021
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Abstract

The success of any company depends significantly on the realization of new products, which in turn depends on the selection of the best initial concept. Concept evaluations and selections during product development are critical decision-making steps and involve multiple-criteria decision-making (MCDM). This work proposes a concept evaluation and selection model which considers not only customer requirements (CR) but also the quality of the product features, defined in terms of feature quality levels (FQLs) and manufacturer's ability (MA) to fabricate the product, i.e. product manufacturability. The work evaluates quantitative weights assigned to CR (i.e. w_c) and FQL with the help of the analytical hierarchy process (AHP) so that rather than random weights considered by the designers, the system takes into account the structured weights. The work also considers MA during concept selection in the form of weights (w_m). The work proposes an extended PROMETHEE technique, where the weights of CR (w_c) and MA (w_m) are applied concurrently at the conceptual design stage itself into the PROMETHEE to select the most appropriate concept that leads to product development by including the criteria from customers as well as manufacturers' perspectives.

Keywords Multi-criteria decision-making · PROMETHEE · AHP · Concept selection · Customer requirement · Manufacturer abilities

1 Introduction

The dynamic customer needs and competitive market settings desire that the developed products must fulfil the identified customer requirements (CR), possess the anticipated product feature quality (PFQ) and must consider the manufacturer ability (MA) to produce the product. Product concepts are evolved at the conceptual design stage of the product development process and greatly influence the CR, PFQ and MA of the final products. Concept evaluation and selection during product design is an activity where possible alternatives are evaluated, and accordingly, the decision is made to select the best concept for the succeeding design stages. Inappropriate decision-making during concept selection may lead to product failure. Thus, the success of a product depends significantly on the initial concepts that evolved during the early design stages of the product development process. As customer demands fluctuate widely, concept selection typically becomes a multiple-criteria decision-making (MCDM) problem, where the designer evaluates concepts by focusing on CR and keeping the designer and manufacturer intentions in mind. Subsequently, many researchers had indicated concept selection as one of the most significant concerns in design [1]. Further, nearly 70–80% of the product cost is committed during the conceptual design phase in the product life cycle [2].

Selecting the most apposite new product(s) is considered a critical decision that is impacting the manufacturer's financial benefits [3]. It is observed that the consumer's perception of a product varies significantly, and it is not possible to fulfil all the CR with the desired quality, particularly with the present design approaches. This work proposes to convert the customer perception into a numerical value, i.e. the weight of CR (w_c), with the help of the analytical hierarchy process (AHP). It is also realized that the selected concept may not lead to the desired product unless and until the manufacturers' constraints are also analysed. An early

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analysis of manufacturer constraints is critical to minimize the product cost and lead time. This work takes into account some of the issues related to product manufacturability by considering the manufacturer constraints on a numerical scale, defined in terms of weight of manufacturer ability (w_m). These numerical values of CR and MA are utilized in the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) to obtain the best choice from a finite set of possible concepts.

Further, the customer purchasing decision depends on the fulfilment of several among the desired needs. It is not advisable for a manufacturer to create a product that meets each of the CR with equal PFQ. To identify which CR should be met with high-quality features, this work employs the arithmetic mean of w_c obtained by AHP. With the classification of PFQs set in, the work also helps in identifying feature quality levels (FQLs), where each product feature would set in from the product cost and customer satisfaction perspective. The objectives of this work are twofold, i.e.

- Selection of most appropriate concept that considers the criteria for product development from customers' expectation and sympathetically considers manufacturers' perspectives,
- Prioritization and mass customization of the product feature quality (PFQ), where each product feature would set in from customer satisfaction and product cost perspective.

To achieve the first objective, this work presents a concept evaluation and selection model by integrating analytical hierarchy process (AHP) and Preference Ranking Organizational Method for Enrichment Evaluation (PROMETHEE) techniques, where both customers and manufacturers' perspectives are considered. For the second objective, i.e. to identify PFQ, this work employs the arithmetic mean of customer requirement weight (w_c) (obtained by AHP).

2 Related Work

The success or failure of any product mainly depends on the concepts generated during its development. Concept generation and selection are linked with customer utility and technical and economic feasibility [4]. It also involves uncertainty due to imperfect information or knowledge [5]. It is said that a good concept may not guarantee a good product design, while a bad concept would surely lead to a bad design. Therefore, several researchers have developed many tools and techniques for concept selection [6–8]. Pugh concept selection [9] is one of the widely accepted and the simplest techniques. The technique involves the comparison of each concept to a reference or datum concept against the available criteria. The primary advantage of this technique is that it can handle many decision criteria. However, it requires a datum concept to compare, which may not necessarily exist sometimes. Ulrich and Eppinger presented a weighted rating technique (WRT), where each alternative concept is qualitatively evaluated and weighted accordingly [10]. Another most commonly used concept scoring technique is Saaty's analytical hierarchy process (AHP) [11] method.

