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Radical innovation of product design using an effect solving method

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ABSTRACT

Innovation activities are required for industry to develop competitive products in response to rapid changes of the market. Radical innovation (RI) enables products long-term technical advantages and market competitiveness. However, the existing RI research focuses on areas of the business and management. There is a lack of an effective method of RI for product development. This paper proposes a systematic effect solving method (ESM) for radical innovation of product design. The ESM includes the problem identification, function analysis, key problem determination, effect selection, structure mapping and scheme evaluation. The proposed method can not only improve the possibility of developing RI products, but also save time in design. The method is applied to develop a new type of wind turbines with a granted patent. Feasibility and effectiveness of the proposed method is proved.

1. Introduction

Innovation activities are required for industry to develop competitive products in response to rapid changes of the market (Domínguez-Escrig, Broch, Lapiedra, & Chiva, 2018). Radical innovation (RI) can significantly improve the product core technology, performance, and even product service mode, which has attracted extensive attentions of the academic and industrial community (Blank & Naveh, 2019; Slater, Mohr, & Sengupta, 2014). RI is the revolution improvement of a product or process (Hajhashem & Khorasani, 2015; Lin & Patel, 2018). A product is not developed linearly, but through stages of infancy, growth, maturity and decline as an S-curve (Labouriau & Naveiro, 2015). Performance of an early RI product may be poorer than the existing product, but its potential is much greater.

The existing RI research is mainly in the field of business and management, such as research of the internal organizational relationship and external market environment (Aarikka-Stenroos & Sandberg, 2012; Zhou & Li, 2012). RI is commonly verified based on hypothesis through the statistical analysis of the questionnaire (Delgado-Verde, Martín-de Castro, & Amores-Salvadó, 2016; Shen, Mei, & Gao, 2019). These RI methods cannot be used in RI process of the product development (Slayton & Spinardi, 2016). Although there are different methods proposed to improve RI for product design such as methods of using axiomatic design (Li, Song, Mao, & Suh, 2019) and modular design (Bai, Zhang, Ding, & Sun, 2018), it is only possible to accidentally get a solution of RI. RI has high uncertainty using these methods (Kamuriwo, Baden-Fuller, & Zhang, 2017). Therefore, an effective RI method is required for product development (Wu, Zhou, & Kong, 2020).

TRIZ or Theory of Inventive Problem Solving, is one of the approaches to guide designers and engineers to understand design problems in order to generate appropriate ideas (Asyraf et al., 2020; Sharaf, Ishak, Sapuan, & Yidris, 2020). Multinational companies such as Samsung, Ford, and Siemens have used TRIZ in their product development. Some small and medium-sized enterprises in Europe and the United States also demonstrated advantages of using TRIZ (Azlan, Ariz, & Yusof, 2014). Inventions and innovations using TRIZ follow certain principles and patterns for problem solving (Boavida, Navas, Godina, Carvalho, & Hasegawa, 2020). Effect is not only an important concept of TRIZ, but also one of the tools to solve specific problems of product design.

Effect is the application of scientific laws to solve problems in product design (Sheu & Hong, 2018). Functions provide the value of product (Yuan, Liu, Lin, & Zhao, 2016). Effects can be used to achieve functions. Design for RI products can be considered from the perspective of effect that is considered as an information resource in TRIZ (Sheu & Yen, 2020). Effect searches correlations of product functions and functions' scientific principles in four categories, including the physical effect, chemical effect, geometric effect (Yan, Liu, Zanni-Merk, & Cavallucci, 2015) and biological effect (Guo et al., 2018). There are different levels of innovation measured in TRIZ (Li, Tate, Lane, &

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Adams, 2012). A product designed based on effect belongs to the high-level innovation (Levels 3 or 4). Therefore, effect can be used to improve the RI possibility. However, according to the user feedback (Ilevbare, Probert, & Phaal, 2013), the frequency of using effect in product design is far lower than other methods as there is a lack of operational methods to use effect knowledge for product design.

