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Identification of Innovative Opportunities Based on Product Scenario Evolution

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Abstract: Innovation is a key factor for product development. Identifying innovative opportunities is the first step in innovative product design. Traditional methods of identifying innovative opportunities, such as market surveys and brainstorming, are limited by product users' and designers' experiences and lack systematic approaches to generate breakthrough innovations. This paper proposes a method to identify innovative opportunities based on product scenario evolution. The method models a product scenario based on product scenario elements, states, and behaviors. A Type II hierarchical function model is constructed based on the transformation and abstraction hierarchy of the product function model to identify target elements for the scenario evolution. Based on the theory of basic element extension and needs evolution characteristics, the method of extending target scenario elements is proposed. Based on the new scenario element sets and their impact, diffusion, identification, and evaluation methods are proposed for innovation opportunities. Potential opportunities are explored for product innovation from a scenario evolutionary perspective, which updates knowledge and technology reserves and finds new market opportunities for industries. The feasibility and effectiveness of the method are verified using the innovative design of a polyethylene (PE) pipeline hot-melt welding machine.

Keywords: innovative opportunity; product scenario; scenario evolution; innovative design; polyethylene (PE) pipeline hot-melt welding machine

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1. Introduction

Innovation is key to a given industry's ability to maintain a competitive advantage in the constantly changing market [1,2]. Innovation opportunities provide chances for product developers to improve and meet unsatisfied or incompletely met needs of existing or new products by introducing new technologies, knowledge, or ideas [3,4]. Innovative product design is based on innovation opportunities through using design methods and combining user, technology, business, and other factors to create novel products [5–7]. The innovation opportunity can be defined as "the possibility of realizing the potential economic value inherent in new combinations of resources and market demands that result from changes in the underlying scientific or technological knowledge, customer preferences, or the interrelationships between economic actors" [8]. Therefore, product innovation relies on innovation opportunities that provide a driving force and direction for innovation. Searching for and capturing innovation opportunities, as well as applying effective product innovative design methods, will therefore provide a strong support system for companies attempting to enhance their competitive advantage in the market.

Innovation opportunities come from changes in user needs, social factors, the market environment, technological developments, and competitors [9–14]. These changes can generate new needs, problems, contradictions, or constraints, providing the possibility and motivation for product innovation. For example, developments in the Internet have changed our behaviors and habits in many aspects of life, such as in information acquisition, communication, and shopping. Related changes have brought many innovation opportunities, such as Internet-based search engines, social networks, and e-commerce platforms [15]. Considering a product's lifecycle [16], innovation opportunities may come from different requirements in terms of product design, manufacturing, use, or recycling. According to the source and location, innovation opportunities can be classified as technology- and market-driven opportunities; these rely on the coordination of multiple environmental factors [17]. Overall, innovation opportunities arise from scientific and technological developments, changing user needs and social requirements.

Earlier research has developed a variety of innovation opportunity acquisition methods from multiple perspectives. For determining the necessary routes of product improvement, there are different methods available, such as brainstorming, mind mapping, SCAMPER, and TRIZ [18–21]. For determining the necessary routes of technological developments, there are various methods available, such as technology prediction, bionic designs, and analogical designs [22–24]. For determining shifts in user needs, there are various established methods, such as questionnaires, focus groups, and customer interviews; these approaches gather users' voices and understand users' needs, the problems in existing products, and the gaps that exist between user expectations and reality [25]. For analyzing competitors, there are methods available, such as design-around approaches, reverse engineering, and open innovation [26–28]. These methods provide guidance for accessing innovation opportunities, but they suffer from poor results and low success rates.

The scenario approach was originally developed to meet the needs of the United States Department of Defense's military and was later applied in social analysis and policy development [29]. Beginning in the 1960s, the scenario approach was used to understand future business environments and successfully predicted a significant increase in the price of oil based on the world market [30]. This landmark success was a symbol of the proven practicality and adaptability of the scenario approach, which was then gradually extended to multiple application areas.

The scenario approach has developed three dominant schools: Intuitive Logics, Probabilistic Modified Trends, and La Prospective [29,31]. They emerged from different backgrounds with different characteristics, which has made the scenario approach concept confusing over the years [32]. However, after summarizing and synthesizing numerous previous studies, Matthew, J.S. defines scenarios as a set of possible and reasonable descriptive alternatives based on future external forces [33]. Therefore, scenarios are not simply predictions but a set of plausible alternative assumptions about the future: a non-totally free imagination grounded in the past and present [30,34]. However, few researchers have integrated the concept of the scenario into product function models to identify new opportunities for innovation.

To address the above problems, this paper analyzes product scenarios from different perspectives. The product, users, and usage environments are considered the influencing factors in a scenario. A method is proposed for generating innovative opportunities based on the evolution of the product scenario. The method creatively takes the function execution process of the typical product as a scenario, streamlining stakeholders and only focuses on the relationship between the user, the environment, and the product for the possible future direction in terms of evolution. Based on the theory of basic element extension and needs evolution characteristics, target scenario element extension rules and strategies are formulated to provide guidance for the direction and method concerning product scenario evolution. An automated strategy selection tool is developed using a back propagation (BP) neural network to improve design efficiency and reduce the error rate. A new scenario element matrix is constructed analogously to the morphological matrix. New scenario element sets and impact sets are obtained as initial innovation opportunities (IIOs). The final innovation opportunity (FIO) is obtained after the evaluation and integration of IIOs. Finally, the conceptual design is established to generate solutions based on the FIOs.

The sections of this paper are organized as follows. Section 2 discusses the related research. Section 3 introduces the concept and construction methods of product scenarios. Section 4 describes the proposed method. Firstly, the function model transformation and target scenario element determination methods are presented. Then, rules and strategies for scenario elements extension are developed to obtain future possibilities for target scenario elements. Finally, new scenario element sets are built, and innovation opportunities are obtained based on the impact diffusion. Section 5 verifies the feasibility of the method through the innovative design of a polyethylene (PE) pipeline hot-melt welding machine. Section 6 discusses the advantages, disadvantages, and prospects of the proposed method.

2. Related Research

2.1. Research and Methods of Opportunity Identification

The development and maturity of new technologies such as 5G communication, 3D printing, and artificial intelligence (AI) have brought disruptive innovations to industrial development [35], propelling the growth of Industry 4.0 [36]. This has been accompanied by the integration of cross-domain knowledge [37,38], leading to the continuous emergence of product innovation opportunities. However, determining how to obtain high-value innovation opportunities in advance remains a challenge in enterprise management and product development. For instance, in a survey concerning ASUS's development, Yung et al. found that dynamic capabilities [39] play a crucial role in maintaining enterprise competitiveness [40]. Buganza et al. identified market and technological uncertainties and suggested adopting flexible development processes [41]. Nieto et al. found that the capacity to acquire, digest, utilize, and transform knowledge resources can help enterprises better understand and leverage technological opportunities [42]. Despite the fact that researchers in the management field have recognized the importance of innovation opportunities, they often struggle to accurately and comprehensively identify and perceive them due to the limitations of existing theoretical frameworks and empirical methods.

The identification of innovation opportunities in product design and development is divided into two categories: technology push and demand pull. In terms of product technologies, patent analysis is an effective means for identifying innovation opportunities due to the rich information, standardized coding methods, and high quality of patent technology information [43,44]. Patent analysis is generally divided into two categories: citation network-based and text-based methods. In a citation network, each patent is regarded as a node, and the citation relationship is represented as edges between nodes [45]. Patents that are cited more times usually represent technological innovations and progress in specific fields, as the citation relationship signifies the dissemination of knowledge within patents [46], which can be used to predict future innovation opportunities. For example, You et al. constructed a two-level network model based on citation relationships to identify key patent subclasses [47]. As common citation analysis methods are limited to a single jurisdiction, Higham et al. proposed a multi-level patent citation network to better capture real technological relationships [48]. However, it is time-consuming to generate patent citations and cited relationships, and new patents contain fewer opportunities to be cited [49,50]. Therefore, Yoon et al. constructed a patent map of citation information to explore blank technology points and predict future citation links [51]. Lee et al. proposed a machine learning method to predict the number of future patent citations in the early stages and identify innovation opportunities for new technologies at an early stage [52]. Although patent network analysis can identify promising specific technological fields and related patents, it cannot accurately identify specific technological contents [53]. Therefore, text-based methods are often used in combination with citation-based methods to overcome the limitations of qualitative methods. For example, Seo et al. used text mining and association rule mining techniques to extract product information from patents and measure the potential value of product opportunities based on the target company's capabilities [54]. Jun et al. utilized text mining and support vector clustering techniques to establish a matrix map for patents and identify blank technologies as innovation opportunities [55].

Similarly, Son et al. proposed a generative topographic mapping (GTM)-based patent map to detect the patent vacuum automatically [56]. However, most of these methods are post hoc evaluations of past data and impacts [57], lacking proper guidance for actual R&D planning [51].

Perceived quality refers to the satisfaction level in terms of user needs [58], and its changes have an important effect on the product in the market [59]. From another perspective, user needs are more like a missing resource [60]. Therefore, obtaining and evaluating users' perceived quality becomes an important source of inspiration for R&D and innovation opportunities. Currently, the mainstream approach is to use big data analysis methods to process user's online comments and data. For example, Jang et al. analyzed the subject–agent–object (SAO) structure in user comments and patents to identify unmet needs and corresponding patented technologies by comparing their similarity [61]. This can be used to produce innovation opportunities. Ozcan et al. created a classification model for exploring innovative ideas from social media [62]. Yakubu et al. obtained comment data from e-commerce platforms and developed a customer satisfaction model based on a fuzzy regression method and sentiment analysis to provide a basis for product improvement [63]. Due to the large number of user comment data, it can reflect the true feelings of users. The user group is very concentrated and can even be precise about a certain product model. However, the shortcomings of this method are also obvious, such as the scope of applicable product types being small, the viewpoint relying too much on existing products, and difficulties in terms of generating long-term innovation opportunities. To address the above shortcomings, we propose an innovation opportunity acquisition method based on product scenarios, which promotes product scenario evolution by extending scenario elements, thereby stimulating product ideas that break through the status quo.

2.2. Application of Scenario

In product design we define a product scenario as a purposeful interactive process that occurs when all relevant elements come together under specific conditions to realize a product's functions. For example, a household air conditioner is hung on a wall, connected to the power supply, and controlled by the user through a remote control. The internal compressor controls the heat transfer by controlling the refrigerant to release and absorb heat in the circulation loop through the condenser, expansion valve, evaporator, and pipeline. At the same time, the circulating fan circulates indoor air to control the temperature inside the house. This product scenario contains the air conditioner, user, room, power supply, indoor air, outdoor air, and their relationships, all fulfilling functions in regulating the temperature of the room. It describes the air conditioner within a complex interactive process with multiple elements.

The scenario approach has been applied to a wide range of areas. For example, Saskia et al. projected future supply chain scenarios in six dimensions and used cross-impact balance analysis and consistency analysis to estimate the possibility of future scenarios [64,65]. Bottero et al. used the scenario approach to envision a sustainable future for less developed regions [66], addressing the complexity and uncertainty inherent in the construction of urban strategies through a multi-level, multi-scale, and multi-stakeholder approach [67]. Strengers et al. used comic strips to represent everyday scenarios of future households in order to shed light on future digital technologies and challenges facing the energy sector [68]. Andersen et al. argued that stakeholders play a crucial role in exploring uncertain future scenarios and systematically studied stakeholder inclusion [69]. Therefore, scenario analysis allows for a better understanding of future trends and challenges to cope with complexity and uncertainty and make scientifically sound decisions.

In recent years, a number of scholars have applied the scenario approach to product design in order to obtain new and creative technologies or products that are consistent with future scenarios. For example, Schuh et al. proposed an approach combining scenario planning and simulation to identify the characteristics of future products [70]. Kurakawa et al. devised a process that utilizes meetings to discuss future application scenarios for products to aid in the product conceptual design [71]. Randt et al. considered a variety of alternative future scenarios to derive robust design requirements to cope with future customer needs under uncertainty [72]. Shin et al. developed a scenario generation tool to discover different scenario variants and capture requirements [73]. However, the use of scenario approaches in the field of innovative product design faces complex and variable influencing factors. These influencing factors are usually closely related to the external environment, including the industrial environment, market dynamics, policy regulation, cultural context, and socioeconomic conditions. Their wide range and complexity make it difficult to make accurate predictions, so they can easily interfere with the direction of innovation.

In summary, the identification of innovation opportunities is an important research topic, but it still faces the following challenges: (1) there is a lack of methods to analyze future innovation opportunities; (2) the goals of existing methods are not clear enough; and (3) there are too many factors influencing future innovation opportunities. In response to the above problems, a new systematic method for identifying product innovation opportunities is proposed in this paper.

3. Concept of Product Scenario

The purpose of a product is to meet user needs, which usually relies on a deterministic or controllable function implementation process that is driven and influenced by internal and external factors such as material, energy, and information. Scenario state refers to the set of states of these factors at a given moment in time. The process of scenario development from the initial state to the end state under the actions of the product is called the product scenario. Influencing factors in the scenario state during this process are called scenario elements, which are summarized as environment elements, user elements, product elements, and relationship elements that reflect interactions among the elements. These concepts are introduced in detail as follows.

3.1. Scenario Elements of Product Scenario

Scenario elements (E) are key to the scenario state construction and scenario development. In order to represent the concept clearly, the basic element model of Extenics is used to represent the scenario elements [74,75], as shown in Equation (1), where O represents the concept or attribute name of scenario elements, C is the characteristics of O, V is the state indicator of C, and n represents the number of characteristics of O.

$$E = (O,\ \mathrm{C},\ \mathrm{V}) = \begin{bmatrix} O & C_1 & V_1 \\ & C_2 & V_2 \\ & \vdots & \vdots \\ & C_n & V_n \end{bmatrix}, \tag{1}$$

The basic scenario elements can be classified into environment elements, user elements, and product elements according to the class of associated objects [76]. Environment elements refer to the environmental resources involved in the scenario development process, such as the atmosphere, sunlight, and land. User elements refer to user groups or their characteristics that influence or determine the direction of scenario development, such as occupation, hobby, age, and behavioral habits. Product elements are product-related elements such as principles, functions, technologies, and structures that drive scenario development.

In addition to the three types of basic scenario elements mentioned above, relationship elements are another important component of product scenarios. Relationship elements refer to the stable or controllable relationship between the basic scenario elements, including geometric, physical, chemical, and emotional relationships. Among them, the relationship element between the product and the environment is determined by the characteristics of the elements, and the essence is scientific principles that exist in the objective world.

The other aspect is the operational or emotional relationship between human beings and other elements. Therefore, the relationship element and basic scenario element together constitute the complete scenario element of the product scenario. Their relationship is shown in Figure 1.

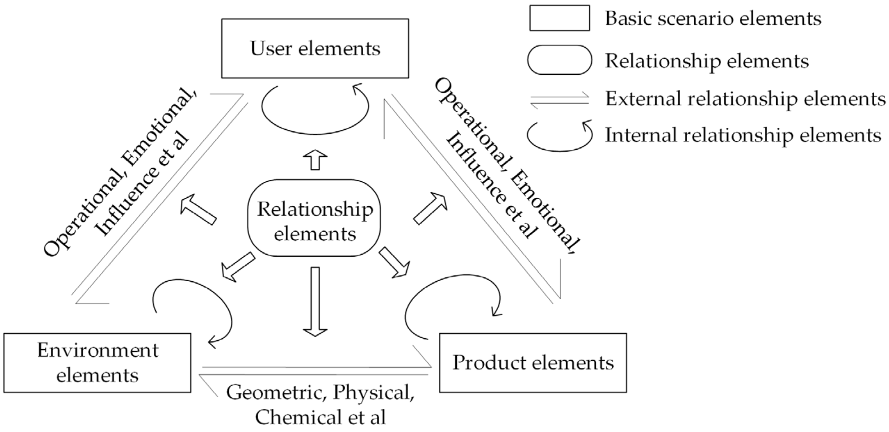


Figure 1. Composition of scenario elements.