AHP is a pairwise comparison [12], where each alternative is compared with the rest of the alternatives. It provides a method to establish relative scales through pairwise comparisons. The scales calibrate the quantitative and qualitative criteria into a numeric scale. AHP is one of the most commonly used techniques for solving concept selection problem. Further, AHP is a flexible approach [13]; therefore, nowadays, it is generally applied in integration with other techniques for the best results, as reported in [14–18]. Byun [19] presented an extended version of AHP for selecting the best car models. To overcome AHP barriers, a combined pairwise comparison with a spreadsheet method using a five-point rating scale was used in this work. Khalil had applied AHP to select the most appropriate project delivery method [20]. The proposed method is easy to use and enables the user to consider all decision-relevant criteria. Hambali et al. [21] had presented AHP-based concept selection for automotive composite bumper beam designs. Here, eight design concepts were evaluated to identify the most appropriate. Vinodh et al. [13] had used AHP for the selection of the most appropriate concept in a lean environment. The literature indicates that the AHP can be used for a wide variety of applications with several advantages in decision-making. Nowadays, it is commonly practised to combine AHP with quality function deployment (QFD), technique for order of preference by similarity to ideal solution (TOPSIS) and axiomatic design (AD) to evolve hybrid decision-making methods. Quality function deployment (QFD) also integrates the principles of concept selection and helps decision-makers to objectively evaluate various alternatives [22]. In QFD, technical parameters are compared with CR; however, there are several difficulties in its applications, duly highlighted in [23, 24]. The integration of the AHP and TOPSIS is also most common for decision-making. However, AHP and TOPSIS have some drawbacks related to a large number of pairwise comparison for calculating weights [24]. The axiomatic design (AD) method carries out a structured and mathematical design evaluation to synthesize and analyse suitable design requirements, solutions and processes [25]. However, in AD the uncoupling or decoupling of matrices is challenging [26].

Vinodh and Girubha [27] had proposed an MCDM method based on PROMETHEE. PROMETHEE is based on mutual comparison of alternative pairs concerning each of the selected criteria. It is one of the most frequently used methods of MCDM, as shown by Mela et al. [28]. Pavic and Babic [29] solved the problem of location choice for production systems using PROMETHEE. They considered ten criteria in their work related to time, cost and process and presented the alternatives for the best solutions of essential location criteria. Vinodh and Girubha applied PROMETHEE to choose the best sustainable concept [27]. In their work, they considered 16 critical criteria related to social, financial and natural sectors, and based on that, they observed PROMETHEE be an efficient and convenient tool for concept selection in a manufacturing environment. Peng et al. [30] employed PROMETHEE to identify the critical product features, which provide in-depth information about different aspects of products. Behzadian et al. [31] had compiled a comprehensive literature review on PROMETHEE applications and methodologies for medicine, agriculture, education, design, government and sports. Ülengin et al. [32] had listed the advantages of PROMETHEE that influenced its choice to rank and select the best concept. However, PROMETHEE has some limitations, e.g. it assumes that decision-makers can accurately assign weights to the criteria [33], although even a slight variation in the criteria weight may significantly influence the results. Besides, since both customer and manufacturer are concerned with a concept, weight assignment should consider both of them without inherent bias. In this work, AHP is employed to determine the value of CR by the survey of the focus group. This focus group included experts and ambitious people for the proposed product. Further, the study has adopted external search techniques, such as Internet search, literature surveys, interaction with experts and patent studies, to evaluate w_{m}. In the proposed work, both customer and manufacturer criteria weights, w_c and w_m, are applied in PROMETHEE for the improved concept selection.

Most of the existing concept selection techniques reported in the literature account assignment of weights based on qualitative data. This necessitates transparency in the weight assignment and accordingly concept selection process that is duly justified and clear to the stakeholders. Further, all the existing concept selection tools and techniques give significant attention to CR and minor importance to the manufacturer constraints. Booker [34] had claimed that any concept with a weak definition of geometry, material choice and manufacturer conditions would never lead to optimal design. Kihlander [20] had indicated that the existing concept selection techniques might be of little or no use in design, and there is a need for a systematic, transparent concept selection approach that will consider both the customer and manufacturer prospectively, preferably numerically, in the form of weights.

2.1 Literature Gap

Nowadays, the perception of a product varies significantly; quick response to varied customer requirements at affordable cost is a persistent challenge to the manufacturers. The current business environment manufacturing department is concerned with minimizing manufacturing costs, whereas marketing division is involved in developing higher-quality products for better customer satisfaction. Therefore, appropriate concurrent engineering techniques are needed to handle these challenges. Based on the available literature, it may be inferred that AHP and PROMETHEE methods are widely used to solve MCDM problems for various applications. Further, product design concept selection is a complex problem, and a single technique may not lead to the best solution. The literature reports applications of integrated AHP and PROMETHEE technique to solve multiple MCDM problems, but to the best of our knowledge, such a technique is not applied for the task of concept selection. Therefore, this work proposes an extended integrated AHP–PROMETHEE technique for concept selection in product design, where weights of both CR (w_c) and MA (w_m) are considered, not only to fulfil the customer aspiration but also to see the manufacturer constraints. This proposed work with expanded features is an extended application of the work of Vinodh et al. [14]. The proposed technique includes the criteria from customers as well as manufacturers' perspectives. However, in this work, to provide a rationale to the determination of weight (w_j) and to give due importance to the customer and the manufacturer, weights of CR (w_c) and MA (w_m) are inputted into the system, and accordingly, the calculation of aggregated preference function is modified. The proposed work also extends its application to identify the space for quality improvement and to identify the importance of various product features as per customer requirements.

