Product Function Redesign Based on Extension Theory

Yafan Dong[1], Qingjin Peng[2], Runhua Tan[3], Junlei Zhang[4], Peng Zhang[5] and Wei Liu[6]

[1]Hebei University of Technology, dyafan@foxmail.com
[2]University of Manitoba, Qingjin.Peng@umanitoba.ca
[3]Hebei University of Technology, rhtan@hebut.edu.cn
[4]Hebei University of Technology, 18032611036@163.com
[5] Hebei University of Technology, zhangpeng@hebut.edu.com
[6]Hebei University of Technology, lwofhebut@126.com

Corresponding author: Runhua Tan, rhtan@hebut.edu.cn

Abstract. Redesign is required for the product improvement. The function design is one of the most important tasks in a redesign process. In order to generate an optimal solution of the product redesign efficiently for enterprises, this paper proposes a function redesign method based on the extension theory. For a target product to be redesigned, a hierarchal function model of the target product is first formed using the function analysis. Degree of the function importance is then determined by applying the triangular fuzzy number. Difficult function units and high important degree functions are decided according to redesign requirements and ranking of function importance degrees. In order to apply the difficult function units and high importance degree functions in the innovative design, a function redesign process model is developed based on the extension theory and TRIZ tools. Feasibility of the proposed method is verified in redesign of an ultrasonic-based measurement device of the paper thickness.

Keywords: Function redesign, Extension theory, Triangular fuzzy number, Functional basic-element, Extension transformation
DOI: https://doi.org/10.14733/cadaps.2021.199-210

1 INTRODUCTION

Following the market change to meet user requirements, many enterprises redesign their products using new technologies or processes to adapt changes of the competitive market [9, 15]. In the product redesign process, the effective function design is significant for innovative solutions [2-5]. TRIZ (Invention Problem Solving Theory) was proposed by Altshuller based on the analysis of patents. It provides tools to solve problems in a redesign process [14, 17]. Many scholars have conducted research on the function design or product redesign process. Ma et al. [13] proposed a method to identify function components for product redesign based on the failure mode and effects analysis (FMEA). Smith et al. [16] developed an innovative redesign method for new products based on the integration of existing similar products in functions and other aspects. Tan et al. [18] proposed three opportunities-driven redesigning paths based on the training process of innovation engineers in China, and emphasized the relation between functions and main innovation processes.

However, most of the existing methods mainly focus on identifying function components to meet design requirements. They are subjective and fuzzy in the analysis of functional levels, which is difficult to be used in the redesign process. The extension theory [21] introduced the basic-element (BE) to establish a formal model with characteristics of formalization of the operation process, and combination of qualitative and quantitative analyses. In recent years, the extension theory has been applied to solve uncertainty problems for the product innovation redesign. Bai et al. [1] formalized the extension transformation for the second class of standard solutions to guide the solution of redesign problems. Lou et al. [12] improved TRIZ based on the extension theory to eliminate contradictions. But there is a lack of research on quantifying functions by applying the extension theory for redesign innovation in the functional level. Important functions can guide the product innovation in a redesign process.

This paper proposes an extension theory-based method for the product function redesign. For a target product to be redesigned, a hierarchal function model of the target product is first built based on the function analysis. The degree of the function importance is then determined by applying the triangular fuzzy number (TFN) [10, 19]. Difficult function unit (DFU) and high importance degree function (HIDF) are determined according to the customers' requirements (CRs) and ranking of function importance degrees. In order to apply DFU and HIDF in the design innovation, a function redesign process model is developed using the extension theory and TRIZ tools. The feasibility of the proposed method is verified in a specific redesign of an ultrasonic-based measurement device of the paper thickness.

2 PROPOSED METHOD

Redesign is commonly required for product improvement to shorten the development cycle and reduce cost of the product [15]. The extension theory is proposed in the paper for the redesign process [4]. The high importance degree function is identified by using the triangular fuzzy number. The identified functions are implemented by applying the extension transformation and TRIZ tools.

2.1 Hierarchal Function Model (HFM)

A target product can be identified according to internal and external changes of an industry. The total functions can then be determined by designers and a functional tree of the target product is formed based on the function analysis. A hierarchal function model shows correlations of the material flow (M, M'), power flow (P, P') and signal flow (S, S') of the target product as shown in Figure 1.

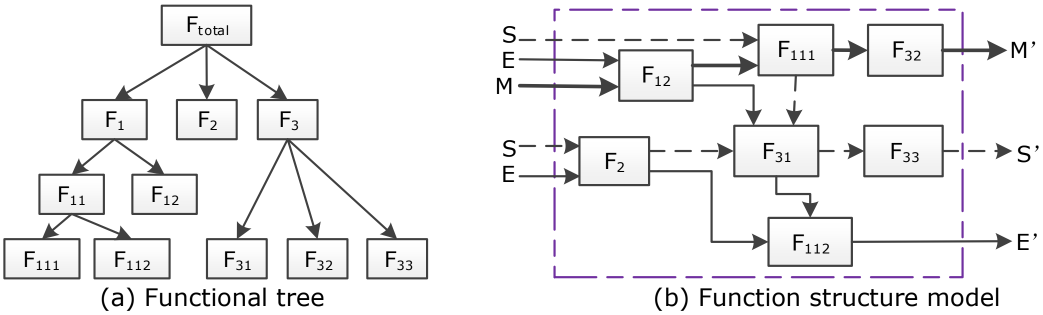


Figure 1: Hierarchal function modeling of a target product.