3.2. Development of Product Scenario

Scenario states are sets of related scenario elements at a given time or moment in the development of a product scenario. The transition between neighboring scenario states is marked by a targeted shift in their internal scenario elements and characteristics. All scenario states in the process of user needs fulfillment or product function execution are connected in a temporal and logical sequence to form a scenario development process. According to their position in scenario development, scenario states can be classified into initial, intermediate, and end scenario states.

To illustrate the scenario development, an example of "wood boiling water" is shown in Figure 2. The main feature of scenario development is the transformation of the scenario state in the direction of user's needs. The whole development process is called the product scenario. In this case, we consider the fire source, firewood, container, and water as product elements of a complete product. User elements include the hands, feeling, and eyesight. The environment elements include the ground, air pressure, and oxygen. The first step of scenario development is the transformation of scenario states A to B, where the changing sign is the change in the position of the "fire source" to "firewood", which raises the temperature of the firewood and consumes oxygen to keep it burning. The transformation sign from B to C is the internal energy of the firewood in the form of a flame that raises the temperature of the "container", while the "container" transfers energy to the "water". The transformation sign from C to D is that the firewood turns into ashes, and the water reaches the boiling point, which satisfies the user's need. The whole process from scenario states A to D is the product scenario of "wood to boil water".

Scenario behavior is the driving force for scenario development, which prompts the attributes or characteristics of elements in the scenario state to change according to certain rules and logic. This causes a change in the scenario state and a transition to the next state, and this driving force is usually provided by the product. This means that the scenario state and scenario behavior are the node and driving force of the scenario development, respectively, and they are fundamentals for constructing product scenarios.

Scenario behaviors can be connected in a causal time sequence to form a scenario behavior chain. The basic scenario behavior chain consists of three types of connections, i.e., series, parallel, and feedback, as shown in Figure 3. They can be connected to form more complex behavior chains. Thus, the combination of scenario states and scenario behavior chains constitutes a complete process of product scenario development.

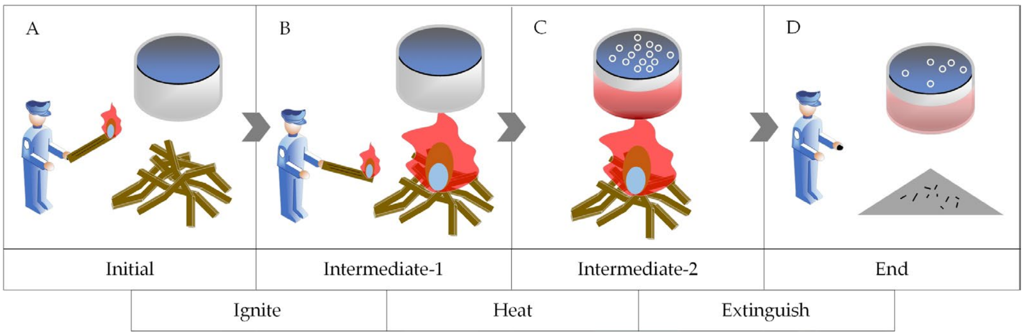


Figure 2. Example of scenario states and development for heating water with firewood: (**A**) is the initial scenario state, (**B**) is the intermediate-1 scenario state, (**C**) is the intermediate-2 scenario state, and (**D**) is the end scenario state.

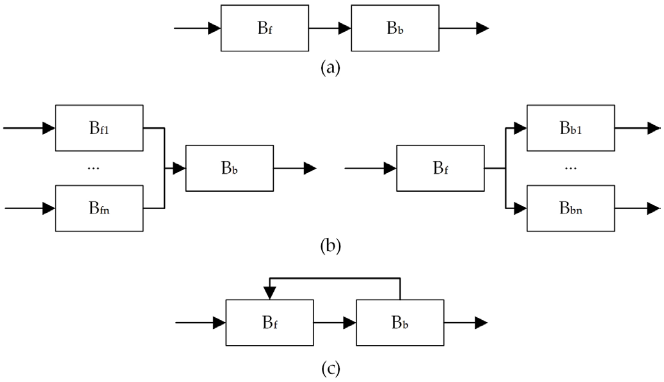


Figure 3. Basic scenario behavior chain: (**a**) serial connection, (**b**) parallel connection, and (**c**) feedback connection.

3.3. Typical Product Scenario Construction

The concept of scenarios is applied in product function modeling to build product scenarios. A typical product is selected according to the market and actual situation of the company, usually a best-selling product in the market or one of the company's main products. The function model of the product is built using the following three steps:

(1) Basic scenario elements of the typical product are analyzed using the reverse fishbone diagram.

(2) Each basic scenario element is clarified.

(3) Relationship elements between the basic scenario elements are identified.

Figure 4 shows the system decomposition of a typical product based on the reverse fishbone diagram, containing module set M and element set E, where M contains product module M_i, environment module M_e, and user module M_u.

Using basic scenario elements and relationship elements, a Type I function model is formed based on the system decomposition results of Figure 4. The Type I function model is based on the C–A–O structure, i.e., the simplest structure with the functional carrier, act, and object [77], as shown in Figure 5. "C" and "O" belong to basic scenario elements of the product scenario, and "A" belongs to relationship elements. The connection of these elements constitutes the Type I function model of the system, as shown in Figure 6. It should be noted that the "C" or "O" identity is determined by the direction of "A", so the "C" may also be an "O" under another "A". The advantage of the Type I function model is that it can show the system function through clear component relationships, i.e., it can show the basic scenario elements and relationship elements, and therefore it is suitable for constructing the scenario state of the product scenario.

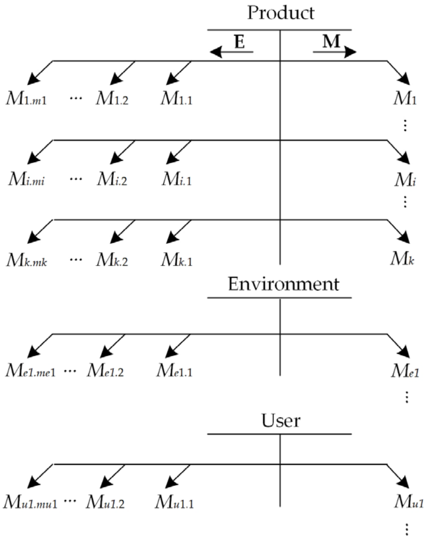


Figure 4. System decomposition of a typical product.

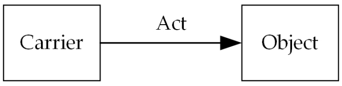


Figure 5. C–A–O structure.

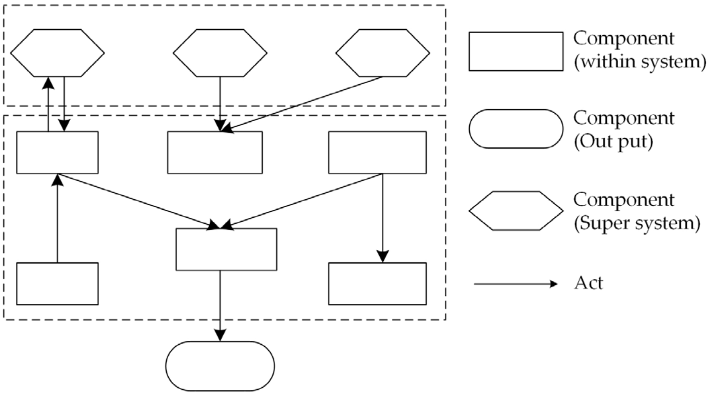


Figure 6. Type I function model.

The static Type I function model is unable to represent the dynamic process of the system function, that is, it is difficult to represent the transformation process of the scenario state from the functional level. Therefore, we introduce the function structure to represent the system function in terms of the dynamic material, energy, and signal flows transferred between function units [78], as shown in Figure 7. Function units, obtained in the overall function decomposition, are the smallest units of function decomposition. Attribute changes in the output flows are the result of function execution. Since the energy and signal are attributes or characteristics of a product, we only use the material flow to construct the function structure to simplify the model.

Function units in the function structure have a high degree of consistency with the scenario behaviors; therefore, we combine the function structure and Type I function model to construct a product scenario, as shown in Figure 8. The function units are used as scenario behaviors to form the scenario behavior chain. Corresponding basic scenario elements are extracted from the inputs and outputs of the function units, respectively, and the corresponding relationship elements are extracted from the Type I function model. They are then combined into scenario states for both sides of the scenario behavior. Scenario behaviors and scenario states together constitute the sub-scenario of a product scenario, i.e., the independent block in Figure 8, which reflects the functional process of the product and all the relevant scenario elements involved in the execution of the function. It shows that the two scenario states in the sub-scenarios are the initial scenario state and the end scenario state of the sub-scenarios. The scenario states form the C–A–O structure in Figure 6, where "C" and "O" represent the product, environment, and user elements, and "A" represents the relationship element. The scenario state consists of scenario elements that are only relevant to the sub-scenarios. The product scenario is obtained by connecting the scenario behaviors and scenario states according to the scenario behavior chain, as shown in Figure 8.

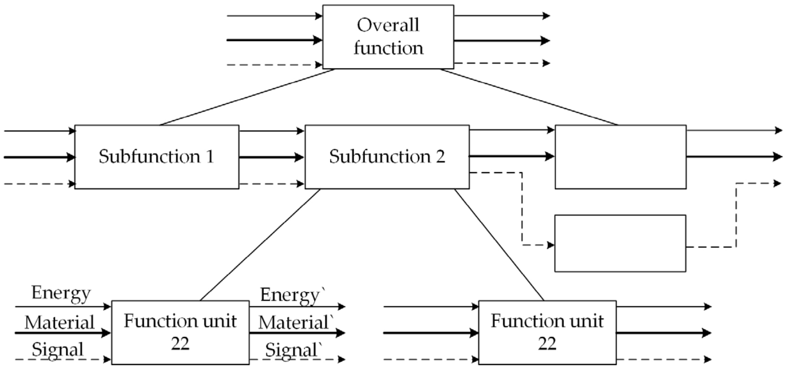


Figure 7. Function structure.

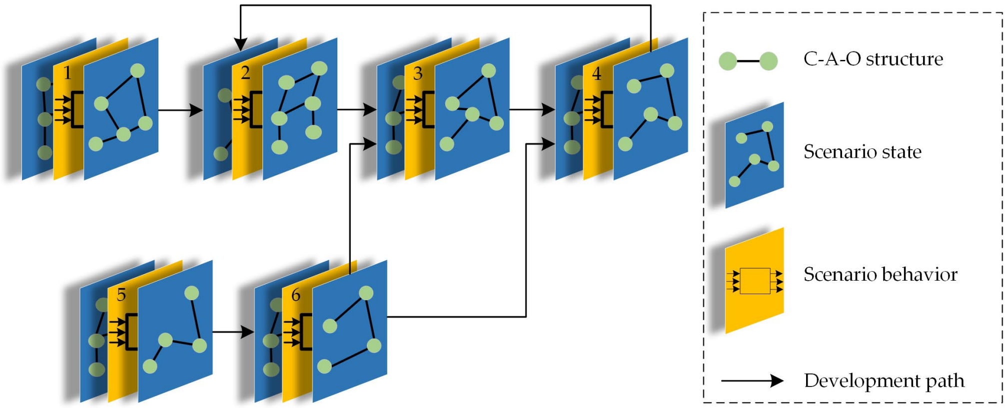


Figure 8. Product scenario.

4. Proposed Method

The future possibilities of product scenarios are important innovation opportunities. Scenario evolution is a reconfiguration of product scenarios based on directed changes in scenario elements, which leads to unforeseen discoveries, i.e., innovation opportunities. Designers can obtain new design requirements based on future-oriented changes in scenario elements and their impact areas, therefore realizing product innovation.

Therefore, innovation opportunity identification can be carried out in terms of both internal scenario exploration and external scenario expansion, as shown in Figure 9. First, new scenario elements are obtained through scenario element extension. Then, the new scenario elements are re-injected into the original product scenario, and the new scenario state is obtained based on the impact diffusion analysis. The new product scenario is obtained by redesigning the new scenario behaviors based on the new scenario states.

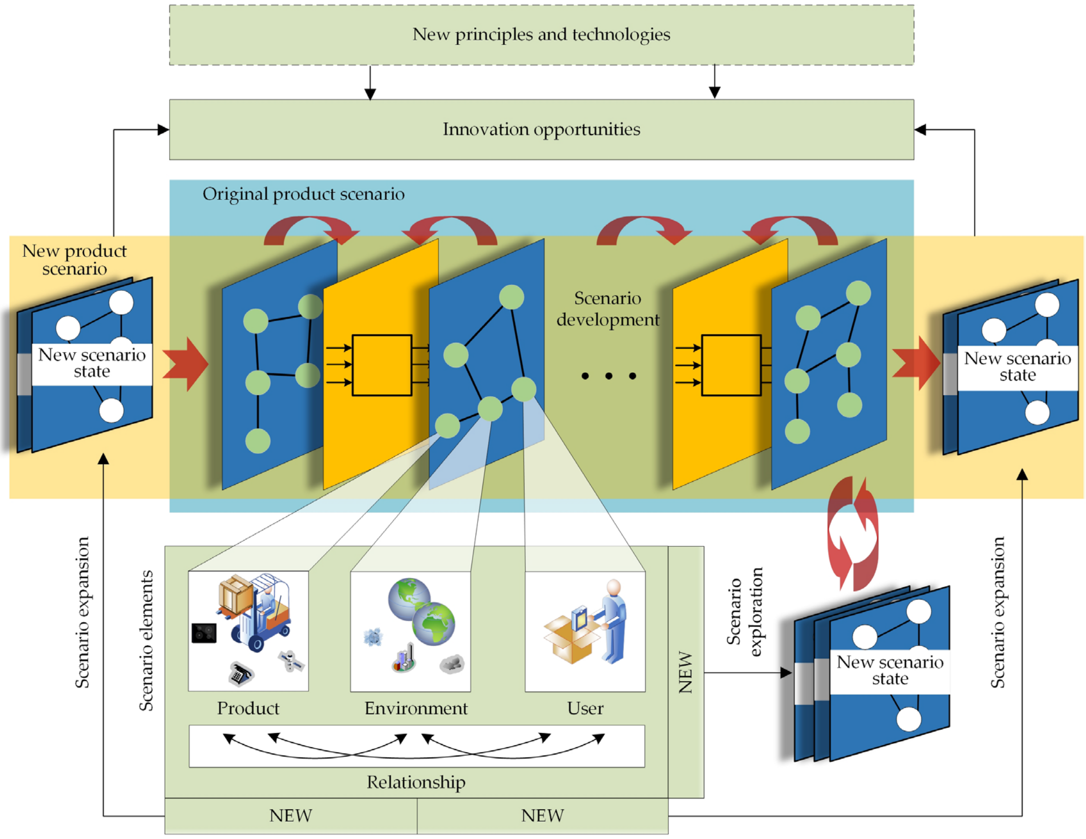


Figure 9. Schematic for identifying innovation opportunities based on product scenarios.

4.1. The Target Scenario Elements for Extension

In general, the function analysis uses the Type I function model shown in Figure 6, but this model is insufficient in terms of displaying the functions, and it is difficult to determine the importance level. Therefore, it is necessary to transform the Type I function model into the Type II function model, as shown in Figure 10. The square in the Type II function model represents the function, and the arrow between the functions represents that the latter function is the prerequisite of the former function. A dotted line indicates that the relationship cannot be obtained directly from the Type I function model. As shown in Figure 10, the following steps are required to transform a Type I function model into a Type II function model:

Step 1: Extracting the C–A–O structure from the Type I function model.

Step 2: Equating the C–A-O structure to a function and determining the connection relationship between functions.

Step 3: Connecting all the functions into a functional network according to the connection relationship in Step 2, i.e., forming a Type II function model.

In order to obtain generalized functions, the C–A–O structure is simplified into the form of "verb + noun" or "verb + noun phrase", and then superlative words relating to the function are extracted according to the technological capability of the company, to construct an abstracted function set. For example, the function of air conditioners is abstracted as "reduce the temperature of gas" or "change the temperature".

