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A paradigm for customer-driven product design approach using extended axiomatic design

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Abstract In the present times, due to increase in customer demands, products complexity is on the rise. This calls for the designers to strike a balance between a wide range of design alternatives and a large set of conflicting criteria. Hence, to take a sound decision by identifying a viable combination of customer requirements and satisfy the conflicting requirements is a difficult task for both the designer and the manufacturer. This work extends the axiomatic design theory to align the customer requirements (CRs) and design parameters (DPs) and generates multiple possible design alternatives based on the weightages of analytic hierarchy process (AHP). Such design alternatives are evaluated on the basis of their overall performance in line with the expected customer attributes, and the best design is identified by integrating the technique for order of preference by similarity to ideal solution, a ranking multi-criteria decision-making method, with AHP. This work unfolds a support tool for decision makers to accurately and effectively select CRs by a useful aggregation of function requirements and DPs. An industrial example is produced to demonstrate the applicability of the proposed method. This intelligent decision-making method is useful from the customers as well as the manufacturers' perspective.

Keywords Product design · Customer requirements · Axiomatic design · Independence axiom · Analytic hierarchy process (AHP) · The technique for order of preference by similarity to ideal solution (TOPSIS) · Design possibilities

Introduction

Manufacturing companies have to face the challenge of intense competition in most of the markets. Customer demands are at times complex and vary widely by nature. It has always been a challenge to the manufacturer to satisfy all the customer demands and as well as be profitable. Market driven strategies encourage enterprises to produce products as per the customer preferences, and, therefore, improve an enterprise's market position (Harding et al. 2001). When confronted with the task of developing new product solutions, a firm identifies a feasible requirements' set among the list of customer requirements. Most of the problems originate with customer wish list. As the definition of a good customer requirement is not yet properly established, it's difficult to capture proper customer inputs. A customer requirement for an imprecise problem is extensively varying in nature depending on the wide variation in applications of the product (Krishnapillai and Zeid 2006). Many times, the selected requirements may not fully conform to the customer demand or expectation. Some requirements are a must for the customer, whereas to fulfill some other requirements are not feasible for the organization. Further, a small change in the requirement would require a major redesign of the product. As it is important and profitable for any manufacturer to deliver the customers high-quality products at minimal costs, this needs a proper mapping between important customer functional requirements (FRs) and design parameters (DPs).

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The axiomatic design (AD) was introduced by Suh (1990) for design synthesized solutions to satisfy perceived needs through the mapping between FRs and DPs. It is widely used in developing software, hardware, machines and other products (e.g. Yang and Zhang 2000; Gu et al. 2001; Do and Park 2001; Park et al. 2003; Hirani and Suh 2005). The AD approach involves splitting a design problem into distinct FRs in a functional domain and then mapping them into DPs in the physical domain. For improving the quality of the product, Suh (2005) showed that the performance, robustness, reliability, and functionality of products, processes, software, systems, organizations, etc. significantly improve, when axioms are satisfied. Krishnapillai and Zeid (2006) addressed the issues of DPs classification, selection, and eventuality the mapping of parameters. Shirwaiker and Okudan (2008) suggested AD as the most effective in defining and analysing a problem. They applied the theory of inventive problem solving (TRIZ), for developing DPs to satisfy the corresponding FRs. Kremer et al. (2012) presented AD, TRIZ, and mixed integer programming (MIP) to developing innovative designs. Where AD decomposes the big problem into several independent sub-problems, TRIZ creates all feasible design concepts, and MIP optimizes cost and the numerical configuration among available design alternatives. The existing studies are focused on the techniques that satisfy the design axioms. However, nowadays as per the variegated customer requirements, the complexity of product increases, which leads to a few difficulties in maintaining the independence of FRs in general because the number of DPs may be more/less than that of FRs. Therefore, there is much trouble in accurately satisfying the design axiom with respect to customer satisfaction. Besides, existing techniques consider only FRs and do not adequately address non-functional requirements (NFRs), like cost, safety, ergonomics, etc. Moreover, all FRs are considered with equal importance while meeting AD conditions. However, customers give different importance to the different FRs and at times, different NFRs e.g. cost versus speed/movement; reliability versus portability, etc. Therefore, the motive to carry out this work is to understand how to apply the AD principles to synthesize profitable FRs along with NFRs.

To deal with multiple CRs (both FRs and NFRs), Saaty (1990) and Hua Lu et al. (1994) suggested the designers apply analytic hierarchy process (AHP) to identify the priority of CRs. In the literature, AHP has been widely used in solving many complicated decision-making problems (Wang et al. 2015; Dağdeviren 2008; Albayrak and Erensal 2004; Guan et al. 2009). Therefore, in this work AHP is used to prioritize both the functional and non-functional requirements. The AHP weights of FRs are used to modify the design to satisfy the axiomatic conditions.

For any product, numerous design possibilities may evolve (Krishnapillai and Zeid 2006) as per the designer ability to satisfy the axiom of design. The designer may add, subtract or modify any FR or DP to satisfy design axiom and thus, generate several design alternatives. These design possibilities may contain different degrees of function and non-function requirements. Each design possibility has some strength and weakness, and would impact customer satisfaction. Therefore, to identify the most suitable design possibility, this work employs the technique for order of preference by similarity to ideal solution (TOPSIS) with AHP. TOPSIS, introduced by Hwang and Yoon (1981), is one of the most classical multi-criteria decision making (MCDM) methods. It is mostly used in an integrated manner like AHP and TOPSIS (Lin et al. 2008; Bhutia and Phipon 2012); Fuzzy AHP and Fuzzy TOPSIS (Junior et al. 2014), Taguchi loss function, TOPSIS and multi-criteria goal programming (Sharma and Balan 2013), etc. Kim et al. (1997) and Shih et al. (2007) highlighted several TOPSIS advantages, and this influenced the choice in favor of TOPSIS, in this work, for ranking and selection of the best design possibility. As the first step in this work, AHP is used to calculate the weights to be assigned to individual customer requirements to assess the user's degree of expectations from a product. In the second step, these weights are considered and used in TOPSIS to evaluate positive ideal design possibility. The overall objective of AHP–TOPSIS integration is to avoid inaccuracy that may creep in if any arbitrary weights are assigned and to provide the optimal design possibility to maximize the customer satisfaction. Thus, this work aims to:

- Prioritize the customer functional and non-functional requirements.
- Map appropriate product attributes to quantitative requirements and generates valid product design possibilities.
- Resolve or eliminate the unavoidable conflicts among functional requirements and design parameters, and satisfy design axiom.
- Determine the best design among the proposed designs to achieve desired customer satisfaction.

