An Attribute-based Method for Identifying Implicit Contradictions in Product Development

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Abstract. Contradiction indicates that a technical solution has both beneficial and harmful effects to product. The implicit contradiction gradually appears during the product use, which can cause great losses to users. The existing research on contradictions mainly focuses on the solution of existing contradictions. This paper proposes an attribute-based method to identify and solve implicit contradictions in product development to improve the safety and reliability of the product. Using the relationship between product attributes and functions, the anticipatory failure determination and resource attribute similarity are proposed to identify implicit contradictions comprehensively and effectively. TRIZ tools and function-behavior-effect oriented search are applied to solve implicit contradictions. A pipe cutter is analyzed in a case study to illustrate the feasibility of the proposed method.

Keywords: Implicit contradictions, Attributes, Anticipatory Failure Determination (AFD), Innovation design, Pipe cutter.
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1 INTRODUCTION

Innovation increases the success rate of mechanical products in the market and plays an important role in the product development. The innovation translates customer needs and desires into the final product implementation [28]. Innovative products attract interests of customers [14]. Innovation generates value for money, quality and safety. Innovation is not randomly formed; it requires a systematic methodology [2]. As studies show that the concept design determines 80% of the cost of new product development [38], an innovative method of product design can effectively improve the product performance and reduce waste of resources.

The stage-gate model is commonly used in the area of mechanical product design to manage the product innovation process. This model was first proposed by Cooper in 1988 and is based on successful product development experience with a large number of large and successful companies [11]. The development process is divided into stages, including the complete development process from Idea Generation to Launch. Evaluative "gates" between phases determine whether the results of the previous stage meet the design requirements and select what to move on to the next stage. Several evaluation sessions and decisions ensure that the project and process are correct, keeping focus on the customer and the market and increasing success and efficiency. Over the years, researchers and companies have optimized the Stage-Gate process to accommodate design development processes for products with different characteristics [12].

The root of innovation is to solve key technical problems [34]. Mainstream innovative design methods focus on the transformation of requirements to product design indicators [36], such as QFD (Quality Function Deployment), FBS (function behavior structure) and AD (axial design). However, there is a lack of the effective solution to contradiction problems encountered in the design process. TRIZ (the theory of innovative problem solving) [1] provides tools for solving contradictions in design. The evolution of the technology system or product is a spiral development, accompanied by the settlement of contradictions.

Contradictions mean that the change of a technical index can lead to both beneficial and harmful effects. For example, increasing the battery capacity of a cell phone will produce two effects: improving battery life and bulkiness. There are technical and physical contradictions of the technical system in the engineering field. The technical contradiction refers to the opposite characteristics in a subsystem or component. The physical contradiction is the opposite characteristics between two or more subsystems. According to the degree of prominence, contradictions can be divided into explicit and implicit contradictions. The explicit contradiction refers to a kind of contradictions that are obviously to produce harmful results and can be solved immediately, otherwise the system cannot work normally. The implicit contradiction is one that does not have negative impacts on the system at present, but will gradually appear with the change of time, environment, or other factors. The implicit contradiction in product, when it occurs, will cause great losses to users.

Contradictions are ubiquitous, dynamic and obstruction in the product development. We must accurately find and completely solve contradictions rather than to alleviate them using compromise methods [39]. Classic TRIZ uses engineering parameters and contradiction matrix to determine contradictions and invention principles. OTSM-TRIZ uses the ENV model to express contradictions for the internal relationship between contradictions, which is good at solving interdisciplinary complex problems [6]. The Root Case Analysis (RCA) analyzes contradictions through the hierarchical decomposition of cause and effect of problems [24] to deeply excavate contradictions that are easy to be ignored. Some studies have used QFD to assist in finding and identifying key contradictions [16], which can improve the effectiveness of contradiction identification.

The existing research on contradictions focuses on the contradictions that have occurred, and pays less attention to implicit contradictions. This paper explores the implicit contradiction according to product attributes and their relations to improve objectivity and comprehensiveness of design solutions. Methods of Anticipatory Failure Determination (AFD) and Function-Behavior-Effect oriented search (FBEOS) are used to find and solve implicit contradictions. A pipe cuter is developed as an example to illustrate feasibility of the proposed method.

2 RELATED WORK

2.1 Methods of Anticipatory Failure Determination

There are different theories and methods for fault diagnosis. Failure Mode and Effects Analysis (FMEA) is a common tool for the fault analysis [29][35]. The critical view is that FMEA is a basic process commonly used in the industry, but it is unable to find all potential faults [18]. Methods of

Anticipatory Failure Determination (AFD) is a failure analysis and prediction tool based on TRIZ. It can analyze the potential failure modes of a system and produce high-quality solutions using TRIZ. AFD reverses the traditional idea of failure analysis from "why failure" to "how to make it fail" [35]. The unique feature of this method is to deliberately invent failure, which is based on the Subversion Analysis, also known as Sabotage Analysis [9]. Silva [35] compared AFD and FMEA in theory and practice, and found that AFD is more suitable for product design and development. There are two main AFD methods, AFD-1 and AFD-2. AFD-1 is used to identify faults that have occurred and AFD-2 is used to predict faults that have not yet occurred. AFD-2 is used, for convenience, called as AFD in this paper.

The combination of AFD and other theories is a trend. Bai [3] proposed a failure prediction and solution method combining AFD, CREAM and TRIZ, focusing on the failure cause to form a complete analysis process. Thurnes [37] hybridized FMEA and AFD for a new failure prediction method, which combines advantages of FMEA and AFD, but the process is complex. Zhang [42] developed a general failure prediction model based on the interaction of material attributes in the function and AFD. But the process is complicated and not applicable to complex systems. Jensen [21] proposed a system risk identification method by combining AFD and FRAM (functional resonance analysis method), and using a creative approach to invent potential hazards and threats in complex systems, but its accuracy needs further validation.

AFD plays an important role in practical product design. Chen [8] used AFD to identify problems in product systems and used TRIZ to complete an improved design of battery explosion-proof equipment for lithium batteries. Chybowski [10] presented the application of AFD in the conceptual design stage, assessing potential failures through multiple evaluation metrics for analyzing devices to reduce hull resistance. Rau [30] proposed a green product design method using AFD and TRIZ to reduce the environmental impact of products. Chen [7] proposed an eco-friendly AFD approach for a failure expression method based on the inverse standard solution to assist designers in addressing potential ecological risks in engineering systems.