A Length-Time dimension (L-T) chart is an ordered combination of physical quantities (Bushuev, 2017; Zhang et al., 2020). We find that the L-T chart is similar to the contradiction matrix in TRIZ theory. The former determines the physical quantity through the length and time dimensions, while the latter determines the invention principle by improving parameters and deteriorating parameters. In this paper, the L-T chart is used to find physical quantities that are difficult to find using the existing method. Corresponding relationships of these physical quantities and effects are decided using an effect table to expand the scope of the effect search.

Therefore, this paper develops a method to use effect in RI design. The scientific contribution of this study is a systematic effect solving method (ESM) for radical innovation of product development. Using the mature quantitative analysis and evaluation tools, ESM reduces the dependence on experts to enhance the objectivity of design solutions. The proposed method also provides a flow-process chart and effect table for designers to learn and use ESM step by step. Although ESM reduces the subjectivity of the design process, it cannot completely eliminate the dependence on experts. A computer-aided innovation system is in the development to improve applications of the method.

Following parts of this paper are organized as follows. Section 2 reviews the RI research, and summarizes benefits and problems of the effect and L-T chart. Section 3 introduces steps of the proposed ESM including the problem definition, function analysis, key problem determination, effect selection, structure mapping and scheme evaluation. Section 4 presents the design process of a wind turbine to verify the effectiveness of the proposed method for RI. Section 5 discusses contributions and shortcomings of the method and suggests the future work.

2. Related research

2.1. Radical innovation

RI occurs in the replacement phase of S-curve from points c to d as shown in Fig. 1. There are other two similar concepts of RI: incremental innovation and disruptive innovation. Incremental innovation (Kim, Park, & Lee, 2019) is a continuous improvement of the existing technology or product. Although improvement of the technology or product

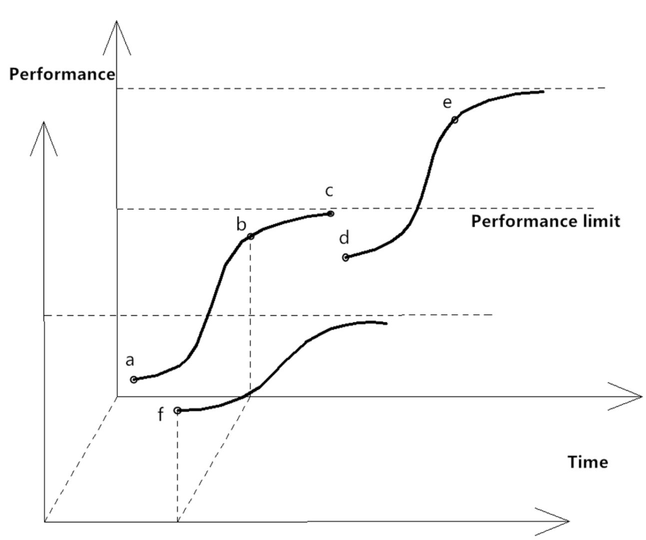


Fig. 1. Three types of innovation.

in a single incremental innovation is less than RI, a large number of incremental innovations can form a cumulative economic effect (Souto, 2015). Incremental innovation occurs from points a to c or from points d to e in the S-curve. Disruptive innovation is a kind of unconventional innovations to replace main-flow products with some unique features such as the simpler, lower margins and easier to use (Guo, Tan, Sun, Cao, & Zhang, 2016). Disruptive innovation mostly occurs in the middle or late stages of the S-curve from points b to f (Lin, Li, & Wu, 2018). Breaking performance limit is not the main goal of the disruptive innovation.