2.2 Determination of Functions for Extension

The structure model in Figure 1 shows relations of the product function relation, but the direction of innovative design. Although it can identify the difficult function unit based on the structure and implementation of a product, it neglects the high importance degree function which is to be decided by applying the triangular fuzzy number (TFN) in the functional level.

Degrees of the function importance can be searched by introducing TFN in a hierarchal function model. A fuzzy rough set for the function importance comparison between ith and jth functions is defined in Table 1. For a product with the total function units *n,* based on the pair-wise comparison of their importance, a triangular fuzzy number matrix (TFNM) [6, 20, 22] can be formed as shown in Equation (2.1).

Values	Description of importance
0.9	Extremely important
0.8	Strongly important
0.7	Obviously important
0.6	Slightly important
0.5	Equally important
0.4-0.1	Contrary to the above

Table 1: Fuzzy rough set for the importance comparison between functions.

$$F=\begin{bmatrix} f_{11} & \dots & f_{1n} \\ \dots & f_{ij} & \dots \\ f_{n1} & \dots & f_{nn} \end{bmatrix}=\begin{bmatrix} (f_{11}^{L},f_{11}^{M},f_{11}^{U}) & \dots & (f_{1n}^{L},f_{1n}^{M},f_{1n}^{U}) \\ \dots & (f_{ij}^{L},f_{ij}^{M},f_{ij}^{U}) & \dots \\ (f_{n1}^{L},f_{n1}^{M},f_{n1}^{U}) & \dots & (f_{nn}^{L},f_{nn}^{M},f_{nn}^{U}) \end{bmatrix} \tag{2.1}$$

where f_{ij} is a fuzzy value of the function importance compared between i^{th} and j^{th} functions. $f_{ij}^{L}+f_{ji}^{U}=f_{ij}^{M}+f_{ji}^{M}=f_{ij}^{U}+f_{ji}^{L}=1, f_{ii}^{L}=f_{ii}^{M}=f_{ii}^{U}=0.5, f_{ij}^{L}\le f_{ij}^{M}\le f_{ij}^{U}; \; i,j=1,2,\dots n$

TFNM is then processed by the importance ranking management software (KC V1.0) [11] to decide degrees of the function importance using fuzzy ordered weighted averaging (FOWA) operators [11, 22] such as $D=(d_1, d_2, \dots, d_n)^T$. The ranking of function importance degrees is used to decide the high importance degree function (HIDF). The highest importance degree function is chosen as $d_k>d_t$, t=1,2,⋯, k-1, k+1,⋯, n. Considering requirements and constraints of the product, secondary importance degree functions can also be used as extension objects.

2.3 Functional Extension Transformation Based on Extension Theory

According to the extension theory, DFU and HIDF can be represented in a form of the functional basic-element as $B_F=(O, c, v)$. Where *O* is DFU or HIDF, *c* is the functional characteristic, and *v* is the value of *O* concerning *c*. We can obtain function extension set B_E by applying the extension analysis theory including divergent tree method and implication system method as shown in Figure 2.

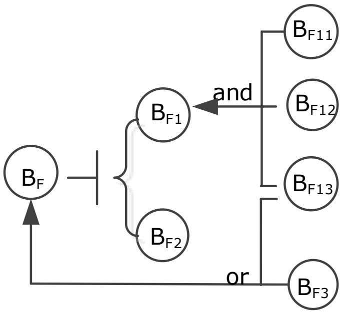


Figure 2: Extension analysis of functional basic-element.

Figure 2 forms several new routes to guide design searching for the functional basic-element BF. However, it only provides some possibilities for generating ideas using the extension analysis theory. In order to find innovative solutions, an extension transformation is introduced to B_F. There are five basic extension transformations including displacement, addition or deletion, expansion (0<α<1, T is reduction), decomposition, and copy, as shown in Equation (2.2). Furthermore, TRIZ tools are used to solve contradictions in a new way of the functional level.

$$TB_F = \begin{cases} B_{Fi} & T \in displacement \\ B_F \pm B_{Fi} & T \in \text{addition \& deletion} \\ \alpha B_F & \alpha > 0, T \in \text{expansion} \\ \{B_{F1}, B_{F2}, \ldots\} & T \in \text{decomposition} \\ \{B_F, B_F^*\} & T \in \text{copy} \end{cases} \tag{2.2}$$

2.4 Priority Degree Evaluation

The priority degree evaluation is the basic method to evaluate the quality of an object in extenics [8]. Its steps are as follows: (1) determining measurement indicators $C=\{C_1, C_2, \cdots, C_m\}$; (2) deciding weight coefficients $W=\{W_1, W_2, \cdots, W_m\}$; (3) evaluating solutions with necessary conditions; (4) establishing correlation function K_i and calculating correlation degree $k=\{k_1, k_2, \cdots, k_m\}$ using Equation (2.3); (5) calculating the priority degree G using Equation (2.4).

$$k_{ij} = \frac{K_i(S_i)}{\max\limits_{q \in \{1,2,\ldots,m\}} \left| K_i(S_q) \right|}, \text{ j=1, 2, 3,} \cdots \text{, n} \tag{2.3}$$

$$G = \sum_{i=1}^{n} W_i \times k_i \tag{2.4}$$

An innovative solution can be developed using the above steps. The product function redesign model can then be formed using the extension theory as shown in Figure 3.