In conclusion, AFD has advantages in failure prediction and can be improved by combining with other methods. AFD has a wide range of applications and can be used to assist in product concept design as well as in redesign. Due to its advantages for the failure prediction, AFD can be used to assist in finding implicit contradictions in systems. But its accuracy and operability of the predictions must be improved.

2.2 Attributes

Attributes are the unavoidable, essential and indivisible properties of tangible or intangible matter that are the basis of distinction between substances [42]. Attributes are divided into essential and non-essential attributes. Essential attributes are the unique and important characteristics of something that is different from other things in a system or product. Based on the previous work [4], the attributes can be divided into physical, chemical, process, material and geometric attributes, 128 in total. For example, attributes can be prescribed and calculated measures of material properties. The common measure of temperature is degrees Celsius. Thermal conductivity is the ratio of heat transferred to time. Attributes can change over time and over space in nature [41].

Function is the result of the effect of attributes. The substance-field model theory stipulates that field F of substance S_2 acts on substance S_1 to form a function. According to the ideal degree, effects can be classified as standard, harmful, insufficient, or excessive results. A field is a special attribute in the form of one or more specific substances S_x [4], such as electric fields, magnetic fields, forces, etc. Functions of system components depend on the interaction of attributes shown in the maintenance or change of attributes [4]. For example, the protection of a cell phone mainly uses physical attributes of the shell to maintain the function. Obviously, the function is the attribute effect of components in a product, according to user expectations. However, with expected results there are unexpected results. If the unexpected result breaks the implementation of the function, attributes can cause harmful effects between components. For example, the inner side of automobile windshields are easy to be covered by fog in winter because the temperature attribute of glass changes the state attribute of water vapor from gaseous state to liquid. Theoretically, after determining attributes and correlations of a system and system components, potential problems or implicit contradictions can be identified in advance.

3 PROPOSED METHOD

3.1 The Concept of Requirements

Obtaining requirements at the beginning of product development is the key to success, and requirements are present throughout almost the entire development process [13]. Requirements Engineering is a subfield of software engineering that aims to specify the problems to be solved, including requirements development and management. Requirements acquisition is the most important branch of requirements development to be addressed first, followed by the analysis, organization and validation of the obtained requirements. The key to requirements acquisition is to synthesize a large number of abstracted requirements from various stakeholders, which are not clear and are limited by business or technology constraints. Requirements may be vague or incomplete [33], as no user or designer can correctly summarize all the requirements of a project. Requirements can change from time to time due to changes in the external environment, etc., and are difficult to anticipate. All these reasons make requirements acquisition a difficult process.

Mechanical product development also needs design goals and limitations, i.e., requirements. The product concept generation and development process is all about addressing customer needs. Comprehensive and accurate requirements are the key to product design. The general process of requirements analysis consists of information gathering, requirements identification, evaluation and specification [27]. The first two steps are the key and difficult points of the analysis. Common analysis methods include Stakeholder Analysis, Secondary Market Research, Context of Use Analysis and User Surveys, Focus Groups, and Future Workshops. The above methods can obtain customer needs in a low-cost and fast way, and can predict some future needs to a certain extent, which helps to produce innovative results. However, the information may be too complicated and difficult to distinguish, leading to more analysis time, and it is not easy to avoid the influence of the personal thoughts on the results, and it is difficult to predict the hidden needs due to the potential risks.

According to the timeline, requirements are divided into existing and future requirements [32]. Implicit conflicts are an important part of future requirements but have not yet affected the product functionality and therefore cannot be known by customers or users for now. Implicit conflict analysis is a developer's reassessment of the existing product to detect future requirements, the resolution of which can lead to a more reliable and innovative conceptual design. In this paper, implicit conflicts are analyzed from potential failures as a goal for product design and improvement.

3.2 AFD-based Failure Mode Determination

A functional model of the system is required for the failure analysis. Due to complexity of system functions, it is difficult to analyze them as a whole and therefore functions are classified based on their type. A complete product technology system consists of four parts: energy system, transmission system, control system and actuation system [15]. The energy system is the source of energy and its conversion, the transmission system is the part that transmits energy, the control system ensures the controllability of the actuation process, and the actuation system ultimately has a valuable effect on the target. The actuation system is the key to the function and the other three parts play an important supporting role to the actuation system. All four parts must perform properly in order to ensure the overall functionality. Sometimes the four parts of a system may not all be present, such as the control system.

The success model of each subsystem function is formulated according to the classification using the AFD method. The model shows the expected functional state completed at a certain time or stage of the system, which is the premise of determining the failure model. A success model can be measured based on recommendations in Table 1. There is only one correct process and outcome for the success of a function, as expected by the designer. For example, the success model of a pencil's writing function is that the graphite particles adhere to the paper and leave specific marks through friction between the lead and paper.

<table>
<tr><th>Technical system</th><th colspan="2">Success model</th></tr>
<tr><td>Energy system</td><td>• Energy output is stable
• Energy conversion is smooth</td><td rowspan="4">• Actions between components are executed properly to meet the desired effect.
• Insufficient, excessive and harmful actions are corrected.
• No undesired effects on system functions are produced by super-system or outside the system.</td></tr>
<tr><td>Transmission system</td><td>• Energy delivery is smooth
• Energy is transferred from the energy system to the actuator system as required</td></tr>
<tr><td>Control system</td><td>• Controlled items are within set limits
• Control behavior is consistently effective</td></tr>
<tr><td>Actuation system</td><td>• Perform the corresponding functions according to the design requests.
• Targets generate the right changes</td></tr>
</table>

Table 1: Suggestions of success model.

Failure means that part or all of the technical system cannot perform the specific function according to design requirements. AFD-based failure prediction uses reverse thinking, that is, finding ways to make a normal function fail. According to the success model, ask "how to make it fail" for any point in the model to get a series of failure modes. Since the success of the function depends on the full realization of all the success modes. As long as there is one failure mode, it represents the failure of the entire system. These failure modes are summarized to get the failure modes of the system, as shown in Table 2.

Technical system	*Success model*	*Failure mode*
Energy system	Success models for energy system	mode 1 mode 2
Transmission system	Success models of transmission system	…
Control system	Success models of control system	…
actuation system	Success models of actuation system	… mode N

Table 2: Summary of success and failure modes.

