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ORIGINAL RESEARCH

Multi-objective optimization approach for cost management during product design at the conceptual phase

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Abstract The effective cost management during the conceptual design phase of a product is essential to develop a product with minimum cost and desired quality. The integration of the methodologies of quality function deployment (QFD), value engineering (VE) and target costing (TC) could be applied to the continuous improvement of any product during product development. To optimize customer satisfaction and total cost of a product, a mathematical model is established in this paper. This model integrates QFD, VE and TC under multi-objective optimization frame work. A case study on domestic refrigerator is presented to show the performance of the proposed model. Goal programming is adopted to attain the goals of maximum customer satisfaction and minimum cost of the product.

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Introduction

The cost and customer perceived quality of a product are the two faces of a coin. In the current market scenario, it is essential to develop a product at minimum cost and quality as desired by the customer. Product design and development is a techno-economic process, hence there is always a trade-off between design goals and cost constraints (Sharma 2012). Decisions made during the design phase have a significant influence on development and life cycle costs. It is generally known that ~80 % of the manufacturing cost of a product is determined by the design of the product (Ernst and Kamarad 2000). The product designers have to balance cost, quality and functionality in their designs to develop a product with minimum cost and greater customer satisfaction. To achieve this, it is required to manage product costs throughout the design stage. Target costing is a widely used technique for cost management during product development (Dekker and Smidt 2003; Filomena et al. 2009). It is a proactive cost management tool, which requires continuous market research where price considerations and trend changes are closely monitored to understand the perceived quality and functionality of target customers as well as the price they are willing to pay for demanded features. It is also a strategic management tool involving other managerial tools and techniques namely quality function deployment (QFD) and value engineering (VE). Cost management techniques cannot be implemented successfully without the support of QFD and VE analysis (Zengin and Ada 2010). As VE allows the identification of where cost reduction could be achieved and the TC shows the target to be achieved to assure the long-term profitability plan of a company, VE and TC are complementary processes (Ibusuki and Kaminski 2007).

A mechanical design process is generally divided into conceptual, configuration and detailed design phases. The

main objective of conceptual design is to develop concepts to meet design specifications (Zeng and Gu 1999). This paper aims to design a product at the conceptual phase that compromises customer satisfaction and cost. A multi-objective optimization frame work is established to design a product by integrating QFD, VE and TC. It is observed from the literature that the earlier researchers focused on designing a product by integrating VE and TC in the first phase of QFD. But, there is a scope to alter the parts characteristics of a product in response to customer needs in the second phase of QFD. The second phase of QFD called Part Planning Matrix (PPM), which is the best choice for applying VE to obtain different levels of the part characteristics and then it is suitable to implement target costing approach (Jariri and Zegordi 2008a). Therefore, in this work PPM of QFD is considered for product design. Jariri and Zegordi (2008b) established a mathematical model by considering single-objective optimization approach which incorporates the first phase of QFD called house of quality (HOQ) and TC into a single model.

In this paper, a mathematical model is developed on the basis of QFD, VE and TC integration for effective cost management during the conceptual phase of product design. The model is solved under multi-objective optimization to obtain trade-off between customer satisfaction and cost of the product. In the multi-objective decision-making problems, the objectives may be competitive among themselves. Unlike a unique optimal solution in the case of single-objective decision making, the decision maker can get efficient or non-dominated solution in the case of multi-objective decision-making problems. Goal programming (GP) is the most useful multi-objective technique (Gosh and Roy 2013). In the present work, GP technique is employed for multi-objective optimization with a view to optimize customer satisfaction index and total cost of the product simultaneously. The conceptual phase of designing a domestic refrigerator is considered to illustrate the proposed methodology.

The rest of the paper is organized as follows. The literature related to the techniques QFD, VE and TC is briefly reviewed in the "Literature review". In "Methodology", proposed methodology is presented. The application of the proposed methodology is described in "Illustrative example" with an illustrative example by considering conceptual design of a domestic refrigerator. The results and discussions are made in "Results and discussion". Finally, conclusions are discussed in "Conclusions".

Literature review

Quality function deployment

Quality function deployment is a customer-oriented design technique, which was conceptualized in the late 1960s. It has been adopted in various industries with a view to add quality, value and customer satisfaction during the design and development of new products and services. QFD is a four-phase structured methodology to translate the customer needs into design requirements, and subsequently into parts characteristics, process plans, and production requirements associated with its manufacture (Hassan et al. 2009). It consists of a series of correspondence matrices which are sequenced to reflect a typical path in the product development process such that outputs of a matrix are inputs in a succeeding matrix (Fogliatto et al. 2003). Product planning matrix is the first matrix, which is known as HOQ and it maps prioritized list of customer needs to appropriate design requirements. The outcome of HOQ analysis is the list of priority ratings of the design requirements. The second matrix of QFD approach is the assembly/parts planning matrix which maps the prioritized design requirements to critical parts characteristics. The other matrices are process planning matrix and production planning matrix.

Most of the QFD studies focused on enhancing customer satisfaction by increasing the functionality of the product. The financial factor was almost neglected in the earlier QFD applications (Tang et al. 2002). But in the present difficult economic times, it is necessary to integrate cost deployment into QFD (Ross and Mazur 2009). The objective of cost deployment is to achieve the target cost while keeping a balance with quality (Jiang et al. 2007). Bode and Fung (1998) integrates design costs into the QFD frame work, which facilitates the designers to optimize product development resources towards customer satisfaction. Eversheim et al. (1998) presented a methodology to integrate cost modeling and QFD for making trade-off decisions between quality and cost at the early stages of product design. Tsai and Chang (2004) developed a method of quick cost estimation based on function characteristics and the QFD technique. Iranmanesh et al. (2005) presented an integrated approach to optimize cost while respecting the customer perception of a product using a modified QFD method. Takai and Ishii (2006) proposed a method of decomposition of QFD matrices simultaneously for both requirements and structure to allocate the worth and target cost of the modules in a system.

