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Integration of ECQFD, TRIZ, and AHP for innovative and sustainable product development

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ABSTRACT

Automotive organizations need to adopt sustainability principles to survive in a competitive environment. The rapidly changing marketplace also means that organizations need to include innovation in product development. We propose a model that integrates environmentally conscious quality function deployment (ECQFD), the theory of inventive problem-solving (TRIZ), and an analytical hierarchy process (AHP) for innovative and sustainable product development of automotive components. The voice of the customer (VOC) was captured and translated to engineering characteristics using ECQFD. Design options were identified using ECQFD and correlated with TRIZ to identify innovative design alternatives. Selection of the best design alternatives under many criteria is a typical multicriteria decision-making problem. We used AHP to identify the best design in terms of innovation and sustainability. These design changes were then incorporated in the component. A case study involving design of an automotive component demonstrates the applicability of our approach.

1. Introduction

Design development for technology plays a crucial role in modern economic growth. Design researchers and practitioners made advances in sustainable design by developing methodologies and tools to examine the economic and environmental impacts of the total life-cycle of a product. In design, capture of customer requirements for translation to engineering characteristics is a vital process. Environmentally conscious quality function deployment (ECQFD) is used to include innovation and environmental features in the product development process and consists of four phases. Phases I and II involve identifying potential improvements in terms of the environment and innovation. In phases III and IV, possible design improvements for components are considered and the improvement rate and effect of design changes are determined [1]. Trade-offs among conflicting performance parameters are often considered in mechanical design, a process that emerged in Russia denoted by the acronym TRIZ (theory of inventive problem-solving) [2]. The approach used in TRIZ methodology is shown in Fig. 1. TRIZ involves contradictions, 40 inventive principles, a contradiction matrix [3], the ideal final result [4], scientific effects [5], ARIZ (Russian acronym for algorithm of inventive problem-solving) [6], substance-field analysis modeling, and the laws of evolution [7]. The tool we use here is a contradiction matrix comprising 40 principles and 39 parameters. Contradiction involves the simultaneous existence of a worsening engineering parameter (avoiding degradation parameter, ADP) and an improving parameter (IP). Finally, an appropriate inventive principle is selected for innovative design of a product. Analytical hierarchy process (AHP) is one of the most commonly used methods for selection of alternatives. Our study was conducted in an Indian automotive organization to identify the best design for a selected

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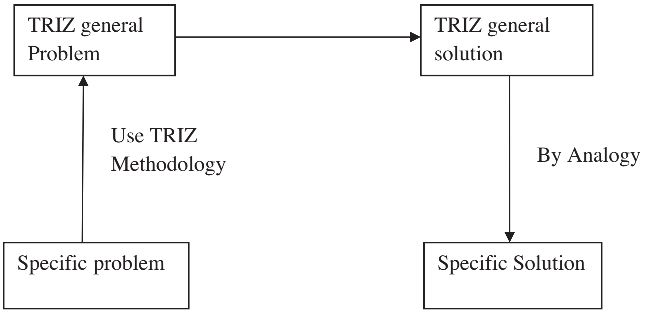


Fig. 1. Approach for the TRIZ methodology.

product. The study novelty is the proposal of an integrated ECQFD–TRIZ–AHP approach for sustainable and innovative product design.

2. Literature review

We reviewed the literature on applying QFD, TRIZ, and AHP for sustainable product design.

2.1. Sustainable product design using QFD

Kaebernick et al. described some of the tools for individual stages in the sustainable product development process [8]. They discussed four methodologies and decision tools for the most important sources of environmental impacts of a product: ECQFD, a sustainable trade-off model for design, life cycle assessment (LCA), and end-of-life options (EOL). A case study demonstrated that implementation of the new paradigm led to new market opportunities for a company.

Kuo et al. developed an eco-QFD approach that considers environmental concerns for product design [9]. To reduce vagueness and uncertainty in group decision-making, a fuzzy group method was applied to eco-QFD in product development planning. They obtained an optimal balance between environmental acceptability and overall customer satisfaction using an interactive approach and illustrated the application of the proposed model with a case study.

Liu developed a product design and selection (PDS) approach by integrating fuzzy QFD and a prototype product selection model [10]. In fuzzy QFD, a fuzzy set is calculated for each component by considering competitive analysis and correlations among engineering characteristics. Engineering characteristics and the factors involved in product development were considered for prototype selection. To select the best prototype, a fuzzy multi-criteria decision making (MCDM) approach was proposed. The research steps for the proposed PDS method were illustrated for a case study.

Vinod and Rathod focused on application of ECQFD [11]. The first two ECQFD phases involve improving environmental sustainability and the last two phases are used to formulate design options with regard to environmental improvements. ECQFD can be applied in early product design and development stages to ensure sustainability. Design options were generated for an electric vehicle using ECQFD to develop an environmentally sustainable product.

Vinod and Rathod also developed a sustainable product development model that integrates ECQFD and LCA approaches [1]. Data and outcomes from a study of a manufacturing organization confirmed that this methodology for sustainable product design is feasible. The organization reported that integration of ECQFD and LCA facilitated improvements in its sustainability.

2.2. TRIZ applications

D'Anna and Cascini proposed a sustainability map as a tool to overcome problems during the first phases of design [12]. This tool is based on two key items of TRIZ: laws describing the evolution of engineering systems; and a system operator. They conducted a case study in the garment cleaning industry. This new approach moves a designer systematically in different directions.

Li combined TRIZ and AHP for the design of automated manufacturing systems [7]. TRIZ was applied to propose innovative automated design alternatives and the best feasible alternative was selected under multiple criteria using AHP. A case study involving the design of an automated connector for an assembly line demonstrated the application of the proposed approach.

Stratton and Mann integrated two parallel but independent theories on inventive problem-solving: TRIZ and the theory of constraints (TOC) [13]. The common principle underlying these approaches is systematic innovation. The authors concluded that traditional thinking on manufacturing strategies could be enhanced by embedding systematic innovation concepts in TRIZ and TOC and they used an evaporating clouds diagram for practical integration.