Background information on axiomatic design, analytic hierarchy process and TOPSIS

This section aims to elucidate briefly axiomatic design (AD), analytic hierarchy process (AHP), and TOPSIS methods so as to understand their utility for the proposed methodology.

Axiomatic design

AD is a general design framework, which defines design as the creation of synthesized solutions that satisfy perceived needs through the mapping between FRs and DPs (Do and Park 2001). The mapping between all the FRs and DPs can be mathematically expressed as:

$$\left[FR_{1,2,3,\ldots n}\right] = [\mathrm{A}]\left[DP_{1,2,3,\ldots n}\right] \tag{1}$$

where [A] is the design matrix that relates FRs to DPs and describe the distinctive nature of product design. Equation (1) is known as design equation used for product design. There are two design laws in the form of axioms: the independence axiom and the information axiom. In order to satisfy the independence axiom, an optimal design always maintains the independence of FRs or in other words, design matrix [A] must be a diagonal matrix. Suppose we have three FRs and three DPs, then design equation is given as:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{2}$$

This would lead to

$$\mathrm{FR}_1 = \mathrm{A}_{11} \times \mathrm{DP}_1 + \mathrm{A}_{12} \times \mathrm{DP}_2 + \mathrm{A}_{13} \times \mathrm{DP}_3.$$
$$\text{If } \mathrm{A}_{12} = \mathrm{A}_{13} = 0, \quad \text{then}$$
$$\mathrm{FR}_1 = \mathrm{A}_{11} \times \mathrm{DP}_1$$

Similarly,

$$\mathrm{FR}_2 = \mathrm{A}_{22} \times \mathrm{DP}_2, \quad \text{for} \quad \mathrm{A}_{22} = \mathrm{A}_{23} = 0, \quad \text{and}$$
$$\mathrm{FR}_3 = \mathrm{A}_{33} \times \mathrm{DP}_3, \quad \text{for} \quad \mathrm{A}_{32} = \mathrm{A}_{33} = 0.$$

This would lead to uncoupled design.

Suh (1990) had proposed the independence axiom of having uncoupled designs with a one to one relationship between FR and DP. In other words, when design matrix [A] is a diagonal matrix, it is an uncoupled design. This ensures the independence of each DP. When design matrix [A] is triangular, it is a decoupled design, which also satisfies the independence axiom, provided that DPs are changed in a particular sequence. All other designs are coupled designs. According to Suh (1990) to manufacture quality products, it is necessary to develop designs that are uncoupled or, at least, decoupled.

Second axiom, information axiom, states that among the design solutions that satisfy the independence axiom, the best solution is the one that has the lowest information content. The present work confirms to independence axiom of AD only.

As nowadays, the complexity of products is increasing, it is a challenge to achieve a one-to-one mapping among FRs and DPs in product architecture. Hence to eliminate the coupling effect, it is essential to either change or modify the design parameters or introduce a new design parameter. However, while manipulating the DPs to satisfy the axiomatic conditions, capturing the design intent itself is a challenge (Krishnapillai and Zeid 2006). Hence, in this work, we extended the independence axiom by adding, subtracting or modifying concerned FRs or DPs in each step so as to generate a complete, valid and feasible design solution to meet customer satisfaction in a better way and manufacture quality products.

Table 1 Pair wise comparisons matrix

Criteria	C_1	C_2	…	C_n
C_1	1	c_{12}	…	c_{1n}
C_2	c_{21}	1	…	c_{2n}
$\vdots$	$\vdots$	$\vdots$	…	$\vdots$
C_n	c_{n1}	c_{n2}	…	1

Analytic hierarchy process

Saaty (1980) introduced AHP for complex systems to prioritize criteria (requirement) by pairwise comparison. It is a method to derive ratio scales from paired comparisons. The pairwise comparison, compare each criteria at the corresponding level and gauge them on the numerical scale. In this work, AHP is used to measure the customer interest, feelings, and emotions regarding products specific criteria for systematically improving DPs for better customer satisfaction. A three step AHP procedure employed in this work is as follows:

Step 1: *Develop a paired comparison matrix for customer requirements*

Conduct the pairwise comparisons between each requirement to evaluate the users' degree of expectations from a product. If a set of 'n' requirements (or criteria), $C_1, C_2, \ldots,$ C_n is compared in pairs and their relative degree of importance in terms of weights is c_{ij} (on a scale of 1–9), where $i, j = 1, 2, \ldots, n$, and then the pairwise comparison matrix (C) may be represented as shown in Table 1.

The diagonal elements (c_{11}, c_{22}, c_{nn}) in the matrix are the result of comparison of criterion (or customer requirements) to itself, and thus $c_{ij} = 1$, when $i = j$. The off-diagonal values in the matrix represent the strength of the relative importance of the ith element in comparison to the jth element. Further, $c_{ij} = 1/c_{ji}$, where $c_{ij} > 0$, and $i \neq j$.

Step 2: *Calculate the importance degrees of customer requirements*

To find importance degree of each customer requirement, we first generate normalization metric $\left(X_{ij}\right)$ by

$$\left(X_{ij}\right) = \frac{c_{ij}}{\sum_{i=1}^{n} c_{ij}} \qquad i, j = 1, 2, \ldots, n$$

and then evaluating the weight or importance degree of customer requirements (w_i) by

$$(w_i) = \frac{\sum_{j=1}^{n} X_{ij}}{n} \qquad i = 1, 2, \ldots, n$$

Step 3: *Test the consistency of the importance degrees of customer requirements*
The strength of AHP is that it ensures reasonable and acceptable comparison. A consistency check is performed to compare the inputs. In practice, a consistency ratio $(\varphi) \leq 0.1$ is considered acceptable. Any higher value at any level indicates that the judgments need to be examined. Han and Tsay (1998) explained that the biggest eigenvalue $(\lambda_{\max})$ is required to determine φ. Consistency vector (cv_i) is obtained as:

$$cv_i = \frac{\sum_{j=1}^{n} c_{ij} \cdot w_j}{w_i} \qquad i = 1, 2, \ldots, n$$

Therefore,

$$\lambda_{\max} = \sum\nolimits_{i=1}^{n} cv_i$$

However, to avoid the inconsistency when using different measurement scales in the evaluation process, Saaty (1980) suggested the use of maximal eigenvalue $\lambda_{\max}$ to evaluate the effectiveness of measurements. The maximal eigenvalue $\lambda_{\max}$ can be determined by

$$\lambda_{\max} = \frac{\sum_{i=1}^{n} cv_i}{n}, \quad i = 1, 2, \ldots, n$$

This leads to the definition of consistency index (CI) as follows:

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

Consistency ratio (φ) is evaluated as:

$$\varphi = \frac{CI}{RI}$$

where RI is random inconsistency indices and Table 2 shows the RI for the matrices of order (n) 1–10 (Saaty 1980).