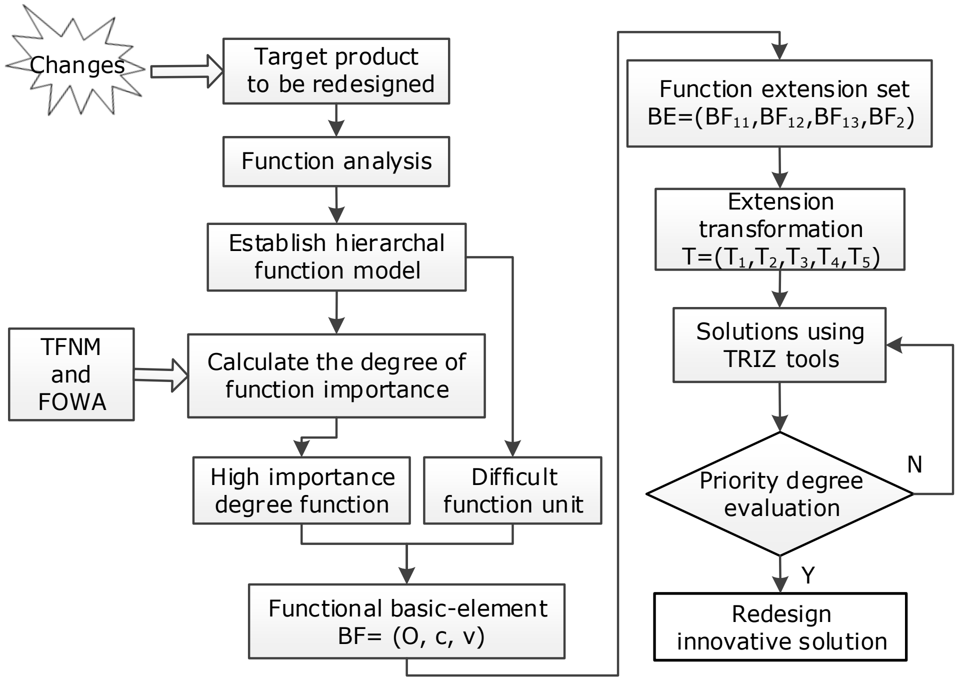
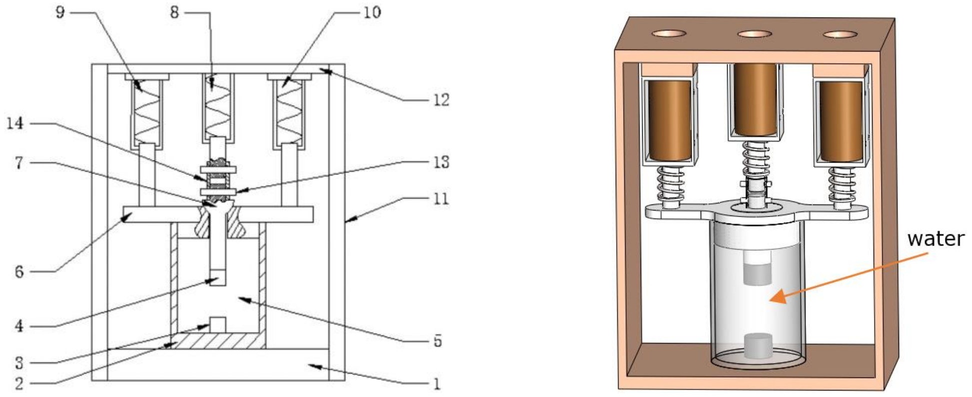


Figure 3: The product function redesign model based on the extension theory.

3 CASE STUDY



(a) Structure of the measurement device [23] (b) Prototype of the measurement device

1- Paper holder, 2-tank body, 3- transmitting probe,
4- receiving probe, 5-medium, 6- top cover of tank, 7-halfsphere valve, 8-electromagnet I,
9-electromagnet II, 10-electromagnet III, 11-support frame, 12-upper frame, 13-Fixed pin, 14-casing pipe

Figure 4: Existing measurement device.

Figure 4(a) shows an existing ultrasonic-based device of measuring the paper thickness [23] (Hereinafter referred to as "the measurement device"). In order to improve the measurement accuracy, water is usually used to replace gas as ultrasonic medium as shown in Figure 4(b).

However, as a certain amount of air will be dissolved in the water medium, bubbles will be generated and gradually gather on the surface of the receiving probe over time. This will reduce the energy of the signal to enter the receiving probe. The measurement accuracy would be reduced. In addition, more energy is consumed because of the large-sized tank body. The case study is to redesign the device for the improvement.

3.1 Hierarchal Function Model (HFM)

Function is an abstract description of input/output of a system, and generally expressed as a "verb + noun", such as "measure thickness". The function of the device is the "measure paper thickness". A functional tree of the measurement device is developed based on the proposed function analysis as shown in Figure 5 (a). Considering three flows of the M/M'-paper, P/P'-electrical power and S/S'-thickness information, a hierarchal function model of the measurement device is built to search function units as shown in Figure 5 (b). There are eight function units identified, including F_1-transmit ultrasonic, F_2-drive electromagnet, F_3-record time, F_4-process data, F_5-display information, F_6-receive ultrasonic, F_7-press papers, and F_8-loose papers.