Since its concept was proposed, RI has experienced more than 40 years in development. The research topics range from the identification of influencing factors to different models, and the fusion and application of multiple theories. For example, It was found that IT management capability, IT-enabled capability and IT infrastructure capability have significant positive effects on RI (Li, Han, Kumar, & Feng, 2019). In order to solve problems of the low success rate of RI in high-tech enterprises, an opportunity-evolutionary game theory (WoO-EGT) model (Zhang & Yu, 2019) was developed to analyze dynamic evolutions of the RI process. An experience-fuzzy front end (UX-FFE) model (Lecossier, Pallot, Crubleau, & Richir, 2019) was built for the process of systematic innovation considering the social, economic and methodological aspects. An agency theory (Shaikh & Colarelli O'Connor, 2020) was proposed to analyze the RI investment and benefits of firms. In order to gain profits, enterprises must consider potential risks related to RI, including process complexity and uncertainty of results. The stewardship theory (Zhang, Wei, Yang, & Zhu, 2018) shows that the relationship of large shareholders and managers plays an important role in maximizing returns and controlling risks in RI.

RI can be developed in following three directions. (1) Reducing technical uncertainty. Both technological and social aspects should be considered to reduce uncertainty in different processes (Delgado-Verde et al., 2016). In the highly uncertain market, only enterprises with dynamic capabilities can keep consistent with user needs at all times (Slater et al., 2014). RI can be improved using machine learning in the big data background (Li, Zhang, & Zheng, 2018). (2) Clearing the internal structure of organizations. A flat or adaptive organizational structure can strengthen relationships of various cooperative behaviors through timely and accurate communication (Roy & Sarkar, 2016). Providing effective control mechanism in the organization (Perkins, Lean, & Newbery, 2017) and improving individual participation enthusiasm (Baker, Sinkula, Grinstein, & Rosenzweig, 2014) can also promote the formation of RI. (3) Creating the high business value. Customer integration has a significant impact on RI (Schweitzer, Van den Hende, & Hultink, 2020). The object range of the value creation can be expanded from existing market customers to non-customers who are not bound by the existing product categories. Because non-customers have a higher awareness of their own needs, they are more likely to change the thinking and behavior of customers in the existing market for RI (Rosenzweig, 2017).

Although RI can bring a great business success, many enterprises do not have the RI ability, especially small and medium-sized industries. The high risk of RI from the technology uncertainty makes enterprises more prefer incremental innovation. In addition to develop the effective organizational structure and protect existing products, it is essential to have an operable RI product design method. RI needs to be systematically researched.

2.2. Effect

Effect refers to the application of scientific laws to solve problems in product design (Sheu & Hong, 2018), which is an important tool of the TRIZ theory. TRIZ was developed by Altshuller who studied about 400,000 technology patents for creation regularities (Sheu, Chiu, & Cayard, 2020). In recent years, the application of TRIZ has been expanded (Aguilar-Lasserre et al., 2020). Unlike other design theories, TRIZ does not go directly from specific problems to solutions because its process is generally difficult to achieve (Fiorineschi, Frillici, & Rotini, 2018). As shown in Fig. 2, TRIZ first abstracts a specific problem into conceptual problems, TRIZ tools are then used to solve the conceptual problems for the design solution (Chechurin & Borgianni, 2016).

Effect includes Peltier effect, Joule-Lentz effect, Lanc-Hirsch effect, Dufour effect, etc (Production Inspiration, 2019). These effects provide a theoretical basis for realization of product functions. Using effect for design problems can generate a large number of design schemes for selection. For example, using "Venturi effect" as key words, 363 related patents can be searched with different solutions of covering machinery, transportation, construction and metallurgy (Patsnap, 2019). In addition, effect has an explanatory function to promote the product commercialization. For example, the structure of woodpecker's skull can be used to illustrate the safety of a helmet in protection of the human head for the severe vibration.

Effect provides a very important problem solving tool to reduce requirements for professional knowledge (Rantanen, Conley, & Domb, 2017). For example, a recommendation method of design knowledge was proposed for manufacturing based on the morphological similarity between manufacturing requirements and multi-domain effect knowledge (Geng, Zhang, & Hui, 2018). A representation was also proposed (Yan, Zanni-Merk, Cavallucci, & Collet, 2014) for the knowledge of physical effects using an ontology web language (OWL). Rules of retrieving physical effects were interpreted and represented using the semantic web rule language (SWRL).

