A Hybrid Model for Acquisition and Evaluation of Product Innovation Solutions

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Abstract. The fusion of Quality Function Deployment (QFD) and Theory of the Solution of Inventive Problems (TRIZ) can identify customer requirements for product design to effective search the design solution. Existing studies of QFD and TRIZ are mainly based on experience of designers to extract the product characteristics for customer requirements. A single evaluation indicator is used in the solution evaluation. This paper proposes a scenario-based evolution method to map customer requirements and technical characteristics. The defective technical characteristics is identified in the design evolution process. Design conflicts of technical characteristics are solved using tools in TRIZ. A mixed information evaluation method is used for selection of the final solution. A hybrid model is developed for acquisition and evaluation of product innovation solutions. The innovative design of a car satellite antenna verifies the proposed method.

Keywords: Scenario, QFD, TRIZ, Mixed information
DOI: https://doi.org/10.14733/cadaps.2023.119-132

1 INTRODUCTION

The Quality Function Deployment (QFD) method can identify customer needs in product lifecycle. Its key element is House of Quality (HOQ) to map customer requirements (CRs) and product characteristics for the priority of CRs and ranking product characteristics [7, 11, 20]. As QFD does not provide solutions for product design to meet CRs, different methods have been proposed to fuse the Theory of the Solution of Inventive Problems (TRIZ) and QFD for the solution search. For example, Wang used QFD and TRIZ in developing multi-functional smart phones [18]. Caligiana fused QFD and TRIZ to enhance fabrication of the direct open mould [2]. Chen integrated QFD, TRIZ and AHP. QFD was used to uncover core requirements of customer, AHP was used to determine the weight of CRs in HOQ, and inventive principles of TRIZ were used to find design solutions [4].

The core of using HOQ is the search for CRs and technical characteristics associated with CRs. The existing study of the technical characteristics identification for CRs relies on the subjective vision of designers [10, 15, 19, 23]. In the innovative product design, CRs usually express their requirements through problems with the existing product. The problems are often expressed in the form of insufficient or harmful functions [21]. Ma extracted product technical characteristics by establishing a relationship between CRs and components of product insufficient functions, but the CRs were not always matched by function components within the technical system [13]. The main function of a product is realized through the combination of several sub-functions. The implementation of each sub-function results in a transition from one state to another for objectives of the product action. CRs are usually not enough to achieve the need of the state transformation of a product that is implemented by some insufficient sub-functions. This study proposes a process based on the scenario evolution [12, 16] from CRs to technical characteristics for the product design.

Using TRIZ to solve conflicts of the characteristics relationship matrix may result in multiple solutions. After solutions are aggregated, a final solution with the best overall performance can be selected as the final solution based on evaluation indicators. Zhang used the FTOPSIS algorithm for the preference of solutions after the fusion of QFD and TRIZ, but there is only a single indicator used in the solution evaluation [24]. Some indicators can be expressed as precise numbers, some can be expressed as interval numbers, and some can only be represented in subjective words. Different types of evaluation indicators may occur simultaneously in the evaluation, which does not facilitate the aggregation of the final evaluation results. This study therefore uses a mixed-information type of the solution evaluation method for the solution preference.

In summary, this paper proposes a hybrid model of the innovative design method based on the scenario evolution for the technical characteristics acquisition in HOQ, TRIZ tools for problem solving and mixed information for solution evaluation. The novelty of this research is as follows.

1. Scenario analysis is used to assist in the extraction of CRs to technical characteristics in the HOQ, which reduces the subjective dependence on the designer.

2. Mixed-information type of the solution evaluation method is used to solve the problem of inconsistent evaluation indicators of parameter types.

Following parts of the paper are organized as follows. Section 2 introduces steps of the proposed hybrid model including the scenario-based technical characteristics acquisition, construction of HOQ, TRIZ tools for problem-solving and solution evaluation. Section 3 presents the design process of a car satellite antenna to verify the effectiveness of the proposed method. Section 4 summarizes the paper and suggests the future work.

2 PROPOSED METHOD

A hybrid model is proposed for acquisition and evaluation of product innovation solutions. As shown in Figure 1, it creates a scenario evolution process based on the product workflow. CRs are matched in a sub-evolution process to find insufficient technical characteristics corresponding to this sub-evolution process. The HOQ is formed based on CRs and insufficient technical characteristics. Conflicts are identified between technical characteristics. Aggregated solutions are evaluated using a mixed information method to select the best innovative solution.