3 Methodology

The proposed methodology includes the following stages:

I. *Identifying the customer's requirements (CR)* The success of any manufacturing products depends on the degree of satisfaction of the customers. Hence, it is necessary to accurately identify CR in terms of product attributes. Surveys, interviews, questionnaires, and observation are the most common ways for this.

II. *Determining the weight of customer's requirements* (w_c) For any product, customers have multiple needs, generally having unequal importance. The customer has higher desire, interest, feelings or emotions for some requirements and less for others. Therefore, to measure the customer desire for a requirement, this work employs AHP to segregate the important CR from relatively less important ones, in the form of weight of CR (w_c) with the help of the following steps:

Step 1 Development of paired comparison matrix for CR

A set of '*n*' customer requirements (criteria) is pairwise compared, and their relative degree of importance, in terms of weights a_{ij} (on a scale of 1–9), is evaluated, which would provide the users' degree of expectations.

Step 2 Calculation of the weight/importance degrees of CR

To find the importance degree of each CR, normalization metric is generated as:

$$\left(N_{\mathrm{ij}}\right) = \frac{a_{\mathrm{ij}}}{\left(\sum_{i=1}^{n} a_{\mathrm{ij}}\right)/n} \quad i,j = 1,2,\ldots,n. \tag{1}$$

The weight or importance degree of CR (w_c) is generated with the help of

$$\left(w_c\right) = \frac{\sum_{j=1}^{n} N_{\mathrm{ij}}}{n} \quad i = 1,2,\ldots,n. \tag{2}$$

Step 3 Testing the consistency of the weights

Saaty [21] had suggested that consistency ratios (ø) having values less than 0.1 are considered acceptable and values higher than 0.1, at any level, indicate re-examination of the judgment. However, repeating the survey is time-consuming and costly. Besides, some pairwise comparison matrices even with ø > *0.2* give reasonable weight and are typically considered tolerable [19].

To test the consistency, consistency index (CI) is determined first by

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

where λ_{max} is the maximum eigenvalue, and accordingly, the consistency ratio (ϕ) is evaluated as

$$\phi = \frac{CI}{RI} \tag{4}$$

where *RI* is the random inconsistency indices and given in [21].

III. *Concept generation* Some of the most popular concept generations techniques are brainstorming, SCAMPER (substitute, combine, adapt, modify, put to other use), concept fan, user narrative, descriptive recombination, user creation, brainwriting, problem decomposition, cause and effect tree. At this stage, the designer should generate concepts to satisfy the CR having high weight first.

IV. *Determining the weight of the manufacturer's abilities* (w_m) It is not advisable and may not be possible for a manufacturer to meet all the design criteria with product features of equal quality. This work proposes to quantitatively determine the ability of a manufacturer to satisfy the design criteria and accordingly identify the manufacturer constraints; designated as manufacturer ability (MA) weight (w_m), by brainstorming with the manufacturers and literature survey.

V. *Determining the best concept* PROMETHEE can be applied to select the most suitable concept among a given set of concepts when multiple decision criteria are involved. However, PROMETHEE uses the weight (w_k) of criterion F_k, and this weight is assigned by the decision-maker on his/her own and may lead to an inaccurate result. This work utilizes the weight (w_c) obtained with the help of AHP in PROMETHEE for better results.

VI. The steps involved in this work for ranking the best concept are listed as follows:

Step 1 Development of decision matrix

This step identifies the degree of importance (X_{ij}) of each criterion (*i*th) on a scale of 1–9, where 9–1 means 'perfect', 'absolute', 'very good', 'fairly good', 'good', 'preferable', 'not bad', 'weak advantage' and 'weak', respectively.

Step 2 Normalization of the decision matrix

The normalized matrix (R_{ij}) for beneficial and non-beneficial criteria, respectively, is evaluated as:

$$R_{\mathrm{ij}} = \left[X_{ij} - \min\left(X_{\mathrm{ij}}\right)\right] / \left[\max(X_{\mathrm{ij}}) - \min\left(X_{\mathrm{ij}}\right)\right] \tag{5}$$

$$R_{\mathrm{ij}} = \left[\max\left(X_{\mathrm{ij}}\right) - X_{\mathrm{ij}}\right] / \left[\max(X_{\mathrm{ij}}) - \min\left(X_{\mathrm{ij}}\right)\right] \tag{6}$$

where i = 1, 2, …, n and j = 1,2,…,m,

Step 3 Calculation of the alternative differences with respect to other alternatives

This step finds out the differences in criteria values between different alternatives pairwise.

Step 4 Calculation of preference function, $P_{J(i,i')}$.