Butdee and Vignat analyzed methods for compensating thermal deformations using TRIZ tools (principles, contradictions, substance field analysis, development trends) [14]. The authors applied TRIZ principles and parameters to the design of a lightweight bus body and compared this to the existing design. The bus body model was created using CAD and data were transferred to CAE using finite element (FE) analysis. FE analysis results for the new lightweight design were acceptable and suitable for design and manufacture.

Kobayashi proposed an innovative eco-design methodology based on a life-cycle planning framework [15]. TRIZ was used to generate an idea, evaluate the design uncertainty, and propose an eco-efficiency indicator for the product. The effectiveness of the methodology was demonstrated for an actual refrigerator.

2.3. AHP applications

Yavuz et al. selected the optimum design for the support for the main transport road for a Turkish mine using AHP [16]. They considered eight main objectives for selection: four different displacement values for historical locations; a safety factor; costs; labor; and an applicability factor. After applying several numerical models for different designs, the AHP method was incorporated to evaluate these designs according to pre-determined criteria. The results showed that AHP helped engineers in evaluating system alternatives for an underground mine.

Lo and Wen proposed a fuzzy-AHP-based technique for selecting the best design for a massively multiplayer online role-playing game (MMORPG) [17]. They included two systems, nine design components, and 36 design features in a survey of 221 Taiwanese MMORPG players. The top 10 important design features and specific design guidelines for MMORPG implementation were identified.

Lin et al. developed a framework that integrated AHP and a technique for order preference by similarity to ideal solution (TOPSIS) [18]. They applied AHP to evaluate the relative overall importance of customer requirements and design characteristics, and TOPSIS was used to perform competitive benchmarking. The performance of the proposed approach was illustrated and validated using a personal digital assistant as a design example. The results showed that the proposed approach is capable of identifying key design objectives and optimal conceptual alternatives.

Duran and Aguilo proposed a model for evaluation and justification of an advanced manufacturing system using an AHP based on a fuzzy number multi-attribute method [19]. A case study was conducted on machine tool selection to illustrate and validate the proposed approach.

Hambali et al. proposed a model that concurrently selects a design concept and materials for composite automotive components at the conceptual design stage using AHP [20]. The model was explained by considering eight design concepts for a composite automotive bumper beam and the most appropriate design was selected using AHP. Sensitivity analysis was performed to observe the effect of different factors in selecting the best decision option.

2.4. Research gap

Although ECQFD, TRIZ, and AHP have been used individually by various researchers for certain purposes, these approaches have not been integrated for sustainable and innovative product design. To fill this research gap, we carried out a study on innovative product design.

3. Methodology

Here we propose an integrated ECQFD–TRIZ–AHP design approach for innovative and sustainable product development. The study methodology is shown in Fig. 2. We first reviewed the literature on ECQFD, TRIZ, and AHP for sustainable product design. We then identified and selected candidate automotive components. ECQFD was used to include the voice of the customer (VOC) and translate the ideas into design options. These design options were correlated in a contradiction matrix using TRIZ and design changes were incorporated in the component. Finally, the best design was selected using AHP.

4. Case study

We carried out a case study for an automotive parts company located in Bangalore, India, that manufactures an overflow valve. The valve consists of a spring, a locating cap, a mounting nut, an outlet valve, a washer, a rubber O ring, and a knob. The spring maintains and withstands fluid pressure up to 6 bar. The locating cap allows no oil to flow through the valve when the fluid pressure is less than a specified threshold that depends on process requirements. When the fluid pressure in the inlet exceeds the specified pressure, the spring pushes up the locating cap and fluid can then flow through the valve. The mounting nut holds the locating cap and supports the outlet valve. The outlet valve allows fluid flow and breakage of the knob under the worst condition (>6 bar). The washer allows fluid to flow through the hole. The rubber O ring helps to hold the washer and mounting nut in position. The knob holds the other end of the spring; it breaks at >6 bar and stops the flow in the outlet valve. The aim of the case study was to find the possible design options using ECQFD, improve the design using TRIZ, and select the best design using AHP.

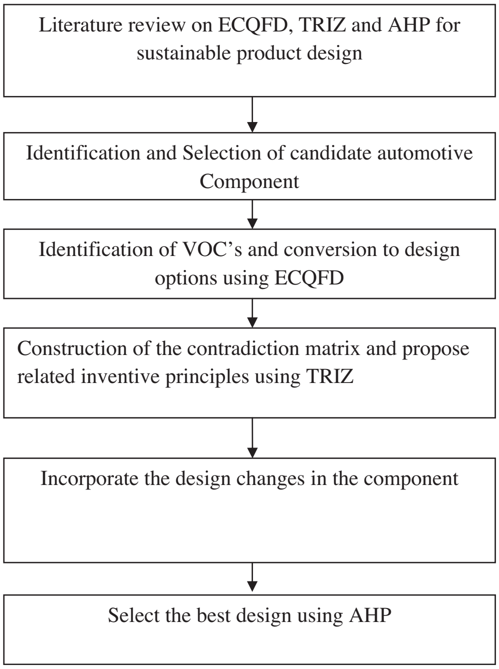


Fig. 2. Flow chart of the methodology.

4.1. ECQFD

This section describes various steps involved in ECQFD.

4.1.1. Identification of environmental VOCs and engineering metrics

The requirements and attributes that should be considered from environmental and innovation perspectives throughout the life cycle of the product were identified and integrated in a set of feasible VOCs and engineering metrics (EMs).

4.1.2. Environmental VOCs

Environmental VOCs include reliability of the overflow valve, durability, safe operation, ease of operation, serviceability, easy of disassembly during maintenance, cost effectiveness, and enhanced functionality.

4.1.3. Environmental EMs

Environmental EMs comprise technical and engineering characteristics of the overflow valve. These include increased physical lifetime, increased rate of recycled material, reduced defects, reduced weight, increased flow rate, increased strength, temperature, and reduced number of parts.