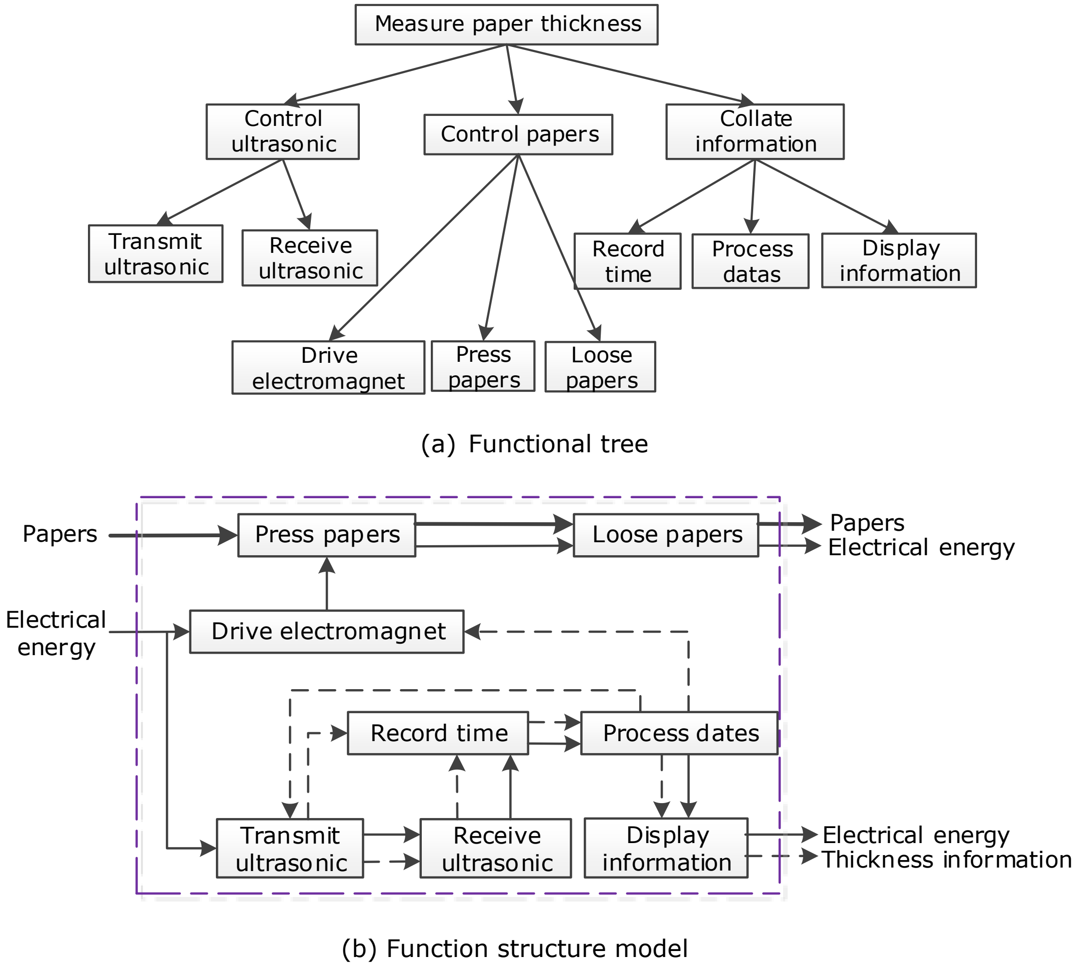


Figure 5: Functional tree and function structure model of the measurement device.

3.2 Determination of Functions Extension

Because bubbles gather on the surface of the receiving probe over time, they affect the measurement accuracy of the measurement device. As the bubbles affect the function unit F_6-receive ultrasonic poorer, F_6 is identified as the difficult function unit.

The high importance degree function can be determined by using TFN and FOWA as shown in Figure 5, including eight function units $F = \{F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8\}$. Based on pair-wise comparisons of their importance, TFNM is then formed as $F = [f_{ij}^L, f_{ij}^M, f_{ij}^U]_{8\times 8}$ using Equation (2.1) as shown in Equation (3.1).