Value engineering

Value engineering is a systematic and function-based approach to improve the value of products. The purpose of VE is to attain the desired function at minimum cost. It is an organized creative technique directed at analyzing the functions of a product with the purpose of achieving the required functions at the lowest overall cost constituent with all the requirements, which comprise its value. VE is a

process in which a product is analyzed in terms of the functions performed by the product. Costs associated with these functions, and disparity of value, in terms of the cost to importance of the functions are identified and targeted for improvement (Mendoza et al. 2003). This approach can be termed as functional cost analysis in which weightages for the functions of each part can be compared with the relative costs of the corresponding parts and can be expressed as the ratio of function to cost, called value ratio (Yoshikawa et al. 1994). On the basis of value ratio, the levels of the parts characteristics can be established. It is performed before the production stage. The motivating force behind VE is to ensure that the product achieves its basic function in a way that satisfies the customer at an acceptable cost. Consequently, VE programs are the domain of the product engineer, not the accountant. The application of VE is appropriate during the conceptual design stage of a product (Cooper and Slagmulder 1997). Since QFD is particularly useful for conceptual design of a product, the integration of QFD and VE together leads to the reduction of costs and improvements of service/product or performance (Farsi and Hakiminezhad 2012).

Target costing

Target costing (TC) process is a strategic profit planning and cost management technique in which a product, that is to be manufactured in accordance with the functionality and quality demanded by the customer and determined by market research, is sold at an estimated sale price, by determining the product cost which will provide the profitability level requested by the company (Kocsoy et al. 2008). TC is considered a strategic management accounting system. This implies that its main focus is on long-term cost management rather than short-term focus adopted by more traditional cost accounting systems (Ewert and Ernst 1999). This process begins with the definition of the product, carries through setting the target cost, finding ways to achieve and achieving the target, and then maintaining a competitive cost during the life cycle of the product (Clifton et al. 2003). The target cost is derived from the target price and is calculated by the simple equation Target Cost = Target price − Target profit. Both price and profit are the independent variables in the above equation. Prices are decided by what customers are willing to pay, and profit is determined by what financial markets expect as a return from that particular industry. The dependent variable is cost, which implies that a firm has to manage its cost to meet the external constraints compelled by the product and financial markets in which it operates (Ansari et al. 2006).Target cost is simply the allowable cost of a product that yields the required rate of return. TC places customer needs at the heart of the firm's efforts to develop and deploy product strategies. Target costing views meeting or exceeding customer requirements for quality, functionality, and price as key to attain and sustain product competitiveness (Archie Lockamy and Wilbur 2000). TC uses price information in the market to determine product cost. The application of TC in the product design stage has the greatest cost reduction potential (Gagne and Discenza 1995). It is appropriate for designing assembly type products (Helms et al. 2005). Filomena et al. (2009) developed a model to operationalize TC by breaking down cost targets into product parts, features and common elements, focusing on creating parameters for cost control during product development.

Target costing significantly relies upon QFD and VE for its effective implementation (Gandhinathan et al. 2004). VE is an essential technique to implement TC methodology (Noda and Tanaka 1997). TC helps to develop a right product and VE shows the best way of performing it. Both VE and TC are intertwined (Al Chen et al. 2008). Sharma et al. (2006) developed a synergistic management approach, in which QFD, TC and VE techniques are utilized to facilitate cross-functional product design and development, integrating both organizational and functional aspects of the development process so as to maximize value creation. The integration of QFD, TC and VE provides a competitive cost advantage to the manufacturing companies (Rezaei et al. 2013). Jariri and Zegordi (2008b) suggested that the part planning matrix of QFD is the best choice for applying VE to obtain different levels of the part characteristics and then it is suitable to implement TC approach.