3.3 Risk Attributes Extraction

Failure modes arise when some attributes disrupt the original order of relations between attributes of a successful mode. These attributes are called failure source attributes (a_f). Each failure mode contains a set of failure source attributes that form a failure attribute group $A_n = \{a_1, a_2, ..., a_m\}$. The failure attribute group is formed to a potential resource (PR_n) with the same failure source attributes, $n \in [1, N]$. The potential resource is proposed for corresponding attributes. The set of potential resources is $U_V = \{PR_1, PR_2, ..., PR_N\}$ and the set of attributes of any potential resource PR_n is $U_{va} = \{a_1, a_2, ..., a_m\}$. Introduction of these potential resources makes some functions of the original system to be affected for failure in performance according to design specifications.

Potential resources are uncertain assumptions that do not actually occur exactly according to the failure modes listed, so it is necessary to select the failure mode with a high probability. The occurrence of failure modes is dependent on resources and attributes involved. Failure modes are likely to occur if resources with similar attributes are readily available. A thorough resource analysis can help to improve the rate of success in failure prediction. The analysis of resources should not only be comprehensive, but also be within right limits. An excessive scope would be meaningless, so we set resources in a system and supersystem context, including the present and future. Attributes of resources are determined from the 128 attributes.

Potential resources with collected system and supersystem resources are compared to screen potential failure modes with the high similarity. The resource comparison is based on the attribute similarity [4] with appropriate refinements. High attribute similarity means that the resource is prone to failure. The calculation process is as follows.

3.4 Attributes Similarity

The complete process of calculating the similarity of resource attributes is shown in Figure 1. Comparing properties of system resources with a potential resource, the system resources with non-empty intersections of properties are summarized as similar resources (S_i), $i \in [1, M]$, $M \leqslant N$. The set of similar resources is $U_S = \{S_1, S_2, ..., S_M\}$. The set of attributes of similar resources is $U_{sb} = \{b_1, b_2, ..., b_k\}$.

The set of potential resource attributes U_{va} and the set of similar resource attributes U_{sb} form a unified attribute set U_a, $U_a = U_{va} \cup U_{sb} = \{c_1, c_2, ..., c_j\}$. Transforming each resource attribute into a space vector, sub-vector $\mathbf{e_r} = 1$ if the resource has attribute c_r and $e_r = 0$ otherwise, where $r \in [1, j]$. Vector $\mathbf{X_n} = (x_1, x_2, ..., x_j)$ is formed for potential resources and vector $\mathbf{E_i} = (e_1, e_2, ..., e_j)$ for similar resources, where the values of x_r and e_r are 0 or 1.

Attribute weights ω_{xr} and ω_{er} of potential resources and similar resources are obtained by using Analytic Hierarchy Process (AHP). Experts scored the attributes of one potential resource and multiple similar resources within the same group. According to the influence of the attributes to failure, a scoring rule of 1 to 5 was used, representing "equally important", "slightly important", "obviously important", "strongly important", and "extremely important", and then constructed a judgment matrix as shown in the following Table 3. Next, we calculated the feature vectors, feature roots and weight values, and then conducted the consistency test. If the consistency test passes then the weight values are plausible.

Index	*Attribute 1*	*Attribute 2*	*Attribute 3*
Attribute 1	1	1/2	1/3
Attribute 2	2	1	1/4
Attribute 3	3	4	1

Table 3: Summary of success and failure modes.

To improve weights of common attributes, Equations (3.1) and (3.2) are applied to calculate the attribute weights for two types of resource attribute comparison cases, as α_{xr} and α_{er}, respectively. The attribute comparison weights are normalized as $\hat{\alpha}_{xr}$ and $\hat{\alpha}_{er}$, according to the normalization formula $\hat{y}_i = y_i / \sum y_i$.

$$a_{xr} = \frac{\omega_{xr} \cdot x_r \cdot k}{2l} \tag{3.1}$$

$$a_{er} = \frac{\omega_{xr} \cdot e_r \cdot k}{2l} \tag{3.2}$$

where x_r and e_r are sub-variables of the potential resource vector and similar resource vector, respectively. k is the sum of the number of attributes possessed by the two resources, k = 1 if only one has the attribute and k = 2 if both have it. l is the number of all attributes when the two resources are compared, i.e. the number of elements of the unified attribute set U_a.

Equation (3.3), using the angle cosine method to calculate the attribute similarity $S_{Xn,Ei}$ of potential and similar resources. Comparing the similarity of each similar resource with the potential resource, the similar resource is selected with the greatest possibility of failure mode, called the risk resource.

$$S_{X_n,E_i} = \frac{\sum_{r=1}^{j} \hat{a}_{xr} \times \hat{a}_{er}}{\sqrt{\sum_{r=1}^{j} \hat{a}_{xr}^{\ 2}} \times \sqrt{\sum_{r=1}^{j} \hat{a}_{er}^{\ 2}}} \tag{3.3}$$