The abstraction level of functions is an important concept in innovative product design. As the abstraction level decreases, the technical or solution information of the function will be gradually apparent, but the degree of innovation is reduced accordingly. Therefore, the degree of innovation and innovation priority of functions is directly proportional to the abstraction level, and functions with a high abstraction level receive more attention in subsequent innovation activities. The solution and technology of the function constitute the evaluation criteria for the abstraction level, which is divided into three levels: F_{H1}, F_{H2}, and $F_{H3.}$ The criteria are as follows:

(1) F_{H1} is not concerned with specific technical means and solutions but only describes the purpose or effect that things or systems can achieve.

(2) F_{H2} is not related to the technology but is related to the solution and is able to envision the general content of the solution but does not contain specific details of its realization.

(3) F_{H3} is clearly related to the technology and solution with detailed information about the technical solution and its realization methods.

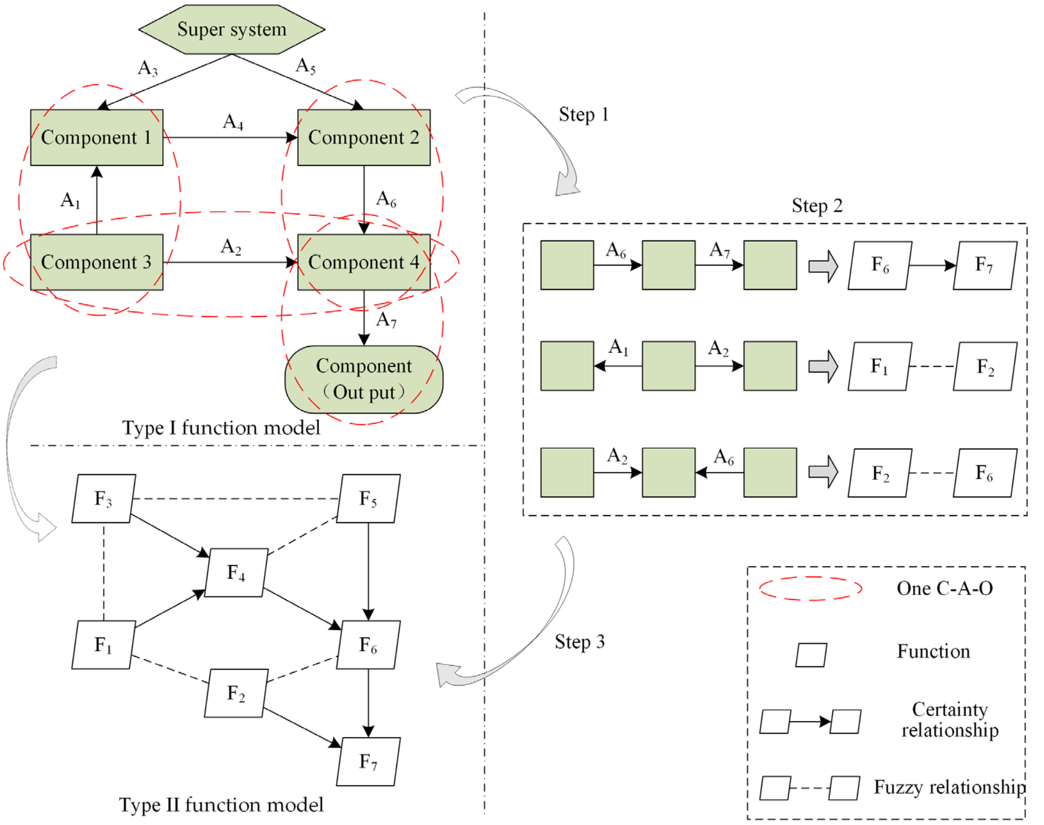


Figure 10. Function model transformation.

The Dempster–Shafer (D–S) theory from uncertainty reasoning is used to determine the level of abstraction of a function [79,80]. If there exists a finite space containing all subsets of possibilities, represented by Θ, function $m : 2^{\Theta} \rightarrow [0, 1]$ and satisfies $m(\varnothing) = 0$ and $\sum_{E \subseteq \Theta} m(E) = 1$, then m is called a basic probability assignment (BPA) function on 2^{Θ}. The BPA of each function is determined based on the judgment criteria of the functional abstraction level. Table 1 shows three different assessment relations, the assumption space is $\Theta = \{H_1, H_2, H_3\}$, E_1, E_2, and E_3 are subsets of Θ under different assessments, and $m_1(E_1)$, $m_2(E_2)$, and $m_3(E_3)$ are three mutually independent BPA functions corresponding to the assessment relations. According to Dempster's combination rule, the above three BPA functions forms a new BPA function (m_s), as follows:

$$m_{si} = K^{-1} \cdot \sum_{E_1 \cap E_2 \cap E_3 = \{H_i\}} m_1(E_1) \cdot m_2(E_2) \cdot m_3(E_3), \tag{2}$$

$$K = \sum_{E_1 \cap E_2 \cap E_3 \neq} m_1(E_1) \cdot m_2(E_2) \cdot m_3(E_3), \tag{3}$$

Table 1. Basic probability assignments at the function abstraction level.

Level	$m_1(\mathrm{E}_1)$	$m_2(\mathrm{E}_2)$	$m_3(\mathrm{E}_3)$	m_s
H_1	p_{11}	p_{12}	p_{13}	m_{s1}
H_2	p_{21}	p_{22}	p_{23}	m_{s2}
H_3	p_{31}	p_{32}	p_{33}	m_{s3}
$\{\mathrm{H}_1, \mathrm{H}_2, \mathrm{H}_3\}$	$p_{\Theta 1}$	$p_{\Theta 2}$	$p_{\Theta 3}$	$m_{s\Theta}$

After the functions are divided into hierarchical levels according to the D–S theory, a Type II hierarchical function model is constructed by rearranging the functions of the Type II function model according to the hierarchy, as shown in Figure 11. The higher the abstraction level of the function, the greater the extension space of its corresponding scenario elements. This is more conducive to generating new and highly creative scenario elements, which also implies the direction of product scenario evolution. Therefore, the basic scenario elements in the functions at the H_1 level should be preferred as target scenario elements.

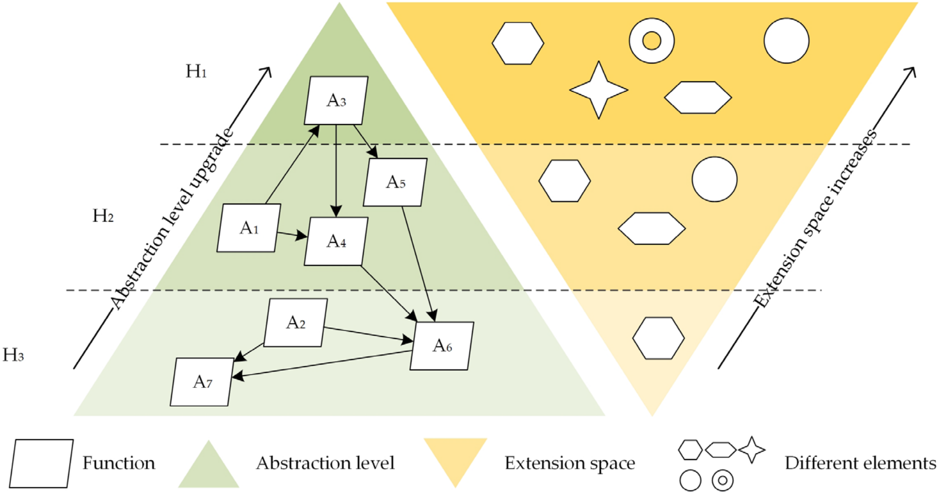


Figure 11. Type II hierarchical function model.

4.2. Methods for Extending Target Scenario Elements

In previous studies, we recognized that product innovation opportunities are closely related to changes in scenario elements. Although these changes may originate from multiple drivers, such as market demand, technological development, and adjustments in policies and regulations, they will ultimately be reflected in changes in scenario elements. Therefore, by combining the theory of basic element extension and the characteristics of needs evolution, rules and strategies of the scenario element extension are formed. A strategy selection method can then be proposed.

4.2.1. Scenario Elements Extension Rules

The extension rules of scenario elements are developed by drawing on the transformation methods of basic elements in Extenics. The basic expansion of basic elements includes divergence analysis, correlation analysis, implication analysis, and expandability analysis, while the basic transformations include substitution, addition and deletion, expansion and contraction, and decomposition and replication [81]. The former is used to obtain related new basic elements, and the latter is used to integrate these basic elements to obtain new basic elements. According to the basic element transformation methods, we summarize nine rules applicable to the extension of scenario elements, as shown in Table 2. The specifics of several special concepts, such as correlation, implication, and combination, are introduced, as follows:

Table 2. Scenario element extension rules.

No.	Name	Explanation	Symbolic
Rule 1	Same-object multi-characteristic extension	Increasing the involvement or importance of different characteristics that have not been attended to, thus changing the original scenario elements.	$(O,\ c,\ v) \rightarrow \begin{bmatrix} O, & c, & v \\ & c_1, & v_1 \\ & \vdots & \vdots \\ & c_n, & v_n \end{bmatrix}$
Rule 2	Same-characteristic divergence	Changing the type of object while keeping the characteristics unchanged. Usually, this operation also changes the value of the characteristics and the type of scenario elements.	$(O,\ c,\ v) \rightarrow \begin{Bmatrix} (O_1, & c, & v_1) \\ (O_2, & c, & v_2) \\ & \cdots & \\ (O_n, & c, & v_n) \end{Bmatrix}$
Rule 3	Same-characteristic and same-value divergence	Exploring different objects with the same characteristics and values to discover diverse scenario elements with the same characteristics.	$(O,\ c,\ v) \rightarrow \begin{Bmatrix} (O_1, & c, & v) \\ (O_2, & c, & v) \\ & \cdots & \\ (O_n, & c, & v) \end{Bmatrix}$
Rule 4	Same-object and same-characteristic divergence	Change the value of a characteristic to change the category of an object or to increase the diversity of a characteristic.	$(O,\ c,\ v) \rightarrow \begin{Bmatrix} (O, & c, & v_1) \\ (O, & c, & v_2) \\ & \cdots & \\ (O, & c, & v_n) \end{Bmatrix}$
Rule 5	Change of correlation	There are six types of changes: disappearance or addition of correlation, stronger or weaker correlation, and exchange of linear and non-linear correlation.	$\begin{cases} (A \sim B) \rightleftarrows (A,\ B) \\ \left(A \overset{\text{Strong}}{\sim} B\right) \rightleftarrows \left(A \overset{\text{Weak}}{\sim} B\right) \\ \left(A \overset{\text{Linearity}}{\sim} B\right) \rightleftarrows \left(A \overset{\text{Nonlinearity}}{\sim} B\right) \end{cases}$
Rule 6	Extension by implication relations	Discover new scenario elements from the context of the scenario elements based on their implication relationships.	$\cdots \underset{\leftarrow}{B_{n-1}} \Rightarrow B_n \Rightarrow \underset{\rightarrow}{B_{n+1}} \cdots$
Rule 7	Combination extension	Combine two or more scenario elements into a new scenario element through combination.	$B_1 \rightarrow B_1 \oplus B_2$
Rule 8	Replication	This rule can be considered a special case of combination extension, which is the combination of multiple scenario elements that are the same or similar.	$B \rightarrow B \oplus B \oplus B \oplus \cdots$
Rule 9	Delete	This is the reverse of combination extension, where deleting some or all of the decomposed values, characteristics, or objects can change the original scenario element.	$(O,\ c,\ v) \rightarrow \begin{cases} (O,\ c,\ v_i),\ (v_i \oplus v_j = v) \\ (O,\ c_i,\ v),\ (c_i \oplus c_j = c) \\ (O_i,\ c,\ v),\ (O_i \oplus O_j = O) \end{cases}$

(1) Correlation: If there is a dependency between a basic element and characteristic values of other basic elements, they are called correlated. Correlation includes single-direction correlation and two-direction correlation, and furthermore, it includes correlation between the characteristics within a basic element and logical correlation ("and" and "or") of multiple elements. Correlations are symbolized as follows:

$$A \sim B, \tag{4}$$

(2) Implication: basic element B_1 is considered to imply B_2 if the realization of B_1 contains the realization of B_2. In addition, if this implication relation must exist under certain conditions, it is a conditional implication relation. Complex logical implication relations also exist between multiple basic elements. An important property is the transitive nature of the implication relation, i.e., if B_1 implies B_2 and B_2 implies B_3, then B_1 implies B_3. Implication relations are symbolized as follows:

$$B_1 \Rightarrow B_2 \Rightarrow B_3, \tag{5}$$

(3) Combination: Combination is the combination of more than two basic elements into a new basic element and contains three cases, as shown in Equation (6). Case one is where the new basic element adds different characteristics, case two is the combined change in the attributes and characteristic values of the new basic element, and case three is where the new basic element possesses two characteristics from different basic elements at the same time, and the values undergo a combined change. The combined change is

not a simple addition but creates a completely new original function or property upon the original base, such as a bimetal strip.

$$B_1 \oplus B_2 = \begin{cases} \begin{bmatrix} O_1, & c_1, & v_1 \\ & c_2, & v_2 \end{bmatrix} & ,(O_1 = O_2,\ c_1 \neq c_2) \\ (O_1 \oplus O_2,\ c_1,\ v_1 \oplus v_2) & ,(O_1 \neq O_2,\ c_1 = c_2), \\ \begin{bmatrix} O_1 \oplus O_2, & c_1, & v_1 \oplus c_1(O_2) \\ & c_2, & c_2(O_2) \oplus v_2 \end{bmatrix} & ,(O_1 \neq O_2,\ c_1 \neq c_2) \end{cases} \tag{6}$$

4.2.2. Scenario Elements Extension Strategies

The extension rules provide a method applicable to product scenario element extension, but the process is highly stochastic. Therefore, it is critical to find a way to guide the scenario elements for highly feasible and innovative changes. The essence of product scenario evolution originates from the user needs. In order to provide a clear target and direction for the extension of scenario elements, this paper uses the laws concerning needs evolution to guide the selection and use of scenario elements extension rules.

After analyzing the laws of needs evolution, 16 needs evolution characteristics (NECs) are extracted to predict the future scenario elements of the product, as shown in Table 3. The NECs constitute extension strategies in an independent or combined way. A suitable extension strategy can only be maximized by combining it with the corresponding extension rules. In general, designers have to select NECs based on their experience; however, this is inefficient.

Table 3. Needs evolution characteristics.

No.	NEC	Suggested Extension Rules	Cases
1	Adapting to changes in parameters within the product.	Rule 1, Rule 4, Rule 5	Car cooling fan adjusts speed according to engine temperature.
2	Function execution time is dynamic.	Rule 1, Rule 4, Rule 5	Solar concentrator rotates with the sun.
3	Function execution space is dynamic.	Rule 1, Rule 2, Rule 3, Rule 4, Rule 5	Electromagnetic suspension adjusts the height and stiffness of the chassis according to the road surface.
4	Product structure in space and time is dynamic.	Rule 5, Rule 7, Rule 8, Rule 9	Structural changes of a laptop computer when used on a desktop and when transported in a backpack.
5	Adapting product functions to environment parameters.	Rule 1, Rule 5	Air conditioner compressor speed adjusted to room temperature.
6	Precise targeting of users.	Rule 1, Rule 5, Rule 6, Rule 9	Change of user age of clothes to 0–3 years old to get baby and toddler clothes.
7	Reducing human involvement.	Rule 5, Rule 9	A light-sensitive energy-saving lamp that automatically switches on and off according to light intensity.
8	Replication of product functions.	Rule 7, Rule 8, Rule 9	A large number of small LED screens forming a large LED screen.
9	Integration of needs in different environments.	Rule 2, Rule 3, Rule 6	Integrated dual-use drone for underwater and airborne use.
10	Integration of different user needs.	Rule 1, Rule 2, Rule 3, Rule 4	A foldable smart phone that can satisfy both large and small-screen users.
11	Integration of functions with different needs.	Rule 1, Rule 3, Rule 6, Rule 7	Integration of beer bottle opener and lighter.
12	Integration of functions with opposite needs.	Rule 6, Rule 7	Integration of eraser and pencil.
13	Reducing harmful effects on users.	Rule 2, Rule 3, Rule 5, Rule 7, Rule 9	Anti-blue-light coating for eyeglass lenses.