Table 2 Random consistency index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3 Structure of a decision matrix

	Criterion → Alternative ↓	C_1	C_2	…	C_j	…	C_n
$A =$	D_1	x_{11}	x_{12}	…	x_{1j}	…	x_{1n}
	D_2	x_{21}	x_{22}	….	x_{2j}	…	x_{2n}
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	D_i	x_{i1}	x_{i2}	…	x_{ij}	…	x_{in}
	D_m	x_{m1}	x_{m2}	…	x_{mj}	…	x_{mn}

Technique for order preference by similarity to ideal solution

The technique for order preference by similarity to ideal solution (TOPSIS) introduced by Hwang and Yoon (1981) helps a decision maker to select the best choice on the basis of the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. The positive ideal solution maximizes the benefits criteria and minimizes the cost criteria, whereas the negative ideal solution maximizes the cost criteria and minimizes the benefits criteria (Behzadian et al. 2012). The procedure of TOPSIS used in this work is as follow:
Step 1: *Generate decision matrix*
Let the decision matrix A $(m \times n$ matrix) have m alternatives (here, design possibilities) and n criteria (here, customer requirements). Let x_{ij} be the score of alternative i on criterion j where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$. Table 3 shows the structure of the decision matrix:
Step 2: *Normalize the decision matrix A*
Suppose x_{ij} is original score and r_{ij} be the normalized score of ith decision variant under jth criterion, then:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\left(\sum x_{ij}^2\right)}}, \quad \text{for} \quad i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n$$

Step 3: *Construct the weighted normalized decision matrix*
Let the assigned arbitrary weight, based on surveys and questionnaires, for each criteria be w_j, where $j = 1, 2, \ldots, n$, then weighted normalized value for each alternative on each criteria (v_{ij}) is calculated as:

$$v_{ij} = w_j \cdot r_{ij}$$

Step 4: *Determine the ideal and negative ideal solutions*
Let the ideal alternative be A^+, which is the set having maximum weights for each criterion (attribute value 'v_i') among proposed design solutions (j) in the decision matrix and the negative ideal alternative be A^-, which has the worst (mini-

mum) attribute values among the proposed design solutions, then:

$$A^{+} = \left\{v_1^{+}, v_2^{+} \cdots v_n^{+}\right\}, \quad \text{where} \quad v_i^{+} = \left(max\, v_{ij}\right), \quad \text{and}$$
$$A^{-} = \left\{v_1^{-}, v_2^{-} \cdots v_n^{-}\right\}, \quad \text{where} \quad v_i^{-} = \left(min\, v_{ij}\right)$$

Step 5: *Calculate the separation measures for each alternative*
The separation from the ideal alternative is:

$$S_i^{+} = \sqrt{\left(v_i^{+} - v_{ij}\right)^2}, \quad \text{where} \quad i = 1, 2, 3, \ldots, m$$

Separation of each design alternative from the ideal alternative is computed as $\left(S^{+}\right)$, the sum of all S_i^{+}, for jth design.

Similarly, the separation from the negative ideal alternative is:

$$S_i^{-} = \sqrt{\left(v_i^{-} - v_{ij}\right)^2}, \quad \text{where} \quad i = 1, 2, 3, \ldots, m$$

Separation of each design alternative from the negative ideal alternative is computed as $\left(S^{-}\right)$, the sum of all S_i^{-}, for jth design.
Step 6: *Calculate the relative closeness to the ideal solution* C_i

$$C_i = \frac{S^{-}}{\left(S^{+} + S^{-}\right)}$$

Since $S^{+}, S^{-} \geq 0$, then clearly $C_i \in [0, 1]$.

Select the alternative with C_i closest to 1.

The major issue with the traditional TOPSIS approach, as reported in the literature, is that the assigned arbitrary weights (as in step 3) are subjective and based on surveys and questionnaires (Kumar et al. 2014). This leads to inaccurate results as it is tough to assign accurately numbers to criteria. Hence, in continuation of the earlier work done by some of the researcher (Kumar et al. 2014; Bhutia and Phipon 2012; Lin et al. 2008), this work also integrates AHP with TOPSIS to identify the weight of individual criterion. The weights for each criterion evaluated on AHP are reused in the TOPSIS method to assign accurately w_j. Although, AHP weight is also subjective and based on surveys and questionnaires but AHP facilitates consistency check in such a way that if φ have value higher than 0.1 than the weights used in AHP would be re-examined and reassigned. The overall benefit of AHP–TOPSIS integration is to avoid, as far as possible, assigned of erroneous weights.

The proposed model

This section discusses the proposed methodology for generating design possibilities and selecting the best solution as per the customer desires and manufacturer perspectives. Since customer requirements and design parameters are two most important components of product design, and designers should always make an effort to balance appropriately both. The proposed model maintains this balance by utilizing AD theory. With the application of AD and AHP, several design possibilities are produced. Hence, to select the best design possibility as per the customer perspective, AHP and TOPSIS are applied. Figure 1 illustrates the overall flow of the proposed design procedure integrating AD, AHP and TOPSIS.

The proposed design procedure consists of six components. They are:

1. Identification of customer requirements or product expectations
   With today's fierce competition, leading companies must capture as soon and as precisely, customers' requirements (Cui and Wu 2015). Hence, it is necessary to identify accurately customer requirements or expectations in terms of product attributes. Surveys and interviews are the easiest and most common way for this.
2. Translation of ambiguous requirements to perfect and acquirable requirements
   At times, the customer definitions of his/her requirements of a new product are ambiguous. S/he might be having a broad idea about the requirements, but may not be able to define clearly and crisply about the requirements, particularly the core requirements. The design team with the help of experts or available tools should translate ambiguous customer requirements to precise requirements. In the case of complexity, deliverable requirements are generated with the help of quality functional development (QFD).
3. Determination of requirements weight
   As customer requirements are widely varying, it may not be possible for any organization to satisfy all the requirements at the same level. In fact, it may not be beneficial for the organization too. Many reports had cited that in spite of almost same functional features, some product alternatives are more successful than others. This is due to the mismatch between customer and manufacturer expectations and preferences. It is advisable to focus more on the customer requirements that matter most. Hence, to understand customers' rating of the individual requirement in new product development process, this work employs AHP to determine weights of customer needs.
4. Classification of the requirements
   In general, customers have two types of requirements from a product, namely, functional and non-functional (NFR). Functional requirements describe the desired features while NFRs detail constraints on the product. NFRs