2.1 Scenario-based Technical Characteristics Acquisition

The term scenario describes of possible futures and means to achieve objectives [9]. In the field of product design, a scenario is defined as the description of hypothetical states of actions of a product at some points of its lifecycle, which is the product evolution driven from the initial state to expected state [1, 17]. In the product design process, scenarios are composed of an initial scenario state (IS), a scenario evolution (SE), and an end scenario state (ES). Each scenario state contains multiple scenario elements. Sets of scenario elements in IS and ES are referred as the pre-situation element set (Pre-Se) and post-situation element set (Post-Se). The scenario evolution process is expressed as a $Pre\text{-}se \xrightarrow{SE} Post\text{-}se$.

An entire product scenario is a scenario unit. A complete product scenario can be decomposed into multiple sub-scenario units according to order of the product function execution. Scenario nodes can be decomposed into $SN = \{SN_1, SN_2, \cdots, SN_n\}$, where $IS=SN_1$, $ES=SN_n$. Two adjacent scenario nodes and their evolution form a sub-situation unit, $SE = \{SE_1, SE_2, \cdots, SE_{n-1}\}$. The scenario evolution process is shown in Figure 2.

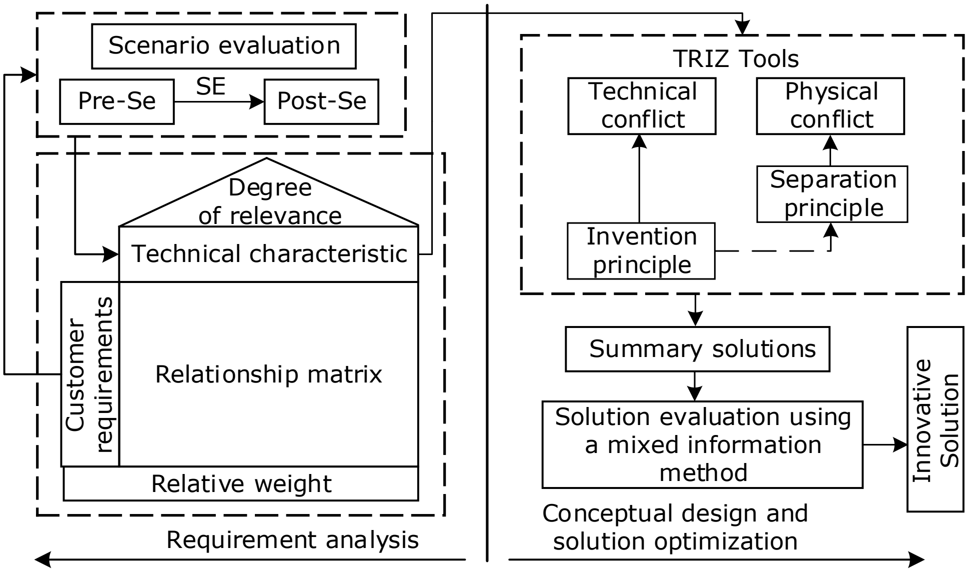


Figure 1: Proposed hybrid model for acquisition and evaluation of product innovation solutions.

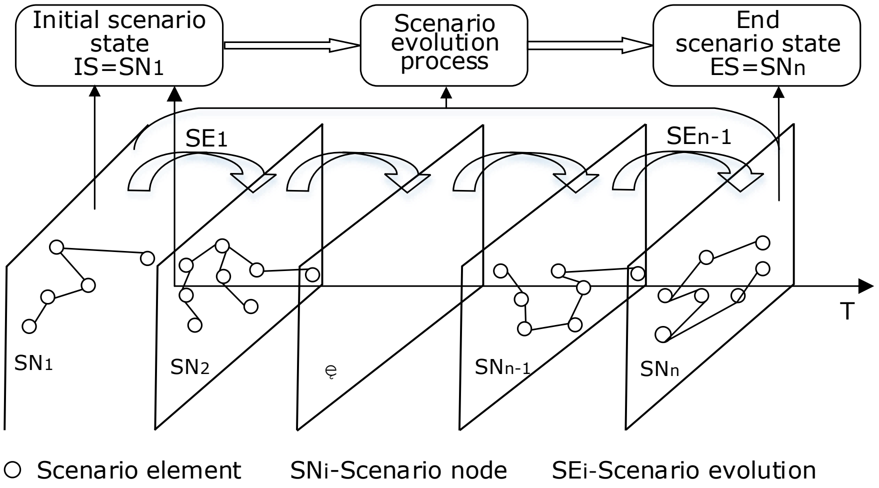


Figure 2: Product scenario evolution process.

In the product innovation design process, SE_i can be considered as the total function that changes the state of a scenario of the product from SN_i to SN_{i+1}. CRs arise from the inadequate performance of a SE_i in the scenario evolution process. In order to meet CR_i, the evolutionary process SE_i is improved for executable operations corresponding to technical characteristics C_{ij}. Each scenario state SN_i contains element E_{ij} and corresponding value V_{ij}, where, Element represents design features that need to be changed in a scenario state; Volume denotes necessary features to produce the corresponding change based on the design purpose of Element. The process extracts technical characteristics based on CRs are shown in Figure 3.