Table 3. *Cont.*

No.	NEC	Suggested Extension Rules	Cases
14	Reducing harmful effects on the environment.	Rule 2, Rule 3, Rule 5, Rule 7, Rule 9	Electrical enclosures made from recycled waste.
15	Reducing harmful effects on the product.	Rule 2, Rule 3, Rule 5, Rule 7, Rule 9	Surface carburizing of metal parts.
16	Improving the quality of needs.	Rule 2, Rule 3, Rule 7, Rule 9	Upgrading of mercury thermometers to infrared thermometers.

4.2.3. Selection Strategies for Extending Scenario Elements

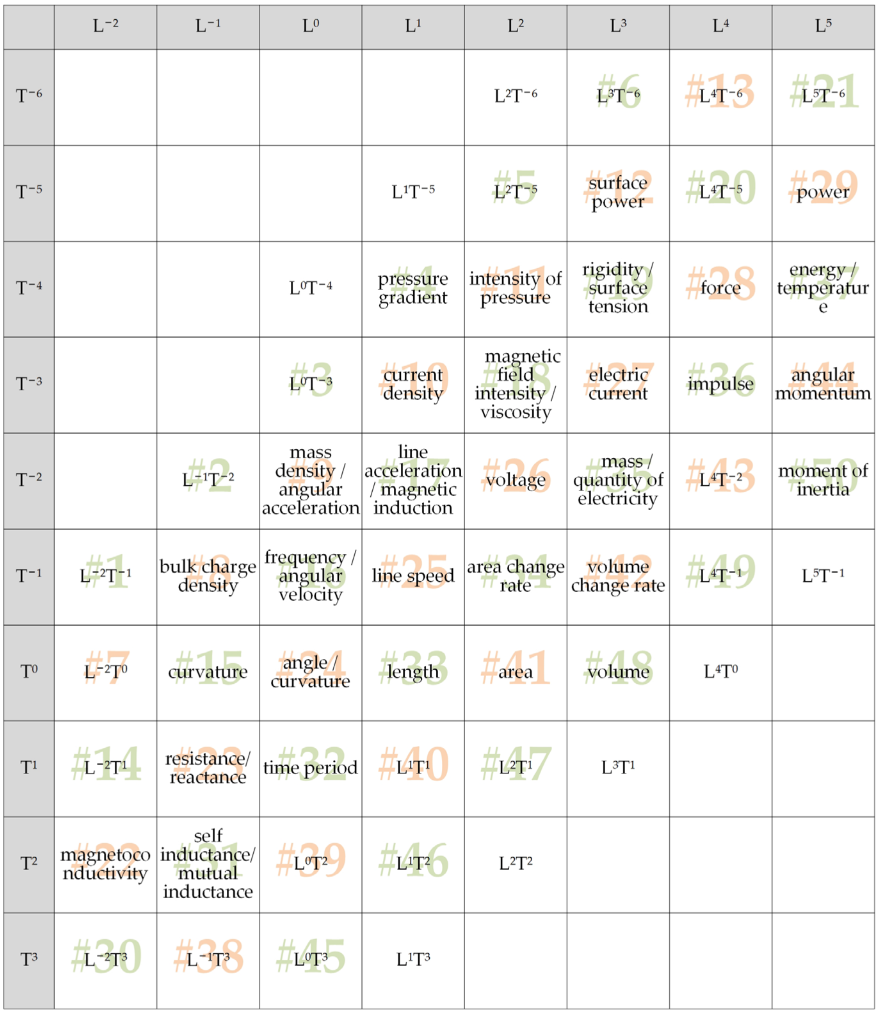
Due to the designers' inertial thinking and inconsistent level of innovation, it is generally difficult to select the appropriate NEC as the element extension strategy. Therefore, we developed a tool to automatically predict NECs using MATLAB and a BP neural network, as follows.

First, a portfolio of 100 real-life product innovation cases was collected and identified; all of them have the common characteristic of being a significant evolution in satisfying user needs compared to the previous generation. Then, we extracted valid information from these samples as sample data. The sample data mainly contain the product characteristics and NECs. In order to study the relationship between product characteristics and NECs, the characteristics of changed scenario elements in two generations of products were extracted from the sample data as inputs to the BP neural network model, and the corresponding numbers of conforming NECs were considered outputs. Since the characteristics of the scenario elements are described in a natural language, which is difficult to recognize when using computers, LT dimensions were used to replace these characteristics.

The LT dimension is a highly abstract representation of physical quantities, which aims to represent arbitrary physical quantities using the product of different powers of length (L) and time (T) dimensions [82,83], e.g., the LT dimension of "pressure" is L^2T^{-4}. As with some kinds of unified relationships between different physical quantities, group theory and topological methods are used to obtain the analytic relationship of physical constants for the LT chart (Figure 12) [83,84]. As shown in Figure 12, there are a total of 50 numbered LT dimensions in the LT chart. The characteristics of a scenario element are the physical attributes that reflect the essence of the element, such as the strength, size, and resistance of the part. The fundamental reason for the outward manifestation of scenario elements and their specific relationships with other elements is the role played by their specific attributes, and thus, the collection of these characteristics constitutes the physical ontology of the element.

The original sample data are finally organized into 100 pieces of available sample data, each containing a set of LT dimension numbers and a NEC ordinal number. They are used as inputs and outputs of the BP neural network, respectively, and some of the data are shown in Table 4. The sample data are input into the BP neural network model for training. The results in Figure 13b show that the training error is minimized when the number of hidden layer nodes is 75, and the error level stabilizes at an order of magnitude of 10^{-2} (Figure 13c), which is a very low error level. Figure 13d shows a prediction accuracy of 90% for the 20 test samples.

In practice, the LT dimension of the target scenario elements is extracted and input into the BP neural network model to obtain the recommended NEC. Designers can extend the target scenario elements guided by the NEC and recommended element extension rules. A large number of new scenario elements can be obtained.



	L^{-2}	L^{-1}	L^{0}	L^{1}	L^{2}	L^{3}	L^{4}	L^{5}
T^{-6}					L^2T^{-6}	#6 L^3T^{-6}	#13 L^4T^{-6}	#21 L^5T^{-6}
T^{-5}				L^1T^{-5}	#5 L^2T^{-5}	#12 surface power	#20 L^4T^{-5}	#29 power
T^{-4}			L^0T^{-4}	#4 pressure gradient	#11 intensity of pressure	#19 rigidity / surface tension	#28 force	#37 energy / temperature
T^{-3}			#3 L^0T^{-3}	#10 current density	#18 magnetic field intensity / viscosity	#27 electric current	#36 impulse	#44 angular momentum
T^{-2}		#2 $L^{-1}T^{-2}$	#9 mass density / angular acceleration	#17 line acceleration / magnetic induction	#26 voltage	#35 mass / quantity of electricity	#43 L^4T^{-2}	#50 moment of inertia
T^{-1}	#1 $L^{-2}T^{-1}$	#8 bulk charge density	#16 frequency / angular velocity	#25 line speed	#34 area change rate	#42 volume change rate	#49 L^4T^{-1}	L^5T^{-1}
T^{0}	#7 $L^{-2}T^0$	#15 curvature	#24 angle / curvature	#33 length	#41 area	#48 volume	L^4T^0	
T^{1}	#14 $L^{-2}T^1$	#23 resistance/ reactance	#32 time period	#40 L^1T^1	#47 L^2T^1	L^3T^1		
T^{2}	#22 magnetoconductivity	#31 self inductance/ mutual inductance	#39 L^0T^2	#46 L^1T^2	L^2T^2			
T^{3}	#30 $L^{-2}T^3$	#38 $L^{-1}T^3$	#45 L^0T^3	L^1T^3				

Figure 12. LT chart [83], where the numbers in the background are the LT dimension numbers.

Table 4. Sample data (part).

No.	Predecessor Product	Next Generation Product	LT Dimension (Input)	NEC (Output)
1	Mercury thermometer	Electronic thermometer	#37, #48	13
2	Integrated air conditioner	Split air conditioner	#16, #24, #48	13
3	Ground-level garage	Three-dimensional garage	#41	8
4	Naturally aspirated engine	Turbocharged engine	#9, #28, #48	16
5	Cell phone holder	Handheld gimbal	#29, #42, #44	4

4.3. New Scenario Element Sets Construction and Innovation Opportunity Identification

The new scenario elements obtained through the above steps are still in a relatively chaotic state and cannot directly form a clear idea of the new product design. These disorderly new scenario elements may contain potential innovation opportunities. Effective design ideas can only be formed after optimization, classification, and integration. As shown in Figure 14, the discovery of innovation opportunities from the new scenario elements consists of two steps: innovation opportunity generation and evaluation.

4.3.1. Innovation Opportunity Generation Process

As shown in Figure 14, changes in product scenarios are divided into active and passive changes. The former are new scenario elements generated by designers using element extension rules, and the latter are passive changes in scenario states and behaviors caused by the impact diffusion of new scenario elements.

The active change is the diffuse extension of scenario elements according to extension rules, where new relationship elements are created in the process of extension of the basic scenario elements, which is related to the use of specific extension rules. The process is as follows:

(1) Firstly, a matrix of new scenario elements is constructed with the original scenario elements as the first column and new scenario elements as rows, as shown in Figure 14.

(2) Then, like the morphological matrix approach, a few suitable new scenario elements are selected from each row of the new scenario element matrix, and these new elements are formed into a set.

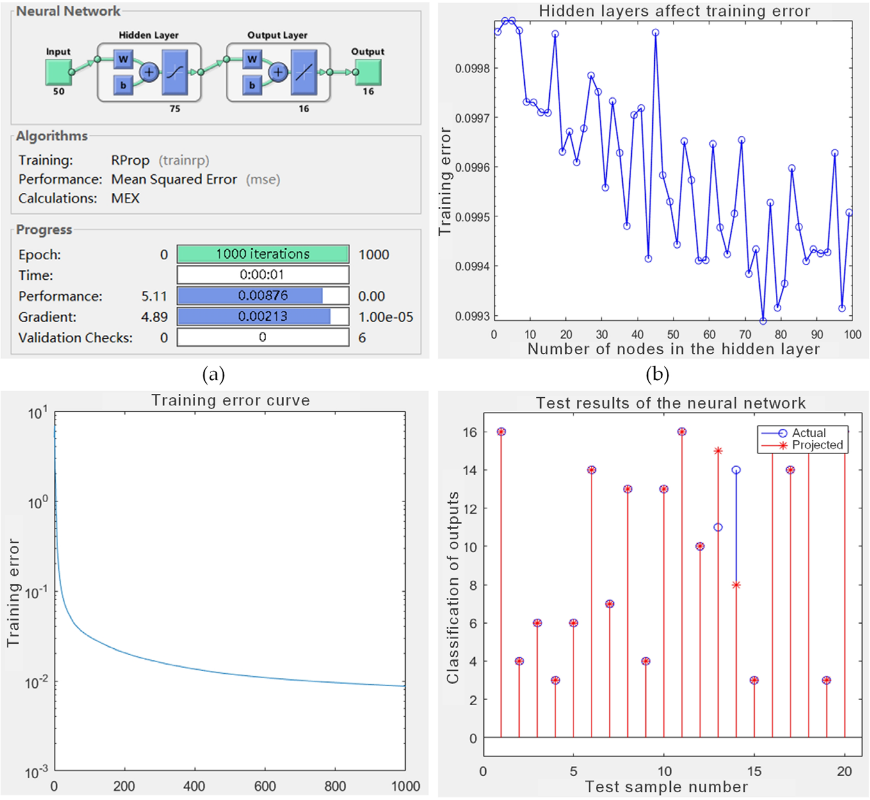
(3) Finally, multiple sets of different new scenario element sets are generated in the same way.

The passive change is the impact diffusion of the active change described above along the scenario development process and is the adaptation of the original system to the active change. The process is as follows:

(1) First, using the original scenario development process as a basis, the location of the starting scenario state affected by the active change is identified.

(2) Then, the way in which product scenarios are adjusted is analyzed along the path of scenario development one by one. This includes the deletion, addition, and modification of scenario states and scenario behaviors. New scenario elements resulting from this process are collected.

(3) Finally, the new scenario elements, scenario states, and scenario behaviors are synthesized, and ways to improve the overall system are identified, resulting in an IIO.



Algorithms
Training: RProp (trainrp)
Performance: Mean Squared Error (mse)
Calculations: MEX

Progress
Epoch: 0 1000 iterations 1000
Time: 0:00:01
Performance: 5.11 0.00876 0.00
Gradient: 4.89 0.00213 1.00e-05
Validation Checks: 0 0 6

(a)

(b)

(c) (d)

Figure 13. BP neural network training results: (**a**) parameter setting interface of neural network, (**b**) curve of the number of nodes in the hidden layer versus the training error, (**c**) curve of the number of training sessions versus the training error, and (**d**) test results of the neural network.

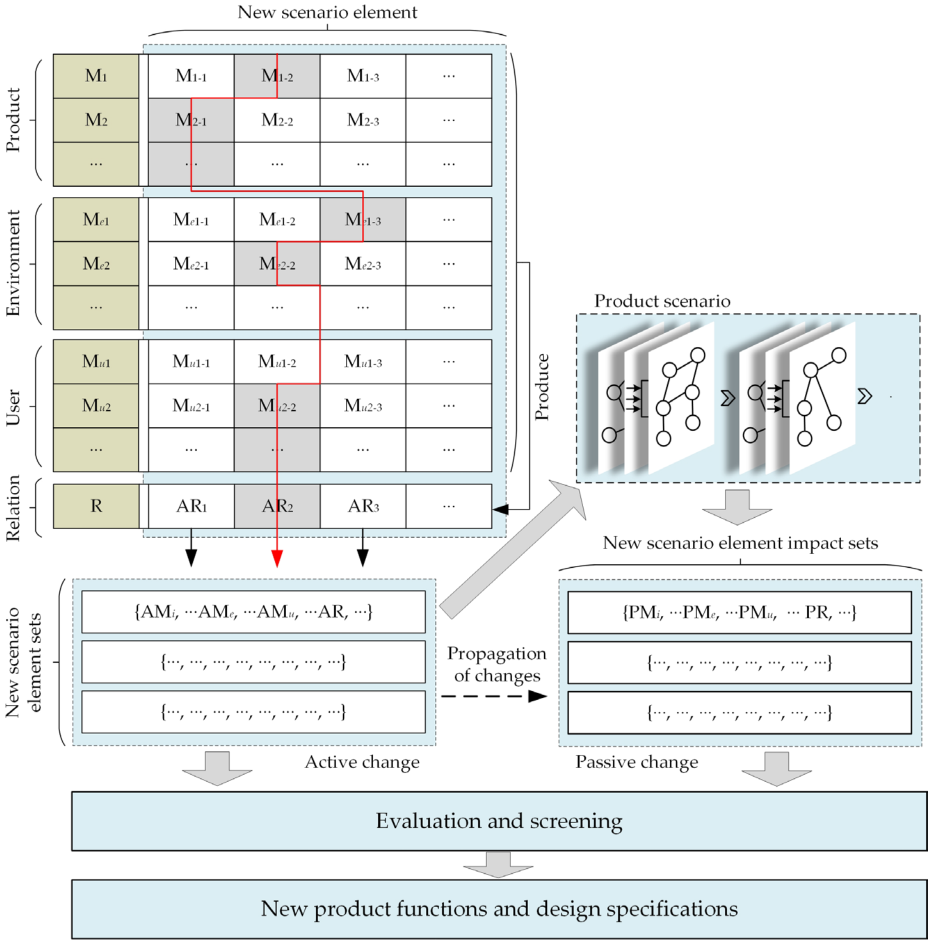


Figure 14. Innovation opportunity generation process.

4.3.2. Innovation Opportunity Evaluation

Active and passive changes together constitute IIOs of the product. Innovation opportunities with development values are screened out through the evaluation of expected novelty and expected values as follows:

(1) Expected novelty evaluation is the screening out of innovation opportunities that are distant or unrelated to existing products. Because the greater distance represents its lower market overlap rate, it is easier to meet the future needs of users and be accepted by the future market. The specifics of changes in the new scenario element sets of active changes are used as evaluation indicators, including values, characteristics, and objects of basic scenario elements as well as the relationship elements. The rules for assigning values to indicators are shown in Table 5. Only one maximum score is recorded for the same element, and the sum of scores in the new scenario element sets is the expected novelty evaluation value of the IIO corresponding to the set.