The preference function adopted in this work is:

$$P_{J(i,i')} = 0 \quad \text{if} R_{ij} \le R_{i',i} \tag{7}$$

$$P_{J(i,i')} = (R_{ij} - R_{i',i}) \quad \text{if} R_{ij} > R_{i',i}. \tag{8}$$

Step 5 Calculation of aggregated preference function, $\pi_{(i,i')}$

$\pi_{(i,i')}$ is calculated as:

$$\pi_{(i,i')} = \sum_{j-1}^{m} P_{J(i,i')} * w_j \tag{9}$$

where w_j is the relative importance (weight) of jth criterion, taken by the decision-maker on the basis of intuition. To provide a rationale to the determination of weight w_j and to give due importance to the customer and the manufacturer, weights of CR (w_c) and MA (w_m) are inputted into the system, and accordingly, Eq. (9) is modified as:

$$\pi_{(i,i')} = \sum_{j-1}^{m} P_{J(i,i')} * w_c * w_m. \tag{10}$$

Step 6 Determination of the leaving and entering flow

Leaving (or positive) flow for the *i*th alternative is determined as

$$\varphi^{+}(i) = \frac{1}{n-1} + \sum_{i'=1}^{n} \pi_{(i,i')}. \tag{11}$$

Entering (or negative) flow for the *i*th alternative is determined as

$$\varphi^{-}(i) = \frac{1}{n-1} + \sum_{i'=1}^{n} \pi_{(i',i)} \tag{12}$$

where n is the number of alternatives (concepts).

Step 7 Calculation of the net outranking flow for each alternative

The net outranking flow for each alternative can be calculated by:

$$\varphi(i) = \varphi^{+}(i) - \varphi^{-}(i). \tag{13}$$

Step 8 Determination of alternatives' ranking

The most preferred alternative is the one having the highest value of $\varphi(i)$..

VII. *Determining the feature quality level (FQL)* During product design, some product features are 'must' for the product, while some features may simply act as 'satisfiers' and 'delighters'. Therefore, to prioritize the feature quality need, the arithmetic mean of w_c is employed here. Based on the arithmetic mean, the product features may be classified into two or three levels, e.g. Level I, Level II and Level III. Level I features must be of the highest design quality, while the quality of Level II features is higher than that of Level III features, if applicable. This work identifies FQL as:

Condition I *Classification in two levels (Level I and Level II).*

In this case, the arithmetic mean of weightages of CR (w_c), denoted as w_{cm}, is determined, and accordingly, the levels are classified as:

- The features having w_c greater or equal to w_{cm} are considered as Level I features.
- The features having w_c less than w_{cm} are considered as Level II features.

Condition II *Classification in three levels (Level I, Level II and Level III).*

In this condition, Level I features are determined as per Condition I. However, for identifying Level II and Level III features, the arithmetic mean of the remaining w_c, i.e. excluding weights of CR included in Level I, denoted as w_{cm2}, is calculated, and accordingly, the features are classified as:

- *Level I* The features having w_c greater or equal to w_{cm} are considered as Level I features.
- *Level II* Among the remaining features, the features having w_c greater or equal to the w_{cm2}, but less than w_{cm}, are considered as Level II features.
- *Level III* The features having w_c less than w_{cm2} are considered as Level III features.

4 Application of Methodology

Mobile phones have become an essential part of human life, primarily for staying connected. Accordingly, the mobile phone business is one of the most rapidly growing industries. A mobile phone provides diverse applications to different users as per their requirements. This motivates mobile phone manufacturers to propose innovative concepts with multiple features for competitive advantages. However, due to demanding and sophisticated customers' needs and rapid changes occurring in innovation, customer purchase decisions for mobile phones are not easy. Hence, it is necessary to accurately identify CR in terms of product attributes to avoid uncertainty in product concept selection. For the design problem, the stages implemented in this work include:

I. *Identifying the customer's requirements (CR)* This research adopted a questionnaire and survey method to identify CR and the customer's purchase decisions. At the time of the survey, users list down various types of requirements and numerous complaints from the present mobile set. This research work considers all these requirements and complaints as the customer expectation based on their technical viability. After the analyses of the questionnaire and survey, 11 CR (CR_i) were identified, which are listed in the following based on the requirement/feature they are related to:

- CR_1: Call and text,
- CR_2: Camera and video,
- CR_3: Display, i.e. type, size, resolution, multi-touch, protection, etc.,
- CR_4: Sensors, i.e. fingerprint accelerometer, gyro, proximity, compass, etc.,
- CR_5: Multimedia option,
- CR_6: Battery backup and charging duration,
- CR_7: Option for dual SIM,
- CR_8: Connectivity, i.e. Wi-Fi hot spot, Bluetooth tethering, USB tethering, etc.,
- CR_9: Network type, e.g. 3G, 4G, 5G, etc.,
- CR_{10}: Memory capacity,
- CR_{11}: Aesthetic, i.e. dimensions, weight, keyboard, colour, etc.

II. *Determining the weight of customer's requirements (w_c)* To prioritize the requirement quantitatively, AHP is employed to determine the weight of CR (w_c) with the help of the following steps:

Step 1 Development of paired comparison matrix for CR

Pairwise comparison between each CR (criteria) was conducted to evaluate the users' degree of expectations from a product. Here, all 11 CR (or criteria) are compared in pairs, and their relative degree of importance was assigned as weights (c_{ij}), on a scale of 1 to 9. This is indicated in Table 1.

Step 2 Calculation of the weight/importance degrees of CR

To find the importance degree of each CR, a normalization metric using Eq. (1) was generated, and then, weights or importance degree of CR (w_c) were evaluated with the help of Eq. (2), as shown in Table 2.

Step 3 Testing the consistency of the weights

Based on Eq. (3), consistency index (CI) was determined as 0.129, where λ_{max} is calculated as 12.296, and $n = 11$. As per Eq. (4), $\emptyset = CI/RI$, where $RI = 1.51$ is for $n = 11$. This gives $\ncong = 0.085$.