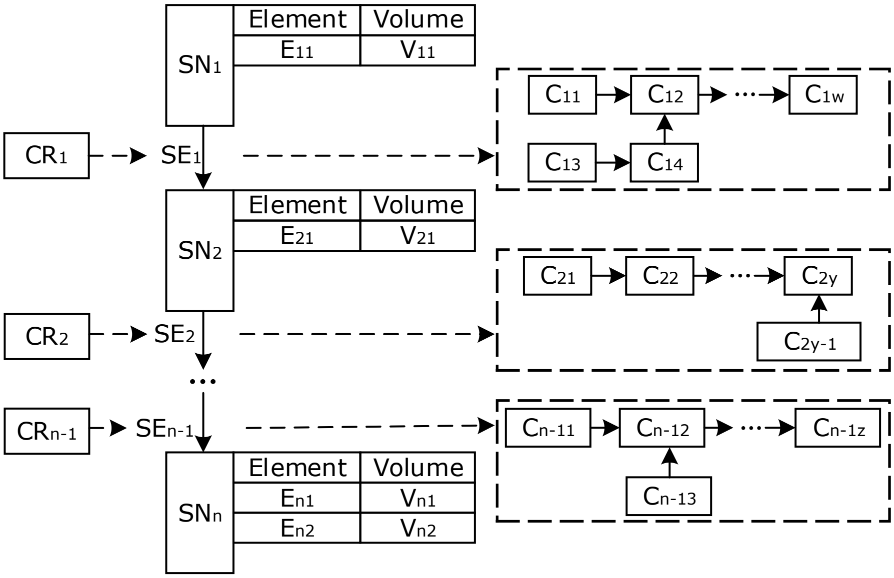


Figure 3: Conversion of CRs to technical characteristics.

The relationship between CRs, scenario evolution and technical characteristics is illustrated by the example of a nail clipper, as shown in Figure 4. The process of the cutting nail consists of two scenarios. One is the open nail clipper. In this scenario, the nail fits link with the nail clipper in its long length. The second is a closed nail clipper. In this scenario, the nail is separated from the nail clipper in short. The evolution of two scenario states is achieved by actions of the relevant technical characteristics for completing the process of cutting nail.

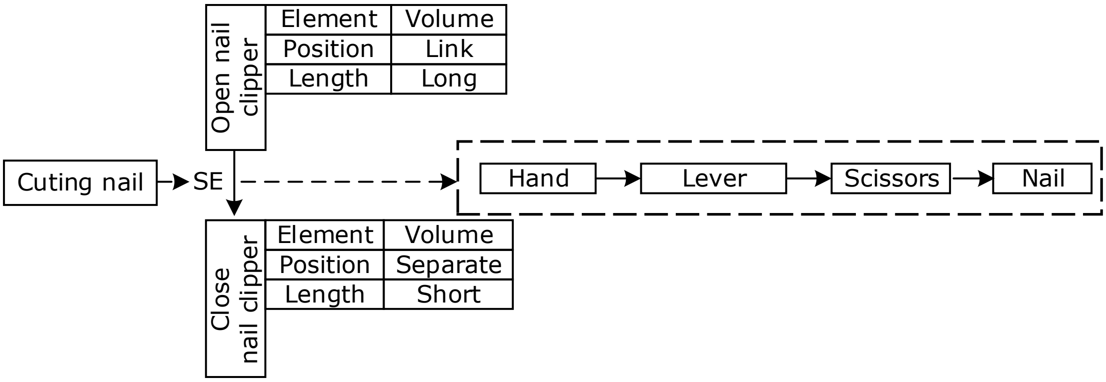


Figure 4: Scenario evolution for a nail clipper.

When a CR is not based on the improvement of a scenario evolution state of the existing system, a new scenario is required. The scenario is first embedded in the workflow of the existing product. The scenario evolution process is then described in terms of function. A function-oriented search is used to find technical characteristics C_{ij} to achieve the function in a patent database [14] or effects database [5].