Methodology

In this paper, an attempt has been made to establish a mathematical model which integrates part planning matrix of QFD, VE and TC under multi-objective approach to optimize customer satisfaction and total cost of the product. The schematic representation of the integration model is shown in Fig. 1. In the model, as VE helps to identify potential part reductions and possible combinations of part functions to keep cost aligned with value, the VE is incorporated in the part planning matrix (PPM) of QFD for obtaining various levels of parts characteristics. Correlations among the parts characteristics and interrelationship between the design requirements and the parts characteristics of the PPM are considered in the establishment of a mathematical model. In accordance with the priorities of the customer needs, the priority ratings of the design requirements are obtained in HOQ. The prioritized design requirements are carried in the PPM of QFD to
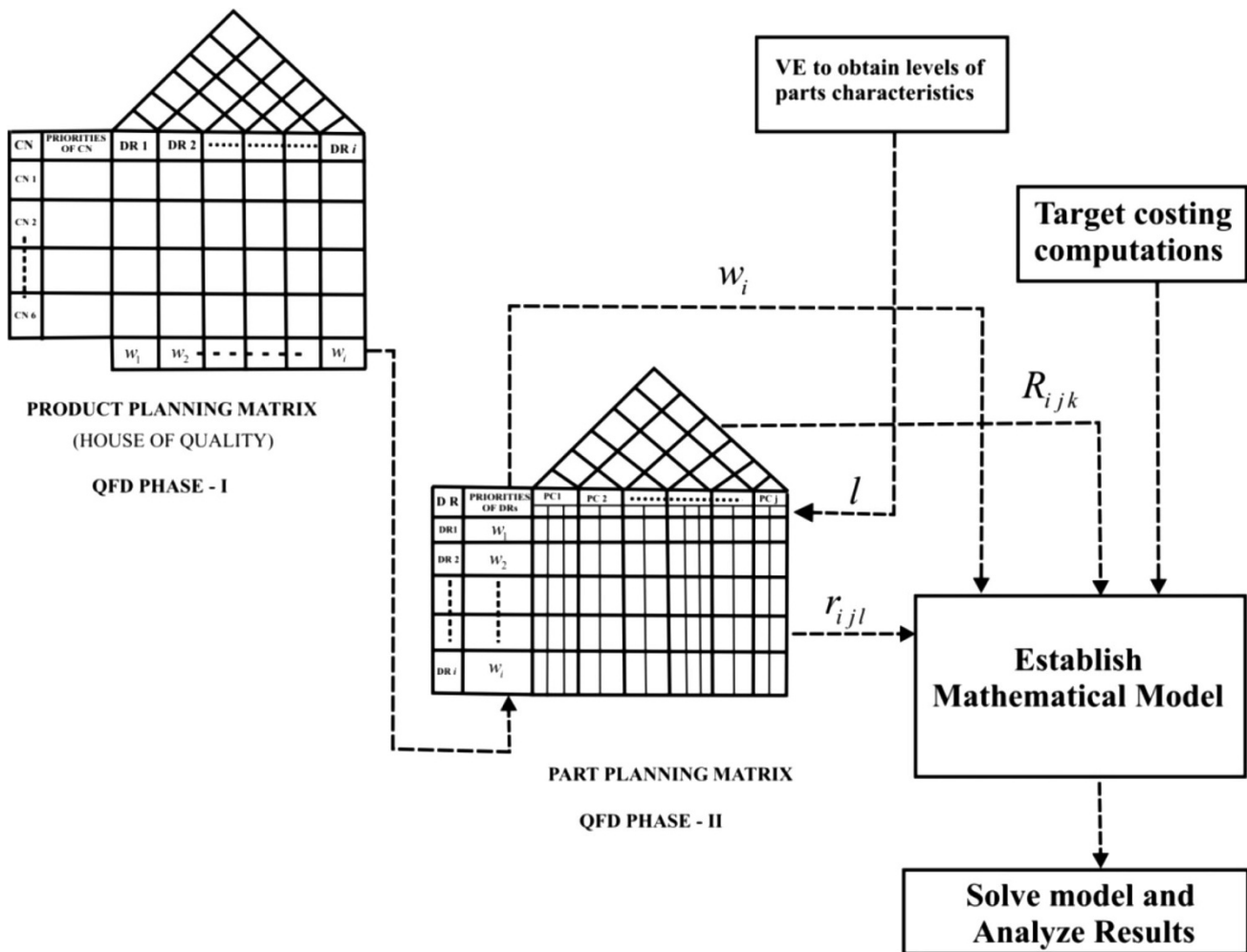
Fig. 1 QFD, VE and TC integration model

deploy customer preferences. Further, the work is carried out to identify the cost of each component using VE and TC with a view to that makes up the final product cost. A mathematical model is formulated under both single- and multi-objective optimization. The model is solved under single-objective optimization to obtain the goals, which are used in multi-objective optimization through goal programming.

Formulation of mathematical model under single-objective optimization

Under single-objective optimization, the customer satisfaction and total cost of the product are optimized individually. These non-linear programming problems (NLPP) are solved using LINGO 8.0 to obtain optimum values of customer satisfaction index and total cost of the product. The single-objective optimization model is discussed below.

Notations

m	Number of design requirements
n	Number of parts characteristics
i	Design requirement, $i = 1, 2, \ldots m$
j	Part characteristic, $j = 1, 2, \ldots n$
l	Level of the parts characteristic, $l = 1, 2, 3$
l_j	Level l of the parts characteristic j
w_i	Priority rating for ith design requirement
r_{ijl}	Inter-relationship values of part planning matrix
R_{ijk}	Elements of the roof of part planning matrix
C_{jl}	Cost of the part j in level l
Y_i	Summation effects of parts characteristics for ith design requirement
TC_j	Target cost of the jth part
x_{jl}	Decision variable
x_{jl}	1, if part characteristic is appropriate at the level l
x_{jl}	0, otherwise

Objectives

Maximize customer satisfaction (Z_1)

$$\text{Maximize } Z_1 = \sum_{i=1}^{m} w_i Y_i \tag{1}$$

Minimize total cost (Z_2)

$$\text{Minimize } Z_2 = \sum_{j=1}^{n} \text{TC}_j \tag{2}$$

Constraints

$$\sum_{l=1}^{l_j} C_{jl} \, x_{jl} \leq \text{TC}_j \tag{3}$$

$$\sum_{l=1}^{l_j} x_{jl} = 1 \;\; \forall j \tag{4}$$

where

$$Y_i = \sum_{j=1}^{j=n} \sum_{l=1}^{l_j} r_{ijl}(x_{jl}) + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} \sum_{l=1}^{l_j} \sum_{u=1}^{l_k} R_{ijk}(x_{jl})(x_{ku}) \tag{5}$$

$$x_{jl} \in \{0,1\} \tag{6}$$

The Eqs. (1) and (2) are the objective functions, maximize customer satisfaction and minimize total cost of the product, respectively. The first term of the fifth equation reflects the impact of the choice of design requirements and the second term indicates the impact of correlation of parts characteristics of the part planning matrix (roof matrix). The inter-relationship values (r_{ijl}) represent the relationship between each design requirement (i) and part characteristic (j) at each level(l). The intensity of the correlation between the parts characteristics j and k for the ith design requirement is represented by R_{ijk}.