$$F = \begin{bmatrix} (0.5, 0.5, 0.5) & (0.3, 0.4, 0.5) & (0.2, 0.3, 0.4) & (0.3, 0.4, 0.5) & (0.55, 0.6, 0.65) & (0.2, 0.3, 0.4) & (0.6, 0.7, 0.8) & (0.7, 0.8, 0.9) \\ (0.5, 0.6, 0.7) & (0.5, 0.5, 0.5) & (0.7, 0.8, 0.9) & (0.6, 0.7, 0.8) & (0.6, 0.7, 0.8) & (0.5, 0.6, 0.7) & (0.5, 0.6, 0.7) & (0.6, 0.7, 0.8) \\ (0.6, 0.7, 0.8) & (0.1, 0.2, 0.3) & (0.5, 0.5, 0.5) & (0.3, 0.4, 0.5) & (0.6, 0.7, 0.8) & (0.2, 0.3, 0.4) & (0.3, 0.4, 0.5) & (0.3, 0.4, 0.5) \\ (0.5, 0.6, 0.7) & (0.2, 0.3, 0.4) & (0.5, 0.6, 0.7) & (0.5, 0.5, 0.5) & (0.7, 0.8, 0.9) & (0.2, 0.3, 0.4) & (0.3, 0.4, 0.5) & (0.3, 0.4, 0.5) \\ (0.35, 0.4, 0.45) & (0.2, 0.3, 0.4) & (0.2, 0.3, 0.4) & (0.1, 0.2, 0.3) & (0.5, 0.5, 0.5) & (0.3, 0.4, 0.5) & (0.2, 0.3, 0.4) & (0.2, 0.3, 0.4) \\ (0.6, 0.7, 0.8) & (0.3, 0.4, 0.5) & (0.6, 0.7, 0.8) & (0.6, 0.7, 0.8) & (0.5, 0.6, 0.7) & (0.5, 0.5, 0.5) & (0.6, 0.7, 0.8) & (0.6, 0.7, 0.8) \\ (0.2, 0.3, 0.4) & (0.3, 0.4, 0.5) & (0.5, 0.6, 0.7) & (0.5, 0.6, 0.7) & (0.6, 0.7, 0.8) & (0.2, 0.3, 0.4) & (0.5, 0.5, 0.5) & (0.5, 0.5, 0.5) \\ (0.1, 0.2, 0.3) & (0.3, 0.4, 0.5) & (0.5, 0.6, 0.7) & (0.5, 0.6, 0.7) & (0.6, 0.7, 0.8) & (0.2, 0.3, 0.4) & (0.5, 0.5, 0.5) & (0.5, 0.5, 0.5) \end{bmatrix} \tag{3.1}$$

TFNM is processed by the importance ranking management software (KC V1.0) [11] to decide degrees of the function importance using FOWA operators [11, 22] as $D = (d_{F1}, d_{F2}, d_{F3}, d_{F4}, d_{F5}, d_{F6}, d_{F7}, d_{F8}) = (0.117, 0.161, 0.106, 0.117, 0.082, 0.171, 0.123, 0.123)$. Table 2 shows that F_6 and F_2 are identified as the most important functions. Therefore, F_6 and F_2 are the HIDF considering the power saving and measurement accuracy.

NO.	Functions	Importance degrees	Ranking
F_1	Transmit ultrasonic	0.117	5
F_2	Drive electromagnet	0.161	2
F_3	Record time	0.106	7
F_4	Process data	0.117	6
F_5	Display information	0.082	8
F_6	Receive ultrasonic	0.171	1
F_7	Press papers	0.123	3
F_8	Loose papers	0.123	4

Table 2: Degrees of the function importance.

3.3 Functional Extension Transformation Based on Extension Theory

Function units F_6 and F_2 are represented in a form of the functional basic-element B_{FF6} and B_{FF2} as shown in Figure 6. Because the function may have many functional characteristics, or functional characteristics may have many values, a divergent tree method can be used to consider changes of the characteristics or values to achieve divergent basic-elements. Due to the implication relationship between functions, extended basic-elements can be developed by the implication system method. Function extension set B_E= {B_{F1}, B_{F2}, B_{F3}, B_{F4}, B_{F5}, B_{F6}} is obtained by applying the extension analysis theory such as the divergent tree and implication system method as shown in Figure 6.

As the extension analysis can only provide some routes to solve problems, the extension transformation is implemented to obtain creative solutions. Alternative solutions can be generated by applying the operation of transformation. According to B_{FF6}, B_{FF2} and B_E, functional basic-element B_{FF6} can be replaced by B_{F2} or B_{F3} applying Equation (2.2) as $TB_{FF6} = B_{F2} = B_{F3}, T \in displacement$. Similarly, functional basic-element B_{FF2} can be realized by B_{F4} and B_{F6} as $TB_{FF2} = B_{F4} + B_{F6}, T \in \text{addition}$.

According to displacement and addition transformation, three solutions are generated by applying TRIZ tools based on the extension transformation in the functional level as follows. Solution 1(S1): the medium is replaced with the distilled water to eliminate bubbles, and electromagnet only drives the receiving probe. Solution 2(S2): separation of measuring surface and tank body, and the measurement device is designed as a horizontal position. Solution 3(S3): surface is measured at the top of the device, and when not working, electromagnet is in the compression state.

3.4 Priority Degree Evaluation

The three solutions are evaluated using the priority degree evaluation in extenics to determine the optimal solution.

(1) Determining the measurement indicators. According to experts' suggestions and specific conditions, the most representative four indicators are sorted out as C= {C_1, C_2, C_3, C_4} = {measurement inaccuracy degree, energy consumption, cost, occupied space}.

(2) Determining the weight coefficient. The Delphi method is used to evaluate the measurement indicators of design solutions of the measurement device. Weight coefficients are W= {W_1, W_2, W_3, W_4} = {0.4, 0.3, 0.2, 0.1}.