Table 2 Importance degrees of CR and rank

Criteria	Weight	Rank
CR_1: Calls and texts	0.3268	1st
CR_2: Camera and video	0.1783	2nd
CR_3: Display	0.0652	6th
CR_4: Sensors	0.0818	5th
CR_5: Multimedia option	0.0826	4th
CR_6: Battery backup and charging hour	0.1004	3rd
CR_7: Dual SIM option	0.0289	10th
CR_8: Connectivity	0.0411	7th
CR_9: Network type	0.0336	9th
CR_{10}: Memory capacity	0.0409	8th
CR_{11}: Aesthetic	0.0202	11th

Table 1 Paired comparison matrix for CR

Criteria	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}
CR_1	1	8	6	7	5	7	5	6	6	5	8
CR_2	1/8	1	5	4	1	5	6	4	5	6	7
CR_3	1/6	1/5	1	1/2	1/2	1/3	5	2	4	1	3
CR_4	1/7	1/5	2	1	2	1	3	2	3	2	4
CR_5	1/5	1	2	1/2	1	1/4	3	3	2	4	3
CR_6	1/7	1/5	3	1	4	1	4	2	3	2	4
CR_7	1/5	1/6	1/5	1/3	1/3	1/4	1	1/2	1	1/2	2
CR_8	1/6	1/4	1/2	1/2	1/3	1/2	2	1	1	1	3
CR_9	1/6	1/2	1/4	1/3	1/2	1/3	1	1	1	1	2
CR_{10}	1/5	1/6	1	1/2	1/4	1/2	2	1	1	1	2
CR_{11}	1/8	1/6	1/3	1/4	1/3	1/4	1/2	1/3	1/2	1/2	1

III. *Concept generation* To meet the above requirements, the designers generated a few concepts, keeping in mind the customer expectations from the next generation of handsets, using external search (e.g. Internet, experts, literature/patent study, etc.).

Concept S_1—Modular mobile phone: This concept involved components that can be independently upgraded or replaced, leading to more freedom for the consumers regarding configurations and specifications selection.

Concept S_2—Wearable mobile phone: In this concept, **the** keypad of the phone was projected on the user's hand. This concept enhanced the chatting experience.

Concept S_3—Leaf mobile phone: This concept was inspired from photosynthesis, with eco-charging ability. In this concept, the mobile phone could be charged through solar cells, apart from electricity.

Concept S_4—Bendable phone: Here, mobile phones were supposed to have flexible screens and the ability to take any shape (e.g. bracelet).

Concept S_5—Script Mobile: In this concept, mobile phones had two touchscreens where the second screen could scroll, in order to increase the display size, e.g. for watching movies or editing documents. It uses a photosensitive nanomaterial for covering the device and charging via sunlight.

IV. *Determining the weight of manufacturer's abilities (w_m)* In this work, external search techniques such as literature study, interaction with experts and patent studies were performed to evaluate w_m. The framework and evaluation models for MA were divided into four major activities, and accordingly, the experts make the judgment of the relative importance of the criteria.

- Production of components, including its limitations, means of production, etc.
- Purchase of parts, including supplier quality, reliability, inspection, etc.
- Assembly, including installation, foundations, bolting, welding, etc.
- Transportation, including material handling, clearance, packaging, etc.

A huge amount of the literature and scientific data is available on the Internet for the above four frameworks. A list of relevant information categories was compiled based on the literature presented, and these data contained rich and complex information that can be challenging to find in traditional information sources. Further, these data are scrutinized and employed in the form of meta-information. This work adopts the five-point Likert scale [35] to quantify the qualitative meta-information of MA (Table 3), where the values of 0, 1, 2, 3 and 4 represent, respectively, impossible, difficult, probably possible, possible and definitely possible. Accordingly, the experts judge the relative importance of the criteria to determine the numeric weight. Finally, the weights for the above-mentioned four activities are used to evaluate the weight of MA (w_m)as shown in Table 3.

V. *Determining the best concept* For the selection of one suitable concept, from a given set of concepts, PROMETHEE was applied, where multiple decision criteria were involved. In the traditional PROMETHEE method, weights of criterion (w_k) are intuitively taken by the decision-maker, and this may lead to non-optimum results. This work applies the weightages of CR (w_c), systematically obtained with the help of AHP in PROMETHEE for better results. Further, to also take into account the manufacturer ability, this work modifies the PROMETHEE technique to extended PROMETHEE, as illustrated in Step 5, by including the weight of MA (w_m). To facilitate the most appropriate concept selection, the steps followed are as follows:

Step 1 Development of decision matrix

The decision matrix was developed for performance evaluation of the five proposed concepts on the basis of 11 criteria and is shown in Table 4.

Table 3 Weight of manufacturer's abilities (MA)

CR criteria → MA criteria ↓	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}
Production of components	4	2	3	2	4	3	2	3	4	2	3
Purchase of components	4	3	3	2	4	4	4	4	4	2	4
Assembly of components	4	3	4	4	3	4	4	3	4	4	2
Transport of components	4	2	2	4	4	4	4	2	4	2	2
Sum	16	10	12	12	15	15	14	12	16	10	11
$\boldsymbol{w_m} = X_{ij/max_{(X_{ij})}}$	1	0.625	0.75	0.75	0.937	0.937	0.875	0.75	1	0.625	0.687

Step 2 Normalization of the decision matrix

Table 5 shows the normalized decision matrix obtained with the help of Eqs. (5) and (6).