Formulation of mathematical model
under multi-objective optimization

Multi-objective optimization is the process of simultaneously optimizing two or more conflicting objectives subject to certain constraints. A decision situation is generally characterized by multiple objectives. Some of these objectives may be complementary, while others may be conflicting in nature. Goal programming allows the decision maker to specify a target or aspiration level for each objective function. A preferred solution is defined as the one that minimizes the sum of the deviations from the prescribed set of aspiration levels.

Goal programming

Goal programming was originally introduced by Charnes and Cooper in early 1961 for a linear model. This approach allows the simultaneous solution of a system of complex objectives (Belmokaddem et al. 2009). GP is a practical and robust tool for use in multi-objective mathematical programming (Ignizio 1983). The principal concept for linear GP is to the original multiple objectives into specific numeric goal for each objective. The objective function is then formulated and a solution is sought which minimizes the sum of deviations from their respective goal. The main idea in GP is to find solutions which attain a predefined target for one or more objective functions (Deb 2001). It attempts to combine the logic of optimization in mathematical programming with the decision maker's desire to satisfy several goals (Delice and Gungor 2011). GP is a suitable tool to assist the QFD planning effort (Tu et al. 2010). Karsak et al. (2002) employed a combined analytic network process (ANP) and zero–one goal programming (ZOGP) approach to incorporate the customer needs and the product technical requirements systematically into the product design phase in QFD. Wang and Ma (2007) adopted ZOGP with ANP to obtain optimum set of product quality characteristics. They presented a case study to show the effectiveness of the methodology for enhancing product design quality.

The formulation of a simple goal programming problem is given by

$$\text{Min. } v(d) = \sum_{i=1}^{k} \left(d_i^- + d_i^+ \right)$$

$$\text{Subject to } Z_i(x) + d_i^- - d_i^+ = b_i \; ; \quad i = 1, 2, \ldots k$$

$$x, d_i^-, d_i^+ \geq 0$$

where b_i = the target for goal i, d_i^- is the underachievement of goal i; d_i^+ is the overachievement of goal i; and $v(d)$ is the function of deviational variables known as achievement function

Goal programming is used in this present work to optimize both customer satisfaction and cost of the product simultaneously with a view to develop a product that satisfies both the objectives. The maximum customer satisfaction and minimum total cost of the product are assumed as goals in the model. GP minimizes the deviations from the target values. The original objectives are expressed as a linear equation with target values and two auxiliary variables. Negative deviation (d^-) and positive deviation (d^+) are two auxiliary variables representing

underachievement of the target value and overachievement of the target value, respectively (Ozcan and Toklu 2009).

The GP approach of the mathematical model for the present work is given below.

$$\text{Minimize } v(d) = d_1^- + d_2^+ \qquad (7)$$

Subject to goal constraints

$$\sum_{i=1}^{i=m} w_i Y_i + d_1^- + d_1^+ = W \qquad (8.1)$$

$$\sum_{j=1}^{j=n} \text{TC}_j + d_2^- - d_2^+ = S \qquad (8.2)$$

$$\sum_{l=1}^{l_j} C_{jl} x_{jl} + d_c^- - d_c^+ = \text{TC}_j \; ; \; j = 3, 4, \ldots n \; ; \; c$$
$$= 3, 4, \ldots 11 \qquad (8.3)$$

where d_c^-, d_c^+ are the deviation variables of gth goal and

$$Y_i = \sum_{j=1}^{j=n} \sum_{l=1}^{l_j} r_{ijl}(x_{jl}) + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} \sum_{l=1}^{l_j} \sum_{u=1}^{l_k} R_{ijk}(x_{jl})(x_{ku})$$

W = goal value of customer satisfaction index
S = goal value of total cost of the product
TC_j = target cost of part j

Subject to hard constraint $\sum_{l=1}^{l_j} x_{jl} = 1 \qquad (9)$

The objective function shown in Eq. (7) indicates the sum of the minimization of the underachievement (d_1^-) of customer satisfaction and overachievement (d_2^+) of the cost of the product. The Eqs. (8.1)–(8.3) represent goal constraints of customer satisfaction, total cost of the product and target cost of each part. Further W, S and TC_j indicate the goal values corresponding to customer satisfaction, total cost of the product and target cost of each part. The equality constraint shown in Eq. (9) indicates the consideration of only one level for the given part characteristic in product design.

Illustrative example

Domestic refrigerator is considered as an example product to demonstrate the proposed model. To obtain the customer expectations in a domestic refrigerator, personal interviews with the customers, market surveys, and brain storming sessions with the targeted customers were conducted. After the comprehensive discussions and then by performing factor analysis, six basic customer needs are identified and conjoint analysis has been carried out to obtain their priority ratings, which are shown in Table 1 (Durga Prasad et al. 2010). Then the experts of the design team established seven design requirements which are shown in Table 2.

The first phase of QFD is the product planning in which house of quality (HOQ) is established. The outcome of the HOQ is the priorities of the design requirements, which are the input to the second phase of QFD. The combination of QFD and analytic network process (ANP) helps to provide most satisfying design for customers (Soota et al. 2011). The following QFD–ANP procedure (Venkata Subbaiah et al. 2011) is employed to obtain the priority ratings of the design requirements.

Step 1: Establish the matrix (W_1) which shows the degree of relative importance of the DRs with respect to each CN

The matrix W_1 is shown in Table 3 is obtained by preparing pair-wise comparisons between the DRs in respect of each CN. Saaty scale (Bayazit 2006) is adopted while preparing the pair-wise comparisons.