4.1.4. Identification of target for design improvement

In phase I, ECQFD is applied for design of the overflow valve. Table 1 lists EM weights for the VOC items. In general, VOC items are weighted according to a market survey to reveal customer weights. A weight of 5 is very important, 3 is important, and 1 is relatively important. The degree of importance of an environmental VOC depends on the concept of the product life cycle. The mapping numbers indicating a factor called relational strength. Similar to the weighting of VOC items, 5 indicates a strong relationship, 3 indicates a medium relationship, and 1 indicates a certain strength. Values for the relational strength between environmental VOC items and environmental EM items aid the designer in the decision-making process. The total sum multiplied by the customer weight and the relational strength is the raw score for each EM. The relative weight for each item is obtained as the raw score divided by the sum of the raw scores [1]. For example, EMs such as physical lifetime (0.167), strength (0.164), and number of parts (0.149) are relatively important for satisfying customer requirements of reliability, ease of disassembly, and safe operation.

Phase II ECQFD involves applying EMs to components of the product. The relative importance of each component is obtained in the same manner as in phase I. As shown in Table 2, the mounting nut, locating cap, and outlet valve were identified as important components.

Table 1
Phase I ECQFD for overflow valve assembly.

No.	Voice of the customer	Customer weight	Engineering metric							
			Physical lifetime	Rate of recycled material	Defects	Weight	Flow rate	Strength	Temperature	Number f parts
1	Reliability	5	5	1	5	3	3	5	3	5
2	Durability	3	5	1	3	5	3	5	3	3
3	Safe operation	5	5	1	3	3	3	5	3	3
4	Ease of operation	3	5	1	3	3	3	3	3	5
5	Serviceability	3	5	1	3	3	1	3	1	5
6	Ease of disassembly	5	3	3	3	5	3	5	1	5
7	Cost effectiveness	5	3	1	5	3	1	3	1	3
8	Enhanced functionality	5	5	3	5	5	3	5	1	3
Raw score			150	54	132	128	86	148	66	134
Relative weight			0.16704	0.0601336	0.146	0.142	0.09577	0.1648	0.073	0.149
Rank			8	1	5	4	3	7	2	6

Table 2
Phase II ECQFD for overflow valve assembly.

No.	Engineering metric	Phase I relative weight	Component						
			Outlet valve	Rubber O ring	Mounting nut	Spring	Washer	Locating cap	Knob
1	Physical lifetime	0.167038	5	5	3	3	5	3	5
2	Rate of recycled material	0.060134	1	3	1	5	5	5	5
3	Defects	0.146993	5	3	1	1	3	5	5
4	Weight	0.142539	1	5	1	3	5	1	3
5	Flow rate	0.095768	1	5	1	5	3	1	5
6	Strength	0.164811	5	5	1	5	1	1	5
7	Temperature	0.073497	3	5	1	5	3	3	1
8	Number of parts	0.14922	1	5	5	1	1	1	1
Raw score			3.06236	4.58575	1.930958	3.19599	3.11136	2.30958	3.82405
Phase II relative weight			0.13907	0.20825	0.087691	0.14514	0.1413	0.10489	0.17366
Rank			3	6	1	5	4	2	6

4.1.5. Evaluation of design improvements

ECQFD phases III and IV involve evaluating any design improvements [1]. In phase III, the effect of a set of design changes on EM items is estimated. Design engineers have two focus options. One is to consider a VOC target. The other is to examine the most important components identified in phase II.

The design options considering the phase I and II results include the following EM combinations.

Option 1:

- The physical lifetime and strength of the component should be high.
- The number of parts should be minimum.

Option 2:

- Defects should be reduced as much as possible.
- The weight of the component should be considerably reduced.
- An improved flow rate should be achieved.

Tables 3 and 4 list the phase III ECQFD data for options 1 and 2, respectively. The improvement rate for each EM item is calculated as [21]

$$\mathrm{mr}_j = \frac{\sum_{k=1}^{k}(b_{j,k}c_{j,k})}{\sum_{k=1}^{k}(b_{j,k})} \quad (j = 1,2,3,\ldots,j), \tag{1}$$

where k is the number of components, j is the EM index, $b_{j,k}$ is the relational strength between EM item j and component k, and $c_{j,k}$ is the improvement rate in EM item j for component k, which was originally allowed to take the real values from 0.0 to 1.0. For simplicity, we allow $c_{j,k}$ to take a value of 1 (improvement possible) or 0 (improvement impossible) [21].

Table 3
Phase III ECQFD for option 1.

Sl. No.	Engineering metric	Phase I relative weight	Component							Score	EM improvement rating
			Outlet valve	Rubber O ring	Mounting nut	Spring	Washer	Locating cap	Knob		
1	Physical lifetime	0.16704	5	5	3	3	5	3	5	29	5.8441
2	Rate of recycled material	0.06013	0	0	0	0	0	0	0	0	0.0000
3	Biodegradability	0.14699	0	0	0	0	0	0	0	0	0.0000
4	Weight	0.14254	0	0	0	0	0	0	0	0	0.0000
5	Flow rate	0.09577	0	0	0	0	0	0	0	0	0.0000
6	Strength	0.16481	5	5	1	5	1	1	5	23	4.7906
7	Temperature	0.0735	0	0	0	0	0	0	0	0	0.0000
8	Number of parts	0.14922	1	5	5	1	1	1	1	15	3.2383

Table 4
Phase III ECQFD for option 2.

No.	Engineering metric	Phase I relative weight	Component							Score	EM improvement rating
			Outlet valve	Rubber O ring	Mounting nut	Spring	Washer	Locating cap	Knob		
1	Physical lifetime	0.16704	0	0	0	0	0	0	0	0	0.0000
2	Rate of recycled material	0.06013	0	0	0	0	0	0	0	0	0.0000
3	Defects	0.14699	5	3	1	1	3	5	5	23	4.3808
4	Weight	0.14254	1	5	1	3	5	1	3	19	3.7082
5	Flow rate	0.09577	1	5	1	5	3	1	5	21	3.0111
6	Strength	0.16481	0	0	0	0	0	0	0	0	0.0000
7	Temperature	0.0735	3	5	1	5	3	3	1	21	2.5434
8	Number of parts	0.14922	0	0	0	0	0	0	0	0	0.0000

Table 5
Phase IV ECQFD for option 1.