Although effect provides many benefits, its potential has not been fully utilized. We propose an effect solving method (ESM) based on the existing effect research. ESM guides the product design process in analyzing design requirements, solving problems and evaluating schemes. The detail is introduced in Section 3.

2.3. L-T chart

A Length-Time dimension (L-T) chart is an ordered combination of physical quantities. The chart also shows the dimensional analysis. Dimension is a fundamental attribute of physical quantities in two categories: the basic quantity and derived quantity. In different fields of applications, the number of basic quantities also changes. There are seven basic units in the international system of unit (SI). There are three basic units in the Gaussian unit system (Garg, 2018) for electromagnetic research: length (L), mass (M) and time (T). Different basic quantity systems can be converted each other. In order to simplify expression and calculation, British physicist Maxwell first proposed the use of only two basic quantities (L and T) (Jurij, 2017). Inspired by this idea, Bartini used mathematical tools such as the group theory and topology theory (di Bartini, 2005) to prove that two dimensions of mass and electric quantity are both L^3T^{-2}. The dimension operation follows the index operation rule in Mathematics. For example, the dimension of velocity in Gaussian unit is $L^{-2}M^1T^1$, which is transformed into two-dimensional L^1T^{-1}. In the same way, all L-M−T dimensions can be transformed into L-T dimensions.

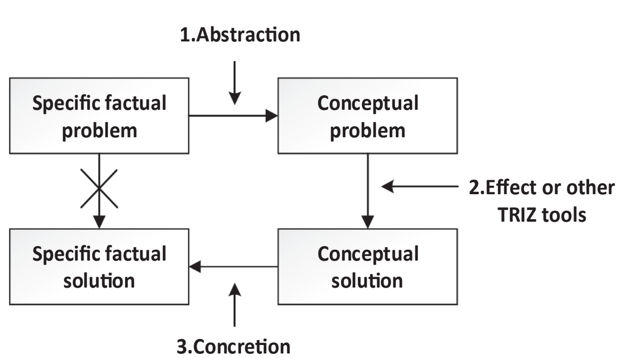


Fig. 2. TRIZ approach to problem solving.

In order to use the two-dimensions unit conveniently, a L-T chart (Zhang et al., 2020) was built as shown in Table 1. Each cell in the L-T chart contains one or more physical quantities. Its row consists of length dimensions from L^{-2} to L^5, and its columns include time dimensions from T^{-5} to T^2. Intersections of rows and columns are used to determine the L-T dimension of physical quantities. The form of L-T chart is not fixed. It can increase or reduce physical quantities involved in different subjects according to the need.

The L-T chart is similar to the contradiction matrix in TRIZ theory for product design. Bushuev considered that the physical quantity in the same cell of the L-T chart has the same resource capacity in the field of technological innovation. A connection can be abstracted as a transfer matrix of block in the form of L-T dimensions (Bushuev, 2017). Kotikov considered the squared speed as a major factor in assessment of the energy intensity of the object motion and medium resistance. The energy efficiency of the railway freight transport can be decided using the L-T chart (Kotikov, 2017). Zhang et al. (2020) also used the L-T chart to find parameters that can cause problems in design of new generation systems to avoid the possible coupling phenomena between these parameters. At present, potential of the L-T chart is not fully explored. Considering advantages of the L-T chart in the problem abstraction, this paper applies it in the effect selection process.