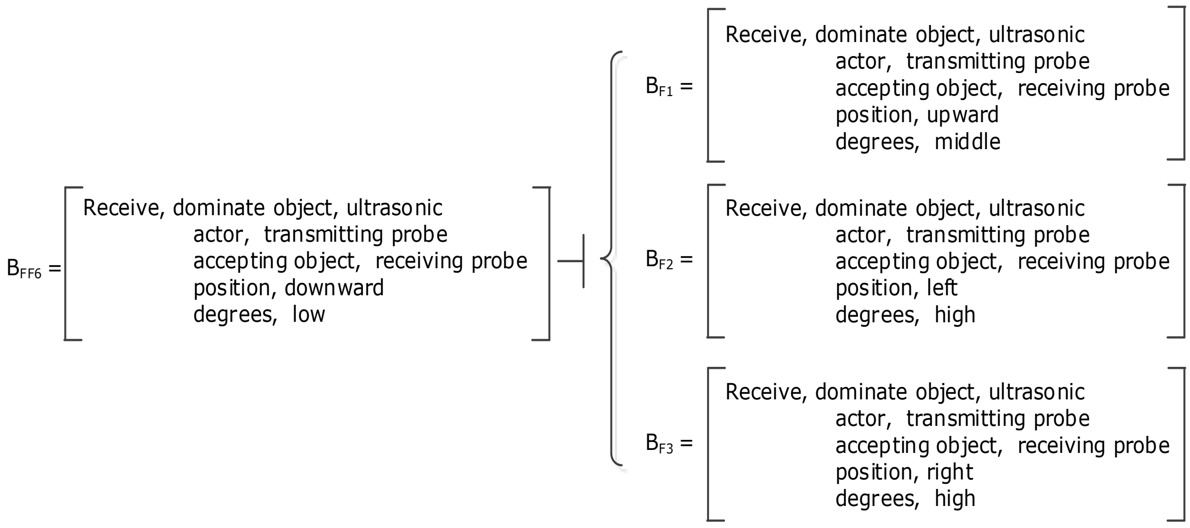
(3) Evaluating solutions with necessary conditions. According to required conditions, we remove solutions that do not meet the conditions. The required service life can be met by these three solutions.

(4) Establishing correlation function and calculating correlation degree. For a characteristic value interval of the service life [0, 100] and values of indicators of the existing design [50, 50, 50], values of the measurement indicators are obtained by comparing with the original design in Figure 4 as shown in Table 3.

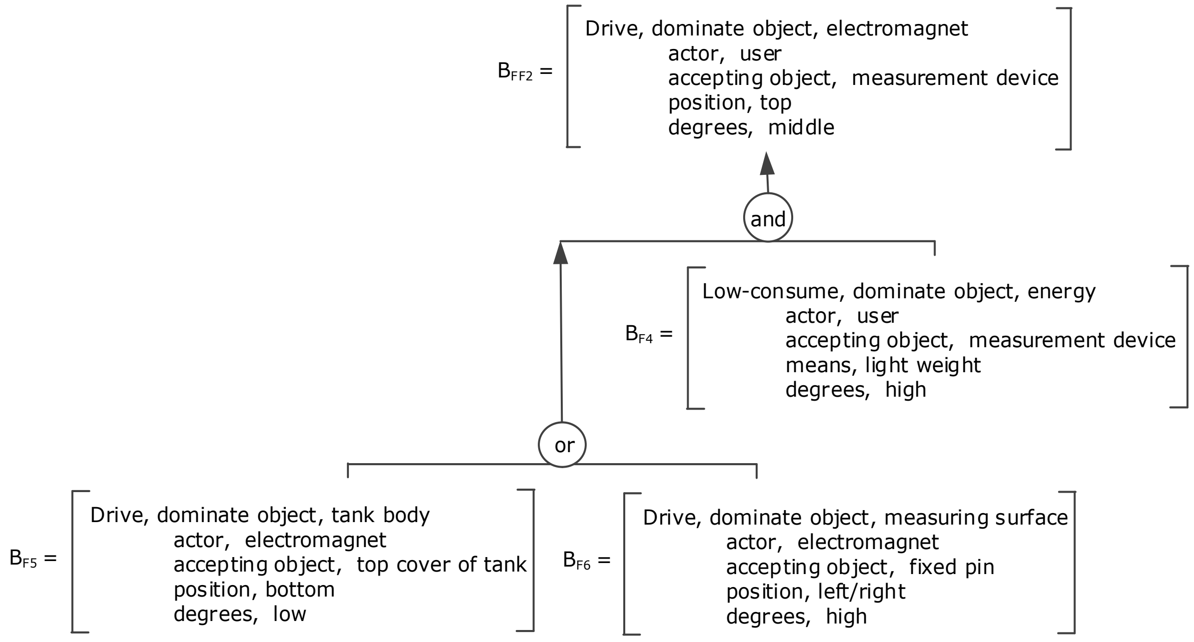
According to K_i =($K_i(S_1)$, $K_i(S_2)$, …, K_i (S_m)) (i = 1, 2, …, n), correlation degrees of solutions on measurement indicators are such as K_1=(50, 45, 70), K_2=(60, 50, 50), K_3=(45, 60, 70), and K_4=(50, 55, 60). Furthermore, standard correlation degrees are calculated using Equation (2.3) as k_1≈ (0.71, 0.64, 1), k_2≈ (1, 0.83, 0.83), k_3≈ (0.64, 0.86, 1), and k_4≈ (0.83, 0.92, 1).

(5) Calculating priority degree. Priority degrees are calculated using Equation (2.4) as G(S1) =0.795, G(S2) =0.769, and G(S3) =0.949.

When the measurement device has high measurement accuracy, low energy consumption, low cost and low occupied space, it meets design requirements. Therefore, values of measurement indicators are reduced, and the measurement accuracy is improved. In other words, the optimal solution has the smallest priority degree. According to Step (5), there is G(S2) < G(S1) < G(S3). Therefore, Solution 2 is selected as the optimal solution.