Step 3 and Step 4 Calculation of the alternative differences with respect to other alternatives and preference function, $P_{J(i,i')}$

Table 6 shows the pairwise differences and preference function ($P_{J(i,i')}$) among various concepts (S_iS_J) for different criteria (CR_k) ($i,j \to 1,\ldots,5;k \to 1,\ldots,11$). Then simplified preference function was evaluated based on Eqs. (7) and (8).

Step 5 Calculation of the aggregated preference function $\pi_{(i,i')}$

Table 4 Decision matrix for concept selection

Criteria → Concept ↓	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}
S_1—Modular mobile	8	8	7	6	8	8	9	5	7	9	7
S_2—Wearable mobile	8	5	5	9	7	6	5	6	6	9	9
S_3—Leaf mobile	9	7	6	8	7	9	6	5	7	7	8
S_4—Bendable phone	8	6	5	5	6	6	7	7	8	8	9
S_5—Script Mobile	7	7	9	7	8	5	7	8	9	6	8

Table 5 Normalization of the decision matrix

Criteria → Concept ↓	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}
S_1—Modular mobile	0.5	1	0.5	0.25	1	0.75	1	0	0.333	1	0
S_2—Wearable mobile	0.5	0	0	1	0.5	0.25	0	0.333	0	1	1
S_3—Leaf mobile	1	0.667	0.25	0.75	0.5	1	0.25	0	0.333	0.333	0.5
S_4—Bendable phone	0.5	0.333	0	0	0	0.25	0.5	0.667	0.667	0.667	1
S_5–Script mobile	0	0.667	1	0.5	1	0	0.5	1	1	0	0.5

Table 6 Alternative differences and the preference function

Criteria → Concept ↓	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}
S_1S_2	0	1	0.5	0	0.5	0.5	1	0	0.3334	0	0
S_1S_3	0	0.3334	0.25	0	0.5	0	0.75	0	0	0.6667	0
S_1S_4	0	0.6667	0.5	0.25	1	0.5	0.5	0	0	0.3334	0
S_1S_5	0.5	0.3334	0	0	0	0.75	0.5	0	0	1	0
S_2S_1	0	0	0	0.75	0	0	0	0.3334	0	0	1
S_2S_3	0	0	0	0.25	0	0	0	0.3334	0	0.6667	0.5
S_2S_4	0	0	0	1	0.5	0	0	0	0	0.3334	0
S_2S_5	0.5	0	0	0.5	0	0.25	0	0	0	1	0.5
S_3S_1	0.5	0	0	0.5	0	0.25	0	0	0	0	0.5
S_3S_2	0.5	0.6667	0.25	0	0	0.75	0.25	0	0.3334	0	0
S_3S_4	0.5	0.3334	0.25	0.75	0.5	0.75	0	0	0	0	0
S_3S_5	1	0	0	0.25	0	1	0	0	0	0.3334	0
S_4S_1	0	0	0	0	0	0	0	0.6667	0.3333	0	1
S_4S_2	0	0.3333	0	0	0	0	0.5	0.3333	0.6667	0	0
S_4S_3	0	0	0	0	0	0	0.25	0.6667	0.3333	0.3333	0.5
S_4S_5	0.5	0	0	0	0	0.25	0	0	0	0.6667	0.5
S_5S_1	0	0	0.5	0.25	0	0	0	1	0.6667	0	0.5
S_5S_2	0	0.6667	1	0	0.5	0	0.5	0.6667	1	0	0
S_5S_3	0	0	0.75	0	0.5	0	0.25	1	0.6667	0	0
S_5S_4	0	0.3333	1	0.5	1	0	0	0.3333	0.3333	0	0

Using Eq. (10), aggregated preference function $\pi_{(i,i')}$ was calculated and is shown in Table 7 by including the concerns of customer and manufacturer, in the form of w_c and w_m.

Step 6 Determination of the leaving and entering flow

Thereafter, leaving and entering outranking was calculated using Eqs. (11) and (12) and is shown in Table 8.

Step 7 and Step 8 Calculation of the net outranking flow for each alternative and determination of the ranking of all the considered alternatives

In step 7, the entering and leaving flow and net flow were calculated, and accordingly, the ranks of concepts were worked out using Eq. (13). As shown in Table 9, evaluation orders of five concepts are as follows: $S_3 > S_1 > S_2 > S_5 > S_4$. The optimal choice of concept for the mobile phone is 'leaf mobile phone S_3'.

This result was checked with the help of the participants by soliciting their feedback on the generated results.