In summary, different tools (Effects Database, 2019; Invention Tool 3.0, 2019) have been proposed to collect and classify effects. However, there is a lack of effective operable methods to solve the RI design problem using effect. By collecting the feedback from industrial experts, three main problems have been identified as follows. (1) The lack of methods to determine key design problem. Effect can be used to achieve product functions by consuming system resources (Liu, Feng, & Wang, 2020). only key problems are worth using effect to solve. (2) The inefficiency of effect selection. There are two contrary situations in the search of effect. If the number of effects obtained is too small, it is not enough to support an innovation. If there are too many effects, their importance cannot be distinguished. (3) The inaccuracy of structure mapping. The level of design concepts obtained may not be stable based on scientific principles or biological prototypes. There should be a clear guidance for effects similar to 40 inventive principles (Na, Song, & Park, 2019) or 76 standard solutions (Davide & Duci, 2015). Based on these identified problems, this paper proposes a systematic effect solving method for RI.

3. Proposed method

3.1. Problem identification and function analysis

Existing products meet a balance in three aspects of the user demand, technical feasibility and enterprise sustainability, but RI needs a breakthrough. Product development has to fully understand the target product based on resources and user requirements. Mainstream products in the market may be selected as benchmarks for function analysis and design evaluation.

Functions perform conversions between input and output flows of the product. Product functions can be decided based on the design task and constraints. A function model is the result of the function analysis. A system boundary is introduced to decide the design target, system components and super-system components. The interaction analysis can be conducted to determine relationships of components. There are four types of function actions including the normal action, insufficient action, excessive action and harmful action as shown in Fig. 3.

3.2. Key problem determination

An initial problem is usually superficial or complex (Li, Ming, He, Zheng, & Xu, 2015), which needs to be further decomposed. Most

Table 1
L-T chart.

Time	Length L^{-2}	L^{-1}	L^{0}	L^{1}	L^{2}	L^{3}	L^{4}	L^{5}
T^{-5}					L^2T^{-5}	Surface power	L^4T^{-5}	Power Temperature variety rate
T^{-4}			L^0T^{-4}	Specific gravity Gradient of pressure	Pressure Density of electromagnetic energy Normal stress Tangential stress Elasticity modulus	Surface tension Rigidity	Force Friction Suction	Force momentum Energy Temperature
T^{-3}			L^0T^{-3}	Current density	Electromagnetic field strength Ductility Dynamic viscosity	Current Loss mass Magnetic potential difference Magnetic motive force	Motion quantity Impulse	Angular Momentum Angular impulse Action
T^{-2}		$L^{-1}T^{-2}$	Mass density Angular-acceleration	Magnetic displacement Acceleration Magnetic reluctance	Potential difference	Quantity of magnetism or electricity	Magnetic flux	Moment of inertia
T^{-1}	$L^{-2}T^{-1}$	Volume charge density	Frequency Magnetic flux density	Velocity	Two-dimensional Velocity of change of the area	Loss volume	L^4T^{-1}	
T^{0}	$L^{-2}T^{0}$	Change Conductance	Dimensionless quantity	Length Capacity Selfinduction Wavelength	Surface Absorption	Volume of space	Distribution of volume along length Moment of inertia of an area	L^5T^0
T^{1}	$L^{-2}T^{1}$	Conductivity	Period Duration	L^1T^1				
T^{2}	Magnetic permeability	$L^{-1}T^{2}$						