2.2 Construction of HOQ

The technical characteristics obtained from the scenario analysis are placed in a HOQ which is then completed according to the relationship of parameters, as shown in Figure 5, where, CR_i is a customer requirement; TC_j is the technical characteristics; ω_{CRi} is the requirement weight; ω_{Tj} is the technical characteristics weight. A strong relationship takes a value of 5, medium relationship takes a value of 3, and weak relationship has a value of 1. V_{TCij} denotes the value of TC_j under CR_i, $V_{TC} = \{1, 3, 5\}$.

$$\omega_{Tj} = \sum_{i=1}^{n} \omega_{CRi} \times V_{TCij} \tag{2.1}$$

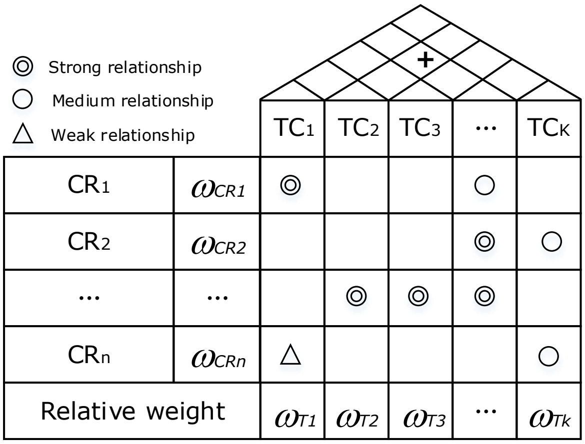


Figure 5: House of Quality (HOQ).

2.3 TRIZ Tools for Problem-solving

Conflicts are identified based on the relationship of influences between technical characteristics in the HOQ. Depending on circumstances, conflicts arising from all technical characteristics are resolved, or some conflicts are resolved in order of importance of technical characteristics. For physical conflicts, principles of the spatial separation, time separation, conditional separation or whole-part separation are used to solve them. For technical conflicts, they are described by terms of 39 standard engineering parameters. The conflict matrix is used to find the corresponding inventive principle [8]. The abstract solution by the principle of invention is converted into a specific solution of the problem.

2.4 Solution Evaluation using a Mixed Information Method

When TRIZ tools are used to solve conflicts of technical characteristics, several technological innovation solutions may be generated. When these solutions are aggregated, several aggregated solutions may be formed. The solution with the highest overall indicator needs is selected as the final design solution. Indicators of evaluating solutions include precise number a, interval number

$[a^L, a^U]$ and fuzzy number (a^L, a^M, a^U). A decision matrix $A = (a_{ij})_{n\times m}$ is formed collectively for mixed information [3, 6, 22].

$\tilde{a} = (a^L, a^M, a^U)$ is triangular fuzzy numbers. Affiliation function $f_a(x)$ is as follows.

$$f_a(x) = \begin{cases} 0 & x \le a^L \\ \dfrac{x - a^L}{a^M - a^L} & a^L \le x \le a^M \\ \dfrac{x - a^U}{a^M - a^U} & a^M \le x \le a^U \\ 0 & a^U \le x \end{cases} \tag{2.2}$$

The distribution of the triangular fuzzy number is shown in Figure 6, with a^L being the most conservative estimate (the lower limit of the triangular fuzzy number), a^M being the most likely estimate and a^U being the most optimistic estimate (the upper limit of the triangular fuzzy number).

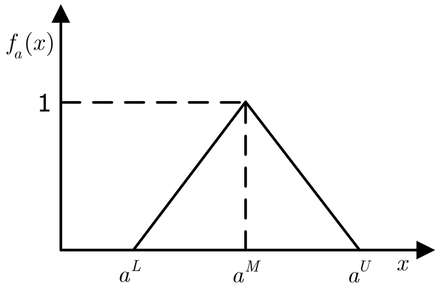


Figure 6: Triangular fuzzy number distribution.

Triangular fuzzy numbers are intuitive and easy to use; they can express multiple language variables well. Fuzzy values and language expressions are listed in Table 1.

Serial number	*Language evaluation*	*Fuzzy number*
1	Low	(0,0.1,0.3)
2	Medium	(0.3,0.5,0.7)
3	Upper middle	(0.5,0.7,0.9)
4	High	(0.7,0.9,1)

Table 1: Trigonometric fuzzy number expression.

Common types of evaluation indicators are benefit type indicators and cost type indicators. A better benefit indicator has a larger value, and a better cost indicator has the smaller value. Depending on the object of evaluation, the evaluation indicators can be precise, interval or fuzzy number. In order to eliminate the influence of different evaluation indicators in decision-making due to different physical scales or magnitudes, evaluation decision matrix $A = (a_{ij})_{n\times m}$ is normalized into matrix $B = (b_{ij})_{n\times m}$. Different types of evaluation indicators are normalized as follows.