No.	Voice of the customer	Customer weight	Engineering metric								CR improvement rate	CR improvement effect
			Physical lifetime	Rate of recycled material	Defects	Weight	Flow rate	Strength	Temperature	Numberof parts		
1	Reliability	5	5	1	5	3	3	5	3	5	0.4624	2.3122
2	Durability	3	5	1	3	5	3	5	3	3	0.7487	2.2460
3	Safe operation	5	5	1	3	3	3	5	3	3	0.4838	2.4188
4	Ease of operation	3	5	1	3	3	3	3	3	5	0.7665	2.2994
5	Serviceability	3	5	1	3	3	1	3	1	5	0.9058	2.7175
6	Ease of disassembly	5	3	3	3	5	3	5	1	5	0.4120	2.0599
7	Cost effectiveness	5	3	1	5	3	1	3	1	3	0.4162	2.0810
8	Enhanced functionality	5	5	3	5	5	3	5	1	3	0.4193	2.0963
EM improvement rate			5.844098	0	0	0	0	4.7906459	0	3.2383073	4.6146	18.2310

The objective of phase IV ECQFD is to translate the effect of design changes on EM into customer requirements. Tables 5 and 6 list the phase IV ECQFD data for options 1 and 2, respectively. The EM improvement rate obtained in phase III is shown at the bottom of the tables. The improvement rate for each VOC is calculated as [21]

$$\mathrm{vr}_i = \frac{\sum_{j=2}^{j}(\mathrm{mr}_j a_{i,j})}{\sum_{j=2}^{j}(a_{i,j})} \quad (i = 1, 2, 3, \ldots, I), \tag{2}$$

where i is the VOC index and $a_{i,j}$ is the relational strength between VOC item i and EM item j. The improvement effect for a VOC considering the customer weight is obtained by multiplying vr_i and customer weight i.

Table 6
Phase IV ECQFD for option 2.

No.	Voice of the customer	Customer weight	Engineering metric								CR improvement rate	CR improvement effect
			Physical lifetime	Rate of recycled material	Bio-degradability	Weight	Flow rate	Strength	Temperature	Number of parts		
1	Reliability	5	5	1	5	3	3	5	3	5	0.3313	1.6564
2	Durability	3	5	1	3	5	3	5	3	3	0.5756	1.7267
3	Safe operation	5	5	1	3	3	3	5	3	3	0.3149	1.5743
4	Ease of operation	3	5	1	3	3	3	3	3	5	0.5248	1.5743
5	Serviceability	3	5	1	3	3	1	3	1	5	0.4518	1.3555
6	Ease of disassembly	5	3	3	3	5	3	5	1	5	0.3090	1.5450
7	Cost effectiveness	5	3	1	5	3	1	3	1	3	0.3858	1.9292
8	Enhanced functionality	5	5	3	5	5	3	5	1	3	0.2232	1.1160
EM improvement rate			0	0	4.3808463	3.7082405	3.0111359	0	2.543429844	0	3.1164	12.4774

4.1.6. Evaluation of design for environmental options

The improvement effect for VOCs with their weights was calculated for each design from an environmental perspective through phases III and IV. Scores of 18.231 and 12.477 were obtained for options 1 and 2, respectively, so option 1 is better.

4.2. TRIZ

Improvement aspects to be incorporated in the design as identified by ECQFD are as follows

- The physical lifetime and strength of the component should be high.
- The number of parts should be minimum.
- Defects should be reduced as much as possible.
- The weight of the component should be considerably reduced.
- The flow rate should be improved.

The first objective was to determine contradictions for the problem and match them with appropriate parameters from the 39 engineering parameters defined in the matrix [4]. A brainstorming session identified the following major contradictions in the system, where # denotes the TRIZ engineering parameter number:

- *Contradiction 1*: Improving the strength (#14) and reliability (#27) does not increase the complexity of control (#37).
- *Contradiction 2*: Improving the manufacturability (#32) does not negatively affect the ease of operation (#34) and repairability (#34).

  Improving the adaptability (#35) does not negatively affect the level of automation (#38).
- *Contradiction 3*: Improving time wasting (#25) negatively affects manufacturability (#32), adaptability (#35), and the complexity of the device (#36).

  Improving the ease of operation (#33) negatively affects the stability of the object (#13), manufacturability (#32), and the complexity of the device (#36).
- *Contradiction 4*: Improving the weight of the moving object (#1) negatively affects the length of the moving object (#3) and shape (#12).
- *Contradiction 5*: Improving the force (#10) negatively affects the shape (#12), strength (#14), and measurement accuracy (#28).

  Improving the temperature (#17) negatively affects the pressure (#11) and complexity of control (#37).

Feasible solutions for the contradictions matrix are shown in Table 7.

For design option 1, the existing material for the overflow valve is steel with CR3 plating. The product could be manufactured using polypropylene according to requirements. Lifetime estimation analysis conducted using ANSYS software revealed that the component is safe up to 100,000 cycles of operation.

For design option 2, to reduce the number of parts, the outlet valve and washer could be unified in the design, as shown in Fig. 3.

For design option 3, to avoid knob breakage under the worst conditions, the knob and locating cap were given provisions to hold the spring, as shown in Fig. 4. This enhances the reusability of the product.

Table 7
Contradictions and related inventive principles.