VI. *Determining the feature quality level (FQL)* A customer considers several features of mobile phones while making the purchasing decision. For this, here, CR are classified into multiple levels as per w_c. The

Table 7 Aggregated preference function

Criteria →	CR_1	CR_2	CR_3	CR_4	CR_5	CR_6	CR_7	CR_8	CR_9	CR_{10}	CR_{11}	$\longleftarrow w_m$
Concept ↓	1	0.625	0.75	0.75	0.937	0.937	0.875	0.75	1	0.625	0.687	$\leftarrow w_c$
	0.3268	0.1783	0.0652	0.0818	0.0826	0.1004	0.0289	0.0411	0.0336	0.0409	0.0202	Sum↓
S_1S_2	0	0.1114	0.0245	0	0.0387	0.0470	0.0254	0	0.0112	0	0	0.2582
S_1S_3	0	0.0371	0.0122	0	0.0387	0	0.0190	0	0	0.0170	0	0.1245
S_1S_4	0	0.0742	0.0244	0.01533	0.0774	0.0470	0.0126	0	0	0.0085	0	0.2597
S_1S_5	0.1634	0.0371	0	0	0	0.0706	0.0126	0	0	0.0255	0	0.3094
S_2S_1	0	0	0	0.0460	0	0	0	0.0102	0	0	0.0139	0.0702
S_2S_3	0	0	0	0.0153	0	0	0	0.0102	0	0.0170	0.0069	0.0496
S_2S_4	0	0	0	0.0613	0.0387	0	0	0	0	0.0085	0	0.1085
S_2S_5	0.1634	0	0	0.0306	0	0.0235	0	0	0	0.0255	0.0069	0.2501
S_3S_1	0.1634	0	0	0.0306	0	0.0235	0	0	0	0	0.0069	0.2245
S_3S_2	0.1634	0.0743	0.0122	0	0	0.0705	0.0063	0	0.0112	0	0	0.3380
S_3S_4	0.1634	0.0371	0.0122	0.0460	0.0387	0.0706	0	0	0	0	0	0.3680
S_3S_5	0.3268	0	0	0.0153	0	0.0941	0	0	0	0.0085	0	0.4447
S_4S_1	0	0	0	0	0	0	0	0.0205	0.0112	0	0.0139	0.0457
S_4S_2	0	0.0371	0	0	0	0	0.0126	0.0102	0.0224	0	0	0.0825
S_4S_3	0	0	0	0	0	0	0.0063	0.0205	0.0112	0.0085	0.0069	0.0536
S_4S_5	0.1634	0	0	0	0	0.0235	0	0	0	0.0170	0.0069	0.2109
S_5S_1	0	0	0.0245	0.0153	0	0	0	0.0308	0.0224	0	0.0069	0.1000
S_5S_2	0	0.0742	0.0489	0	0.0387	0	0.0126	0.0205	0.0336	0	0	0.2288
S_5S_3	0	0	0.0366	0	0.0387	0	0.0063	0.0308	0.0224	0	0	0.1350
S_5S_4	0	0.0371	0.0489	0.0306	0.0774	0	0	0.0102	0.0112	0	0	0.2156

Table 8 Leaving and entering outranking flow

Concept	S_1	S_2	S_3	S_4	S_5	Leaving flow
S_1	0	0.2582	0.1242	0.2597	0.3093	0.3575
S_2	0.0702	0	0.0496	0.1085	0.2501	0.1196
S_3	0.2245	0.3380	0	0.3680	0.4447	0.3438
S_4	0.0457	0.0825	0.0536	0	0.2109	0.0981
S_5	0.1000	0.2288	0.1350	0.2156	0	0.1698
Entering flow	0.1101	0.2269	0.0906	0.2380	0.3038	0.2723

Table 9 Net outranking flow and concept rank

Concept	Leaving flow	Entering flow	Net flow	Rank
S_1	0.3575	0.1101	0.2474	Rank 2
S_2	0.1196	0.2269	−0.1073	Rank 3
S_3	0.3438	0.0907	0.2533	Rank 1
S_4	0.0981	0.2380	−0.1399	Rank 5
S_5	0.1699	0.3038	−0.1339	Rank 4

work is implemented for both two and three levels of classification, shown in the following:

Condition I *Classification in two levels (Level I and Level II)*

Arithmetic mean of w_c for CR_1 to CR_{11} is determined, and it comes out to be 0.0909. Accordingly, the FQL is classified, with CR details and associated w_c, as.

- *Level I*

CR_1: Call and text	0.3268
CR_2: Camera and video	0.1783
CR_6: Battery backup and charging hour	0.1004

- *Level II*

CR_3: Display	0.0652
CR_4: Sensors	0.0818
CR_5: Multimedia option	0.0826
CR_7: Dual SIM option	0.0289
CR_8: Connectivity	0.0411
CR_9: Network type	0.0336
CR_{10}: Memory capacity	0.0409
CR_{11}: Aesthetic	0.0202

Condition II *Classification in three levels (Level I, Level II and Level III)*

For classification of features of a mobile phone into three levels, w_{cm} and w_{cm2} were determined as 0.09090909 and 0.049317, as illustrated in Stage VI of Sect. 3. The three-level classified FQL, with CR information and associated w_c, is illustrated as follows:

- *Level I*

CR_1: Calls and texts	0.3268
CR_2: Camera and video	0.1783
CR_6: Battery backup and charging hour	0.1004

- *Level II*

CR_3: Display	0.0653
CR_4: Sensors	0.0818
CR_5: Multimedia option	0.0826

- *Level III*

CR_7: Dual SIM option	0.0289
CR_8: Connectivity	0.0411
CR_9: Network type	0.0336
CR_{10}: Memory capacity	0.0409
CR_{11}: Aesthetic	0.0202

5 Comparison with Previous Work

This section presents a brief comparison among the proposed and previously published concept selection techniques. In this work, the weight of criteria is obtained with the help of AHP based on customer desire, whereas, in the traditional methods, it is arbitrarily assigned by designer/expert. Thus, this work leads to non-biased comparisons and results aligned to customer expectations. Besides, the proposed work also takes into account, during concept selection, the manufacturer perspective in the form of MA weight (w_m).