Precise number

$$b_{ij}=\frac{a_{ij}}{\sqrt{\sum_{i=1}^{n}a_{ij}^{2}}} \tag{2.3}$$

Benefit type of interval number

$$b_{ij}^{L(U)}=\frac{a_{ij}^{L(U)}}{\sqrt{\sum_{i=1}^{n}(a_{ij}^{U(L)})^{2}}} \tag{2.4}$$

Cost type of interval number

$$b_{ij}^{L(U)}=\frac{1/a_{ij}^{U(L)}}{\sqrt{\sum_{i=1}^{n}(1/a_{ij}^{L(U)})^{2}}} \tag{2.5}$$

Benefit type of fuzzy number

$$b_{ij}^{L(U)}=\frac{a_{ij}^{L(U)}}{\sqrt{\sum_{i=1}^{n}(a_{ij}^{U(L)})^{2}}} \quad b_{ij}^{M}=\frac{a_{ij}^{M}}{\sqrt{\sum_{i=1}^{n}(a_{ij}^{M})^{2}}} \tag{2.6}$$

Cost type of fuzzy number

$$b_{ij}^{L(U)}=\frac{1/a_{ij}^{U(L)}}{\sqrt{\sum_{i=1}^{n}(1/a_{ij}^{L(U)})^{2}}} \quad b_{ij}^{M}=\frac{1/a_{ij}^{M}}{\sqrt{\sum_{i=1}^{n}(1/a_{ij}^{M})^{2}}} \tag{2.7}$$

According to weight $\omega=(\omega_1 \quad \omega_2 \quad \cdots \quad \omega_m)$ of each evaluation indicator, weighted normative matrix $R=(r_{ij})_{n\times m}$ is acquired, where, $r_{ij}=b_{ij}\times\omega_j$. For each indicator, the optimal value of the indicator is selected as the positive ideal solution. The worst value is the negative ideal solution from all the solutions evaluated. The relative closeness of each solution to the positive ideal solution is decided using Equations (2.8-2.10). The solution with the greatest relative closeness is selected as the final design solution.

$$d_i^{+}=d(X_i \quad X^{+})=\sqrt{(d_{i1}^{+})^2+(d_{i2}^{+})^2+\cdots+(d_{ik}^{+})^2} \tag{2.8}$$

$$d_i^{-}=d(X_i \quad X^{-})=\sqrt{(d_{i1}^{-})^2+(d_{i2}^{-})^2+\cdots+(d_{ik}^{-})^2} \tag{2.9}$$

$$d_i=\frac{d_i^{-}}{d_i^{-}+d_i^{+}} \tag{2.10}$$

where, X^{+} and X^{-} denote the positive ideal solution and negative ideal solution, respectively, d_{ij}^{+} and are distances of the j th evaluation indicator in solution i to the positive ideal solution and to the negative ideal solution of them counterpart; d_i^{+} and d_i^{-} are distances of each solution to the positive and negative ideal solutions; d_i is relative closeness.

3 CASE STUDY

The car satellite antenna is installed in the car. By receiving the TV signal sent from the coverage area of the satellite signal and decoding it for display, it enables the seamless connection of satellite TV. The 045 car satellite antenna is shown in Figure 7. According to the customer feedbacks in the product use, there are following four main problems for improvement: 1). rain decay is serious; 2). rainwater beads on the parabolic surface in rainy days; 3). there is a blind area for signal search; 4). the height of the antenna is too high when it is not working, which is difficult to store.

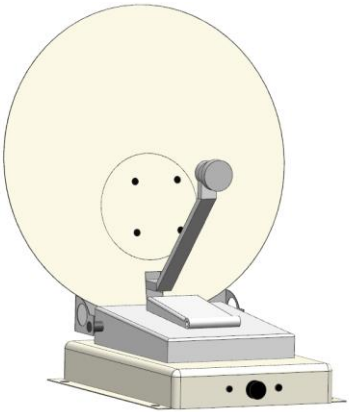


Figure 7: 045 car satellite antenna.

3.1 Technical Characteristics Extraction based on Scenario Evolution

According to problems from the customer and working process of the product, a model of CRs for technical characteristics acquisition is created, as shown in Figure 8, where the rain decay, signal blind area and storage difficulty are identified for improvement for the current technical system with the corresponding technical characteristics. The relevant technical characteristics are the paraboloid caliber, paraboloid height, pitching limiter and rotating limiter. Cleaning rainwater is a completely new CR. A function-oriented search is used to find technical characteristics outside the system to fulfil this requirement. A search of the patent database is conducted using the function "clean rainwater" as a keyword. The available technical characteristics is found to be a protective layer of hydrophobic Nano-coating materials.

3.2 Construction of HOQ

CRs and relevant technical characteristics are placed in a HOQ. Other elements in the HOQ are completed according to the importance of CRs and technical characteristics, as shown in Figure 9.