Decision	Improving parameter	Worsening parameter	Related inventive principles
D1	#14 Strength	#37 Complexity of control	#27 – Service life – not applicable #3 – Local quality – not applicable #15 – Variability or dynamicism – not applicable #40 – Composite materials – a suitable material is selected to reduce the environmental impact
	#27 Reliability	#37 Complexity of control	#27 – Service life – not applicable #28 – Mechanics substitution – not applicable #40 – Composite materials – a suitable material is selected to reduce the environmental impact
D2	#32 Manufacturability	#33 Ease of operation	#2 – Takeout – not valid applicable #5 – Merging – design unification for the washer and outlet valve #13 – Other way round – not applicable #16 – Partial or excessive action – not applicable
		#34 Repairability	#35 – Change physical or chemical parameter – design unification for the washer and outlet valve #1 – Segmentation – not applicable #11 – Beforehand cushioning – not applicable #9 – Preliminary anti-action – not applicable
	#35 Adaptability	#38 Level of automation	#27 – Service life – not applicable #34 – Discard and recover – not applicable #35 – Change physical or chemical parameter – design unification for the washer and outlet valve
D3	#25 Waste of time	#32 Manufacturability	#35 – Change physical or chemical parameter – foolproof design for locating cap #28 – Mechanics substitution – not applicable #34 – Discard and recover – not applicable #4 – Asymmetry – not applicable
		#35 Adaptability	#35 – Change physical or chemical parameter – foolproof design for locating cap #28 – Mechanics substitution – not applicable
		#36 Complexity of device	#6 – Universality – foolproof design for locating cap #29 – Pneumatic or hydraulic construction – not applicable
	#33 Ease of operation	#13 Stability of object	#2 – Take out – not applicable #35 – Change physical or chemical parameter – simplify the shape of the locating cap
		#32 Manufacturability	#1 – Segmentation – not applicable #35 – Change physical or chemical parameter – simplify the shape of the locating cap #11 – Beforehand cushioning – not applicable #10 – Preliminary action – not applicable
		#36 Complexity of device	#35 – Change physical or chemical parameter – simplify the shape of the locating cap #1 – Segmentation – not applicable #13 – Other way round – not applicable #11 – Beforehand cushioning – not applicable
D4	#1 Weight of moving object	#3 Length of moving object	#8 – Anti-weight – reduce the mounting nut and outlet valve thickness by changing the material #15 – Dynamics – not applicable #29 – Pneumatic or hydraulic construction – not applicable #34 – Discard and recover – not applicable
		#12 Shape	#10 – Preliminary action – not applicable #14 – Spheroidality – not applicable #35 – Change physical or chemical parameter – reduce the mounting nut and outlet valve thickness by changing the material #40 – Composite materials
D5	#10 Force	#12 Shape	#10 – Preliminary action – not applicable #35 – Change physical or chemical parameter – change the pressure to check whether the

(*continued on next page*)

Table 7 (*continued*)

Decision	Improving parameter	Worsening parameter	Related inventive principles
			valve withstands pressure using flow analysis #40 – Composite materials #34 – Discard and recover – not applicable
		#14 Strength	#35 – Change physical or chemical parameter – change the pressure to check whether the valve withstands pressure using flow analysis #10 – Preliminary action – not applicable #14 – Spheroidality – not applicable #27 – Service life – not applicable
		#28 Accuracy of measurement	#35 – Change physical or chemical parameter – change the pressure to check whether the valve withstands pressure using flow analysis #10 – Preliminary action – not applicable #23 – Feedback – not applicable #24 – Intermediary – not applicable
	#17 Temperature	#11 Tension, pressure	#35 – Change physical or chemical parameter – change the pressure to check whether the valve withstands pressure using flow analysis #39 – Inert atmosphere – not applicable #19 – Periodic action – not applicable #2 – Take out – not applicable
		#37 Complexity of control	#3 – Local quality – not applicable #27 – Service life – not applicable #35 – Change physical or chemical parameter – change the pressure to check whether the valve withstands pressure using flow analysis #31 – Porous material – not applicable

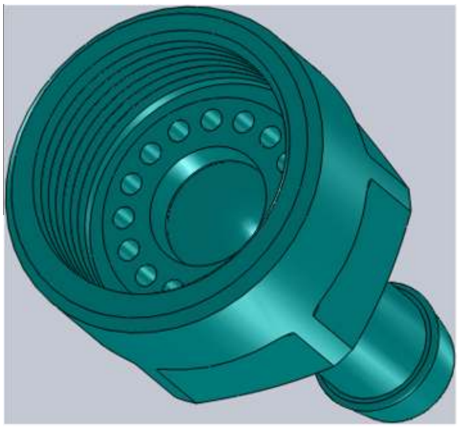


Fig. 3. Innovative design for option 2.

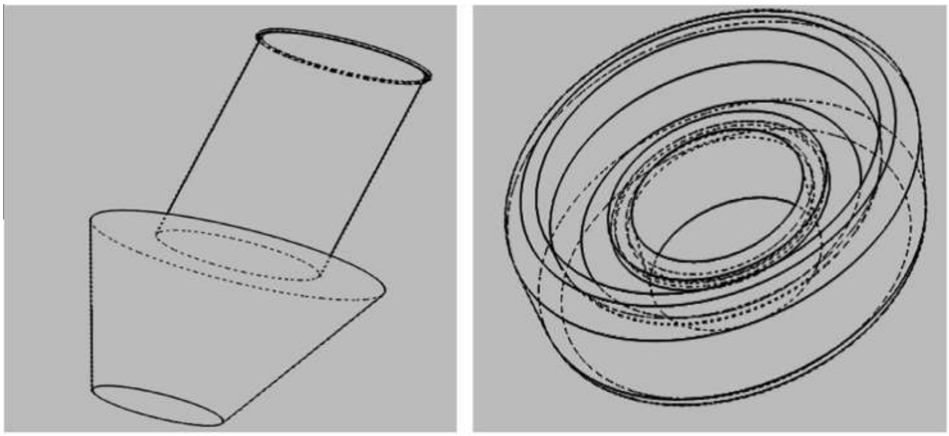


Fig. 4. Innovative design for option 3.