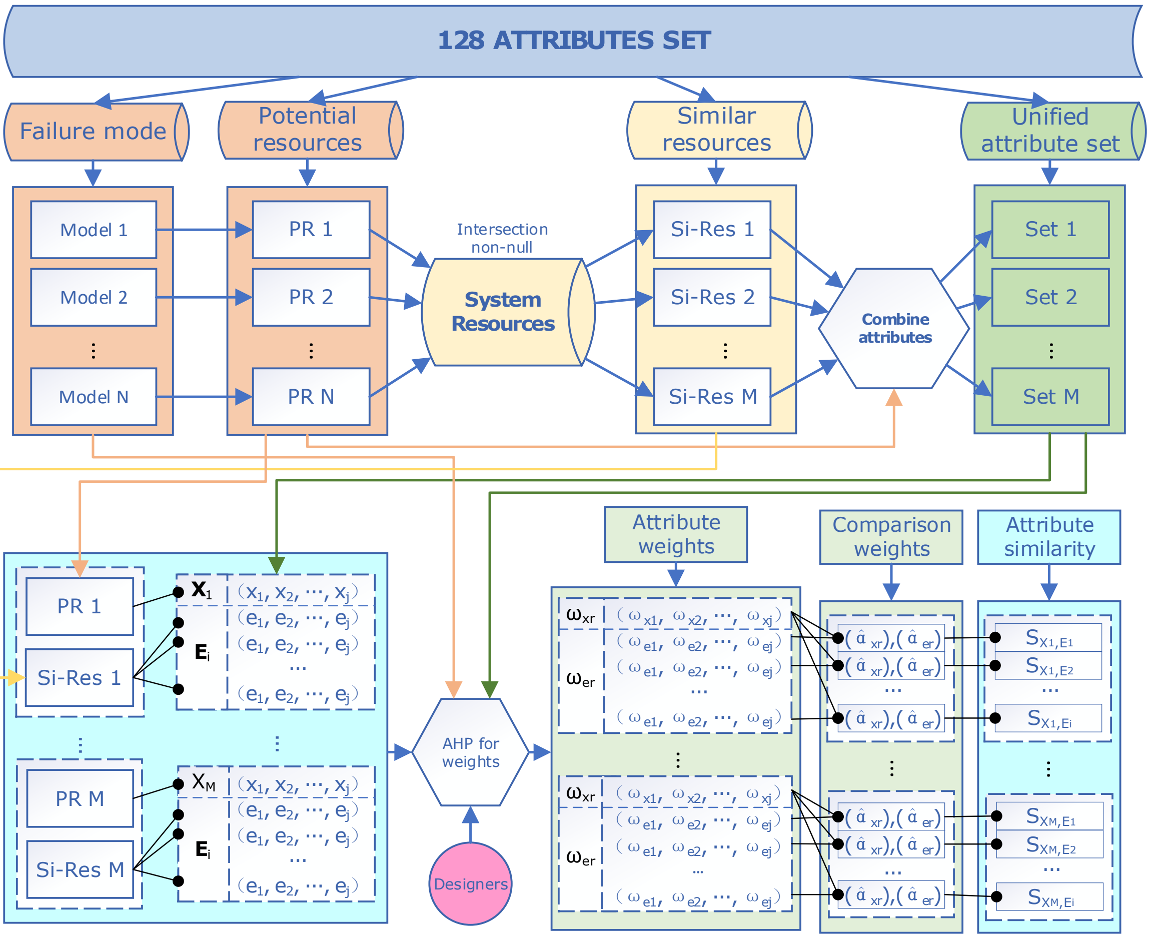

Figure 1: The process of calculating the similarity of resource.

3.5 Identifying Implicit Contradictions

Implicit contradictions are anticipated and solved before they arise to avoid risks and improve product quality. There are potentially harmful interactions between risky resources and system components that may cause insufficient, excessive or harmful functionality of the product. These potential problems should be avoided. Attempts to solve potential problems caused by risk attributes. When the resolution of a potential problem results in a new problem, it means that there is an implicit contradiction. The process of identifying implicit contradictions is shown in Figure 2.

Using the Element-Name-Value (ENV) model [40] to represent the contradiction, control parameters in the contradiction change in two directions, which causes different evaluation parameters to change in opposite directions. One of the evaluation parameters comes from the problem, the change in the control parameter is the initial solution and the new problem caused by the solution is the other evaluation parameter. Their coupling forms the implicit contradiction in design process. Obviously, the initial solution is not the final solution. Contradictions must be eliminated before they can be completely solved.

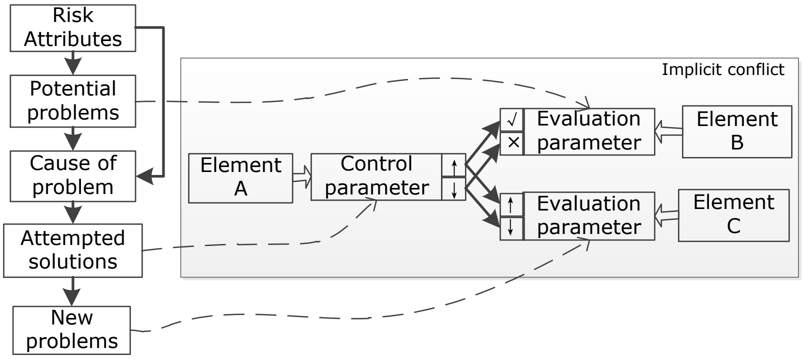

Figure 2: Implicit contradiction determination process.

Contradictions are a challenge in design, but also an opportunity, as solving them means producing high level innovative designs. TRIZ theory provides a variety of methods for solving contradictions, such as the invention principle, the separation principle and effect searching. It can form a systematic process for a new knowledge search method for solving contradictions.

Function/Behavior/Effect-Oriented Search (FBEOS) [25] is an effective method for searching innovative knowledge. This method, as shown in Figure 3, first analyzes and summarizes functions of the research object, then expands behaviors and principles (effects) corresponding to functions, and extracts keywords, finally, constructs patent search sentences according to the logical relationship of keywords, and filters valuable innovation knowledge from patents. It gradually concretizes the abstract function concept and obtains multiple possible function implementation paths to find appropriate knowledge for innovative design. In the subsequent design process, we can use the obtained knowledge to gain design solutions.

4 CASE STUDY

The pipe cutter is a widely used tool in manufacturing, construction and firefighting applications. We use the proposed method to analyze the implicit contradictions of a pipe cutter shown in the Figure 4 [19]. This pipe cutter includes a cutting mechanism, a clamping mechanism, and a control mechanism. It is easy to operate with a flat cutting surface and can cut a wide range of materials.

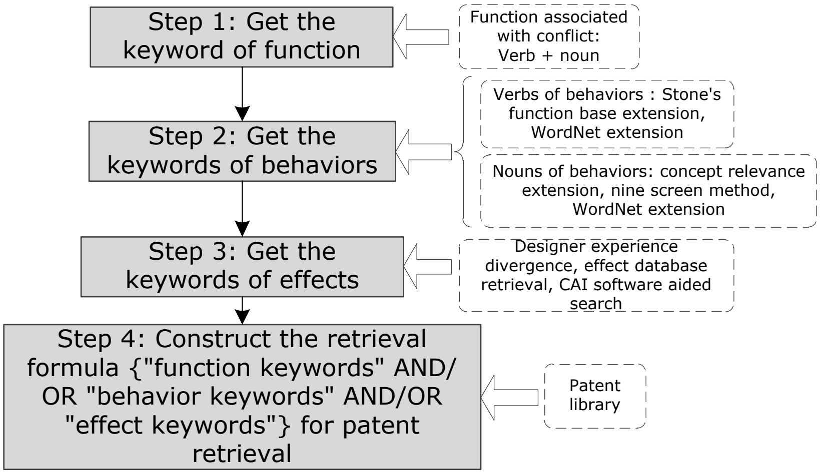

Figure 3: Process of FBEOS.

Figure 4: A pipe cutter.