Step 2: Establish the inner dependence matrix (W_2) of the CNs with respect to each CN

With the help of pair-wise comparisons, the inner dependencies among the customer needs are calculated by analyzing the impact of each customer need on other

Table 2 List of design requirements

Design requirements (DRs)
DR-1: Enhancing compressor performance (ECOMP)
DR-2: Enhancing condenser performance (ECONP)
DR-3: Enhancing evaporator performance (EEP)
DR-4: Use good thermal insulation material (UGTIM)
DR-5: Quick response to trouble shooting (QRTS)
DR-6: Effective refrigerator controls (ERC)
DR-7: Optimum design of refrigerator compartments (ODRC)

Table 1 Customer needs and their priority ratings

Customer needs (CNs)	Service reliability (SR)	Preservation (PRE)	Refrigeration effect (RE)	Storage volume (SV)	Price (PR)	Energy consumption (EC)
Priority ratings (W)	17.47	14.579	11.459	11.482	13.699	31.311

Table 3 Degree of relative importance of the DRs with respect to CNs (W_1)

DR	CN					
	SR	PRE	RE	SV	PR	EC
ECOMP	0.1568	0.1568	0.3700	0.1568	0.3745	0.2450
ECONP	0.0983	0.0607	0.1578	0.0607	0.2450	0.1568
EEP	0.0607	0.0983	0.2462	0.0983	0.1568	0.0983
UGTIM	0.0388	0.2450	0.0989	0.2450	0.0607	0.3745
QRTS	0.3745	0.0260	0.0262	0.0260	0.0260	0.0260
ERC	0.2450	0.0388	0.0611	0.0388	0.0388	0.0607
ODRC	0.0260	0.3745	0.0398	0.3745	0.0983	0.0388

customer need. The inner dependence matrix of the customer needs is shown in Table 4.

Step 3: Establish inner dependence matrix(W_3) of the DRs with respect to each DR

The inner dependencies among the design requirements are obtained through analyzing the impact of each design requirement on other design requirement by establishing pair-wise comparisons. The inner dependence matrix of the design requirements is shown in Table 5.

Step 4: Determine the interdependent priority matrix (W_C) of the customer needs using

$$W_C = W_2 \times W$$

where W = the matrix of priority ratings of customer needs

Table 4 The inner dependence matrix of the customer needs (W_2)

CN	CN					
	SR	PRE	RE	SV	PR	EC
SR	0.3975	0.3277	0.0642	0.1346	0.3247	0.3963
PRE	0.1527	0.1080	0.2541	0.2501	0.1176	0.1322
RE	0.2565	0.2486	0.1969	0.2358	0.1555	0.1131
SV	0.1360	0.2007	0.0376	0.1559	0.2768	0.2206
PR	0.0280	0.0340	0.2191	0.0399	0.0607	0.0413
EC	0.0727	0.0811	0.2281	0.1838	0.0647	0.0965

Step 6: Determine the overall priorities of the design requirements (w) using $w = W_A \times W_C$

$$w = \begin{bmatrix} ECOMP \\ ECONP \\ EEP \\ UGTIM \\ QRTS \\ ERC \\ ODRC \end{bmatrix} = \begin{bmatrix} 27.31 \\ 18.55 \\ 14.45 \\ 11.34 \\ 7.010 \\ 5.940 \\ 15.40 \end{bmatrix}$$

These priority ratings of the design requirements (w) are carried in the establishment of mathematical model. After the first phase of QFD, the second phase of QFD is initiated by identifying the parts characteristics.

$$W_C = \begin{bmatrix} 0.397491 & 0.327707 & 0.064182 & 0.134597 & 0.324716 & 0.276778 \\ 0.152674 & 0.107983 & 0.254061 & 0.250076 & 0.117574 & 0.132215 \\ 0.256510 & 0.248594 & 0.196918 & 0.235793 & 0.155520 & 0.113110 \\ 0.136012 & 0.200706 & 0.037593 & 0.155874 & 0.276778 & 0.081051 \\ 0.028048 & 0.033959 & 0.219138 & 0.039852 & 0.060665 & 0.041319 \\ 0.072669 & 0.081051 & 0.228108 & 0.183808 & 0.064747 & 0.072669 \end{bmatrix} \times \begin{bmatrix} 17.470 \\ 14.579 \\ 11.459 \\ 11.482 \\ 13.699 \\ 31.311 \end{bmatrix} = \begin{bmatrix} 27.112 \\ 15.775 \\ 18.741 \\ 13.852 \\ 6.0785 \\ 10.338 \end{bmatrix}$$

Step 5: Determine the interdependent priority matrix (W_A) of the design requirements using

$$W_A = W_3 \times W_1$$

The experts of the design team used VE approach to identify the parts characteristics and their levels to meet the design requirements. In this approach, brain storming sessions are conducted among the design team members. The parts of the refrigerator are identified and the

$$W_A = \begin{bmatrix} 0.312710 & 0.233701 & 0.315315 & 0.233701 & 0.296413 & 0.306985 \\ 0.211446 & 0.173990 & 0.190051 & 0.173990 & 0.205208 & 0.202843 \\ 0.187223 & 0.058957 & 0.180141 & 0.186106 & 0.176183 & 0.058957 \\ 0.113487 & 0.117523 & 0.123078 & 0.117523 & 0.115266 & 0.121478 \\ 0.081099 & 0.063105 & 0.076713 & 0.063105 & 0.070516 & 0.077345 \\ 0.058957 & 0.065610 & 0.060438 & 0.065610 & 0.059888 & 0.058957 \\ 0.166692 & 0.058957 & 0.315315 & 0.065610 & 0.183364 & 0.167648 \end{bmatrix}$$