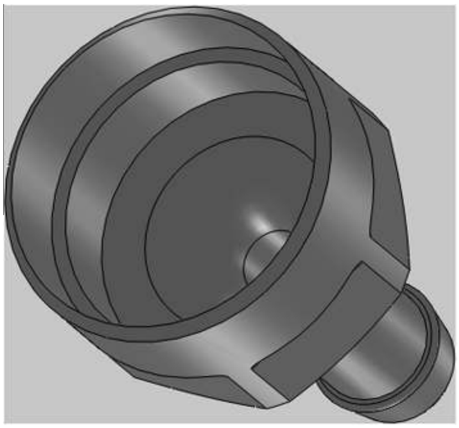
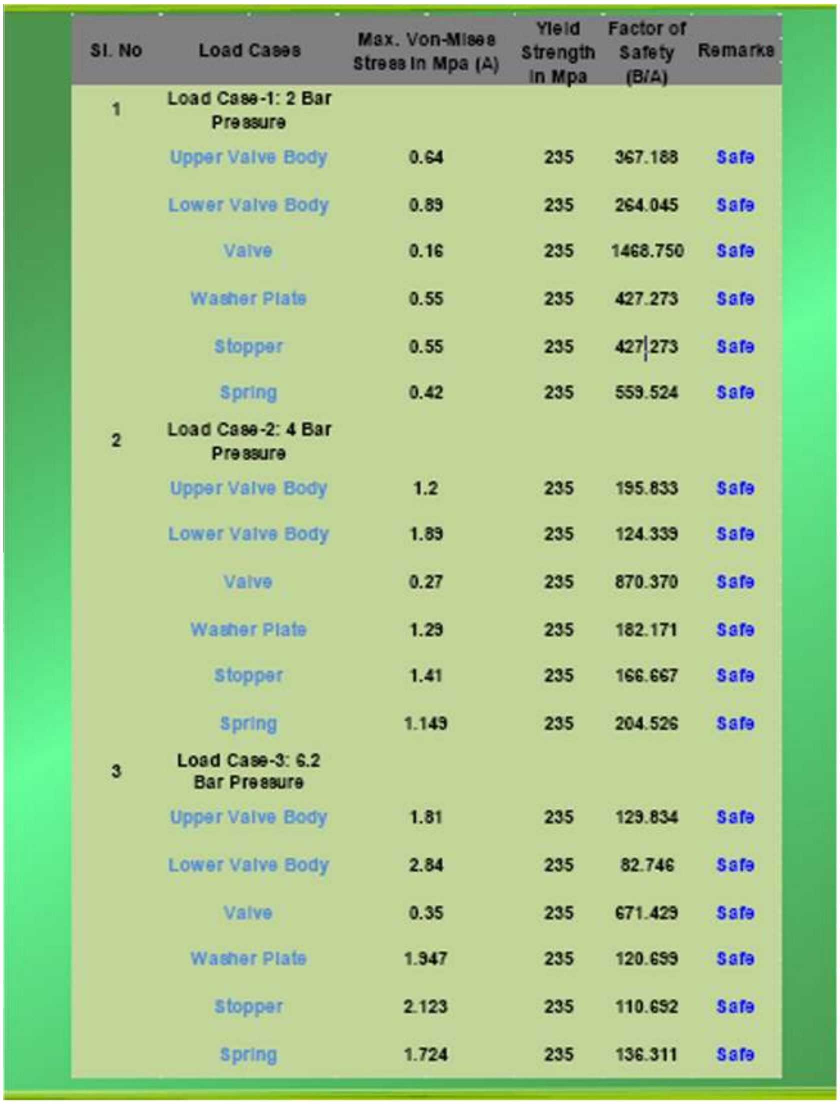


Fig. 5. Innovative design for option 5.



Sl. No	Load Cases	Max. Von-Mises Stress In Mpa (A)	Yield Strength In Mpa	Factor of Safety (B/A)	Remarks
1	Load Case-1: 2 Bar Pressure				
	Upper Valve Body	0.64	235	367.188	Safe
	Lower Valve Body	0.89	235	264.045	Safe
	Valve	0.16	235	1468.750	Safe
	Washer Plate	0.55	235	427.273	Safe
	Stopper	0.55	235	427.273	Safe
	Spring	0.42	235	559.524	Safe
2	Load Case-2: 4 Bar Pressure				
	Upper Valve Body	1.2	235	195.833	Safe
	Lower Valve Body	1.89	235	124.339	Safe
	Valve	0.27	235	870.370	Safe
	Washer Plate	1.29	235	182.171	Safe
	Stopper	1.41	235	166.667	Safe
	Spring	1.149	235	204.526	Safe
3	Load Case-3: 6.2 Bar Pressure				
	Upper Valve Body	1.81	235	129.834	Safe
	Lower Valve Body	2.84	235	82.746	Safe
	Valve	0.35	235	671.429	Safe
	Washer Plate	1.947	235	120.699	Safe
	Stopper	2.123	235	110.692	Safe
	Spring	1.724	235	136.311	Safe

Fig. 6. Summary of the static analysis results.

For design option 4, the weight of the locating cap and outlet valve was reduced by minimizing the thickness without affecting the other flow parameters, as shown in Fig. 5. Reducing the weight in turn reduces the manufacturing costs and improves the EOL disposal characteristics, making the product more environmentally sustainable.

For design option 5, uniform pressure was applied to the inner cavity walls to simulate the worst case conditions. Static pressure analysis was carried out for fluid pressure of 2, 4, and 6 bar using ANSYS software. The results are shown in Fig. 6. The maximum stress observed was 0.89, 1.89, and 2.84 MPa for fluid pressure of 2, 4, and 6 bar, respectively. These stresses are much lower than the yield strength of 235 MPa. Hence, the design is considered safe.

4.3. AHP

Selection of the best design according to various criteria is an MCDM problem. AHP was used to find the best design. The hierarchical structure used is shown in Fig. 7.The selection criteria were product lifespan (C1), innovativeness (C2), carbon footprint (C3), market attractiveness (C4), EOL disposal (C5), technological capability (C6), weight (C7), and profitability (C8). In AHP, decision-makers express their preferences for pairwise comparisons use a scale of 1–9. The scale is shown in Table 8.