4.1 Determining Failure Mode of the Pipe Cutter

The pipe cutter has 23 components. Its functional model is built as shown in Figure 5. The pipe cutter includes two complete sets of sub-functions, a cutting function with practical value and a clamping function to support the cutting function. Specifically, the energy system is generated by the power supply and operator. The transmission system is the power from the motor to the saw blade and the clamping knob to the end of the clamping device. The actuation system is the clamping device to clamp the pipe and saw blade to cut the pipe. The control system is for operator to control the motor and control the pipe adjustment position by means of the handle. The others are supporting functions.

The above functions are divided into two technical subsystems according to needs of energy, transmission, actuation and control. The success modes of each part are determined based on suggestions in Table 1. Seven success modes are obtained for proper functions of the pipe cutter. Using the reverse thinking of AFD to find how the function can be failed, appropriate failure modes are obtained. The results are shown in Table 4 with 6 main failure modes.

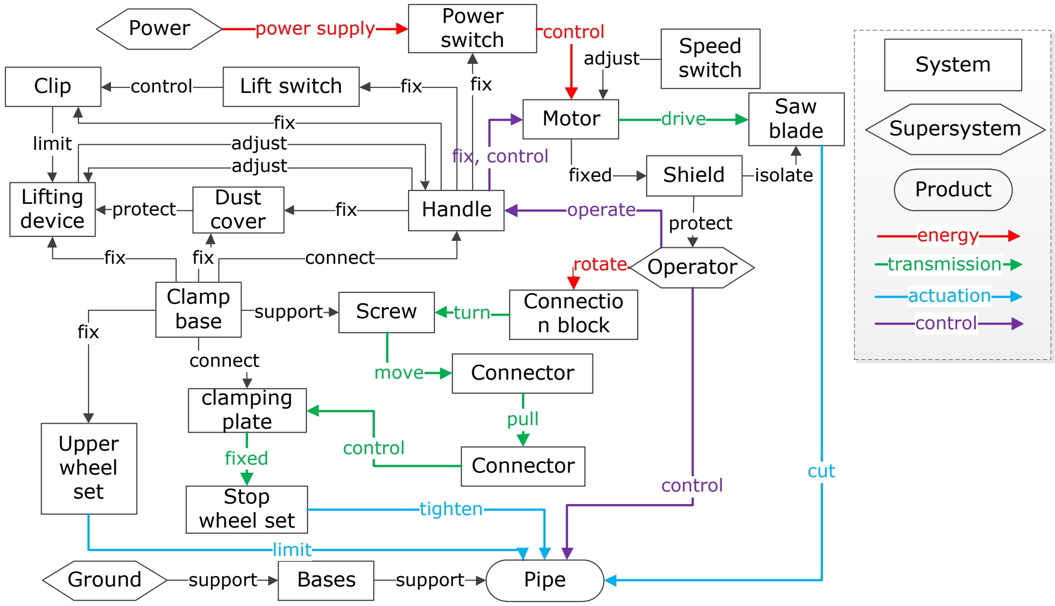

Figure 5: Function model of the pipe cutter.

Technical system	*Function*	*Success model*	*Failure mode*
Energy 1	The operator turns the clamping knob	The clamping knob can be rotated forward and backward normally.	1.Cannot tighten or loosen the clamping knob
Actuation 1	Stop wheel set clamping the pipe	The stop wheel set and upper wheel set form a stable triangle to control the pipe in the defined position.	2.Inability to fix and clamp the pipe
	…		
Actuation 2	Saw blade cutting the pipe	The basis on the ground supports the pipe, which rotates smoothly on the basis. The saw blade cuts the pipe smoothly. The shield effectively prevents danger.	3.Saw blade thermal decay
	…		4.The location of the pipe changes
Control 2	The operator operates the handle	Before the cutting operation, turn on the lifting switch, adjust the position of the lifting device using the handle to set the right amount of feed and turn off the lifting switch. The dust cover prevents the lifting device from being contaminated. During the cutting operation, control the handle to cut forward and pause after a certain angle. Rotate the pipe backwards to the right position and continue cutting until the cut is done.	5.Excessive resistance to the advance of the pipe cutter
	…		6.The cutting process is not smooth

Table 4: Success and failure modes of the pipe cutter.

4.2 Extracting Risk Attribute Sets

The failure attribute group is determined based on failures in the list of 128 attributes and failure modes. The set of attributes is equated to potential resource PR_n, and results are shown in Table 5.

Failure mode	*Failure attribute group (Potential resource PR_n)*
1. Cannot tighten or loosen the clamping knob	{humidity, viscosity, absorptivity, hardness, fluxility}
2. Inability to fix and clamp the pipe	{diameter}
3. Saw blade thermal decay	{friction, Thermal conductivity, time, temperature}
4. The location of the pipe changes	{friction, frequency, flatness}
5. Excessive resistance to the advance of the pipe cutter	{force, friction, pressure}
6. The cutting process is not smooth	{force, frequency}

Table 5: PR_n of the pipe cuter.

A comprehensive analysis of the resources and attributes of the system and supersystem, both at this time and in the future, is shown in Table 6 (partial list).

System resources	*Attributes*	*Supersystem Resources*	*Attributes*
Power switch	Conductivity, Corrosion resistance, Flammability	Power	Electric current
Speed switch	Conductivity, Corrosion Resistance, Flammability	Ground	Friction, Humidity, Hardness, Smoothness
Motor	Frequency, Speed, Acceleration, Force, Magnetic, Mass, Sound, Temperature	Operator	Force, Mass
Saw blade	Force, Friction, Speed, Density, Conductivity, Frequency, Thermal Conductivity, Temperature, Sound, Hardness	Oil stain	Viscosity, Adsorptivity, Fluxility
Lift switch	Conductivity, Corrosion Resistance, Flammability	Water	Conductivity, Humidity, Volatility, Endothermic, Viscosit, Fluxility
…	…	…	…

Table 6: Resources and their attributes.

4.3 Calculating Attribute Similarity

Failure mode 1 is used as an example to illustrate the attribute similarity calculation process. The set of attributes of potential resource PR_1 is U_{va} = {Humidity, Viscosity, Adsorptivity, Hardness, Fluxility}. PR_1 is compared with the system resource. The set of similar resources is summarized as U_S= {ground, oil stain, dust, water, air}, and the set of attributes is U_{sb}= {friction, humidity, hardness, fluxility, viscosity, adsorptivity, smoothness, volume, water absorption, Conductivity, volatility, Endothermic, density, oxidizability}.