3.3 Conflict-solving for Technical Characteristics

According to CRs, all problems of the product need to be solved. Therefore, conflicts between technical characteristics are to be solved. Among the technical characteristics of the HOQ, the protective layer is found through a function-oriented search in order to meet new requirements. There is no interaction with other technical characteristics. Therefore, no conflicts arise in relation to the protective layer.

In order to reduce the rain decay phenomenon, it is necessary to increase the parabolic caliber, but this leads to difficulties in storing cars. Converting the problem to a standard parametric description, the improvement parameter is related to the area of stationary objects; the deterioration parameter is adaptability and versatility. The available inventive principle 16, partial or excessive actions, is obtained by the conflict matrix. The space in which the paraboloid can be lowered is altered. The existing horizontal frame and pitching bracket are altered so that the paraboloid can be lowered further, as shown in Figure 10.

In order to improve the signal blind area, a small size rotating limiter is required. To ensure reliability in a limited space, a large size rotating limiter is required. This creates a physical conflict. The invention principle 3, local quality, corresponds to the spatial separation principle for resolving physical conflicts is adopted. The size of the trigger head of the rotating limiter has been reduced. At the same time its stiffness is improved, as shown in Figure 11 for the red and yellow elements. According to invention principle 7, nesting doll, two limiters are employed. One rotates within a sector and the other within a circular area, as shown in Figure 12.

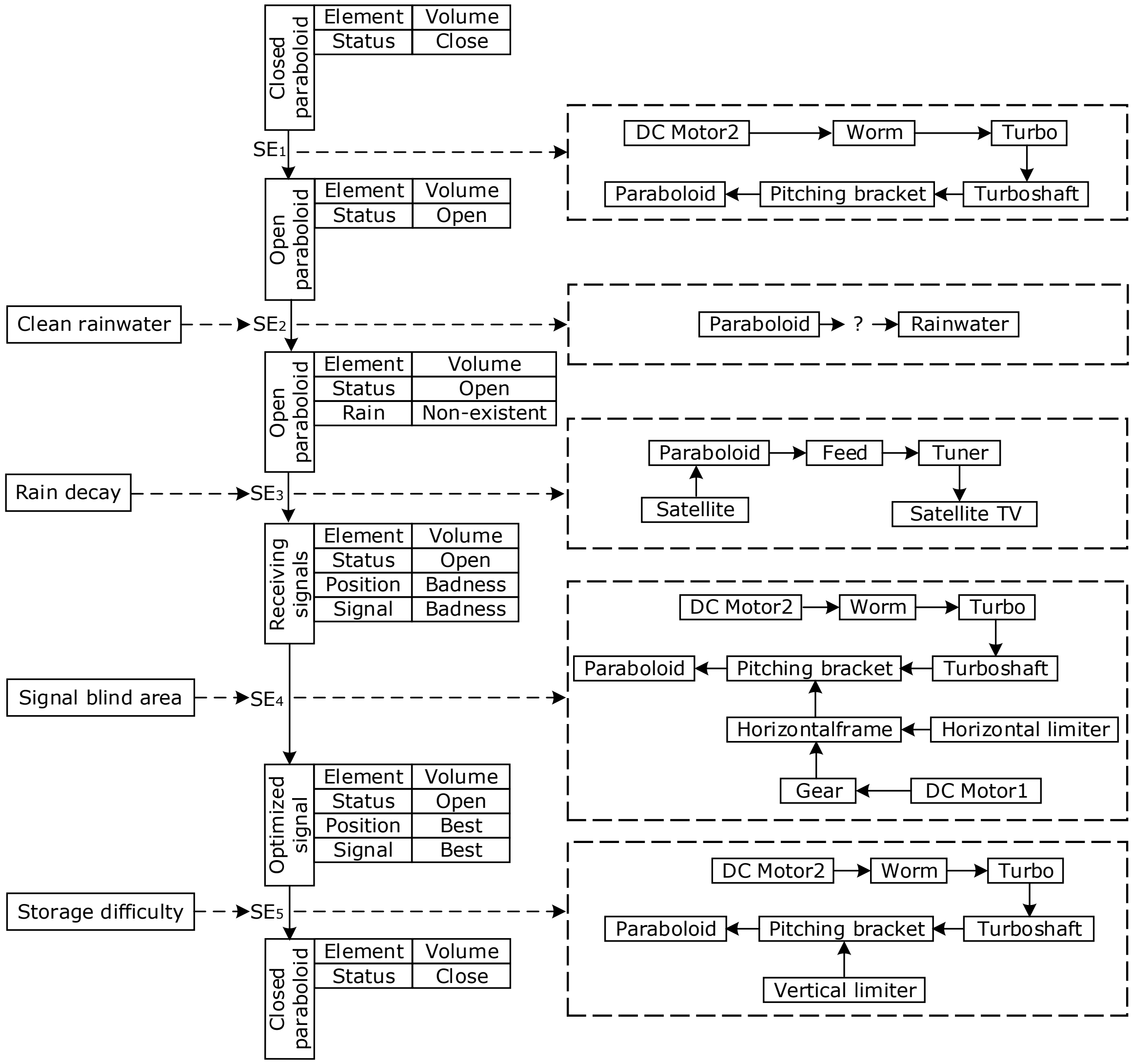
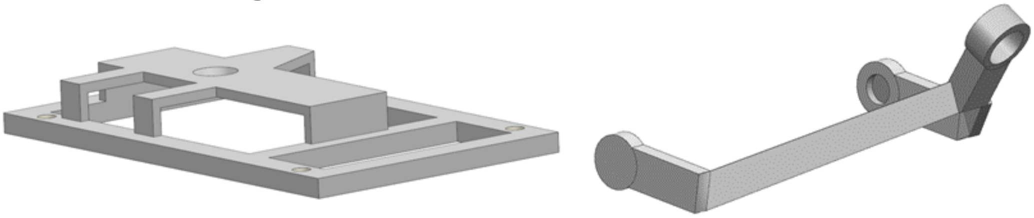