Table 5. Rules for assigning values to expected novelty indicators.

No.	Indicators	Score
1	Changing of basic scenario element value	1
2	Changing of basic scenario element characteristic	2
3	Changing of basic scenario element object	3
4	Changing of relationship scenario element	1

(2) Expected value evaluation is the screening out of high-value innovation opportunities from the perspective of function changes in the product. The premise of this evaluation is that all function changes are considered to have future values, so the greater the function changes, the higher the expected value of the innovation opportunity. Therefore, the number of changed functions, including improvements, additions, and deletions, is counted from the passively changed content as the evaluation value of the expected value of the IIO.

The highest-scoring IIO is determined based on the sum of the two evaluation values. Based on the content of the innovation opportunity, the product function improvement objectives and design requirements are organized. At the same time, the valuable content of the other IIOs is absorbed to construct a new product design specification, thus forming the FIO. The product is redesigned based on FIOs to obtain a product concept that meets expectations.

4.4. Summary

We reconstruct the product function model using the concept of scenarios and constructed product scenarios. Scenario elements' extension targets are determined using the transformation of Type I and Type II function models and the D–S theory. Scenario element extension rules based on the transformation methods of basic elements in Extenics provide the theoretical basis and method for obtaining new scenario elements. The NEC extracted from the laws of needs evolution forms the element extension strategy, which provides the direction for product scenario evolution. An automated tool for selecting strategies is developed using the LT dimension and BP neural network to reduce the randomness of human judgment. Designers can obtain a large number of new scenario elements based on the element extension strategy and rules. The matrix of new scenario elements is obtained by analogy with the morphological matrix. The FIO is obtained after the optimization, classification, integration, and evaluation processes. This innovation opportunity generation method is easy to operate and highly reliable, which can help companies obtain novel innovation opportunities, reserve innovation knowledge, and maintain competitiveness in the future market. Finally, a seven-step process model of the innovation opportunity generation method based on product scenario evolution is formed, as shown in Figure 15.

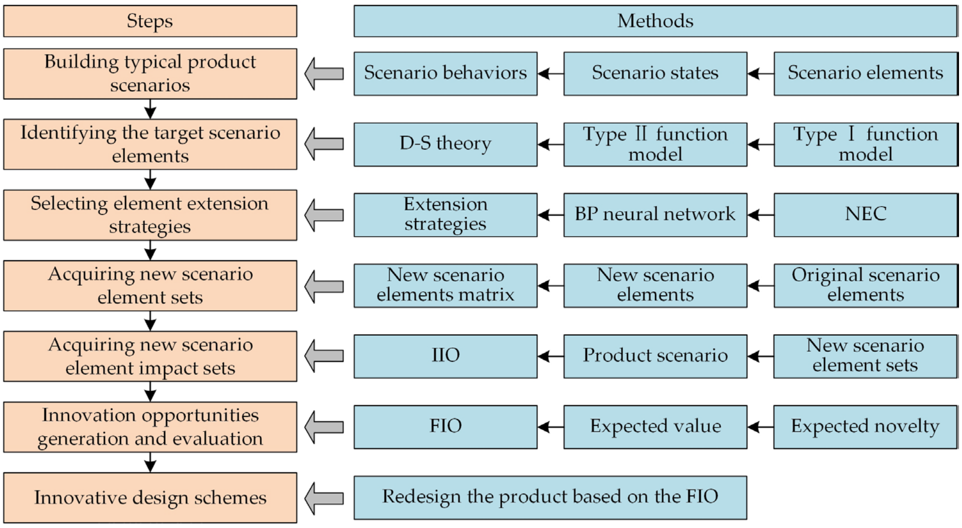


Figure 15. Process model of innovation opportunity generation based on product scenario evolution.

5. Case Study

The PE pipeline hot-melt welding machine (PE-WM) is used as an example to demonstrate the proposed method in generating innovation opportunities based on product scenario evolution. PE-WM is a semi-automated device for connecting gas transmission pipelines. We select a PE-WM as the typical product. Figure 16 shows the product, which mainly consists of a pump station, an electrical box, a heating plate, a milling plate, fixtures, hydraulic cylinders, and a frame, among other parts. Figure 17 shows key steps of the PE-WM working, namely milling the pipe ends, heating the pipes, and butt jointing the pipes.

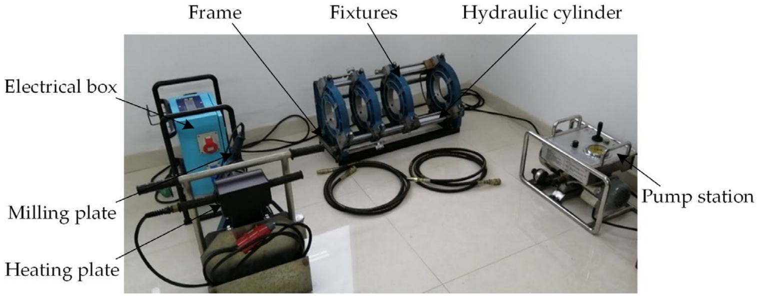


Figure 16. PE pipeline hot-melt welding machine.

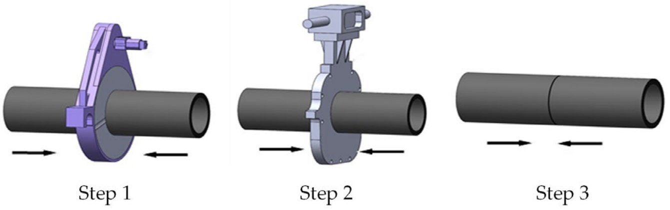


Figure 17. PE-WM key working steps.

5.1. Product Scenario of PE-WM

The PE-WM is decomposed using a reverse fishbone diagram to obtain the basic scenario elements, as shown in Figure 18.

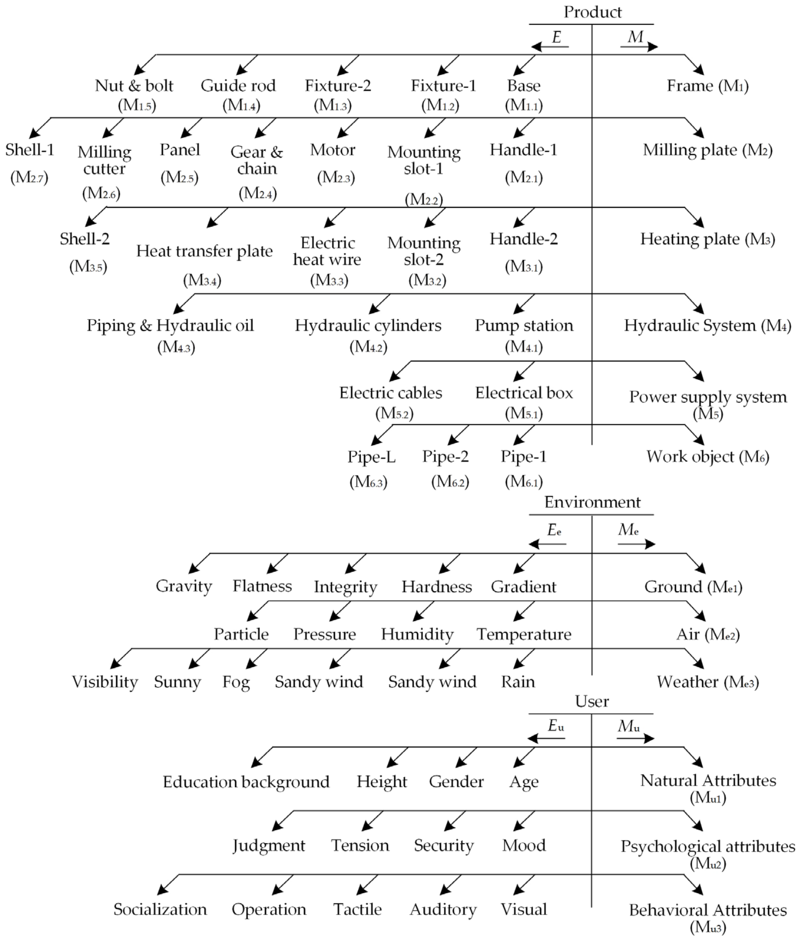


Figure 18. Reverse fishbone diagram of PE-WM.

The Type I function model of PE-WM is constructed, as shown in Figure 19. According to the model, the product, environment, user, and relationship elements in the product scenario are obtained, and scenario elements are connected to form the product scenario state.

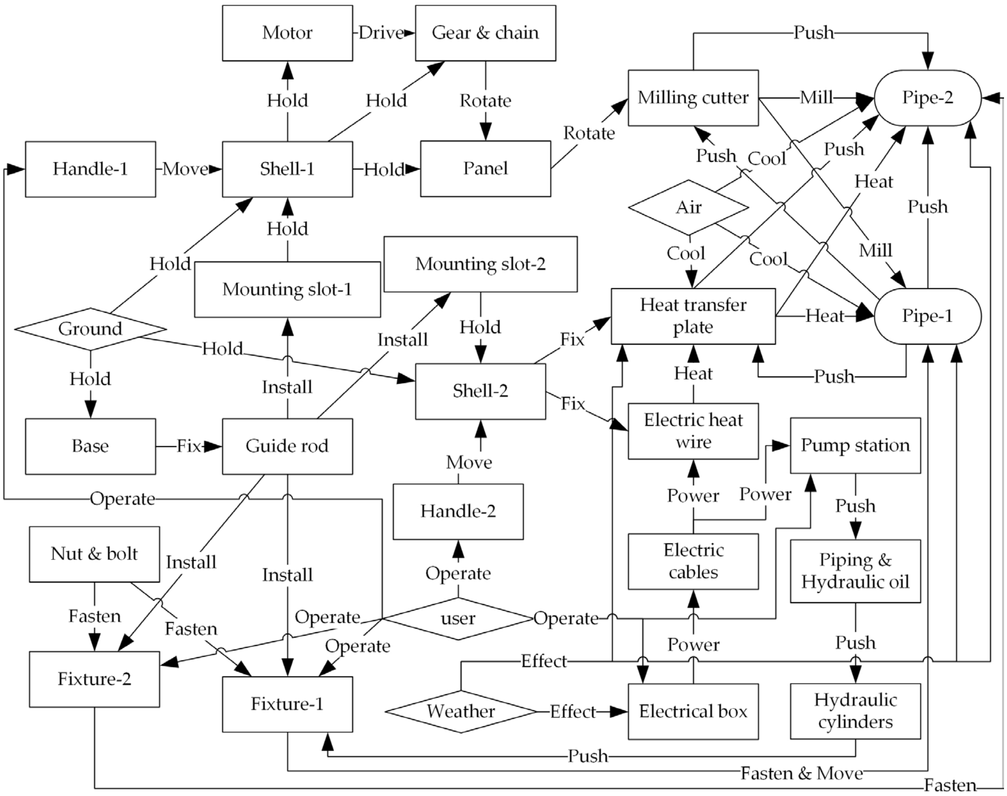


Figure 19. Type I function model of PE-WM.

In order to obtain the PE-WM scenario behavior chain, the function structure shown in Figure 20 was constructed. Obviously, concerning scenario behavior, the function unit's input and output correspond to two different scenario states; for example, the two changing scenario states of "Install pipe" are "Pipe position moves from ground to fixture" and "Fixture changes from open to locked". The output scenario states are inputs for the next scenario behavior, "Close pipe". Since only the scenario elements and scenario behaviors are shown in the function structure, the specific scenario states need to be determined in conjunction with the Type I function model, as shown in Figure 19.

The above two models are integrated in order to form product scenarios for PE-WM. For ease of representation, sequence numbers in Figure 18 are used to represent each basic scenario element, and scenario states on both sides of each scenario behavior are then determined based on the Type I function model and function structure. A total of 14 scenario behaviors are numbered sequentially in the order from left to right in Figure 20. All scenario behaviors and their corresponding scenario states are connected to form the product scenario of PE-WM, as shown in Figure 21.

The rectangles containing only numbers are scenario behaviors (consistent with the serial numbers in Figure 20), and the rectangles on both sides are scenario states, with inputs on the left and outputs on the right. The connecting line between the scenario states represents that part of the output of the previous scenario behavior is the input of the next scenario behavior, i.e., there is an inheritance of scenario states between the two scenario behaviors. Input scenario states that have no inheritance are initial scenario states, such as the left side of scenario behaviors 1 and 6. The output scenario states that are not being inherited are the end scenario states, such as the right side of scenario behaviors 13 and 14. Obviously, after the scenario development, separated "Pipe-1" and "Pipe-2" change from the input of scenario behavior 2 to the combined "Pipe-L" in the output of scenario behavior 13.

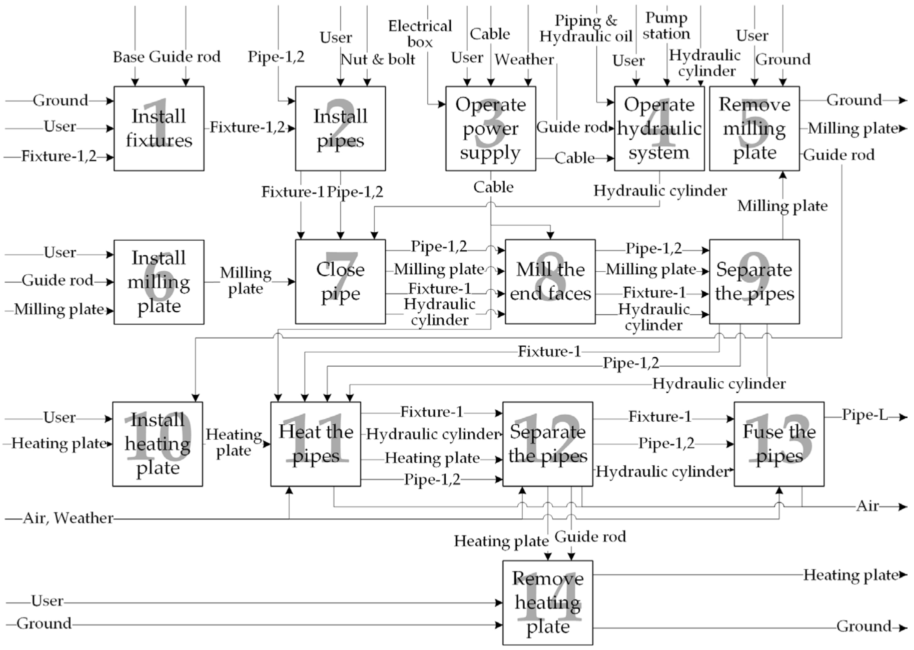


Figure 20. Function structure of PE-WM.