(a) The extension analysis of function units F_6

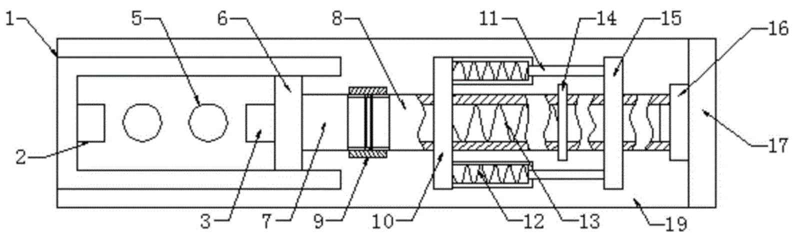


(b) The extension analysis of function units F_2

Figure 6: Function extension analysis.

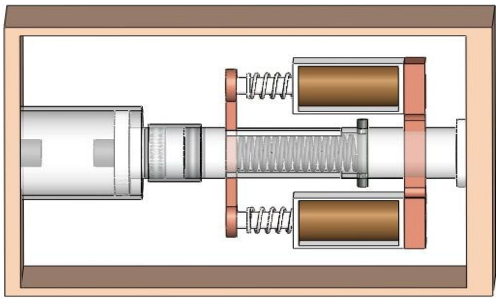
Measurement indicator	Solution 1	Solution 2	Solution 3
measurement inaccuracy degree	50	45	70
energy consumption	60	50	50
cost	45	60	70
occupied space	50	55	60

Table 3: Values of the measurement indicators.

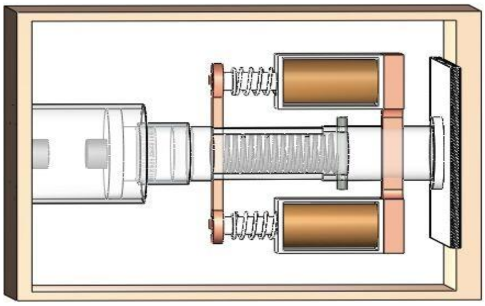


1-tank body, 2-transmitting probe, 3-receiving probe, 4-medium, 5-breathing pipe, 6-piston, 7-left cylindrical tube, 8-right cylindrical tube, 9-casing pipe, 10-fixed pin, 11-upper electromagnet, 12-lower electromagnet, 13-spring, 14-locking pin, 15-connection pin, 16- measuring surface, 17-paper-holden surface, 18-floor

Figure 7: Redesign innovative solutions of the measurement device [24].



(a) The beginning of the measurement



(b) Paper-holden surface with tested paper

Figure 8: Prototype of the redesign measurement device.

The working process of the new design shown in Figure 7 is as follows. The water medium 4 is imported through breathing pipe 5 until transmitting probe 2 and receiving probe 3 are all in the water. When the measurement device doesn’t work, spring 13 is slightly compressed to ensure measurement surface 16 and paper-holden surface 17 contact.

There are two stages when the measurement device starts work. Stage 1: the tested paper is not put on paper-holden surface 17 as shown in Figure 7 and Figure 8(a). Receiving probe 3 receives a pulse signal taken as the measurement signal from transmitting probe 2. Distance D1 from transmitting probe 2 to receiving probe 3 is decided through the analysis and calculation of information processing unit of the measurement device. Stage 2: measuring surface 16 is moved left by compressing spring 13 and separated from paper-holden surface 17. The tested paper is put on paper-holden surface 17 as shown in Figure 8(b), and measuring surface 16 is moved right to compress the tested paper tightly. Similarly, receiving probe 3 receives the measurement signal from transmitting probe 2. Distance D2 from transmitting probe 2 to receiving probe 3 is calculated and recorded. Thickness D of the paper can be decided using D=D1-D2.

In Solution 2, the measuring surface is separated from the tank body to reduce the driving weight. Meanwhile, the receiving probe is placed horizontally with the piston to solve the interference of the medium bubble as shown in Figure 7 and Figure 8. Therefore, the redesign solution greatly improves the measurement accuracy, reduces cost and saves energy.

4 CONCLUSIONS

A function redesign method was proposed for the product innovation based on the extension theory. The method provided ways to innovate product for engineers in the functional level. A triangular fuzzy number was applied to decide the function importance degree for an extension function decision-making process. The DFU and HIDF were determined and represented in a form of the functional basic-element based extension theory. Routes of design innovation were decided by the extension transformation of the functional basic-element. Solutions were achieved by applying TRIZ tools. The optimal solution was decided by the priority degree evaluation method. The proposed method was verified in an innovative redesign of the ultrasonic-based device for the paper thickness measurement.

5 ACKNOWLEDGEMENTS

This research is sponsored by the Natural Science Foundation of China (No.51675159, No. 51975181) and the Central Government Guides Local Science and Technology Development Project (No.18241837G).