Table 5 The inner dependence matrix of the design requirements (W_3)

DR	DR						
	ECOMP	ECONP	EEP	UGTIM	QRTS	ERC	ODRC
ECOMP	0.3420	0.2727	0.3389	0.3088	0.3131	0.3273	0.0901
ECONP	0.1638	0.3421	0.1299	0.1927	0.2155	0.2137	0.1433
EEP	0.1949	0.1356	0.1779	0.2024	0.2136	0.1631	0.1826
UGTIM	0.1078	0.0952	0.1647	0.1325	0.1028	0.1262	0.1031
QRTS	0.0882	0.0448	0.0791	0.0852	0.0839	0.0918	0.0325
ERC	0.0624	0.0474	0.0652	0.0586	0.0495	0.0600	0.0763
ODRC	0.1838	0.0622	0.1870	0.1626	0.1645	0.1608	0.5046

function of each part is evaluated and then classified into three levels on the basis of value index. Finally, the principal parts along with their levels are established and are shown in Table 6.

In this study, same correlation between the parts characteristics for all the design requirements is assumed.

To assign the relationship values while establishing the parts planning matrix by the design team, a three-point ordinal scale 1–3–9 (1, weak; 3, medium; and 9, strong) (Franceschini and Rupil 1999) is employed. For instance, the relation between DR-1(Enhancing compressor performance) and PC-1 at the level I (1/3 hp Hermetic compressor) is strong and hence value 9 is assigned in the corresponding cell of the matrix. As there is a medium relation between DR-1 and the PC-1 at the level II (1/6 hp Hermetic compressor), the value 3 is assigned. The relation between the DR-1 and the PC-1 at the level III (1/8 hp Hermetic compressor) is weak and hence value 1 is assigned in the corresponding cell of the matrix. Similarly, the inter-relationship matrix is completely filled by the appropriate relationship values. The intensity of the correlation among the parts characteristics is also quantified using the same three-point ordinal scale. For example, the correlation between PC-1 (Hermetic compressor) and PC-2 (Wire on tube condenser) in respect of enhancing the compressor performance (DR-1) is strong and the correlation value 9 is assigned to the corresponding cell in the roof of the matrix. In the same manner, the roof matrix is prepared. The completely filled parts planning matrix is shown in Fig. 2.

Mathematical model

Under single-objective optimization, the objectives such as customer satisfaction and total cost of the product are optimized individually subject to constraints (3), (4) and (6) mentioned in the "Formulation of mathematical model under single objective optimization" using LINGO 8.0 solver. While optimizing customer satisfaction, the

customer satisfaction index is 27,579, whereas optimizing the total cost of the product yields total cost of the refrigerator is Rs. 6,203. If the former criterion of optimization is used to manufacture a refrigerator, the cost of the refrigerator is Rs. 9,616. This cost may not be affordable to the customer even though it possesses high customer satisfaction index. The refrigerator is manufactured by considering the criterion of cost minimization, the cost of the refrigerator is decreased to Rs. 6,203. But customer satisfaction index is drastically reduced to 13,329 and it indicates that the refrigerator cannot give complete satisfaction to the customers. In view of attaining both the objectives, the following multi-objective model is developed using GP.

In GP approach, the designer has to set a goal to be attained for each objective and a measure of deviations of the objective functions from their respective goals is minimized. The goal values considered in this model are 27,579 and Rs. 6,203 for customer satisfaction index and total cost of the refrigerator respectively.

Minimize $v(d) = d_1^- + d_2^+ + d_3^+ + d_4^+ + d_5^+ + d_6^+ + d_7^+ + d_8^+ + d_9^+ + d_{10}^+ + d_{11}^+$

Subject to goal constraints

$$27.31(Y_1) + 18.55(Y_2) + 14.45(Y_3) + 11.34(Y_4)$$
$$+ 7.01(Y_5) + 5.94(Y_6) + 15.4(Y_7) - d_1^+ + d_1^- = 27,579$$
$$TC_1 + TC_2 + TC_3 + TC_4 + TC_5 + TC_6 + TC_7 + TC_8$$
$$+ TC_9 - d_2^+ + d_2^- = 6,203$$
$$2,800(x_{11}) + 2,350(x_{12}) + 2,000(x_{13}) - d_3^+ + d_3^- = TC_1$$
$$700(x_{21}) + 500(x_{22}) + 450(x_{23}) - d_4^+ + d_4^- = TC_2$$
$$1,500(x_{31}) + 1,200(x_{32}) + 1,000(x_{33}) - d_5^+ + d_5^- = TC_3$$
$$66(x_{41}) + 62(x_{42}) + 48(x_{43}) - d_6^+ + d_6^- = TC_4$$
$$250(x_{51}) + 180(x_{52}) - d_7^+ + d_7^- = TC_5$$
$$900(x_{61}) + 600(x_{62}) - d_8^+ + d_8^- = TC_6$$
$$2,000(x_{71}) + 1,000(x_{72}) - d_9^+ + d_9^- = TC_7$$
$$500(x_{81}) + 325(x_{82}) - d_{10}^+ + d_{10}^- = TC_8$$
$$900(x_{91}) + 700(x_{92}) + 600(x_{93}) - d_{11}^+ + d_{11}^- = TC_9$$

Table 6 Costs of various parts of the refrigerator corresponding to different levels