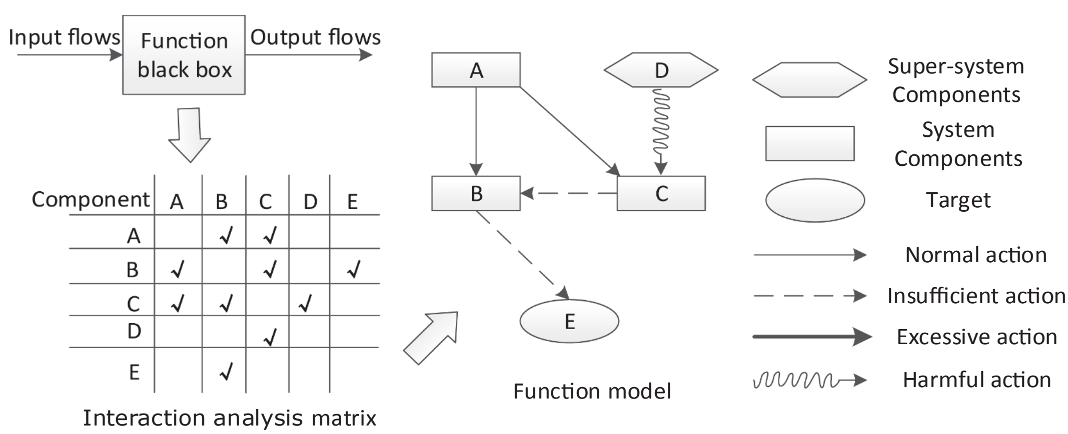


Fig. 3. Function analysis.

problems in a complex technology system exist in the form of a network (Fiorineschi, Frillici, & Rissone, 2015). After key problems are solved, less important problems associated with them may be alleviated or even eliminated (Wang, Peng, Tan, Sun, & Chen, 2020). At present, the determination of key problems mainly depends on the expert judgment (Razmi, Haghighi, & Babazadeh, 2018), which is subjective. In order to decide key problems of products objectively, the relative importance of problems needs to be determined quantitatively. In this paper, a method is proposed for the quantitative analysis of the problem network in product design as follows.

Based on the task background and relevant patent information, we can identify several major problems (Pb) in a product. Further analysis of causes of these problems can form a series of sub-problems. When the sub-problems of all problems are analyzed, a problem network of the product can be formed. A complete problem network is a premise of the quantitative analysis. There are three parameters that influence the problem importance degree (D_i): Hierarchy (H_i), Scope of influence (S_i) and Correlation (C_i). H_i describes the depth of thinking for a problem i with a size equated to the distance between the problem i and initial problem. For the example in Fig. 4, the distance between Pb1.4 and Pb is

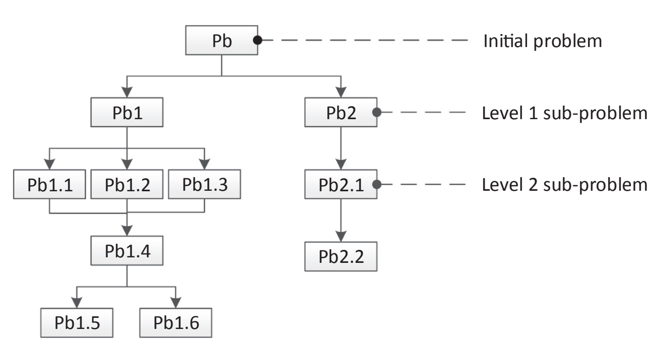


Fig. 4. Problem network.

3, $H_{1.4} = 3$. Pb1.1, Pb1.2 and Pb1.3 are located in the same hierarchy, $H_{1.1} = H_{1.2} = H_{1.3} = 2$. S_i describes ability of a problem i to affect other problems. The size of S_i is equal to the number of related problems to the problem i. Pb1.5 is only related to Pb1.4, $S_{1.5} = 1$. Pb1.4 is also connected to other four sub-problems, $S_{1.4} = 5$. C_i describes the correlation degree between a problem i and product main function, the size of C_i is determined by the level 1 sub-problem corresponding to the problem i. If Fig. 4 is a problem network of electronic clinical thermometers, Pb1 is low measurement accuracy, and Pb2 is poor human–computer interaction. Although existing electronic clinical thermometers have additional functions such as wireless communication, touch-screen operation, and voice broadcast, their main function is always to measure the body temperature. Pb1 is therefore more relevant to the product main function than Pb2, that is $C_1 = \ldots = C_{1.4} = C_{1.5} = C_{1.6} = 2$, and $C_2 = C_{2.1} = C_{2.2} = 1$. The maximum value of C_i is equal to the number of level 1 sub-problems.