Unified attribute set is $U_a = U_{va} \cup U_{sb}$={humidity, viscosity, adsorptivity, hardness, fluxility, friction, smoothness, volume, water absorption, Conductivity, volatility, Endothermic, density, oxidizability}. Each resource attributes are transformed into space vectors as follows.

$$X_1, E_1 \sim E_4 = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{4.1}$$

The weight of each resource attributes is decided using AHP, the results are shown in Table 7. The similarity between similar resources and potential resources are searched using Equations (3.1) to (3.3). It is found that oil stain and water have the highest degree of similarity. As a result, oil stain and water in the environment can be decided as risky resources that may lead to the failure of the clamping knob function.

Date	*PR_1*	*Ground*	*Oil stain*	*Dust*	*Water*	*Air*
Humidity	0.1544	0.0688	0	0	0.3382	0.096
Viscosity	0.2163	0	0.4161	0	0.1155	0
Adsorptivity	0.148	0	0.2579	0.1894	0	0
Hardness	0.074	0.2304	0	0.3493	0	0
Fluxility	0.4072	0	0.326	0.0323	0.3382	0.2735
Friction	0	0.6023	0	0	0	0
Smoothness	0	0.0985	0	0	0	0
Volume	0	0	0	0.3041	0	0
Water absorption	0	0	0	0.125	0	0
Conductivity	0	0	0	0	0.0609	0
Volatility	0	0	0	0	0.0422	0
Endothermic	0	0	0	0	0.105	0.2146
Density	0	0	0	0	0	0.4852
Oxidizability	0	0	0	0	0	0.2691
Attribute similarity (compared to PR_1)		0.2402	0.9021	0.3385	0.8781	0.6659

Table 7: Resource attribute weight.

The similarity of the remaining potential resources to their corresponding similar resources is calculated in the same way, the results are shown in Table 8.

4.4 Identification and Solution of Implicit Contradictions

According to potential problems as well as new problems found when solving them, the implicit contradictions of the system are identified as shown in Figure 6.

For contradiction 1: According to the invention principle No. 28, the interaction with the object is accomplished with electric and magnetic fields as well as electromagnetic fields, the solution is to use electric clamping instead of manual operations.

Potential resources	*Risk resources*	*Potential problems*
PR_1	Oil stain, Water	Oil or water sticks to the clamping knob and the friction of the operation rotation is too low to operate.
PR_2	Pipe	The machining range is limited and the pipe diameter cannot be clamped when it is outside the specified range.
PR_3	Saw blade, Pipe	The saw blade rubs against the pipe over a long period of time generating a lot of heat
PR_4	Ground, Bases	The base is not fixed to the floor and the pipe tends to move during the process
PR_5	Clamping plate	The clamping plate exerts too much force on the pipe, making it difficult to move the saw blade
PR_6	Clamping plate	Low pressure between the clamping plate and the pipe to limit the non-essential relative movement of the pipe cutter to the pipe

Table 8: Risk resources and potential problems.

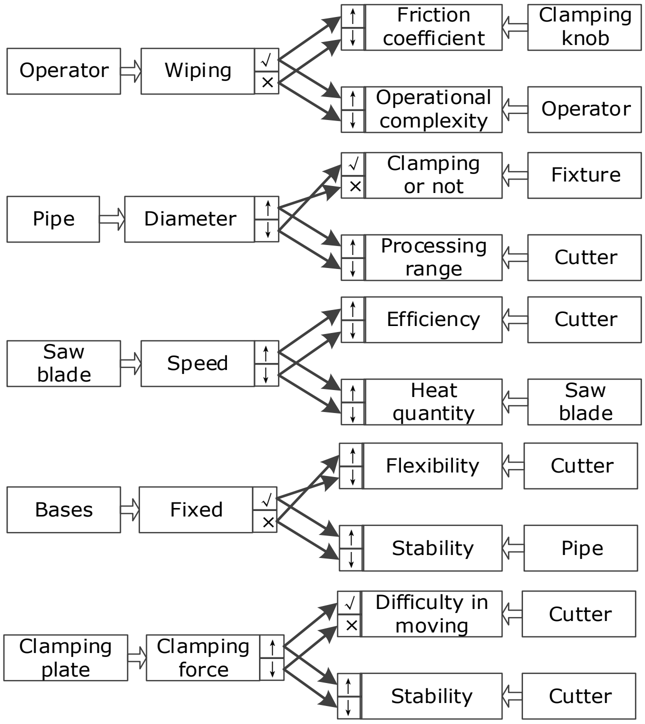

Figure 6: The implicit contradictions of the pipe cutter.

For contradiction 2: According to the invention principle No. 35, changing the flexibility of the object, the solution is to change the rigid clamping plate into a flexible one.

For contradiction 3: According to the invention principle No. 28, changing a static field into a dynamic field, the solution is to add a wind cooling device.

For contradiction 4: Searching for effects on Constrain Solid and Rotate Solid, respectively, it is found that effects available are Static Friction and Axle, the solution is to add a friction wheel to help rotate the pipe when cutting to replace manual control.

For contradiction 5: Searching for patents based on the keywords {clamping pipes and dynamic} and find a patent titled "An adaptive welding track for pipe ellipticity and extract the elastic feet technology." Installing elastic feet on the fixture allows the clamping force to change dynamically and not to be too tight or too loose.

Combining the above solutions results in a conceptual design solution as shown in Figure 7. This solution resolves the above contradictions. Using flexible clamps allows the length to be changed as required. Flexible legs are fitted to each piece of the clamp to avoid excessive clamping forces. Using a motor to control the clamping and piping improves controllability and stability. Adding a wind cooling turbine prevents the saw blade from overheating.

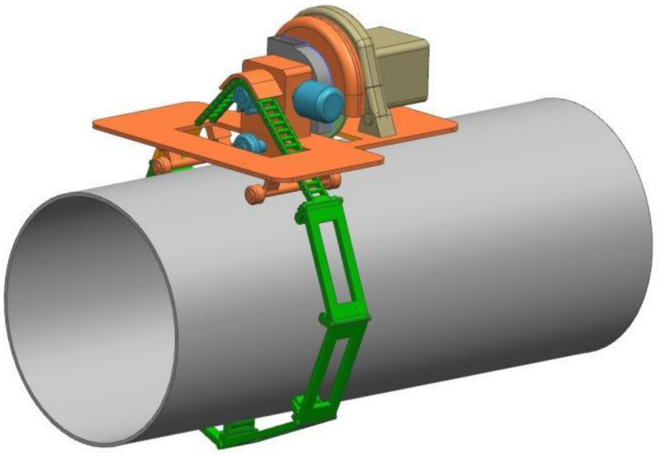

Figure 7: Concept design proposal for the pipe cutter.