The next step involves collection of expert opinions using a comparison scale of 1–9. The pairwise comparisons matrix is shown in Table 9. The criteria were prioritized and the criteria weights were calculated. The geometric mean for each cell and the eigenvalue $\lambda_{\max} = 8.953$ were calculated for the comparison matrix. The matrix dimension is $n = 8$ and the random index is RI $(n) = 1.410$. The consistency index (CI) and consistency ratio (CR) for the matrix were calculated according to [7]

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

and

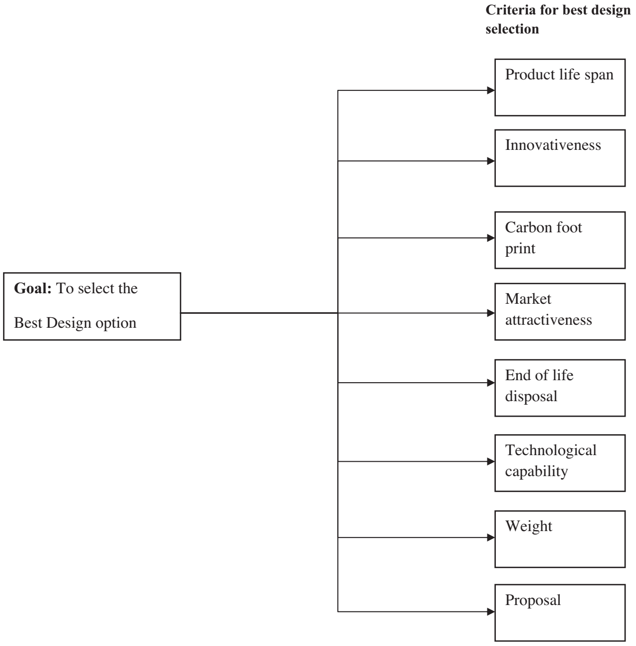


Fig. 7. Hierarchy for selection of the best design using AHP.

Table 8
Pairwise comparison judgment.

Score	Importance
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2, 4, 6, 8	Intermediate values
Reciprocals	Inverse comparison

Table 9
Pairwise comparison of criteria.

	Product lifespan	Innovativeness	Carbon footprint	Market attractiveness	End-of-life disposal	Technological capability	Weight	Profitability
Product lifespan	1.000	3.000	3.000	5.000	5.000	7.000	7.000	7.000
Innovativeness	0.333	1.000	3.000	3.000	5.000	5.000	5.000	7.000
Carbon	0.333	0.333	1.000	3.000	3.000	3.000	5.000	7.000
Market attractiveness	0.200	0.333	0.333	1.000	3.000	3.000	3.000	5.000
End-of-life disposal	0.200	0.200	0.333	0.333	1.000	3.000	3.000	5.000
Technological capability	0.143	0.200	0.333	0.333	0.333	1.000	3.000	3.000
Weight	0.143	0.200	0.200	0.333	0.333	0.333	1.000	3.000
Profitability	0.143	0.143	0.143	0.200	0.200	0.333	0.333	1.000

Table 10
Normalized matrix for all the criteria.

	Product lifespan	Innovativeness	Carbon footprint	Market attractiveness	End-of-life disposal	Technological capability	Weight	Profitability	Criterion weight
Product lifespan	0.401	0.555	0.360	0.379	0.280	0.309	0.256	0.184	0.340
Innovativeness	0.134	0.185	0.360	0.227	0.280	0.221	0.183	0.184	0.222
Carbon footprint	0.134	0.062	0.120	0.227	0.168	0.132	0.183	0.184	0.151
Market attractiveness	0.080	0.062	0.040	0.076	0.168	0.132	0.110	0.132	0.100
End-of-life disposal	0.080	0.037	0.040	0.025	0.056	0.132	0.110	0.132	0.076
Technological capability	0.057	0.037	0.040	0.025	0.019	0.044	0.110	0.079	0.051
Weight	0.057	0.037	0.024	0.025	0.019	0.015	0.037	0.079	0.037
Profitability	0.057	0.026	0.017	0.015	0.011	0.015	0.012	0.026	0.023
λ	0.994	1.075	1.094	1.084	1.174	1.090	1.135	1.307	8.953

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{4}$$

where RI is the random index table value. We calculated CI = 0.1361 and CR = 0.09 (Table 10). CR is <0.1, which confirms that judgment of the comparisons matrix was acceptable.

5. Results and discussion

ECQFD analysis generated useful information on the importance of product properties in meeting customer requirements. The design options considering the results from phases I and II include the following EM combinations. For option 1 the physical lifetime and strength of the component should be high and the number of parts should be minimum. For option 2 the defects should be reduced as much as possible, the component weight should be considerably reduced, and an improved flow rate should be achieved. The weight calculated was 18.231 and 12.477 for options 1 and 2, respectively, so option 1 is better. Conflicts among technical requirements were solved using TRIZ. For example, improving the weight of a moving object (#1) negatively affects the length of a moving object (#3) and shape (#12). Hence, the TRIZ solution from the contradiction matrix is: #10 (preliminary action), not applicable; #14 (spheroidality), not applicable; and #35 (change physical or chemical parameter), applicable for this case. Thus, the thickness of the mounting nut and the outlet valve weight can be reduced. Similar solutions can be identified from the contradiction matrix to identify design alternatives. AHP was used to find the best design alternative. The criteria were ranked as C1 > C2 > C3 > C4 > C5 > C6 > C7 > C8 (Fig. 8), with life-

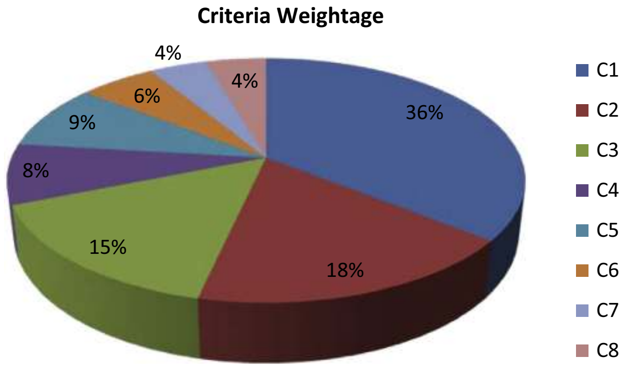


Fig. 8. Weightings for the criteria.