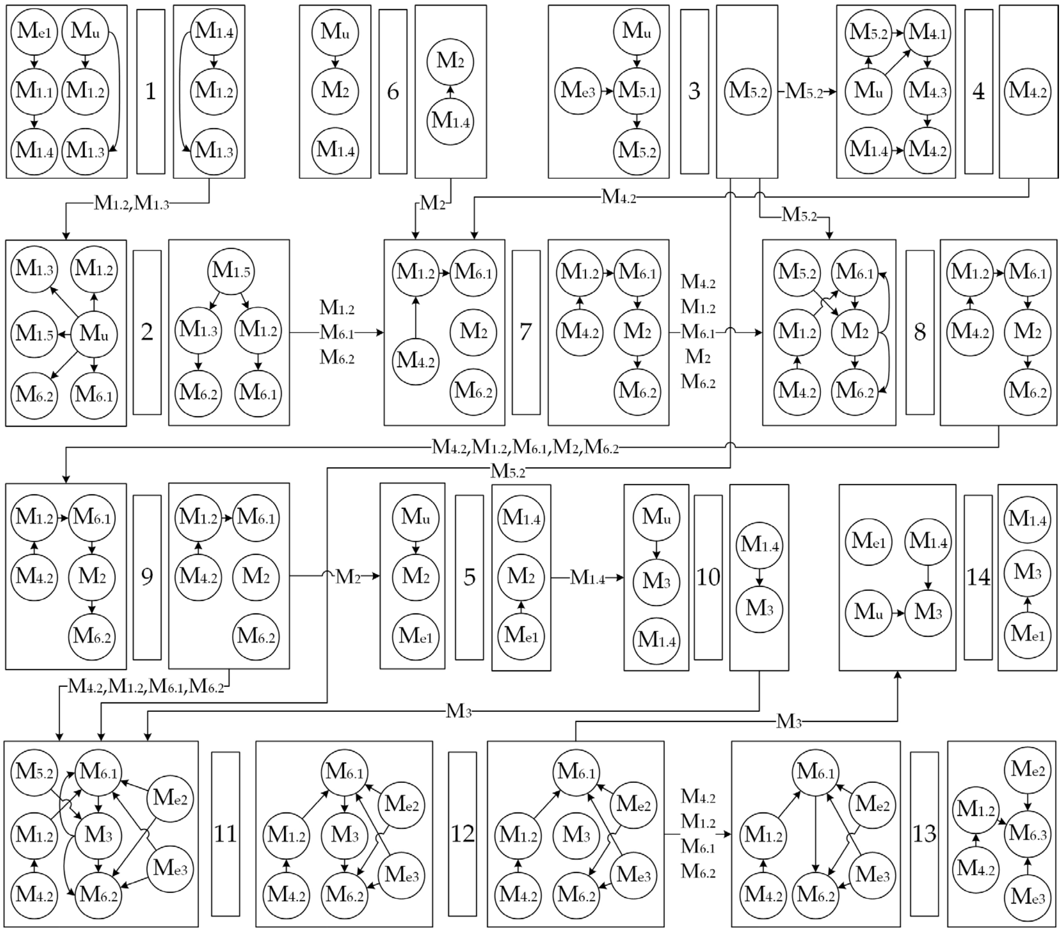


Figure 21. Product scenario of PE-WM.

5.2. PE-WM's Target Extension Scenario Elements

In order to define the scenario extension targets, it is necessary to construct a Type II function model of the PE-WM. In order to be consistent with the product scenario in Figure 21, the "milling plate" and "heating plate" in the Type I function model are considered separate components. Functions in the Type I function model (Figure 19) are then extracted to obtain a total of 31 relevant functions. These functions are converted into more abstract functions, as shown in Table 6. According to the relationship between the functions, the Type II function model is formed, as shown in Figure 22.

Table 6. Abstracted function set.

No.	Function	No.	Function	No.	Function
A_1	Operate fixtures	A_{12}	Maintain clamping force	A_{23}	Increase stability
A_2	Load and unload milling plate	A_{13}	Maintain clamping force	A_{24}	Flattens solid surface
A_3	Load and unload heating plate	A_{14}	Constrain solid's movement direction	A_{25}	Increase contact surface pressure
A_4	Operate fixtures	A_{15}	Stabilize position	A_{26}	Fixed pipe position
A_5	Connect fluid	A_{16}	Fix guide rod	A_{27}	Flattens solid surface
A_6	Switch on the power	A_{17}	Stabilize position	A_{28}	Increase contact surface pressure
A_7	Transmit current	A_{18}	Constrain solid's movement direction	A_{29}	Increase contact area
A_8	Convert electricity	A_{19}	Change solid's position	A_{30}	Increase solid temperature
A_9	Increase liquid's pressure	A_{20}	Increase solid temperature	A_{31}	Combine solids
A_{10}	Drive hydraulic cylinder	A_{21}	Increase contact area		
A_{11}	Move solid linearly	A_{22}	Input electric energy		

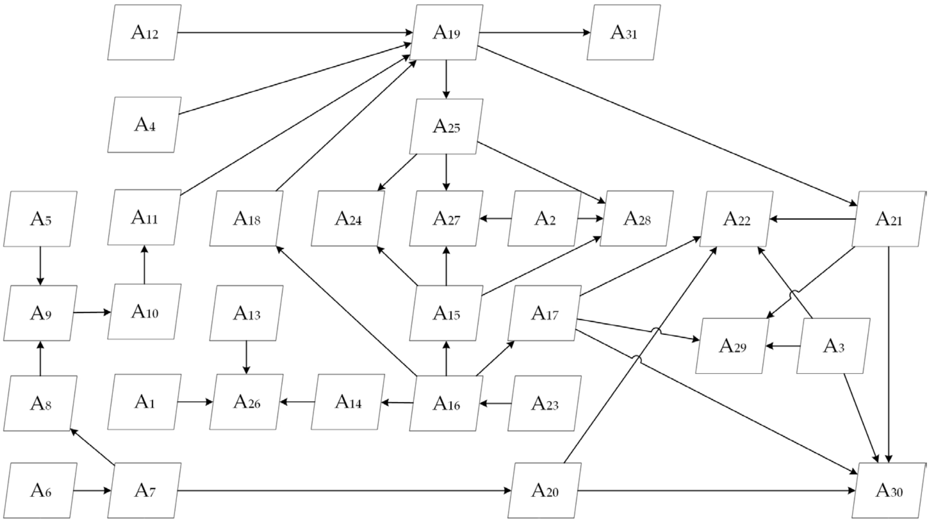


Figure 22. Type II function model of PE-WM.

According to the method proposed in Section 4.1, the abstraction level of the above functions is determined according to the D–S theory. Three PhD students engaged in product innovation design research participated in the evaluation. They have at least three years of design experience in this field. The evaluators decided the abstraction level of the above functions independently and assigned BPA functions to each function according to the D–S theory. The results are shown in Table A1 in Appendix A. According to Dempster's synthesis rule and Equations (2) and (3), BPA functions are calculated after the synthesis of the evidence, and the results are shown in Table A2. The results show that functions A_{22}, A_{23}, A_{24}, A_{27}, A_{30}, and A_{31} belong to level H_1, functions A_{11}, A_{19}, A_{21}, A_{25}, A_{26}, A_{28}, and A_{29} belong to level H_2, and the remaining functions belong to level H_3. Therefore, a Type II hierarchical function model is constructed, as shown in Figure 23. The scenario elements are extracted from level H_1 as extension targets. As shown in Table A3, the target scenario elements included in the functions of level H_1 are the heating plate, pipe-1, ground, base, milling plate, and pipe-2.

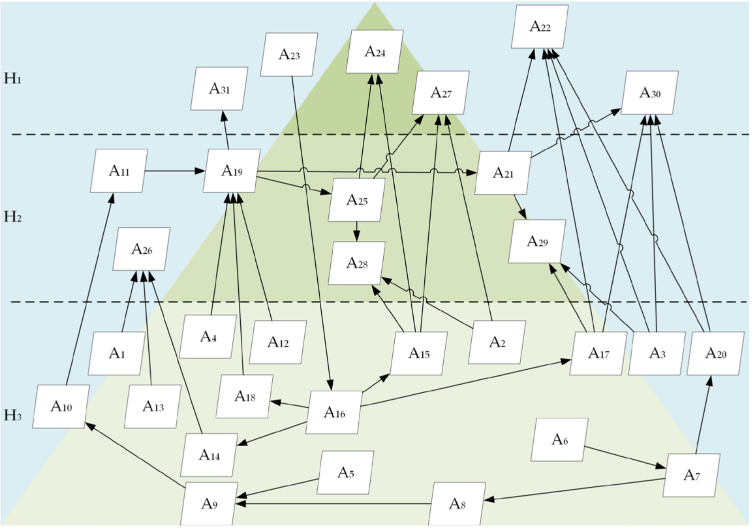
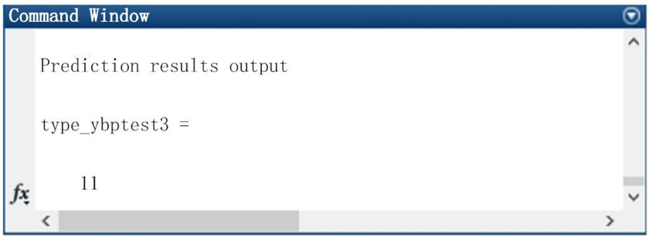


Figure 23. Type II hierarchical function model of PE-WM.

5.3. Selection of Element Extension Strategies

Taking the selection of extension strategy for "heating plate" as an example, the LT dimension numbers of the heating plate are input into the BP neural network prediction model. The output NEC number is 11, as shown in Figure 24. The LT dimension numbers of other target scenario elements are extracted, and their corresponding NECs are obtained in the same way. The results are shown in Table 7.