Figure 8: Modeling of customer requirements for technical characteristics acquisition of 045 satellite antenna.

◎ Strong relationship
○ Medium relationship
△ Weak relationship

		Parabolid caliber	Parabolid height	Pitching limiter	Rotating limiter	Protective layer
Rain decay	5	◎				○
Clean rainwater	3					◎
Signal blind area	4				◎	
Storage difficulty	2	△	◎	◎		
Relative weight		27	10	10	20	30

Figure 9: The HOQ of 045 car satellite antenna.



(a) (b)

Figure 10: Solutions to conflicts caused by increasing the parabolic caliber: (a) Improved solution for the horizontal frame, (b) Improved solution for the pitching bracket.

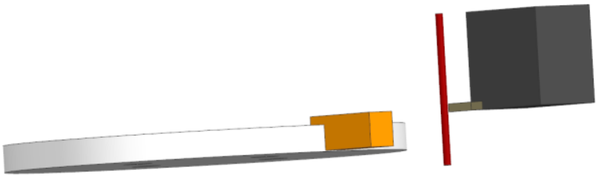
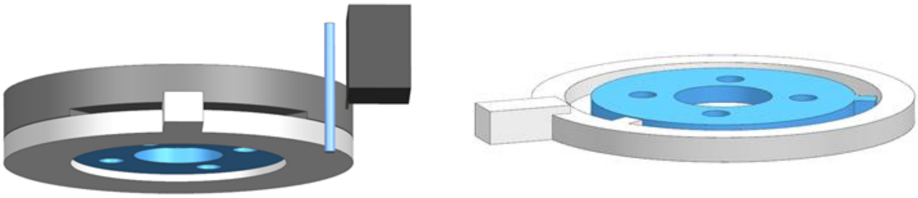


Figure 11: Improved solution of local mass for rotating limiter.



(a) (b)

Figure 12: Improved solution of nestification for rotating limiter: (a) Assembly drawing of rotating limiter, (b) Partial drawing of rotating limiter.

To improve the storage difficulty due to the parabolic height, it is necessary that the pitching limiter is not present, but this would result in no monitoring device when the satellite antenna is reset. The problem is converted into a standard engineering parameter description. The improvement parameter is the harmful factors generated by the object; the deterioration parameter is the degree of difficulty in monitoring and testing. The available invention principle 2, taking out, is found in the conflict matrix. The existing limit device is detached from its current position to a position where it is rotated 20 degrees anticlockwise, thereby reducing the height at which the paraboloid drops, as shown in Figure 13.

After combining the above conflict-solving solutions, 2 summary solutions are formed. Summary solution 1 uses a large caliber paraboloid with protective layer, improved horizontal frame, improved pitching bracket, and limiter of local mass improvement. Summary solution 2 has a large caliber paraboloid with protective layer, improved horizontal frame, improved pitching bracket, and limiter of notification.

(a) (b)

Figure 13: Improved solution for pitching limiter: (a) Original solution, (b) Improved solution.

3.4 Solution Evaluation

The original solution and two aggregated innovative solutions are evaluated. The evaluation indicators are the horizontal rotation angle, paraboloid height, paraboloid caliber and cost, as shown in Table 2, where 0 represents the original solution, 1 represents the solution 1, and 2 represents the solution 2. According to the influence relationship of each evaluation indicator on the solutions, the weight of each indicator is $\omega = \; 0.4 \quad 0.2 \quad 0.3 \quad 0.1$.