Table 11
Final ranking of design alternatives.

	C1	C2	C3	C4	C5	C6	C7	C8	Final alternative weight	Rank
D1	0.3967	0.44485	0.4013	0.4317	0.43817	0.43638	0.49273	0.43641	0.421	1
D2	0.33541	0.25882	0.28641	0.26865	0.20464	0.25389	0.25883	0.28122	0.287	2
D3	0.13429	0.16107	0.17213	0.17312	0.23413	0.18717	0.13163	0.15801	0.160	3
D4	0.08653	0.08761	0.10195	0.0894	0.08068	0.08035	0.06915	0.0776	0.087	4
D5	0.04707	0.04766	0.03822	0.03712	0.04238	0.04221	0.04766	0.04675	0.044	5
Criterion weight	0.357	0.177	0.153	0.080	0.086	0.057	0.043	0.045		

span (C1), innovativeness (C2), and carbon footprint (C3) the most important. The results for the weights and final aggregates are summarized in Table 11. According to the aggregate weights, the alternatives were ranked as D1 > D2 > D3 > D4 > D5. A suitable material change (D1) is considered the best design option, with a value of 0.421. This is followed by unification of the mounting nut and outlet valve (D2, 0.287), simplification of the locating cap shape (D3, 0.160), weight reduction for the mounting nut and outlet valve (D4, 0.087), and flow analysis (D5, 0.044). The design options were identified using ECQFD and validated using TRIZ via correlation with contradiction principles. The designs were evaluated using various AHP criteria and the best design was selected.

6. Conclusions

We developed a model that integrates ECQFD, TRIZ, and AHP. Design options were identified using ECQFD, which facilitates the design of environmentally sustainable products [10]. TRIZ was applied to manage trade-offs among conflicting performance parameters for design options identified by ECQFD. Five designs were feasible, so AHP was used to evaluate and identify the most suitable design in an MCDM approach. The study results indicate the practical feasibility of our integrated model, which includes a VOC translation mechanism, an innovative design tool, and an MCDM framework for innovative and sustainable product development.

References

[1] S. Vinodh, G. Rathod, Integration of ECQFD and LCA for sustainable product design, J. Clean. Prod. 18 (2010) 833–842.
[2] G. Altshuller, The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity, Technical Innovation Centre, Worcester, MA, 1999.
[3] Z. Zoyzen, Solving contradictions in development of new generation products using TRIZ, TRIZ J. 1997 (2) (1997) 2 (<http://www.triz-journal.com/archives/1997/02/b/>).
[4] E. Domb, The idea final result: tutorial, TRIZ J. 1997 (2) (1997) 1 (<http://www.triz-journal.com/archives/1997/02/a/>).
[5] G. Frenklach, Classifying the technical effects, TRIZ J. 1998 (1998) (<http://www.triz-journal.com/archives/1998/03/a/>).
[6] B. Zlotin, A. Zusman, ARIZ on the move. TRIZ J. 1998 (3) (1998) 5 (<http://www.triz-journal.com/archives/1999/03/e/>).
[7] T.S. Li, Applying TRIZ and AHP to develop innovative design for automated assembly systems, Int. J. Adv. Manuf. Technol. 46 (2010) 301–313.
[8] H. Kaebernick, S. Kara, M. Sun, Sustainable product development and manufacturing by considering environmental requirements, Rob. Comput. Integr. Manuf. 19 (2003) 461–468.
[9] T.-C. Kuo, H.-H. Wu, J.-I. Shieh, Integration of environmental considerations in quality function deployment by using fuzzy logic, Expert Syst. Appl. 36 (2009) 7148–7156.
[10] H.-T. Liu, Product design and selection using fuzzy QFD and fuzzy MCDM approaches, Appl. Math. Model. 35 (2011) 482–496.
[11] S. Vinodh, G. Rathod, Application of ECQFD for enabling environmentally conscious design and sustainable development in an electric vehicle, Clean Technol. Environ. Policy 13 (2011) 381–396.
[12] W. D'Anna, G. Cascini, Supporting sustainable innovation through TRIZ system thinking, Proc. Eng. 9 (2011) 145–156.
[13] R. Stratton, D. Mann, Systematic innovation and the underlying principles behind TRIZ and TOC, J. Mater. Process. Technol. 139 (2003) 120–126.
[14] S. Butdee, F. Vignat, TRIZ method for light weight bus body structure design, J. Achiev. Mater. Manuf. Eng. 31 (2008) 456–462.
[15] H. Kobayashi, A systematic approach to eco-innovative product design based on life cycle planning, Adv. Eng. Inf. 20 (2006) 113–125.
[16] M. Yavuz, M. Iphar, G. Once, The optimum support design selection by using AHP method for the main haulage road in WLC Tuncbilek colliery, Tunnel. Underground Space Technol. 23 (2008) 111–119.
[17] Y.-F. Lo, M.-H. Wen, A fuzzy-AHP-based technique for the decision of design feature selection in massively multiplayer online role-playing game development, Expert Syst. Appl. 37 (2010) 8685–8693.
[18] M.-C. Lin, C.-C. Wang, M.-S. Chen, A. Chang, Using AHP and TOPSIS approaches in customer-driven product design process, Comput. Ind. 59 (2008) 17–31.
[19] O. Duran, J. Aguilo, Computer-aided machine-tool selection based on a fuzzy-AHP approach, Expert Syst. Appl. 34 (2008) 1787–1794.
[20] A. Hambali, S.M. Sapuan, N. Ismai, Y. Nukman, Application of analytical hierarchy process in the design concept selection of automotive composite bumper beam during the conceptual design stage, Sci. Res. Essay 4 (2009) 198–211.
[21] K. Masui, T. Sakao, M. Kobayashi, A. Inaba, Applying quality function deployment to environmentally conscious design, Int. J. Qual. Reliab. Manage. 20 (2003) 90–106.