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Prediction results output

type_ybptest3 =

    11
```

Figure 24. Example of BP neural network prediction output.

Table 7. Predicted results of NECs.

Target	LT Dimension Numbers	NEC	Suggested Extension Rules
Heating plate	#37, #41, #23, #29, #11	11	Rule 1; Rule 3; Rule 6; Rule 7
Pipe-1	#15, #24, #33, #25, #11, #19, #37	9	Rule 2; Rule 3; Rule 6
Ground	#15, #24, #19	15	Rule 2; Rule 3; Rule 5; Rule 7; Rule 9
Base	#33, #11, 19	3	Rule 1; Rule 2; Rule 3; Rule 4; Rule 5
Milling plate	#16, #24, #32, #11, #41, #19, #35, #48, #28, #29	4	Rule 5; Rule 7; Rule 8; Rule 9
Pipe-2	#15, #24, #33, #11, #19, #37	14	Rule 2; Rule 3; Rule 5; Rule 7; Rule 9

According to the suggested extension rules, the target scenario elements are extended, and the results are shown in Tables 8–13. There are six target scenario elements in total; among them, "ground" belongs to the environment element, and the others belong to the product element. As a result of the extension, nine new relationship elements are generated, namely $M_{e1\text{-}5}$~$M_{e1\text{-}9}$, $M_{2\text{-}1}$~$M_{2\text{-}3}$, and $M_{6.2\text{-}7}$.

Table 8. Scenario element extending results (M_3).

No.	Heating Plate			Rule	No.	New Scenario Elements		
M_3	Heating plate	Temp	220 °C	Rule 1	$M_{3\text{-}1}$	Heating plate	Temp	220 °C
		Shape	Round				Shape	Round
		Weight	Heavy				Weight	Heavy
		Resistance	$14 \sim 19\Omega$				Resistance	$14 \sim 19\Omega$
		Object	Pipe end face				Object	Pipe end face
							Thickness	5cm
							Position	Ground & Guide rod
							Shape change	Expand & Contraction
							Handling	Manual
							Tem_grad	Uneven
				Rule 2	$M_{3\text{-}2}$	Thermit reaction	Temp	High
							Environment	Wild
					$M_{3\text{-}3}$	Induction heat	Temp	High
							Heating speed	Fast
					$M_{3\text{-}4}$	Friction	Temp	High
				Rule 3	$M_{3\text{-}5}$	Fire	Temp	High
							Environment	Wild
					$M_{3\text{-}7}$	Heating wire	Resistance	$14 \sim 19\Omega$
							Temp	> 220 °C
					$M_{3\text{-}7}$	Heat transfer plate	Shape	Round
							Object	Pipe end face
							Temp	220 °C
				Rule 4	$M_{3\text{-}8}$	$M_2 \oplus M_3$	Temp	25–220 °C
							Shape	Round
							Weight	Heavy
							Object	Pipe end face
							Resistance	$14 - 19\Omega$
							Driving	Motor
							Speed	150r/min
							Waste	Swarf
					$M_{3\text{-}9}$	$M_3 \oplus M_{1.1}$	Temp	220 °C
							Shap	Round
							Weight	Heavy
							Resistance	$14 - 19\Omega$
							Object	Pipe end face
							Stability	High

Table 9. Scenario element extending results ($M_{6.1}$).

No.	Pipe-1			Rule	No.	New Scenario Elements		
$M_{6.1}$	Pipe-1	Material	PE	Rule 2	$M_{6.1\text{-}1}$	Pipe-1′	Material	New
		Melting point	$100 \sim 130$ °C				Melting point	> 200 °C
		Shape	Cylinder		$M_{6.1\text{-}2}$	Pipe-1′	Shape	Rectangle
		In_diameter	Exist_size		$M_{6.1\text{-}3}$	Pipe-1′	Shape	Ellipse
		End shape	Ring	Rule 3	$M_{6.1\text{-}4}$	Plate	Material	PE
		Angle	180°				Melting point	$100 \sim 130$ °C
		Move speed	Slow		$M_{6.1\text{-}5}$	Solid bar	Material	PE
		Move direction	Axis				Melting point	$100 \sim 130$ °C
							Shape	Cylinder
							Angle	180°
							Move speed	Slow
							Move direction	Axis

Table 10. Scenario element extending results (M_{e1}).

No.	Ground	Rule	No.	New Scenario Elements
M_{e1}	$\begin{bmatrix} \text{Ground} & \text{Slope} & < 0.5\% \\ & \text{Hardness} & \text{High} \\ & \text{Integral} & \text{High} \\ & \text{Flatness} & \text{High} \\ & \text{G} & 10\ \text{m/s}^2 \end{bmatrix}$	Rule 2	$M_{e1\text{-}1}$	$\begin{bmatrix} \text{Sandy ground} & \text{Slope} & < 0.5\% \\ & \text{Hardness} & \text{Low} \\ & \text{Integral} & \text{Low} \\ & \text{Flatness} & \text{Low} \\ & \text{G} & 10\ \text{m/s}^2 \end{bmatrix}$
			$M_{e1\text{-}2}$	$\begin{bmatrix} \text{Mud ground} & \text{Slope} & < 0.5\% \\ & \text{Hardness} & \text{Low} \\ & \text{Integral} & \text{Low} \\ & \text{Flatness} & \text{High} \\ & \text{G} & \text{g} \end{bmatrix}$
			$M_{e1\text{-}3}$	$\begin{bmatrix} \text{Mountains} & \text{Slope} & > 1\% \\ & \text{Hardness} & \text{High} \\ & \text{Integral} & \text{High} \\ & \text{Flatness} & \text{Low} \\ & \text{G} & 10\ \text{m/s}^2 \end{bmatrix}$
		Rule 3	$M_{e1\text{-}4}$	$\begin{bmatrix} \text{Ice surface} & \text{Slope} & < 0.5\% \\ & \text{Hardness} & \text{High} \\ & \text{Integral} & \text{High} \\ & \text{Flatness} & \text{High} \\ & \text{G} & 10\ \text{m/s}^2 \end{bmatrix}$
		Rule 5	$M_{e1\text{-}5}$	$\left(\text{Ground} \overset{\text{Weak}}{\sim} \text{Base}\right)$
			$M_{e1\text{-}6}$	$(\text{Ground},\ \text{Milling plate})$
			$M_{e1\text{-}7}$	$(\text{Ground},\ \text{Heating plate})$
			$M_{e1\text{-}8}$	$(\text{Ground},\ \text{Electrical box})$
			$M_{e1\text{-}9}$	$(\text{Ground},\ \text{Hydraulic system})$

Table 11. Scenario element extending results ($M_{1.1}$).

No.	Base	Rule	No.	New Scenario Elements
$M_{1.1}$	$\begin{bmatrix} \text{Base} & \text{Support\_direc} & \text{Up} \\ & \text{Gravity\_direc} & \text{Down} \\ & \text{Structure} & \text{Frame} \end{bmatrix}$	Rule 1	$M_{1.1\text{-}1}$	$\begin{bmatrix} \text{Base} & \text{Support\_direc} & \text{Up} \\ & \text{Gravity\_direc} & \text{Down} \\ & \text{Structure} & \text{Frame} \\ & \text{Chassis} & \text{Flat} \\ & \text{Opening} & \text{Semi} - \text{open} \\ & \text{Height} & \text{Non} - \text{adjustable} \\ & \text{Moveable} & \text{Non} - \text{movable} \end{bmatrix}$
		Rule 4	$M_{1.1\text{-}2}$	$\begin{bmatrix} \text{Base} & \text{Height} & \text{Adjustable} \end{bmatrix}$
			$M_{1.1\text{-}3}$	$\begin{bmatrix} \text{Base} & \text{Moveable} & \text{Moveable} \end{bmatrix}$

Table 12. Scenario element extending results (M_2).

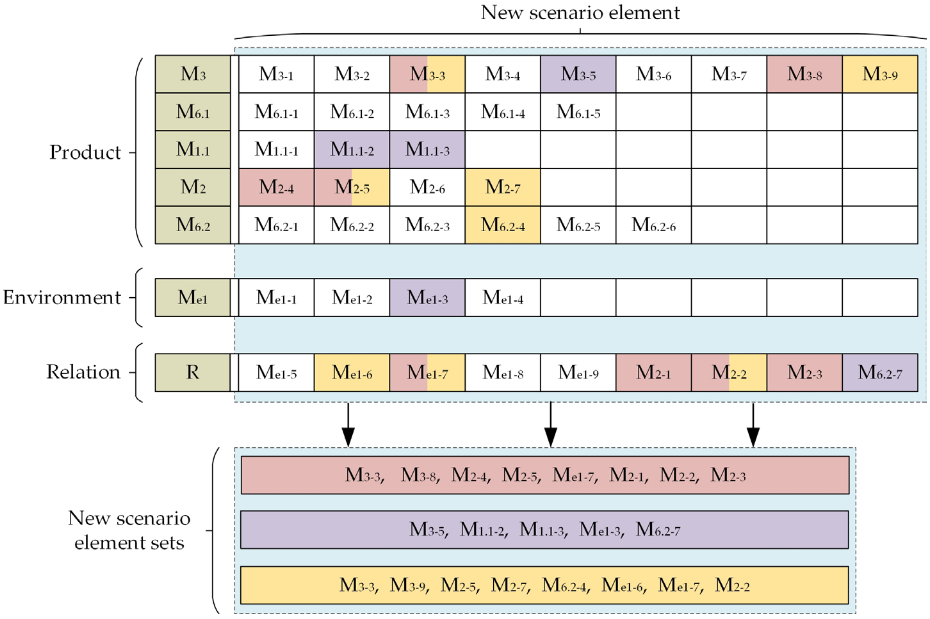
No.	Milling Plate	Rule	No.	New Scenario Elements
M_2	$\begin{bmatrix} \text{Milling plate} & \text{Temp} & 25\ ^\circ\text{C} \\ & \text{Shape} & \text{Round} \\ & \text{Weight} & \text{Heavy} \\ & \text{Driving} & \text{Motor} \\ & \text{Speed} & 150\ \text{r/min} \\ & \text{Waste} & \text{Swarf} \\ & \text{Object} & \text{Pipe end face} \end{bmatrix}$	Rule 5	$M_{2\text{-}1}$	$\left(\text{Milling plate} \overset{\text{Strong}}{\sim} \text{Heating plate}\right)$
			$M_{2\text{-}2}$	$(\text{Milling plate} \sim \text{Base})$
			$M_{2\text{-}3}$	$\left(\text{Milling plate} \overset{\text{Weak}}{\sim} \text{User}\right)$
		Rule 7	$M_{2\text{-}4}$	$\begin{bmatrix} M_2 \oplus M_3 & \text{Temp} & 25\text{–}220\ ^\circ\text{C} \\ & \text{Shape} & \text{Round} \\ & \text{Weight} & \text{Heavy} \\ & \text{Object} & \text{Pipe end face} \\ & \text{Resistance} & 14 - 19\Omega \\ & \text{Driving} & \text{Motor} \\ & \text{Speed} & 150\text{r/min} \\ & \text{Waste} & \text{Swarf} \end{bmatrix}$
			$M_{2\text{-}5}$	$\begin{bmatrix} M_2 \oplus \text{Cylinder}' & \text{Handling method} & \text{Auto} \\ & \text{Safety} & \text{High} \\ & \text{Efficiency} & \text{High} \end{bmatrix}$
		Rule 8	$M_{2\text{-}6}$	$\begin{bmatrix} \text{Milling plate} & \text{Number of cutters} & \geq 2 \end{bmatrix}$
			$M_{2\text{-}7}$	$\begin{bmatrix} \text{Milling plate} & \text{Number} & \geq 2 \end{bmatrix}$

Table 13. Scenario element extending results ($M_{6.2}$).

No.	Pipe-2	Rule	No.	New Scenario Elements
$M_{6.2}$	$\begin{bmatrix} \text{Pipe-2} & \text{Material} & \text{PE} \\ & \text{Melting point} & 100 \sim 130\ ^\circ\text{C} \\ & \text{Shape} & \text{Cylinder} \\ & \text{In\_diameter} & \text{Exist\_size} \\ & \text{End shape} & \text{Ring} \\ & \text{Angle} & 180^\circ \\ & \text{Position} & \text{Fixed} \end{bmatrix}$	Rule 2	$M_{6.2\text{-}1}$	$\begin{bmatrix} \text{Pipe-2}' & \text{Material} & \text{New} \\ & \text{Melting point} & > 200\ ^\circ\text{C} \end{bmatrix}$
			$M_{6.2\text{-}2}$	$[\text{Pipe-2}' \quad \text{Shape} \quad \text{Rectangle}]$
			$M_{6.2\text{-}3}$	$[\text{Pipe-2}' \quad \text{In\_diameter} \quad \text{Different}]$
			$M_{6.2\text{-}4}$	$[\text{Pipe-2}' \quad \text{Angle} \quad 90 \sim 180^\circ]$
		Rule 3	$M_{6.2\text{-}5}$	$\begin{bmatrix} \text{Plat} & \text{Material} & \text{PE} \\ & \text{Melting point} & 100 \sim 130\ ^\circ\text{C} \end{bmatrix}$
			$M_{6.2\text{-}6}$	$\begin{bmatrix} \text{Solid bar} & \text{Material} & \text{PE} \\ & \text{Melting point} & 100 \sim 130\ ^\circ\text{C} \\ & \text{Shape} & \text{Cylinder} \\ & \text{Angle} & 180^\circ \\ & \text{Move speed} & \text{Slow} \\ & \text{Move direction} & \text{Axis} \end{bmatrix}$
		Rule 5	$M_{6.2\text{-}7}$	(Swarf, Environment)

5.4. New Scenario Element Sets and Innovation Opportunities

Based on the target scenario elements and new scenario elements, a matrix of new scenario elements is constructed, as shown in Figure 25. Appropriate new scenario elements are then selected from each row of the matrix to constitute new scenario element sets. Due to space limitations, we only show three new scenario element sets in Figure 25.



Product	M_3	$M_{3\text{-}1}$	$M_{3\text{-}2}$	$M_{3\text{-}3}$	$M_{3\text{-}4}$	$M_{3\text{-}5}$	$M_{3\text{-}6}$	$M_{3\text{-}7}$	$M_{3\text{-}8}$	$M_{3\text{-}9}$
	$M_{6.1}$	$M_{6.1\text{-}1}$	$M_{6.1\text{-}2}$	$M_{6.1\text{-}3}$	$M_{6.1\text{-}4}$	$M_{6.1\text{-}5}$				
	$M_{1.1}$	$M_{1.1\text{-}1}$	$M_{1.1\text{-}2}$	$M_{1.1\text{-}3}$						
	M_2	$M_{2\text{-}4}$	$M_{2\text{-}5}$	$M_{2\text{-}6}$	$M_{2\text{-}7}$					
	$M_{6.2}$	$M_{6.2\text{-}1}$	$M_{6.2\text{-}2}$	$M_{6.2\text{-}3}$	$M_{6.2\text{-}4}$	$M_{6.2\text{-}5}$	$M_{6.2\text{-}6}$			
Environment	M_{e1}	$M_{e1\text{-}1}$	$M_{e1\text{-}2}$	$M_{e1\text{-}3}$	$M_{e1\text{-}4}$					
Relation	R	$M_{e1\text{-}5}$	$M_{e1\text{-}6}$	$M_{e1\text{-}7}$	$M_{e1\text{-}8}$	$M_{e1\text{-}9}$	$M_{2\text{-}1}$	$M_{2\text{-}2}$	$M_{2\text{-}3}$	$M_{6.2\text{-}7}$

New scenario element sets

$M_{3\text{-}3}$, $M_{3\text{-}8}$, $M_{2\text{-}4}$, $M_{2\text{-}5}$, $M_{e1\text{-}7}$, $M_{2\text{-}1}$, $M_{2\text{-}2}$, $M_{2\text{-}3}$

$M_{3\text{-}5}$, $M_{1.1\text{-}2}$, $M_{1.1\text{-}3}$, $M_{e1\text{-}3}$, $M_{6.2\text{-}7}$

$M_{3\text{-}3}$, $M_{3\text{-}9}$, $M_{2\text{-}5}$, $M_{2\text{-}7}$, $M_{6.2\text{-}4}$, $M_{e1\text{-}6}$, $M_{e1\text{-}7}$, $M_{2\text{-}2}$

Figure 25. New scenario elements matrix.

The three new scenario element sets are named S_1, S_2, and S_3. They are then substituted into the product scenario (Figure 21). The impacted scenario states and behaviors are analyzed based on the scenario development process to form the following three IIOs:

(1) IIO-1: After analyzing S_1, it is clear that this set combines the heating and milling plates into a new system with hydraulic cylinders for loading and unloading, and using the principle of induction heating, which has the advantage of increasing the automation of the system. The new scenario elements of S_1 are substituted into Figure 21 to analyze the scenario development process and impact diffusion. It is found that the impacted scenario behaviors are numbers 5, 6, 9, 10, 11, and 14, where scenario behaviors 5 and 9 are no longer needed and should be deleted, functions of 6, 10, and 14 should be performed by hydraulic cylinders, and the heating principle of 11 should be replaced by induction heating.

(2) IIO-2: After analyzing S_2, it is clear that this set forms a PE-WM for working in mountainous environments without electricity and with features that are easy to move

and collect milling swarf. Based on the features of S_2, it is not difficult to deduce that the milling plates and hydraulic cylinders that rely on electricity require new principles. The new scenario elements are substituted into Figure 21; it can be concluded that the impacted scenario behaviors include 3, 4, 7, 8, 9, 11, 12, and 13, and their corresponding scenario states. Specifically, 3 and 4 should be deleted, and new energy sources and transmissions should be utilized to improve 8, 9, 11, 12, and 13 with the addition of a milling swarf collection device and a base adjustment and travel device.

(3) IIO-3: After analyzing S_3, the set forms a PE-WM to make a non-straight pipe (fused at an angle of less than 180°) by using at least two milling plates and an induction heating method to increase the heating efficiency, and hydraulic cylinders for automatic loading and unloading of both the heating and milling plates. The new scenario elements are substituted into Figure 21; it is found that the changed scenario states and behaviors include 1, 5, 6, 8, 10, 11, 12, 13, and 14. In addition, the pipes should be cut into the desired angle before milling the end face, so it is necessary to add functions of cutting pipes before behavior 6 and changing the angle of the milling plate before milling. Using the principle of induction heating to improve the original heating plate, the function of adjusting the pipe angle should be added before behavior 10 in order to make the end faces of the two pipes overlap completely.

According to the method proposed in Section 4.3.2, the above IIOs are evaluated in terms of both expected novelty and value. Based on the actively changing new scenario element sets and contents of IIOs, the specific scores of each IIO can be analyzed as shown in Table 14, which shows that IIO-3 has the highest total score and can be considered as the FIO.

Table 14. Evaluation of the IIOs.

IIO	Expected Novelty	Expected Value	Total Score
IIO-1	3 + 2 + 2 + 1 + 1 + 1 + 1 = 11	6	17
IIO-2	3 + 2 + 2 + 3 + 1 = 11	10	21
IIO-3	3 + 2 + 2 + 1 + 3 + 1 + 1 + 1 = 14	11	25

5.5. Innovative Design Scheme of PE-WM

Based on the contents of IIO-3 and the available parts of IIO-1 and IIO-2, we organize the design requirements for the new product as the FIO for PE-WM. We present the contents of the FIO in the form of a design specification, as shown in Table 15. Following this design specification, we propose a conceptual scheme for the new PE-WM. The conceptual scheme integrates systems as a whole with functions of walking and leveling to adapt to uneven working environments, as shown in Figure 26. The most special feature of the scheme is the ability to weld pipes at an angle of less than 180°, as shown in Figure 27. A gyroscope-like ring support structure is designed to support the heating and milling plates, allowing them to rotate around their vertical axis at the target angle to adapt to the shape of the pipe's end face, as shown in Figure 28. The final design is shown in Figure 29.

5.6. Solution Evaluation and Comparison

Collecting and analyzing patents authorized in recent years, it was found that there are two main types of PE pipeline connection methods: joint and automatic (semi-automatic) types. The former requires customized joints according to demand, and its principle is to electrify the electric heating wire in the joint and pipe combination area to melt the material in the area and then cool it down to realize the connection. The latter, similar to the proposed scheme, is an automated or semi-automated device for connecting by heating and melting the pipe ends to butt the two pipes. As shown in Table 16, some representative patents are analyzed, and the advantages and disadvantages of the two types of schemes are summarized.