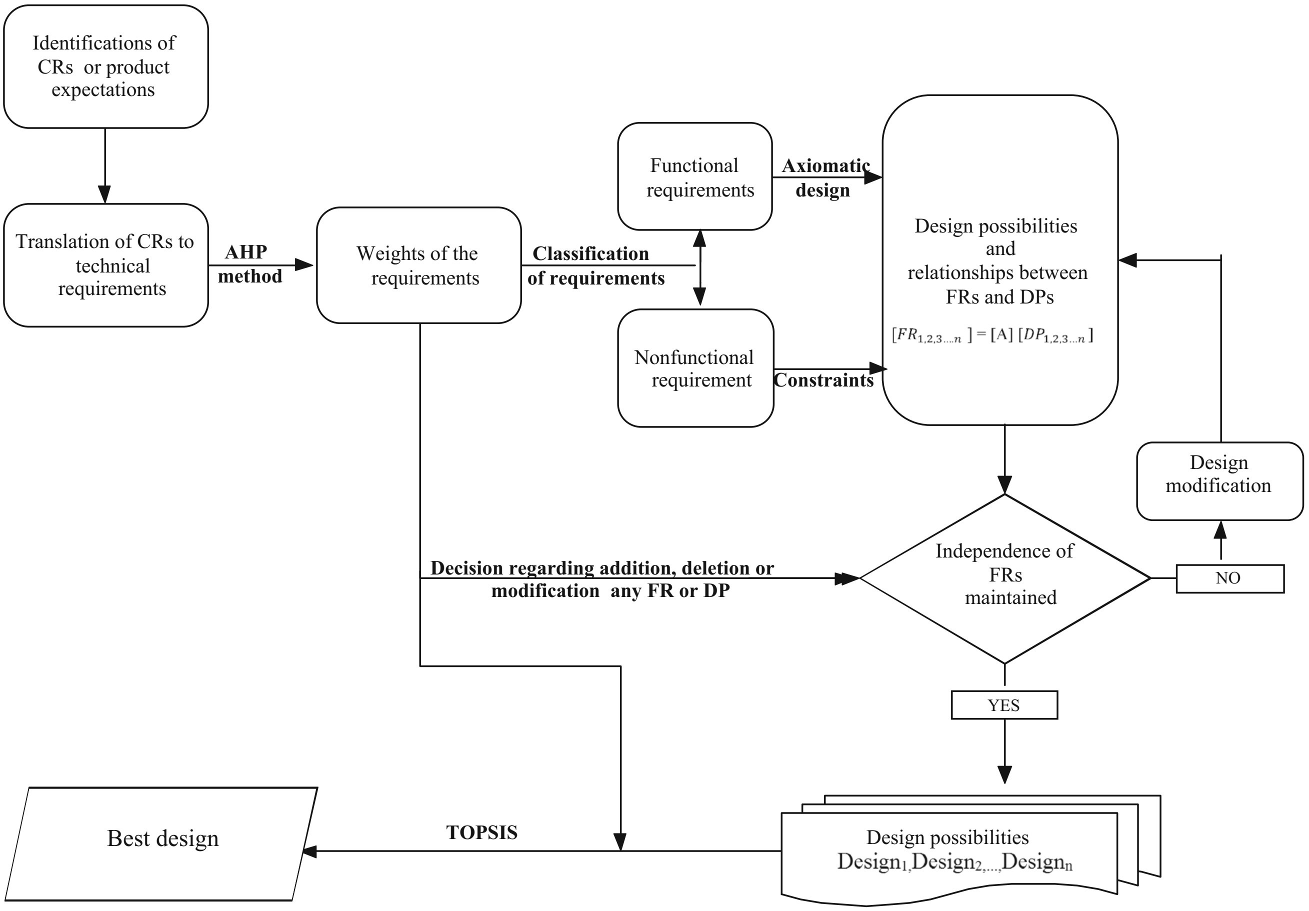

Fig. 1 Conceptual framework of the proposed model

requirements are often called quality attributes. Both are necessary for the success of any product. Hence, classification of the requirements in terms of FRs and NFRs, and accordingly generate the design possibilities is advantageous in the design process.

5. Generation of the design possibilities
   With weights of FRs and NFRs defined, the design objective is to define design possibilities in terms of DPs. AD offers a good approach to characterize FRs in terms of DPs. As per Axiomatic theory (Kusiak 1999; Suh 1990), the mapping between the FRs and DPs is such that each FR can be satisfied without affecting any other FR, which leads to uncoupled design and minimal design information content. Suh (1990) had proposed axioms to improve the independence of FRs. This work extends the AD approach to achieve better customer satisfaction with the help of AHP, which are given below:

Case I Coupling due to insufficient number of DPs (Theorem 1 of general design)
If there are three (FRs), and two (DPs), and the design matrix A is given as then the design Eq. (1) is:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \tag{3}$$

Theorem 1 (Decoupling of a coupled design)
As per the Theorem 2 of general design
"When a design is coupled because of a larger number of FRs than DPs, it may be decoupled by the addition of new DPs so as to make the number of FRs and DPs equal to each other." Thus, Eq. 3 would be modified as:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_n \end{bmatrix} \tag{4}$$

However, due to the addition of new DPn, the cost of the product (a NFR) might increase, and it may have an effect on the other functions too. Hence, in this work, we use AHP weight of CRs to observe the importance of the function requirements. If any FR is less important as per customer perspective, as highlighted by low AHP weight; that FR may be removed to make DPs and FRs equal in number. This would also decrease the cost and improve the reliability of the product due to a lower number of product functions. Say for example, based on customers' requirements, if AHP weight of FR_3 is found to be low, then Eq. 3 would reduce to

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \tag{5}$$

Equation (5) indicates that the design is uncoupled and satisfies the independence axiom.