Inspired by Cavallucci's definition of contradiction clouds, this paper further establishes the problem importance degree Eq. (1), replacing the importance, universality and amplitude in the reference with hierarchy, scope of influence and correlation (Cavallucci, Rousselot, & Zanni, 2008). Comparing with the classic cause-effect chain, the problem network considers not only the depth of the problem, but also the breadth of the problem and the impact of product functions. The new Equation also avoids the subjectivity caused by weighting. Taking Pb1.4 as an example, according to the parameter value obtained in the previous step, $D_{1.4} = 6.16$ (keep two decimal places). The problem with the biggest D_i in the problem network is defined as the key problem which needs to solve by effects.

$$D_i = \left| \sqrt{H_i^2 + S_i^2 + C_i^2} \right| \tag{1}$$

3.3. Effect selection

An effect completes the function by transforming flows of the material, energy and information in product. As all of these processes reflect changes of physical parameters, it is possible to search effects using the physical quantity. In order to obtain a number of effects for selection, an L-T chart is introduced. The physical quantity extracted from the key problem is in a cell of the L-T chart. There are other physical quantities in the same cell. These physical quantities are not random combinations. There is an internal relationship between them in physics. Each physical quantity corresponds to a certain number of effects. The more physical quantities we get in the L-T chart, the more effects we have for design concepts.

To avoid wasting time on the inappropriate effect, effects are ranked. Unlike a product with a specific structure, an effect only provides a conceptual model. The evaluation of effects is a complex and difficult process, which needs to reduce subjective randomness and fuzziness in decision-making. In the absence of an effective evaluation method, fuzzy numbers (Höhle & Rodabaugh, 2012) can express expert views better than exact numbers. Therefore, this paper introduces a fuzzy ordered weighting average (FOWA) model (Baghapour & Shooshtarian, 2017) for the ranking process of effects.

For example, there are four effects to be ranked, n = 4. Running indices i and j have the same domain {1, 2, …, n}. The ranking process is as follows. (1) There are three alternative quantifier domains (a, b): maximum, at least half, as far as possible. The corresponding values are (0.3, 0.8), (0, 0.5) and (0.5, 1). Where Q is a linguistic quantifier to measure the fuzziness of evaluation, and r is an argument. A specific value of r is determined by j/n and (j − 1)/n in Eq. (2). Weighted vector ω can be obtained using Eqs. (2) and (3) (Golfam, Ashofteh, & Loáiciga, 2019). (2) $\tilde{A}$ is formed as a complementary matrix of triangular fuzzy numbers by pairwise comparisons of four effects. Each element $\tilde{a} = (a^L, a^M, a^U)$ in $\tilde{A}$ is a triangular fuzzy number, $0 \leqslant a^L \leqslant a^M \leqslant a^U$. Values of a^L, a^M and a^U are selected from Table 2 to represent experts' ranks, where decision risk $\lambda \in [0, 1]$. The smaller the value of λ, the more conservative the expert is. Expected values $\tilde{A}^{(\lambda)}$ of all elements $\tilde{a}$ are searched using Eq. (4). The new matrix is named as $\tilde{B}$ for a reordered $\tilde{A}$ according to the expected value $\tilde{A}^{(\lambda)}$. (3) Degree $\tilde{d}_i$ of each effect that is superior to other effects can be obtained using Eq. (5). (4) Expected value $\tilde{D}^{(0.5)}$ of $\tilde{D}$ is decided using Eq. (4) again, where $\tilde{D}$ is a set of $\tilde{d}_i$. After a normalization process, a sorting vector ω' is obtained. Ranking results of the four effects are determined according to ω'.

Table 2
The value and meaning of triangular fuzzy numbers.