5 CONCLUSIONS

To address problems in identifying implicit contradictions, this paper proposes a method for determining implicit contradictions in products based on AFD and resource attributes, which enriches the theory of contradiction resolution. Compared with traditional FMEA and FTA, it weakens the mindset of designers and avoids relying only on experience and historical data. Based on AFD, the possibility of failure is considered from the perspective of the attributes of resources, which enables a more comprehensive analysis and improved reliability. The selection of a serious contradiction problems as the object of treatment can improve the efficiency of the solution and increase the innovativeness of the result. The utilization of methods such as TRIZ improves the quality and speed of solving the contradiction problems. The method can detect and resolve implicit contradictions effectively to improve product reliability. An analysis of the pipe cutter illustrates the effectiveness of the method. The method also provides an opportunity for companies to discover new directions of innovation for their products.

The development of mechanical products is similar to the software development process, starting from the acquisition of customer requirements, which as total function can be decomposed into several sub-functions and functional units, and finally outputting products that serve the customers after functional design. The difference is that the former is a combination of physical parts to produce a specific function, while the latter is a computer program code to achieve the required function, which leads to software problems that are not easily detected. TRIZ has been widely used to solve the contradiction problems of mechanical products [26], although the research on using TRIZ in software innovation started early but was not mature. Rea et al. studied the use of TRIZ to solve software problems [31], and some experts took this as the beginning of combining TRIZ with the software field [17]. Ma Jianhong et al. analogized the coupling problem in OOD to the contradiction matrix in TRIZ and abstracted the characteristic parameters for OOD [22]. Kangrok LEE et al. used the su-field model and 76 standard solutions to assist software performance and quality assessment efforts, which extended the experience and knowledge of engineers [23]. Stelian Brad et al. used TRIZ to deal with conflict problems and obstacles and proposed to optimize the Agile-Lean-Design Thinking (ALDET) software development process [5]. Jung Suk Hyun et al. proposed a butterfly model based on TRIZ to define and creatively solve problems through contradictory relationships [20]. The application of TRIZ in the software field is in the exploration stage, focusing on the import and improvement of tools. The idea of contradiction is gradually gaining attention in software development, and the solution of contradiction problems helps to improve software performance. Therefore, the implicit contradiction determination method in this paper may also be inspiring for software development.

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REFERENCES

[1] Altshuller, G.; Al’tov, G.; Altov, H.: And suddenly the inventor appeared: TRIZ, the theory of inventive problem solving, Technical Innovation Center, Inc., 1996.
[2] Amemiya, K.: What Makes the USA So Innovative? An Investigation into the Characteristics of Innovation and an Analysis and Discussion of the Factors that Foster Innovation in the USA, Asia-Pacific Review, 21(2), 2014, 172-194. https://doi.org/10.1080/13439006.2014.970326
[3] Bai, Z.; Chang, M.; Peng, Q.; Xu, B.: Cognitive reliability and error analysis based on anticipatory failure determination, Computer-Aided Design and Applications, 18(1), 2020, 130-143. https://doi.org/10.14733/cadaps.2021.130-143
[4] Bai, ZH.; Zhang, SH.; Yu, F.; Tan, RH.: Research on Trimming Method of Standard Solutions Aided Multi-level System Resource Derivation, Journal of Mechanical Engineering, 56(11), 2020, 108-120. https://doi.org/10.3901/jme.2020.11.108 (in Chinese)
[5] Brad, S.; Brad, E.; Homorodean, D.: CALDET: a TRIZ-driven integrated software development methodology, In International TRIZ Future Conference, 2019, 400-416. Springer, Cham. https://doi.org/10.1007/978-3-030-32497-1_32

[6] Cavallucci, D.; Khomenko, N.: From TRIZ to OTSM-TRIZ: addressing complexity challenges in inventive design, International Journal of Product Development, 4(1-2), 2007, 4-21. https://doi.org/10.1504/ijpd.2007.011530

[7] Chen, J. L.; Hung, C.: Eco-innovation by anticipatory failure determination (AFD) method, Proceedings of the Design Society: International Conference on Engineering Design, Cambridge University Press, 1(1), 2019, 3271-3280. https://doi.org/10.1017/dsi.2019.334

[8] Chen, P.; Zhang, T.; Wang, L.: Improvement design of lithium battery explosion-proof equipment based on TRIZ and AFD, IEEE International Conference on Management of Innovation & Technology, 2010, 1208-1212. https://doi.org/10.1109/ICMIT.2010.5492915

[9] Chybowski, L.; Bejger, A.; Gawdzińska, K.: Application of Subversion Analysis in the Search for the Causes of Cracking in a Marine Engine Injector Nozzle, World Academy of Science, Engineering and Technology International Journal of Industrial and Manufacturing Engineering, 12(4), 2018, 302-308. http://scholar.waset.org/1307-6892/10008702

[10] Chybowski, L.; Gawdzińska, K.; Souchkov, V.: Applying the anticipatory failure determination at a very early stage of a system's development: overview and case study, Multidisciplinary Aspects of Production Engineering, 1(1), 2018, 205-215. https://doi.org/10.2478/mape-2018-0027

[11] Cooper, RG.: What's next?: After stage-gate, Research-Technology Management, 57(1), 2014, 20-31. https://doi.org/10.5437/08956308x5606963

[12] Cooper, RG.; Kleinschmidt, EJ.: Stage gate systems for new product success, Marketing Management, 1(4), 1993, 20-29.

[13] Cooper, RG.: The drivers of success in new-product development, Industrial Marketing Management, 76, 2019, 36-47. https://doi.org/10.1016/j.indmarman.2018.07.005

[14] Di Benedetto, C. A.: Product Design: Research Trends and an Agenda for the Future, Journal of Global Fashion Marketing, 3(3), 2012, 99-107.

[15] Fey, V.; Rivin, E.: Innovation on Demand: New Product Development Using TRIZ, Cambridge University Press, New York, NY, 2005.