Principal parts characteristics	Costs of the parts for three levels					
	Level I	Cost (Rs.)	Level II	Cost (Rs.)	Level III	Cost (Rs.)
PC1: Hermetic compressor (HC)	1/3 hp	2,800	1/6 hp	2,350	1/8 hp	2,000
PC2: Wire-on-tube condenser (WTC)	3/8 in. dia., 30 ft length	700	1/4 in. dia., 20 ft length	500	1/4 in. dia., 12 ft length	450
PC3: Roll-bond evaporator (RBE)	550 × 2,000 mm 1.8 mm thick plate (Aluminum)	1,500	400 × 1,500 mm 1.6 mm thick plate (Aluminum)	1,200	300 × 1,000 mm 1.2 mm thick plate (Aluminum)	1,000
PC4: Capillary tube (CT)	0.036 in.dia., 14.6 ft length	66	0.036 in.dia., 13.6 ft length	62	0.030 in.dia., 10.6 ft length	48
PC5: Overload protector with PTC relay (OLPPTCR)	Open type	250	Box type	180	–	–
PC6: Leak-proof refrigerator cabinet (LRC)	PUF insulation make	900	Glass wool insulation make	600	–	–
PC7: Automatic defrost mechanism (ADM)	Electronic sensors type	2,000	Manual type	1,000	–	–
PC8: Thermostat control (TC)	Electronic sensors type	500	Mechanical type	325	–	–
PC9: Multi-purpose compartment (MPC)	Large size	900	Medium size	700	Small size	600

$$x_{11} + x_{12} + x_{13} = 1$$
$$x_{21} + x_{22} + x_{23} = 1$$
$$x_{31} + x_{32} + x_{33} = 1$$
$$x_{41} + x_{42} + x_{43} = 1$$
$$x_{51} + x_{52} = 1$$
$$x_{61} + x_{62} = 1$$
$$x_{71} + x_{72} = 1$$
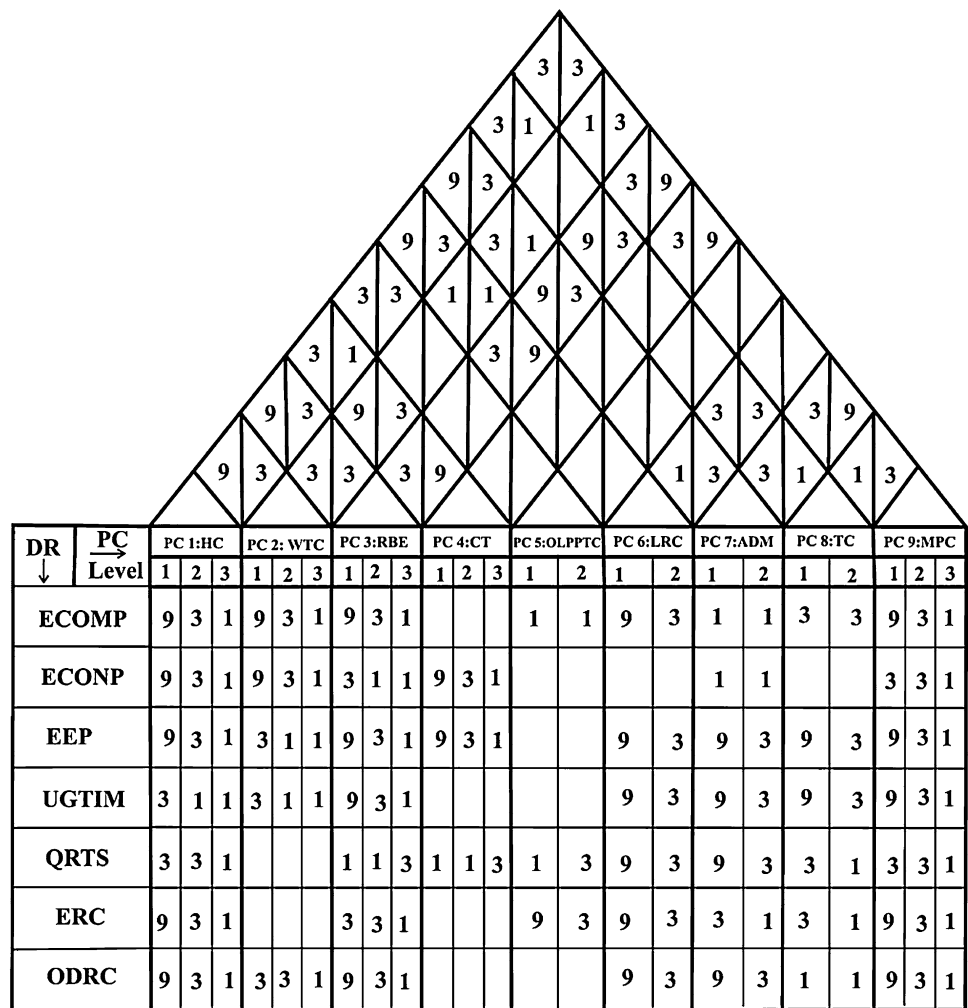$$x_{81} + x_{82} = 1$$
$$x_{91} + x_{92} + x_{93} = 1$$

$$Y_i = \sum_{j=1}^{j=n} \sum_{l=1}^{l_j} r_{ijl}(x_{jl}) + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} \sum_{l=1}^{l_j} \sum_{u=1}^{l_k} R_{ijk}(x_{jl})(x_{ku})$$

Results and discussion

Mathematical model discussed in the previous section is solved using LINGO 8.0 solver and the results are shown in Table 7. The comparison of the results for single-objective optimization and multi-objective optimization approaches is presented in this table. Maximum customer satisfaction and minimum total cost of the product are the objectives considered in case (1) and case (2), respectively, under single-objective approach. In case (3), both these objectives are considered simultaneously under multi-objective approach. The case (1) yields customer satisfaction index as 27,579 and the total cost of the refrigerator is Rs. 9,616. The customer satisfaction index and total cost are reduced to 13,329 and Rs. 6,203, respectively, in case (2). But a customer is expected to purchase a product at minimum cost and to get more satisfaction from the product simultaneously. Therefore, the design team has to concentrate on trade-off the objectives. Goal programming technique is employed in case (3) to attain both the objectives. In this case, the customer satisfaction index and the cost of the refrigerator are 23,642 and Rs. 6,917, respectively. From the Table 7, as compared to the case (1), the case (3) yields 28.06 % of cost reduction in consequent to a decrease of 14.27 % of customer satisfaction. In comparison with case (2), the customer satisfaction is drastically increased by 77.37 % in the case (3) for the increase of 11.5 % of the cost of the refrigerator.