Yafan Dong, http://orcid.org/0000-0001-6977-1530
Qingjin Peng, http://orcid.org/0000-0002-9664-5326
Runhua Tan, http://orcid.org/0000-0002-6797-8199
Junlei Zhang, https://orcid.org/0000-0003-2280-6104
Peng Zhang, https://orcid.org/0000-0002-3986-4282
Wei Liu, https://orcid.org/0000-0001-6111-4149

REFERENCES

[1] Bai, Z. H.; Zhang, M.: Extension transformation expression and application research of TRIZ's second standard solutions, Journal of Machine Design, 36(5), 2019, 122-127.
[2] Bovea, M. D.; Wang B.: Redesign methodology for developing environmentally conscious products, International Journal of Production Research, 45, 2007, 4057-4072. https://doi.org/10.1080/00207540701472678
[3] Cao, D. X.; Fu, M. W.: A Knowledge-Based Prototype System to Support Product Conceptual Design, Computer-Aided Design & Applications, 8(1), 2011,129-147. https://doi.org/10.3722/cadaps.2011.129-147
[4] Chen, Y.; Zhang, Z. N.; Xie, Y. B.: A new model of conceptual design based on Scientific Ontology and intentionality theory. Part I: The conceptual foundation, Design Studies, 37, 2015, 12-36. https://doi.org/10.1016/j.destud.2014.12.002
[5] Dieter, G. E.; Schmidt, L. C.: Engineering Design, McGraw-Hill Science/Engineering/Math, New York, 2015.

[6] Hwang, D.; Park, W.: Design heuristics set for X: A design aid for assistive product concept generation, Design Studies, 58(9), 2018, 89-126. https://doi.org/10.1016/j.destud.2018.04.003

[7] Klemme, U.; KoHler, P.: A Hybrid Redesign Strategy to Derive Load-Adaptive Parts, Computer-Aided Design & Applications, 9(5), 2012, 665-677. https://doi.org/10.3722/cadaps.2012.665-677

[8] Li, R. W.; Peng, W. P.; Zhou, J.: Study on Goodness Evaluation Method in Extenics and Its Application in the Variant Design, Computer Integrated Manufacturing System, 7(4), 2001, 48-51.

[9] Lindskog, E.; Vallhagen, J.; Johansson, B.: Production system redesign using realistic visualisation, International Journal of Production Research, 55(3), 2017, 858-869. https://doi.org/10.1080/00207543.2016.1218085

[10] Liu, F.; Liu, Z. L.; Wu, Y. H.: A group decision making model based on triangular fuzzy additive reciprocal matrices with additive approximation-consistency, Applied Soft Computing, 65(1), 2018, 349–359. https://doi.org/10.1016/j.asoc.2018.01.020

[11] Liu, W.; Tan, R.; Cao, G.; Yu, F. Li, H.: Creative design through knowledge clustering and case-based reasoning, Engineering with Computers, 2019, 1-15. https://doi.org/10.1007/s00366-019-00712-5

[12] Lou, J. J.; Gui, F. Z.; Ren, S. D.: Improved TRIZ based on extension innovation method, Computer Integrated Manufacturing System, 24(1), 2018, 127-135.

[13] Ma, H.; Chu, X.; Li, Y.: An integrated approach to identify function components for product redesign based on analysis of customer requirements and failure risk, Journal of Intelligent & Fuzzy Systems, 2018, 1-15.

[14] Schuh, G.; Susanne, A.; Simon, O.; Johannes, S.: Technology Road mapping for the Production in High-wage Countries, Production Engineering, 5(4), 2011, 463–473. https://doi.org/10.1007/s11740-011-0324-z

[15] Smith, S.; Hsu, L. Y.; Smith, G. C.: Partial disassembly sequence planning based on cost-benefit analysis, Journal of Cleaner Production, 139, 2016, 729-739. https://doi.org/10.1016/j.jclepro.2016.08.095

[16] Smith, S.; Smith, G.; Shen, Y. T.: Redesign for product innovation, Design Studies, 33(2), 2012, 160-184. https://doi.org/10.1016/j.destud.2011.08.003

[17] Tan, R. H: TRIZ and the application, Beijing: Higher Education Press, China, 2010.

[18] Tan, R. H.; Dong, Y. F.; Yang, B. J.; Zhang, P.: Research on Opportunity-Driven Redesign Process to Cooperate with Training Innovative Engineers in China, Chinese Journal of Mechanical Engineering, 31(04), 2018, 148-159. https://doi.org/10.1186/s10033-018-0274-x

[19] Zarandi, M. H. F.; Razaee, Z. S.; Karbasian, M.: A fuzzy case-based reasoning approach to value engineering, Expert Systems with Applications, 38(8), 2011,9334-9339. https://doi.org/10.1016/j.eswa.2011.01.124

[20] Zhang, X.; Mei, C.; Chen, D.; Yang, Y.: A fuzzy rough set-based feature selection method using representative instances, Knowledge-Based Systems, 151(1), 2018,216-229. https://doi.org/10.1016/j.knosys.2018.03.031

[21] Zhao, Y.; Hong, H.; Jiang, G.: Conflict Resolution for Product Performance Requirements Based on Propagation Analysis in the Extension Theory, Advances in Mechanical Engineering, 6,2015,589345-589345. https://doi.org/10.1155/2014/589345

[22] Zhang, J. P.; Peng, Q. J.; Cao, G. Z.; Tan, R. H.: Design for Multi-functional Product by Searching Shareable Functional Components, Computer-Aided Design, 17(4), 2020, 716-726. https://doi.org/10.14733/cadaps.2020.727-739

[23] Zhang, P.; Gao, S. S.; Tan, R. H.: A Vertical Ultrasonic-Based Measurement Device for Paper Thickness, China, Patent, CN103900507B, 2014/4/9.

[24] Zhang, P.; Gao, S. S.; Tan, R. H.: An Ultrasonic-Based Measurement Device for Paper Thickness, China, Patent, CN104006772B, 2016/7/6.