Case II Redundant design (Theorem 3 of general design)
When the DPs are more than FRs, the design is either redundant or coupled. Suppose there are three FRs and four DPs, and the design matrix A is given as then the design Eq. 1 is:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{bmatrix} \tag{6}$$

To satisfy the independence axiom, a new FRn is added to the system even though the customer may not have asked for it. Hence,

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_n \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{bmatrix} \tag{7}$$

However, the addition of new function (FRn) affects other design parameter (here, DP_2), and the constraints (e.g. cost, aesthetic, etc.) may also resist the same. The proposed design strategy analyses the redundant DPs. If the redundant DP and concerned FR is less important (as shown by low AHP weight) and also lead to coupling effect, then the concerned FR and the related DPs may be removed. In the given case (Eq. 6), if FR_2 is identified to be less important requirement, which also lead to coupling effect with DP_2, DP_3, DP_4 then we can remove the FR_2 and concern DPs i.e. DP_2 and DP_4. This would lead to

$$\begin{bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathrm{DP}_1 \\ \mathrm{DP}_3 \end{bmatrix} \tag{8}$$

The above equation indicates that the design is uncoupled, satisfies the independence axiom and in comparison to design equation as in Eq. 7, the complexity of product decreases, which leads to ease in manufacturing.

Case III ideal design (Theorem 4 of general design)
The previous cases tried to resolve the problems of an insufficient number of DPs or FRs. To maintain the independence of FRs, the design matrix has to be converted to diagonal or triangular matrix. If coupled design condition exists, then Suh (1990) suggested that solution should be include change of order of the FRs and DPs to make the design decoupled. However, as the design process is in its initial stages, it is advisable to address the important customers' requirements first. In the proposed strategy as the weights of FRs are known, more attention is given to FRs with higher weights to achieve better customer satisfaction and quality design.

Case IV Need for new design (Theorem 5 of general design)
The need of a new design arises when one or more FRs is changed. The proposed model takes care of this by giving importance to higher weighted FRs. If functions create contradiction or coupling effect, then the FRs that have low weights or customer interests can be avoided.

6. Selection of the best design possibility.

The previous steps show that several design possibilities may satisfy the independence axiom condition. To select the most optimal design among the possible design, this work, employs TOPSIS. However, the traditional TOPSIS approach assigns arbitrary weights $\left(W_j\right)$ for each criterion which leads to inaccuracy in the results. Hence, here, in the first stage, AHP is employed to calculate the weights of CRs to evaluate the users' degree of expectations from a product. In the second stage, AHP weights are reused in the TOPSIS and the preference order of design alternatives according to their relative closeness to the ideal solution is obtained. This positive ideal solution maximizes the benefit criteria. Thus, the solution obtained based on the proposed technique provides the most optimal design, where more important CRs are satisfied on priority.

Application

This work proposes design solutions that eliminate conflicting design requirements using axiomatic design, for a hair dryer. In industry, hair dryers are designed as an electromechanical device to blow normal or hot air over damp hair to dry them. Earlier designs of hair dryer were heavy in weight and hence, quite uncomfortable to use. Furthermore, if the hairdryers accidentally come in contact with water, they would short circuit and may cause electrical shock. With advancements in technology, varied designs of hairdryers came to the market. Nevertheless, customers have some

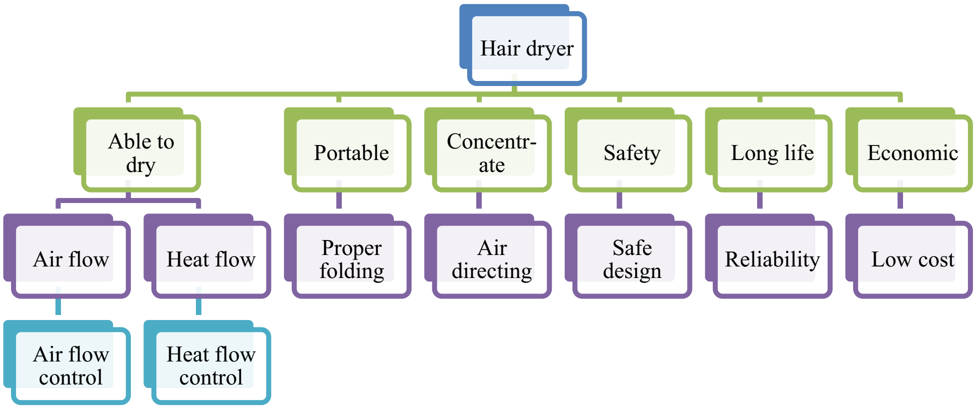

Fig. 2 Customer FRs and NFRs

specific requirements related to a product. For any manufacturer, it is imperative to fulfil the CRs and still do profitable business. This works present a new technique to resolve or eliminate the unavoidable conflicts among FRs and DPs, and determine the most optimal design among the proposed designs for any industrial product to achieve the desired customer satisfaction. The design process has been analysed from the viewpoint of design axioms with respect to customer interest.

1. Identification of customer requirements
   The work initiates with carrying out a customer surveys about the problems they have with the present design of hair dryer and the desired features in it. The complaints that are received from the customers about the product are used as customer inputs. After the analysis of all inputs, the following customer requirements are identified:
   - Ability to dry.
   - Portability.
   - Ability to concentrate air flow.
   - Safe to use.
   - Long life.
   - Economic.
2. Translation of ambiguous requirements to perfect and acquirable requirements
   The spelled customer requirements for this product are very short with no detailing of operational features; hence, they are expanded in terms of FRs and NFRs, as shown in Fig. 2. The NFRs are a constraint on the operational features or FRs.

Thus, after this step, the identified FRs and NFRs for a hair dryer include:

- Desired air flow.
- Desired heat flow.
- Ability to fold (portability).
- Ability to adjust speed range.
- Ability to adjust heat range.
- Ability to concentrate.
- Safety.
- Reliability.
- Low cost.

3. Determination of requirements weight

To evaluate the degree of customers' desire for the FRs and NFRs, three steps AHP procedure is used to rank the customer expectations in terms of AHP weight.

Step 1: *Develop a paired comparison matrix for customer requirement*

To determine the degree of customer expectation and preferences of each factor (on a scale of 1–9), a focus group is developed. The focus group included experts and personnel using the product. The focus group did the pairwise comparisons of each factor, and the results for hair dryer used are shown in Table 4.

Step 2: *Calculate the importance degree of customer requirements*

The pairwise comparison values as in Table 4 are normalized, and the summation of normalized values of each FR and NFR gives the importance degree of customer requirements (Table 5).