Therefore, the refrigerator is manufactured by assembling the principle parts such as hermetic compressor, wire-on-tube condenser, roll-bond evaporator, capillary tube, overload protector with relay, refrigerator cabinet, automatic defrost mechanism, and thermostat control and multi-purpose compartment should be selected in level II to achieve both the objectives simultaneously.

Fig. 2 Part planning matrix of QFD

DR \ PC Level	PC 1:HC 1	2	3	PC 2: WTC 1	2	3	PC 3:RBE 1	2	3	PC 4:CT 1	2	3	PC 5:OLPPTC 1	2	PC 6:LRC 1	2	PC 7:ADM 1	2	PC 8:TC 1	2	PC 9:MPC 1	2	3
ECOMP	9	3	1	9	3	1	9	3	1				1	1	9	3	1	1	3	3	9	3	1
ECONP	9	3	1	9	3	1	3	1	1	9	3	1					1	1			3	3	1
EEP	9	3	1	3	1	1	9	3	1	9	3	1			9	3	9	3	9	3	9	3	1
UGTIM	3	1	1	3	1	1	9	3							9	3	9	3	9	3	9	3	1
QRTS	3	3	1				1	1	3	1	1	3	1	3	9	3	9	3	3	1	3	3	1
ERC	9	3	1				3	3	1				9	3	9	3	3	1	3	1	9	3	1
ODRC	9	3	1	3	3	1	9	3	1						9	3	9	3	1	1	9	3	1

Table 7 Comparison of single-objective and multi-objective approaches

Objectives	Single-objective approach		Multi-objective approach
	Case (1)	Case (2)	Case (3)
Customer satisfaction index	27,579	13,329	23,642
Total cost	Rs. 9,616	Rs. 6,203	Rs. 6,917
Decision variables (x_{jl})	$x_{11}=1,\ x_{12}=0,\ x_{13}=0$ $x_{21}=1, x_{22}=0, x_{23}=0$ $x_{31}=1, x_{32}=0, x_{33}=0$ $x_{41}=1, x_{42}=0, x_{43}=0$ $x_{51}=1, x_{52}=0, x_{53}=0$ $x_{61}=1, x_{62}=0, x_{63}=0$ $x_{71}=1, x_{72}=0, x_{73}=0$ $x_{81}=1, x_{82}=0, x_{83}=0$ $x_{91}=1, x_{92}=0, x_{93}=0$	$x_{11}=0,\ x_{12}=0,\ x_{13}=1$ $x_{21}=0, x_{22}=0, x_{23}=1$ $x_{31}=0, x_{32}=0, x_{33}=1$ $x_{41}=0, x_{42}=0, x_{43}=1$ $x_{51}=0, x_{52}=1, x_{53}=0$ $x_{61}=0, x_{62}=1, x_{63}=0$ $x_{71}=0, x_{72}=1, x_{73}=0$ $x_{81}=0, x_{82}=1, x_{83}=0$ $x_{91}=0, x_{92}=0, x_{93}=1$	$x_{11}=0,\ x_{12}=1,\ x_{13}=0$ $x_{21}=0, x_{22}=1, x_{23}=0$ $x_{31}=0, x_{32}=1, x_{33}=0$ $x_{41}=0, x_{42}=1, x_{43}=0$ $x_{51}=0, x_{52}=1, x_{53}=0$ $x_{61}=0, x_{62}=1, x_{63}=0$ $x_{71}=0, x_{72}=1, x_{73}=0$ $x_{81}=0, x_{82}=1, x_{83}=0$ $x_{91}=0, x_{92}=1, x_{93}=0$

Managerial implications of the study

From the management perspective, the research paves the way for the managers to develop a product with trade-off between customer satisfaction and total cost of the product. The methodology proposed in this paper can be utilized to make critical managerial decisions such as the selection of the parts characteristics of a product in accordance with the customer needs,

estimation of the target cost of each part and categorization of the parts into different levels. Furthermore, it is possible for the managers to take effective decision on selection of suppliers for the parts in the product design stage itself.

Conclusions

The proposed multi-objective optimization frame work improves product development and intends to balance customer satisfaction, cost and functionality of the product. In the QFD process, the actual product design is carried in the second phase. Therefore, part planning matrix is considered in the model with a view to consider the parts characteristics in accordance with the customer views. Target costing is a cost management tool that can be used at design level for cost determination and management. The target costing along with value engineering is appropriate to control and manage the cost of the product during the conceptual design stage. The multi-objective approach adopted in the proposed methodology guides the team to ensure a product with minimum cost and give more satisfaction to the customer. Goal programming is a simple and well-known method for solving multi-objective models. In this work, GP model is formulated to achieve the objectives of maximizing customer satisfaction and minimizing cost. The proposed model can also be used in process industries by considering the third phase (process planning matrix) of QFD.

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