Compared with other designs, the proposed solution has obvious advantages, such as easy construction, easy transportation, self-walking, and adjustable attitude. Most importantly, the proposed design has the function of connecting pipes at any angle, which is not available in other designs. It can reduce the construction difficulty of complex terrain, improve construction efficiency, and reduce cost. Therefore, the proposed design is innovative and has a broad application prospect. In the future, it can be further enhanced by absorbing the advantages of other schemes, such as connecting pipes of different materials and improving the structural load-bearing capacity of the joints.

Table 15. Design specification of a new PE-WM.

Product name: New PE-WM	Overall function: Connect the pipes
Key input: Two separated PE pipes	Key output: A connected complete PE pipe
Important assistant functions: Adjusting the base, Walking, Loading and unloading milling and heating plates, Cutting pipes, Adjusting pipes	
Performance requirements:	The angle of the pipe after welding is 90° to 180°; Adjusting the base to keep the machine level; Automatic loading and unloading of the milling and heating plates by means of hydraulic cylinders; Pipe cutting device and milling plate can be adjusted in angle; Clamps can be rotated and moved;
Environmental characteristics:	The working place is outdoors in a non-flat area; Sunny weather; Power supply is available; Temperature and humidity are normal;
User Characteristics:	Physically active adults engaged in pipeline construction; Have some specialized knowledge; Normal mobility;
Available Resources:	Air, atmospheric pressure, power, manpower, power provided by motors and hydraulics, etc.;
Design Constraints:	Cost should be kept under USD1500; Operation should not be too complicated; Pipe O.D. range from 100 to 4000 mm; Pipe wall thickness less than 30 mm.

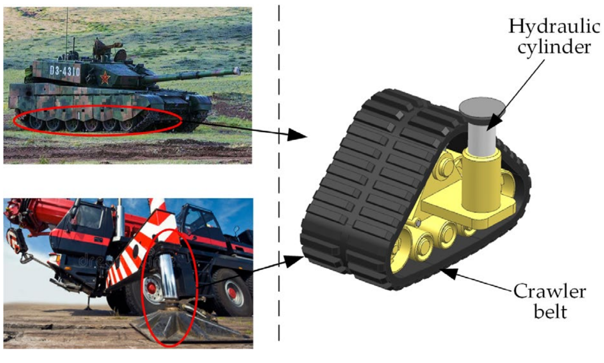


Figure 26. Walking and leveling mechanism.

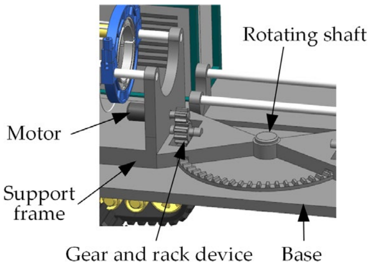


Figure 27. Angle adjusting mechanism.

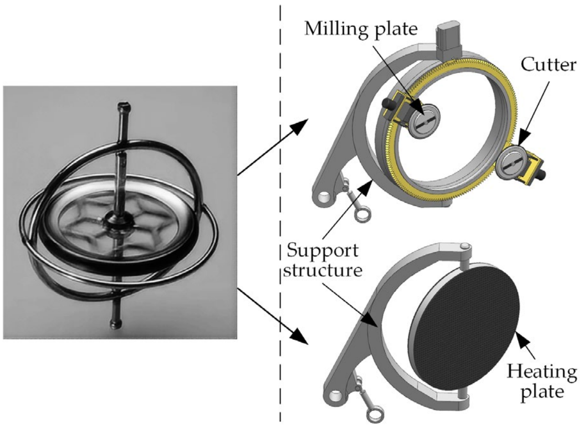


Figure 28. Milling and heating plate structures.

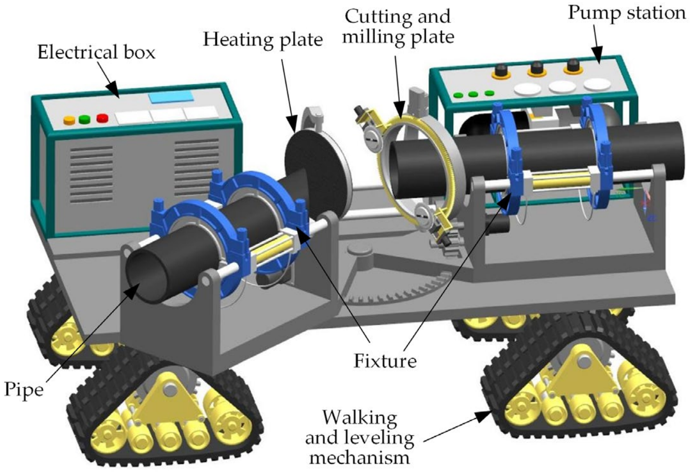


Figure 29. A new concept scheme of PE-WM.

Table 16. Analysis of related patents.

Type	Patent	Advantage	Disadvantage
Joint	CN218719619U: Novel electric fuse connecting pipe fitting for household interface of heat-resistant polyethylene heat supply pipe network CN218645023U: Leakage-proof PE (polyethylene) electric smelting 90-degree elbow CN218582583U: Electrothermal fusion welding structure of pipeline joint coating sleeve after seamless thermal shrinkage CN215721591U: Pipeline connecting structure	1. Ease of construction. 2. Low cost. 3. No complicated equipment required. 4. Can be connected at 90 degrees. 5. Can connect complex shaped joints. 6. Can connect pipes of different materials. 7. Increase structural load bearing capacity.	1. Requires prefabricated parts. 2. Angle cannot be adjusted. 3. Low construction tolerance. 4. Difficulty in ensuring quality of joints. 5. Joints are not universal.
Automatic (semi-automatic)	CN219405477U: A PE drainage pipe thermal welding equipment CN219007064U: PE pipeline hot melting connection fixing device CN218804090U: A PE pipe hot-melt welding equipment with good supporting effect CN218366577U: Polyethylene gas pipe hot melting butt joint pipe fitting CN217862856U: Electric melting welding device for high-density polyethylene pipeline	1. Highly automated. 2. High efficiency. 3. High versatility. 4. Controllable welding quality. 5. High welding quality.	1. Unable to connect pipes of different materials. 2. Unable to connect pipes of different sizes. 3. Unable to connect pipes with angles. 4. Not easy to transport. 5. Cannot be moved by itself.

6. Discussion

This paper proposes an innovation opportunity generation method based on the evolution of product scenarios, where future product scenarios are obtained by analyzing only a small number of the most important stakeholders. It forms a product-centric scenario concept, the essence of which is a scenario state and scenario behavior chain based on scenario elements. Scenario element extension strategies and rules are proposed based on NECs and basic element extension theories to ensure the quality and quantity of innovation opportunities. The construction of new scenario element sets and impact sets enables the formation of IIOs, which is also the process behind the emergence of innovation opportunities. The evaluation of IIOs integrates expected novelty and value to assess the development potential of future products and forms FIOs through appropriate integration. The method explores the innovation opportunities of current products from the perspective of the future for a well-structured method. The innovative design of the PE pipeline hot-melt welding machine shows the effectiveness of the method.

Compared with the existing methods, our method has advantages in terms of its wide range of applicability and low dependence on existing products. Our method is highly maneuverable and friendly to front-line engineers. The proposed target element determination method is based on the function model transformation, which avoids adverse results caused by blind selection to improve the efficiency and quality in terms of obtaining innovative opportunities. We have formulated rules and strategies for the scenario element extension to provide clear guidance and reference for designers, thus helping reduce uncertainty and risks in decision-making. The automatic strategy selection method improves the efficiency of complex system element extension and reduces the effects of human subjectivity. The identification and evaluation of innovative opportunities based on new scenario elements help designers generate a large number of new element combinations with innovative thinking and new product design ideas. The advantages in quantity and novelty can yield breakthrough innovative opportunities with significant differences from existing products. Overall, our method is an efficient innovative opportunity analysis method that forms a theoretical and methodological foundation for automated opportunity analysis.

In contrast to existing opportunity analysis studies, such as demand analysis or patent analysis, this method is an ex ante prediction method. It does not rely on pre-existing data, such as user reviews and patent applications. The generation, collection, organization, and analysis of data can take a lot of time and resources, and the collected data may be biased and incomplete. Our method focuses on forecasting future needs and predicting trends and opportunities by analyzing changes in current technologies, markets, and environments. This foresight enables companies to plan ahead and seize future market opportunities. This method considers the dynamic changes in the future to capture the uncertainty of the market and technological development. It enables companies to flexibly adapt to future changes and adjust their strategies on time.

This method is more efficient, targeted, and forward-looking because it goes directly from the scenario to the solution, which is different to the existing methods. Starting directly from the product scenario, steps of requirements gathering and analysis can be skipped, thus saving time and resources. It can go directly to the conceptual design stage to identify problems and improvement points and then propose innovative solutions. Analyzing new product scenarios allows for more accurate identification of potential improvement spaces and innovation opportunities for product development. In addition, it is possible to anticipate future problems and challenges so that coping strategies can be developed in advance. In contrast, the requirement analysis tends to focus more on current needs and problems and may not be accurate enough to grasp future trends and changes.

According to the KANO model, the most valuable needs for product innovation are excitement needs. However, these kinds of needs cannot usually be captured by analyzing historical data because users are unable to explicitly express such needs. In addition, the excitement needs are characterized by generating attributes that are different from the current product state, which is unexpected by users or exceeds their expectations of the product or service. Our method predicts future needs rather than incrementally improving an existing product. This makes it more effective in generating innovative opportunities to satisfy the excitement need. The analysis of innovation opportunities for the PE pipeline hot-melt welding machine shows that our method can obtain many high-value innovation opportunities, proving the effectiveness of the method.

There are still some limitations of this method. Firstly, the use of the element extension rule still relies on the experience of designers, and different people may produce different results. The diversity and creativity of the results are related to the ability of designers, especially divergent thinking and imagination. This aspect can be improved by organizing multidisciplinary, multilevel, and cross-domain designers to work together to contribute multidimensional knowledge for the element extension. Secondly, the coverage of the sample data of the BP neural network in the method is limited; it may not be applicable to products in other domains. Therefore, more sample data will be collected, and the distance and coverage of the sample data will be expanded to improve the generalizability of our method.

Author Contributions: Conceptualization, F.W. and R.T.; methodology, F.W., K.W. and Y.D.; project administration, R.T.; supervision, R.T.; validation, F.W. and R.T.; visualization, F.W.; writing—original draft, F.W.; writing—review and editing, Q.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author, R.T., upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. BPA functions of the functions (A_1–A_{31}).

	No.	$m_1(E_1)$	$m_2(E_2)$	$m_3(E_3)$	No.	$m_1(E_1)$	$m_2(E_2)$	$m_3(E_3)$	No.	$m_1(E_1)$	$m_2(E_2)$	$m_3(E_3)$
H1	A_1	0.00	0.15	0.11	A_{12}	0.10	0.03	0.09	A_{22}	0.62	0.74	0.69
H2		0.44	0.32	0.15		0.14	0.17	0.36		0.33	0.21	0.20
H3		0.54	0.52	0.72		0.75	0.78	0.53		0.04	0.01	0.07
Θ		0.02	0.01	0.02		0.01	0.02	0.02		0.01	0.04	0.04
H1	A_2	0.20	0.06	0.13	A_{13}	0.10	0.03	0.09	A_{23}	0.68	0.50	0.71
H2		0.23	0.28	0.27		0.14	0.17	0.36		0.26	0.25	0.22
H3		0.55	0.65	0.59		0.75	0.78	0.53		0.04	0.14	0.00
Θ		0.02	0.01	0.01		0.01	0.02	0.02		0.02	0.11	0.07
H1	A_3	0.20	0.06	0.13	A_{14}	0.01	0.06	0.06	A_{24}	0.74	0.38	0.52
H2		0.23	0.28	0.27		0.11	0.21	0.15		0.12	0.36	0.31
H3		0.55	0.65	0.59		0.87	0.71	0.78		0.10	0.20	0.08
Θ		0.02	0.01	0.01		0.01	0.02	0.01		0.04	0.06	0.09
H1	A_4	0.00	0.15	0.11	A_{15}	0.15	0.01	0.03	A_{25}	0.17	0.09	0.18
H2		0.44	0.32	0.15		0.17	0.06	0.21		0.43	0.68	0.70
H3		0.54	0.52	0.72		0.67	0.92	0.74		0.37	0.21	0.11
Θ		0.02	0.01	0.02		0.01	0.01	0.02		0.03	0.02	0.01
H1	A_5	0.08	0.15	0.09	A_{16}	0.00	0.01	0.00	A_{26}	0.16	0.03	0.15
H2		0.18	0.20	0.20		0.04	0.09	0.07		0.71	0.81	0.59
H3		0.72	0.63	0.70		0.95	0.89	0.92		0.11	0.15	0.24
Θ		0.02	0.02	0.01		0.01	0.01	0.01		0.02	0.01	0.02
H1	A_6	0.13	0.02	0.10	A_{17}	0.15	0.01	0.03	A_{27}	0.74	0.38	0.52
H2		0.17	0.09	0.21		0.17	0.06	0.21		0.12	0.36	0.31
H3		0.69	0.88	0.67		0.67	0.92	0.74		0.10	0.20	0.08
Θ		0.01	0.01	0.02		0.01	0.01	0.02		0.04	0.06	0.09

Table A1. *Cont.*

	No.	$m_1(E_1)$	$m_2(E_2)$	$m_3(E_3)$	No.	$m_1(E_1)$	$m_2(E_2)$	$m_3(E_3)$	No.	$m_1(E_1)$	$m_2(E_2)$	$m_3(E_3)$
H1	A_7	0.06	0.02	0.11	A_{18}	0.01	0.06	0.06	A_{28}	0.17	0.09	0.18
H2		0.28	0.19	0.24		0.11	0.21	0.15		0.43	0.68	0.70
H3		0.65	0.78	0.63		0.87	0.71	0.78		0.37	0.21	0.11
Θ		0.01	0.01	0.02		0.01	0.02	0.01		0.03	0.02	0.01
H1	A_8	0.09	0.03	0.05	A_{19}	0.17	0.30	0.14	A_{29}	0.26	0.18	0.22
H2		0.16	0.09	0.23		0.66	0.55	0.84		0.44	0.72	0.62
H3		0.74	0.86	0.71		0.07	0.11	0.01		0.27	0.09	0.14
Θ		0.01	0.02	0.01		0.10	0.04	0.01		0.03	0.01	0.02
H1	A_9	0.14	0.11	0.01	A_{20}	0.03	0.05	0.11	A_{30}	0.62	0.74	0.69
H2		0.19	0.16	0.24		0.20	0.11	0.16		0.33	0.21	0.20
H3		0.65	0.72	0.74		0.76	0.82	0.72		0.04	0.01	0.07
Θ		0.02	0.01	0.01		0.01	0.02	0.01		0.01	0.04	0.04
H1	A_{10}	0.14	0.29	0.26	A_{21}	0.26	0.18	0.22	A_{31}	0.75	0.54	0.63
H2		0.58	0.46	0.51		0.44	0.72	0.62		0.14	0.27	0.29
H3		0.26	0.23	0.22		0.27	0.09	0.14		0.10	0.17	0.07
Θ		0.02	0.02	0.01		0.03	0.01	0.02		0.01	0.02	0.01
H1	A_{11}	0.23	0.13	0.02								
H2		0.52	0.74	0.71								
H3		0.24	0.11	0.26								
Θ		0.01	0.02	0.01								

Table A2. Probability of function belonging to a level.

No.	Probability				No.	Probability			
	H_1	H_2	H_3	Θ		H_1	H_2	H_3	Θ
A_1	0.0016758	0.1049519	0.8933560	0.0000163	A_{17}	0.0003267	0.0059875	0.9936817	0.0000041
A_2	0.0086795	0.0817900	0.9095224	0.0000081	A_{18}	0.0002148	0.0086208	0.9911605	0.0000039
A_3	0.0086795	0.0817900	0.9095224	0.0000081	A_{19}	0.0347296	0.9639804	0.0011889	0.0001012
A_4	0.0016758	0.1049519	0.8933560	0.0000163	A_{20}	0.0007000	0.0097226	0.9895732	0.0000042
A_5	0.0048121	0.0262057	0.9689708	0.0000113	A_{21}	0.0556322	0.9241654	0.0201771	0.0000253
A_6	0.0011553	0.0095234	0.9893167	0.0000046	A_{22}	0.9455432	0.0537319	0.0006827	0.0000422
A_7	0.0007650	0.0425621	0.9566673	0.0000056	A_{23}	0.9170105	0.0800972	0.0024681	0.0004242
A_8	0.0006209	0.0093461	0.9900288	0.0000042	A_{24}	0.8642412	0.1101873	0.0246789	0.0008926
A_9	0.0010156	0.0237232	0.9752559	0.0000053	A_{25}	0.0171186	0.9376036	0.0452532	0.0000246
A_{10}	0.0746915	0.8354868	0.0897994	0.0000223	A_{26}	0.0032816	0.9821718	0.0145359	0.0000108
A_{11}	0.0035949	0.9671421	0.0292563	0.0000067	A_{27}	0.8642412	0.1101873	0.0246789	0.0008926
A_{12}	0.0017379	0.0313047	0.9669459	0.0000116	A_{28}	0.0171186	0.9376036	0.0452532	0.0000246
A_{13}	0.0017379	0.0313047	0.9669459	0.0000116	A_{29}	0.0556322	0.9241654	0.0201771	0.0000253
A_{14}	0.0002148	0.0086208	0.9911605	0.0000039	A_{30}	0.9455432	0.0537319	0.0006827	0.0000422
A_{15}	0.0003267	0.0059875	0.9936817	0.0000041	A_{31}	0.9487290	0.0454473	0.0058167	0.0000070
A_{16}	0.0000012	0.0004963	0.9995012	0.0000012					

Table A3. C–A–O structure of the functions (A_1–A_{31}).

No.	Carrier	Act	Object	No.	Carrier	Act	Object
A_1	User	Operate	Fixture-2	A_{17}	Guide rod	Install	Heating plate
A_2	User	Operate	Milling plate	A_{18}	Guide rod	Install	Fixture-1
A_3	User	Operate	Heating plate	A_{19}	Fixture-1	Fasten and Move	Pipe-1
A_4	User	Operate	Fixture-1	A_{20}	Cabel	Power	Heating plate
A_5	User	Operate	Pump station	A_{21}	Pipe-1	Push	Heating plate
A_6	User	Operate	Electrical box	A_{22}	Heating plate	Heat	Pipe-1
A_7	Weather	Effect	Electrical box	A_{23}	Ground	Hold	Base

Table A3. *Cont.*

No.	Carrier	Act	Object	No.	Carrier	Act	Object
A_8	Cable	Power	Pump station	A_{24}	Milling plate	Mill	Pipe-1
A_9	Pump station	Push	Piping and Hydraulic oil	A_{25}	Pipe-1	Push	Milling plate
A_{10}	Piping and Hydraulic oil	Push	Hydraulic cylinder	A_{26}	Fixture-2	Fasten	Pipe-2
A_{11}	Hydraulic cylinder	Push	Fixture-1	A_{27}	Milling plate	Mill	Pipe-2
A_{12}	Nut and bolt	Fasten	Fixture-1	A_{28}	Milling plate	Push	Pipe-2
A_{13}	Nut and bolt	Fasten	Fixture-2	A_{29}	Heating plate	Push	Pipe-2
A_{14}	Guide rod	Install	Fixture-2	A_{30}	Heating plate	Heat	Pipe-2
A_{15}	Guide rod	Install	Milling plate	A_{31}	Pipe-1	Push	Pipe-2
A_{16}	Base	Fix	Guide rod				

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