Step 3: *Test the consistency of the importance degrees of customer requirements*

To ensure that the evaluation of the pair-wise comparison matrix is reasonable and acceptable, consistency check is performed. For the given test example, maximal eigenvalue ($\lambda_{\max}$) comes out to be 9.88834. The consistency index (CI) is given by:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} = \frac{9.88834 - 9}{9-1} = 0.111043, \quad \text{and}$$

Then, the consistency ratio (φ) is calculated as:

Table 4 Pairwise comparison values

FRs and NFRs#	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
C_1	1	3	5	8	7	6	5	2	2
C_2	1/3	1	5	6	1	1	2	4	1
C_3	1/5	1/5	1	5	6	3	1	4	1
C_4	1/8	1/6	1/5	1	7	7	3	8	1
C_5	1/7	1	1/6	1/7	1	1	1	4	2
C_6	1/6	1	1/3	1/7	1	1	1	2	3
C_7	1/5	1/2	1	1/3	1	1	1	3	2
C_8	1/2	1/4	1/4	1/8	1/4	1/2	1/3	1	1
C_9	1/2	1	1	1	1/2	1/3	1/2	1	1

C_1 desired air flow, C_2 desired heat flow, C_3 ability to fold (portability), C_4 ability to adjust speed range, C_5 ability to adjust heat range, C_6 ability to concentrate, C_7 safety, C_8 reliability, C_9 low cost

$$\varphi = \frac{CI}{RI} = \frac{0.111043}{1.45} = 0.076581$$

(RI = 1.45 for n = 9 as Table 2)

As the φ is below 0.1, hence, pair-wise comparison matrix is reasonable and acceptable.

4. Classification of the requirements

The weights of FRs and NFRs give an idea regarding relative customer expectations of each FR and NFR. For the case of hair dryer, classification of FRs and NFRs is proposed below. FRs:

- FR_1: desired air flow, FR_2: desired heat flow, FR_3: ability to fold (Portability), FR_4: Ability to adjust speed range, FR_5: ability to adjust heat range, FR_6: ability to concentrate

NFRs:

- NFR_1: safety, NFR_2: reliability, NFR_3: low cost.

5. Generation of the design possibilities

To synthesize design solutions to satisfy user's needs mapping is done between FRs and the DPs under the constraints of NFRs. For this extended axiomatic design theory with AHP weight is applied. Desired FRs with the weight taken from Table 5 includes:

FR_1	Proper air flow	0.2812611
FR_2	Proper heat flow	0.1439314
FR_3	Portable	0.1169563
FR_4	Able to adjust air flow speed	0.1431873
FR_5	Able to adjust heat range	0.0692694
FR_6	Able to concentrate	0.0717057

To fulfil the above FRs, the designers initially proposed the following DPs:

DP_1	Fan (having rpm in the range of 6300–19,400)
DP_2	Heating element (consists of Ceramic rod)
DP_3	A mechanism to fold the dryer
DP_4	Regulator to control the air flow speed and heat
DP_5	Nozzle

It is notable that in the above proposed solution, DP_4 (regulator) takes care of both air flow speed (FR_4) and heat range (FR_5) so as to offer portability and cost benefit. The design equation would be:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{bmatrix} \tag{9}$$

Now according to Theorem 2 (decoupling of coupled design), the design equation given by Eq. 9 is coupled as FRs are

Table 5 AHP weights of FRs and NFRs

FRs and NFRs	AHP weight	Customer expectations
C_1: desired air flow	0.2812611	First
C_2: desired heat flow	0.1439314	Second
C_3: ability to fold (portability)	0.1169563	Fourth
C_4: ability to adjust speed range	0.1431873	Third
C_5: ability to adjust heat range	0.0692694	Sixth
C_6: ability to concentrate	0.0717057	Fifth
C_7: safety	0.0682084	Seventh
C_8: reliability	0.0416434	Ninth
C_9: low cost	0.0638371	Eighth

more than DPs. The simplest solution to decouple it could be to add a new DP. Thus, the first solution proposed by designers (Design_1) explores the modification of DP_4 and DP_5, as suggested below:

DP_4	Regulator to control air flow speed
DP_5	Regulator to control heat intensity
DP_6	Nozzle

The modified design equation would be:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \tag{10}$$

which shows that FRs and DPs are equal in number. However, the design matrix indicates that the design is not uncoupled. To satisfy the independence axiom, the design matrix is modified as follows:

1. By changing the heating element (DP_2)
   In the previous design, ceramic heating elements were used. Due to its high heat capacity, all other FRs are influenced. In the modified design, ceramic heating elements are replaced with nichrome bare circular heating elements with proper insulations and positioned in front of electric fans.
2. One of the big challenges of the previous design is device portability due to large number of components (e.g. fan, heater, regulators, etc.). To achieve the function of portability efficiently, a modified design to make the device more portable (DP_3) is proposed.

Hence, the modified design equation (for Design_1) is:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \quad [\text{Design}_1] \tag{11}$$

which is uncoupled and satisfies the independence axiom. However, with the addition of the new DP (DP_5), not only product cost increase and but other DPs and NFRs are also affected. It could be seen that the weight of the functional requirement FR_5 is very low (0.0692694) compared to the other functional requirement, which indicates that this requirement is less preferred by the customers. Thus, the modified design can be further modified by removing FR_5 and the concerned DP i.e. (DP_5) as shown below

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_6 \end{bmatrix} \quad [\text{Design}_2] \tag{12}$$

which makes the design uncoupled and satisfies the independence axiom. With the removal of DP_5, as in Design_2, as the complexity of product reduces, it would improve manufacturability with cost benefits.

Another design possibility proposed by another group of designers differentiates in the design of regulator. Unlike previous design solutions, this design modifies the multi-control regulator (used to achieve FR_4 and FR_5) to a regulator having discrete modes only i.e. high, medium and low. To achieve FR_6, the design of the nozzle is changed to have either a wide nozzle for drying long and thick hairs or, a narrow nozzle for drying fringes or frizzy, wavy and curly hairs i.e. a retrofit design. The FRs with improvised DPs for the hair dryer are shown below:

FR_1	DP_1	Fan (6300–19,400 rpm)
FR_2	DP_2	Heating element
FR_3	DP_3	Mechanism to fold
FR_4	DP_4	Regulator for air flow control with three controls (high, medium, low)
FR_5	DP_5	Regulator for controlling heat intensity with three controls (high, medium, low)
FR_6	DP_6	Nozzle (wide/narrow nozzle)
	DP_7	Chuck to hold different nozzles

Then the design equation would become:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} = \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \end{bmatrix} \tag{13}$$