[16] Geng, L.; Xing, J.; Shi, X.; Zu, L.; Chai, M.: Improved Model for Generating Incremental Product Innovation Schemes, Mathematical Problems in Engineering, 2021. https://doi.org/10.1155/2021/5516260

[17] Govindarajan, UH.; Sheu, DD.; Mann, D.: Review of systematic software innovation using TRIZ, International Journal of Systematic Innovation, 5(3), 2019, 72-90.

[18] Hiltmann, K.: Predicting Unknown Failures, Procedia engineering, 131, 2015, 840-849. https://doi.org/10.1016/j.proeng.2015.12.392

[19] Hu, G.: Pipe cutting machine, Zhejiang: CN303692108S, 2016-06-01. (in Chinese)

[20] Hyun, JS.; Park, CJ.: A conflict-based model for problem-oriented software engineering and its applications solved by dimension change and use of intermediary, In International Conference on Advanced Software Engineering and Its Applications, 2009, 61-69. https://doi.org/10.1007/978-3-642-10619-4_8

[21] Jensen, A.; Aven, T.: Hazard/threat identification: Using functional resonance analysis method in conjunction with the Anticipatory Failure Determination method, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 231(4), 2017, 383-389. https://doi.org/10.1177/1748006X17698067

[22] Jianhong, M.; Quan, Z.; Yanling, W.; Wei, Z.: Research and Application of the TRIZ Contradiction Matrix in OOD, 2009 WRI World Congress on Software Engineering, 2009, 247-251. https://doi.org/10.1109/wcse.2009.244

[23] Kangrok, LEE.; Jaemin, SHIM.; Jinyong, KIM.: Software engineering performance and quality assessment by triz, Acta Technica Napocensis-series: Applied Mathematics, Mechanics, and Engineering, 63(3S), 2020.

[24] Lee, M. G.; Chechurin, L.; Lenyashin, V.: Introduction to cause-effect chain analysis plus with an application in solving manufacturing problems, The International Journal of Advanced Manufacturing Technology, 99(9) 2018, 2159-2169. https://doi.org/10.1007/s00170-018-2217-1

[25] Liu, LM.: Research on Key Technologies to Mechanical Radical Innovation Design Based on Technological Recombination, Ph.D. Thesis, Hebei University of Technology, Tianjin, 2022.
[26] Liu, SY.: The Design and Application of the Mechanical Parts Based on the TRIZ Theory, Applied Mechanics and Materials, Trans Tech Publications Ltd, 556, 2014, 1241-1244. https://doi.org/10.4028/www.scientific.net/AMM.556-562.1241
[27] Maguire, M.; Bevan, N.: User requirements analysis, IFIP world computer congress, 2002, 133-148.
[28] Meinel, M.; Eismann, T. T.; Baccarella, C. V.: Does applying design thinking result in better new product concepts than a traditional innovation approach? An experimental comparison study, European Management Journal, 38(4), 2020, 661-671. https://doi.org/10.1016/j.emj.2020.02.002
[29] Mutlu, N. G.; Altuntas, S.: Risk analysis for occupational safety and health in the textile industry: Integration of FMEA, FTA, and BIFPET methods, International Journal of Industrial Ergonomics, 72, 2019, 222-240. https://doi.org/10.1016/j.ergon.2019.05.013
[30] Rau, H.; Lagapa, M. D. M.; Chen, P. H.: Anticipatory non-green-phenomena determination for designing eco-design products, Sustainability, 13(2), 2021, 621. https://doi.org/10.3390/su13020621
[31] Rea, K. C.: Applying TRIZ to software problems-creatively bridging academia and practice in computing, The TRIZ Journal, 2002.
[32] Rehman, OU.; Ryan, MJ.: A framework for design for sustainable future-proofing, Journal of Cleaner Production, 170, 2018, 715-726. https://doi.org/10.1016/j.jclepro.2017.09.177
[33] Saeeda, H.; Dong, J.; Wang, Y.; Abid, MA.: A proposed framework for improved software requirements elicitation process in SCRUM: Implementation by a real-life Norway-based IT project, Journal of Software: Evolution and Process, 32(7), 2020, e2247. https://doi.org/10.1002/smr.2247
[34] Savransky, S. D.: Engineering of Creativity: Introduction to TRIZ Methodology of Inventive Problem Solving, CRC Press, New York, NY, 2000.
[35] Silva, R. F.; Carvalho, M. A.: Anticipatory Failure Determination (AFD) for product reliability analysis: A comparison between AFD and Failure Mode and Effects Analysis (FMEA) for identifying potential failure modes, Advances in Systematic Creativity, 2019, 181-200. https://doi.org/10.1007/978-3-319-78075-7_12
[36] Tao, F.; Sui, F.; Liu, A.; Qi, Q.; Zhang, M.; Song, B.; Nee, A. Y.: Digital twin-driven product design framework, International Journal of Production Research, 57(12), 2019, 3935-3953. https://doi.org/10.1080/00207543.2018.1443229
[37] Thurnes, C. M.; Zeihsel, F.; Visnepolschi, S.: Using TRIZ to invent failures–concept and application to go beyond traditional FMEA, Procedia engineering, 131, 2015, 426-450. https://doi.org/10.1016/j.proeng.2015.12.439
[38] Tiwari, V.; Jain, P. K.; Tandon, P.: Product design concept evaluation using rough sets and VIKOR method, Advanced Engineering Informatics, 30(1), 2016, 16-25. https://doi.org/10.1016/j.aei.2015.11.005
[39] Wang, K.; Peng, Q.; Tan, R.: Innovative product design based on general theory of powerful thinking, Computer-Aided Design and Applications, 17(5), 2020, 1007-1019. https://doi.org/10.14733/cadaps.2020.1007-1019
[40] Wang, Y.; Peng, QJ.; Tan, RH.; Sun, JG.: Implementation of low-end disruptive innovation based on OTSM-TRIZ, Comput. Aided Des. Appl, 17, 2020, 979-992. https://doi.org/10.14733/cadaps.2020.993-1006
[41] Zhang, W.; Min, Z.; Jin, C.; Wei, Y.: Safc analysis model based on u-triz, Technology Economics, 33(12), 2014, 7-13. http://dx.chinadoi.cn/10.3969/j.issn.1002-980X.2014.12.002 (in Chinese)
[42] Zhang, Y. J.; Yue, Z. Y.; Jiang, G. J.; Yang, X. X.; Pan, D. X.; Xia, X. Y.: Research on product failure prediction based on triz theory, IOP Conference Series: Materials Science and Engineering, 1043(2), 2021, 022059. https://doi.org/10.1088/1757-899X/1043/2/022059