Solution	*Horizontal rotation angle*	*Paraboloid height*	*Paraboloid caliber*	*Cost*
0	[-190,260]	26	45	Medium
1	[-90,265]	17	52	Upper middle
2	[-90,290]	17	52	High

Table 2: Evaluation indicators for the solution.

The evaluation decision matrix is as follows.

$$A=\begin{bmatrix} [-90,260] & 26 & 45 & (0.3,0.5,0.7) \\ [-90,265] & 17 & 52 & (0.5,0.7,0.9) \\ [-90,290] & 17 & 52 & (0.7,0.9,1) \end{bmatrix} \tag{3.1}$$

Normalize the decision matrix A according to Equations (2.3-2.7).

$$B=\begin{bmatrix} [-0.1910,1.6679] & 0.7342 & 0.5220 & (0.3449,0.7415,1.6121) \\ [-0.1910,1.7000] & 0.4801 & 0.6031 & (0.2683,0.5296,0.9673) \\ [-0.1910,1.8604] & 0.4801 & 0.6031 & (0.2415,0.4119,0.6909) \end{bmatrix} \tag{3.2}$$

Weight matrix R of the normalized decision matrix B is formed based on the indicator weight ω.

$$R=\begin{bmatrix} [-0.0764,0.6672] & 0.1468 & 0.1556 & (0.0345,0.0742,0.1612) \\ [-0.0764,0.6800] & 0.0960 & 0.1809 & (0.0268,0.0530,0.0967) \\ [-0.0764,0.7442] & 0.0960 & 0.1809 & (0.0242,0.0412,0.0691) \end{bmatrix} \tag{3.3}$$

The positive ideal solution and negative ideal solution are determined as follows.

$$X^{+}=\left[-0.0764,0.7442\right] \quad 0.0960 \quad 0.1809 \quad \left[0.0345,0.0742,0.1612\right] \tag{3.4}$$

$$X^{-}=\left[-0.0764,0.6672\right] \quad 0.1468 \quad 0.1556 \quad \left[0.0242,0.0412,0.0691\right] \tag{3.5}$$

The relative closeness of each solution to the positive ideal solution is decided using Equations (2.8-2.10).

$$d_0 = 0.452 \qquad d_1 = 0.539 \qquad d_2 = 0.548 \tag{3.6}$$

It can be found that the relative closeness of two new design solutions is greater than the original solution, and solution 2 is greater than solution 1, solution 2 is therefore chosen as the final design solution as shown in Figure 14. The housing of the horizontal frame has not been added for a better presentation of the improved design solution.

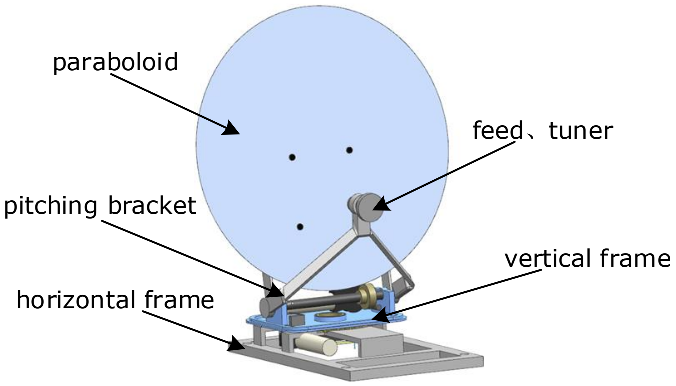


Figure 14: Final innovative design solution.

4 CONCLUSIONS

A detailed description of CRs and technical characteristics is discussed based on the scenario evolution. CRs are mapped into the scenario evolution process to analyze technical characteristics. For new CRs mapped into the scenario evolution process without corresponding technical characteristics, a function-oriented search is proposed to decide the relevant technical characteristics from the patent or effect database. For existing but insufficient CRs mapped to the scenario evolution process, the corresponding technical characteristics is searched for improvement. A complete transformation process is developed from CRs to technical characteristics.

Problems from technical characteristics corresponding to CRs are solved using TRIZ. Solutions are aggregated to form multiple solutions. A mixed-information evaluation method is developed for screening innovative design solutions, which improves the singularity of the type of solution evaluation indicators after the fusion of QFD and TRIZ.

The proposed method has been verified in improvement of the 045 satellite antenna. The limitation of the method is the lack of a software tool to support the whole process in efficiency. Our further work will develop a computer-aided tool to improve efficiency of the proposed method.

ACKNOWLEDGMENTS

This paper is sponsored by the National Natural Science Foundation of China (No.51675159), the Central Government Guides Local Science and Technology Projects of China (No.18241837G), and the National Project on Innovative Methods of China (No.2020IM020600).

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