This section shows the comparison of the proposed work, i.e. extended PROMETHEE with traditional PROMETHEE, AHP–TOPSIS (a technique for order preference by similarity to ideal solution) [36] and Shannon's entropy method [37]. As evident from Table 10, the ranks of the concepts are changed due to consideration of MA weight in extended PROMETHEE, while traditional PROMETHEE considers decision-maker driven customer weights only. In concept selection using AHP–TOPSIS, the system considers only the criteria's weights, while Shannon's entropy employs only the decision matrix. In Shannon's entropy, the calculations are highly reliable and free from experts' bias. However, the deviation takes place due to the fact that the method does not consider the weights assigned to manufacturer ability and customer requirements. Therefore, it may be said that for effective concept selection, it is important not only to consider the CR but also to understand the concerns of the manufacturer, so that the final product is both manufacturable and profitable.

Table 10 Comparison with previous work

Concept↓	Extended PROMETHEE method		PROMETHEE method		AHP–TOPSIS method		Entropy method	
	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
S_1	0.2474	Rank 2	0.3146	Rank 1	0.6388	Rank 2	0.0036	Rank 5
S_2	− 0.1073	Rank 3	− 0.1404	Rank 4	0.3578	Rank 4	0.2633	Rank 1
S_3	0.2533	Rank 1	0.2604	Rank 2	0.6708	Rank 1	0.2403	Rank 3
S_4	− 0.1399	Rank 5	− 0.1737	Rank 5	0.3239	Rank 5	0.2563	Rank 2
S_5	− 0.1339	Rank 4	− 0.1148	Rank 3	0.4494	Rank 3	0.2364	Rank 4

6 Results and Conclusion

The work presents a model that considers both customers' requirements (CR) and manufacturers' ability (MA) to reduce the influence of uncertainty in concept selection during the early phase of product design. This work considers two of the most common sources of uncertainty, namely CR and MA, in the concept selection phase of product design. To mitigate this uncertainty, the work first calculates the weights of the criteria governed by the accumulated CR by employing AHP. Then, the work works out the MA weights with the help of external search techniques.

The work proposes an extended PROMETHEE technique, where the weights of CR (w_c) and MA (w_m) are applied concurrently during the conceptual design stage into the PROMETHEE technique to select the most appropriate. The proposed work by taking into account manufacturer ability updates the order of preference among various concepts of a mobile phone for the case study presented as $S_3 > S_1 > S_2 > S_5 > S_4$, whereas, for the traditional PROMETHEE, which considers only customer weight, the preference order is $S_1 > S_3 > S_5 > S_2 > S_4$. AHP–TOPSIS, which also considers only customer weight, unfolds the preference order of concepts as, $S_3 > S_1 > S_5 > S_2 > S_4$. In the entropy method, no weights are accounted, and accordingly, the rank of the concepts would be $S_2 > S_4 > S_3 > S_5 > S_1$. However, for the product's success in the market, it is essential to consider the customer requirements in the form of CR weights. For ease of manufacturing, it is necessary to consider the MA weight. Therefore, the proposed hybrid method gives an edge over other traditional techniques reported in the literature, as it considers both factors. This work first calculates the criteria weight as per the CR based on AHP, and then, MA weights are determined by external search techniques. The proposed work integrates AHP with extended PROMETHEE to enable the best concept selection. To validate the obtained model, the results of the proposed model and other methods, i.e. PROMETHEE method, AHP–TOPSIS method, and entropy method, are illustrated to the decision-makers. It was marked that the proposed model is the preferred model to the decision-makers. The final result identifies concept S_3 as the best option, and the decision-makers were satisfied with the implementation process.

Further, to identify the space for quality improvement, this work tries to determine the importance of various product features as per customer requirements. For this objective, product features are classified into two/three levels based on w_c. Level I feature must be of high quality to achieve better customer satisfaction and must be complied with by the manufacturer, whereas variations in Level III features quality do not significantly affect the customer satisfaction. Level II features demand moderate-quality requirements. This classification benefits the manufacturer in selecting the most appropriate set of features and creates a product that meets feature needs with desired quality, as expressed by the customer, and enlisted as CR.

However, the proposed method and the implementation of all such techniques greatly depend on the input weights. If the input weights are accurate, the proposed approach will become a powerful tool for the decision-maker, which provides vital support in concept selection. With this respect, further work should be done to conduct a sensitivity analysis to observe how small changes in the input impact the final decision. Since the proposed model is a frictionless method where the integration of the AHP–PROMETHEE is applied to improve the effectiveness of concept selection, there are no significant challenges to deploying the method in the industry for any other products. Accordingly, the proposed method would be helpful in most design and manufacturing companies.

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