According to Theorem 3 of general design, the above design equation is either a redundant design or a coupled design. To satisfy the independence axiom, a new FR (FR_n—‘n’ for new) (i.e. proper positioning of the nozzle for usage) may be added, even though the customers have not asked for it. This would lead to:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_n \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \end{bmatrix} \left[\text{Design}_3\right] \tag{14}$$

The above design equation is uncoupled and satisfies the independence axiom. However, the addition of a new function (FR_n) also affects other design parameters (e.g. DP_3) as well as constraints like NFR_1: safety, NFR_2: reliability, and NFR_3: low cost. Hence, the design strategy should be initiated with the analysis of the redundant function FR_6. The customer expectation from FR_6 is second least important (weightage of 0.0717057). As the concerned FR_6 is less important, hence it is modified to satisfy the axiomatic condition. Therefore, the designers proposed a joint type movable nozzle to accommodate both wide and narrow nozzles, and chuck (DP_7) to hold different types nozzle is not required. The revised design equation would be:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \left[\text{Design}_4\right] \tag{15}$$

Equation 15 indicates that the design is uncoupled and satisfies the independence axiom. As compared to the Design_3, the proposed Design_4 is more reliable, robust and affordable due to low cost.

The four design solutions proposed above (Design_{1-4}) satisfies the independence axiom. However, each design possibility has some weakness and strangeness. Therefore, from customer perspectives, the suitability of the design is still uncertain.

6. Selection of the best design possibility
   Hereafter, TOPSIS is applied to identify the suitability of the design possibility with respect to customer satisfaction. For the present case, scoring is done on a scale of 1–9. The values of 1, 3, 5, 7, and 9 represents poor, fair, good, very good, extremely good, while the values of 2, 4, 6, and 8 represented the intermediate values of adjoining scales.

Step 1: *Generation of decision matrix*
Here, matrix A would be (4 × 9) matrix with 4 design possibilities (alternatives) and 9 customer requirements (both FRs and NFRs i.e. criteria). The scoring of the above proposed designs with respect to the customer desire is shown in Table 6.
Step 2: *Normalization of the decision matrix B*
The normalized decision matrix is shown in Table 7.
Step 3: *Construction the weighted normalized decision matrix*
As mentioned previously, the major issue with traditional TOPSIS approach is that the assigned weights are arbitrary, which leads to inaccurate results. Hence, this work uses AHP weights. Table 8 shows the AHP weighted normalized decision matrix.
Step 4: *Determination the ideal and negative ideal solutions*
Ideal alternative (A^+) is the set having maximum weights (preferences) for each criterion (i.e. desired attributes values) among proposed design solutions in the decision matrix. As shown in the Table 8, the maximum weight of criteria C_1 is 1.33781386. Similarly, the maximum weights for criteria C_2 to C_9 are: C_2: 0.684607369, C_3: 0.815345644, C_4:0.673749739, C_5: 0.380147331, C_6: 0.347900289, C_7: 0.330894634, C_8: 0.219820144, C_9: 0.368383838 respectively. Therefore, ideal alternative (A^+), which has the best attribute values, is:

$$\begin{aligned} A^+ = \{&1.33781386, 0.684607369, 0.815345644, \\ &0.673749739, 0.380147331, 0.347900289, \\ &0.330894634, 0.219820144, 0.368383838\} \end{aligned}$$

Negative alternative (A^-) is the alternative having minimum weight for a given criteria in the decision matrix. As shown in the Table 8, the minimum weight of criteria C_1 is 1.057038111. Similarly, the minimum weights for criteria C_2 to C_9 are: C_2: 0.540924341, C_3: 0.010065996, C_4: 0.378984228, C_5: 0.213832874, C_6: 0.13589855, C_7: 0.129255716, C_8: 0.030912208, C_9: 0.005755997 respectively. Therefore, negative alternative (A^-), which has the worst attribute values, is:

$$\begin{aligned} A^- = \{&1.057038111, 0.540924341, 0.010065996, \\ &0.378984228, 0.213832874, 0.13589855, \\ &0.129255716, 0.030912208, 0.005755997\} \end{aligned}$$

Step 5: *Calculation the separation measures for each alternative*
The separation from the ideal alternative is shown in Table 9.

Table 6 Decision matrix

Criterion →	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Alternative ↓	AHP w_1 0.2812611	AHP w_2 0.1439314	AHP w_3 0.1169563	AHP w_4 0.1431873	AHP w_5 0.0692694	AHP w_6 0.07170	AHP w_7 0.0682084	AHP w_8 0.0416434	AHP w_9 0.0638371
Design_1	8	8	2	8	8	5	5	3	1
Design_2	9	9	9	7	–	6	8	8	8
Design_3	8	8	1	6	6	8	6	5	3
Design_4	9	9	7	6	6	7	7	7	7

Table 7 Normalized decision matrix

Criterion →	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Alternative ↓	AHP w_1 0.2812611	AHP w_2 0.1439314	AHP w_3 0.1169563	AHP w_4 0.1431873	AHP w_5 0.0692694	AHP w_6 0.07170	AHP w_7 0.0682084	AHP w_8 0.0416434	AHP w_9 0.0638371
Design_1	3.758209405	3.758209405	0.344265186	4.705373581	5.487954725	1.895245109	1.895245109	0.742307489	0.090166963
Design_2	4.756483778	4.756483778	6.971370023	3.602551648	–	2.729152957	4.851827479	5.278631033	5.770685662
Design_3	3.758209405	3.758209405	0.086066297	2.64677264	3.086974533	4.851827479	2.729152957	2.061965247	0.811502671
Design_4	4.756483778	4.756483778	4.217248533	2.64677264	3.086974533	3.714680414	3.714680414	4.041451884	4.41818121

Table 8 AHP weighted normalized decision matrix

Criterion →	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Alternative ↓	AHP w_1 0.2812611	AHP w_2 0.1439314	AHP w_3 0.1169563	AHP w_4 0.1431873	AHP w_5 0.0692694	AHP w_6 0.07170	AHP w_7 0.0682084	AHP w_8 0.0416434	AHP w_9 0.0638371
Design_1	1.057038111	0.540924341	0.040263982	0.673749739	0.380147331	0.135898551	0.129255716	0.030912208	0.005755997
Design_2	1.33781386	0.684607369	0.815345644	0.515839644	–	0.195693913	0.330894634	0.219820144	0.368383838
Design_3	1.057038111	0.540924341	0.010065996	0.378984228	0.213832874	0.347900289	0.186128232	0.085867244	0.051803977
Design_4	1.33781386	0.684607369	0.493233785	0.378984228	0.213832874	0.266361159	0.253341204	0.168299797	0.282043876

Separation of each design alternative from the ideal alternative is computed as (S^+), the sum of all S_i^+, for jth design, and given as:

$$S^+ = (2.16471687, 0.310116, 2.286118, 1.080145)$$

The separation from the negative ideal alternative is shown in Table 10.

The separation from the negative ideal alternative would be:

$$S^- = (0.491278, 2.179564, 0.369877, 1.57585)$$

Step 6: *Calculation the relative closeness to the ideal solution C_i*
Closeness coefficient of each design possibility is calculated, and ranking of the design possibility are determined as in Table 11.

Comparison with previous work

By adopting existing AD theory (Suh 1990), it is possible that the designer could have generated any one design among all the four design possibilities, shown in this work, and accordingly headed to obtain the final design. As Design_1 satisfies the independence axiom condition at the very first instant, its probability of selection is very high, and hence, the designer might stop to explore other design possibilities. However, as evident from this work, due to TOPSIS, Design_1 is ranked third and the second possible design solution (i.e. Design_2) has been categorized as the best among all the design possibilities. Therefore, this work does not stop at the first instance, explores other design possibilities and later selects the most optimal design solution as per the customer perspectives. These days, customer centric design is capturing the attention of the market. Therefore, present work provides the most optimal design, where more important CRs are satisfied on priority.

Table 9 Separation from the ideal alternative

Criterion → Alternative ↓	S_1^+	S_2^+	S_3^+	S_4^+	S_5^+	S_6^+	S_7^+	S_8^+	S_9^+	Sum (S^+)
Design$_1$	0.280775748	0.143683028	0.775081661	0	0	0.212001739	0.201638918	0.188907936	0.36262784	2.164717
Design$_2$	0	0	0	0.157910095	–	0.152206377	0	0	0	0.310116
Design$_3$	0.280775748	0.143683028	0.805279648	0.294765511	0.166314457	0	0.144766402	0.1339529	0.31657986	2.286118
Design$_4$	0	0	0.322111859	0.294765511	0.166314457	0.08153913	0.07755343	0.051520346	0.086339962	1.080145

Table 10 Separation from the negative alternative

Criterion → Alternative ↓	S_1^-	S_2^-	S_3^-	S_4^-	S_5^+	S_6^-	S_7^-	S_8^-	S_9^-	Sum (S^-)
Design$_1$	0	0	0.030197987	0.294765511	0.166314457	0	0	0	0	0.491278
Design$_2$	0.280775748	0.143683028	0.805279648	0.136855416	–	0.059795362	0.201638918	0.188907936	0.36262784	2.179564
Design$_3$	0	0	0	0	0	0.212001739	0.056872515	0.054955036	0.04604798	0.369877
Design$_4$	0.280775748	0.143683028	0.483167789	0	0	0.130462609	0.124085488	0.13738759	0.276287878	1.57585

Table 11 Ranking of the design possibility

Design possibility	C_i	Rank
Design_1	0.18496947	3
Design_2	0.875439243	1
Design_3	0.139261292	4
Design_4	0.593318223	2

Previous works in the similar domain had considered all CRs without any differentiation (Do and Park 2001; Krishnapillai and Zeid 2006). However, the present work measures the CRs weight and accordingly proceeds with the design. Previous works were focused on the FRs only (Park et al. 2003) but, the present work includes both FRs and NFRs to compare each design. Furthermore, in the previous work (Krishnapillai and Zeid 2006), the design decision regarding addition and subtraction of FRs is not easy due to the lake of CRs priority. Present work efficiently gives CRs weight and their priority; therefore, it is easy for the designer to take appropriate integrated decision. The traditional AD approach (Suh 2005) works on formal requirements of CRs and knowledge about DPs, whereas the proposed work needs more knowledge about DPs.

Results and discussion

The research primarily focuses on techniques for generating valid and effective product design possibilities and selecting the most optimal solution as per the customer expectations. The main contribution of this paper, over and beyond the previous works, is that it is not only simple and efficient but also yield as many combinatorial solutions as possible, which are analysed and the best among the solutions is selected to facilitate the design of the product. With the help of AD and AHP, design complexity is reduced while maintaining the independence. An experiment is carried out to represent the application of the framework. From the result, as per the relative closeness to the ideal solution, it is observed that Design_2 is the most optimal solution as per the customer expectations for the hair dryer, followed by Design_4, Design_1 and, Design_3 in this sequence. It is notable that Design_2 and Design_4 concentrated on the most desired customer requirements i.e. proper air flow, heat flow, and portability, whereas, Design_1 and Design_3 tried to provide the functions related to speed and heat range settings. After checking the suitable aggregations on various FRs along with DPs under different design, it is observed that the Design_2 is closer to the customer expectations. Design_2 have the meaningful aggregation of the functional and design parameters, which leads to the theory that a design, in spite of fulfilling all the requirements may not be the best design. For any industry to succeed, customer satisfaction has to be the primary concern. This work helps the designer identify the importance of different FRs through AHP and accordingly the designer would develop/evolve DPs to meet the important FRs for an industrial product. The major challenge during product design is maintaining the independence of axiom because the number of DPs is greater/lesser than that of FRs. Therefore, in the present work, a supportive tool, AHP, is employed with AD. AD maps appropriate product attributes to quantitative requirements and generates valid product design possibilities. AHP assists designers in identifying customer requirements for mitigation, subtraction or, addition of FRs and DPs to maintain their independence. The AHP weight prioritizes the customer functional and non-functional requirements; accordingly decisions are taken to make customer centric designs. Furthermore, the quality of design and manufacturability depends on the proper selection of FRs, and the DPs. The application of AD with AHP gives direction to the designer through proper mapping between FRs and DPs and reduces product complexity. This facilitates easy manufacturability of quality products. In this work, AHP and TOPSIS are jointly applied for selection of the most optimal design possibility. Here, AHP is used for determining the weights of the criteria, and these weights are used in TOPSIS to avoid arbitrary weights that might have been assigned and led to inaccurate results. The integration of AHP and TOPSIS approaches enables experts to select efficiently a more suitable design possibility as per the functional and non-functional requirements of the customer. Earlier, it was not clear how to deal with the customers' conflicting requirements and maintain the independence. This work presents a support tool for decision makers to accurately and efficiently select CRs by a useful aggregation of requirements (both FRs and NFRs) and DPs. Since, the proposed technique is a frictionless method where the general technique of AD is integrated with AHP and TOPSIS; therefore, there are not any significant challenges to deployment of the method in the industry for any other products.

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