Value	Meaning
0.9	The former is more important than the latter
0.7	The former is important than the latter
0.5	Both are equally important
0.3	The latter is important than the former
0.1	The latter is more important than the former
0.8, 0.6, 0.4, 0.2	Median of adjacent meanings

$$\omega_j = Q(j/n) - Q[(j-1)/n] \tag{2}$$

$$Q(r) = \begin{cases} 0, & r < a \\ \dfrac{r-a}{b-a}, & a \leqslant r \leqslant b \\ 1, & r > b \end{cases} \tag{3}$$

$$\tilde{a}_{ij}^{(\lambda)} = \frac{1}{2}[(1-\lambda)a_{ij}^L + a_{ij}^M + \lambda a_{ij}^U] \tag{4}$$

$$\tilde{d}_i = \omega_1 \times \tilde{b}_{i1} + \cdots + \omega_n \times \tilde{b}_{in} \tag{5}$$

An effect table is developed as shown in Table 3, including the physical quantity, category, name, content and application examples. Due to the space limitation, the function model diagram corresponding to each example is omitted here. The table is the accumulation of different expert knowledge and experience instead of individual expert's judgment. The physical quantity is extracted from the key problem and searched in Table 3. If the number of corresponding effects is too small, the L-T chart is used to expand the search scope. The FOWA method is used to rank effects when there are enough search results.

3.4. Structure mapping

Mapping the selected effect to a specific product structure is the most important step in ESM. An analogy process is proposed to transfer knowledge from one system to another in design of a structure for the required product function (Jia, Wu, Zhu, & Tan, 2018; Jia, Peng, Tan, & Zhu, 2019). Based on the structure-mapping theory (Liu, Li, Chen, Tao, & Xia, 2019; Wang, 2017), this paper represents the analogy mechanism for effects in the following form.

Selected effect: Effect application <=> Key problem: Problem structure

The implementation of an analogy mechanism is introduced as shown in Fig. 5. For the function model comparison, a function model of the example is built including the working sub-system, transmission sub-system, energy sub-system and control sub-system. The function model of the product can be formed in the step of function analysis. To determine the analogy area in the function model, areas reflecting effects are marked with dotted lines. The existing structure is transferred to generate a new structure through the structure analogy. Lines with an arrow represent transfer processes. All the selected effects in Section 3.3 are analogized in turn. The effect with the high ranking is more likely to generate RI schemes. In the meantime, TRIZ tools such as 40 invention principles can be used to further improve the design solution.

Table 3
Effect table.

No.	Physical quantity	Category	Name	Content	Example
1	Force (L^4T^{-4})	Physical effect	Hooke's law	After a solid material is stressed, there is a linear relationship between stress and strain in the material.	Spring scale
2	Temperature (L^2T^{-3})	Physical effect	Curie's law	The paramagnetic susceptibility is inversely proportional to the absolute temperature.	Rice cooker power off switch
3	Pressure (L^2T^{-4})	Physical effect	Pascal's law	After any point in the incompressible stationary fluid generates a pressure increase due to an external force, this pressure increase is transmitted to the points of the stationary fluid in an instant.	Lifting jack
4	Conductivity ($L^{-1}T^1$)	Physical effect	Superconducting effect	Some metals and alloys lose resistance under ultra-low temperature conditions.	Superconducting material
5	Volume of space (L^3T^0)	Physical effect	Shape memory effect	A solid material with a certain shape undergoes plastic deformation under a certain low-temperature state, and when it is heated to a certain critical temperature above the material, the material returns to its original shape.	Satellite antenna
6	Friction (L^4T^{-4})	Biological effect	Lotus leaf effect	The surface of lotus leaves has super-hydrophobicity and self-cleaning	Self-cleaning window
7	Suction (L^4T^{-4})	Biological effect	Octopus tentacles	Octopus can create a closed vacuum contact surface on the uneven surface of the bottom of the water, which generates a huge suction force.	Sucker
8	Length (L^1T^0)	Geometric effect	Mobius strip	Taking a paper strip and giving it a half-twist, and then joining the ends of the strip to form a loop.	Conveyor belt

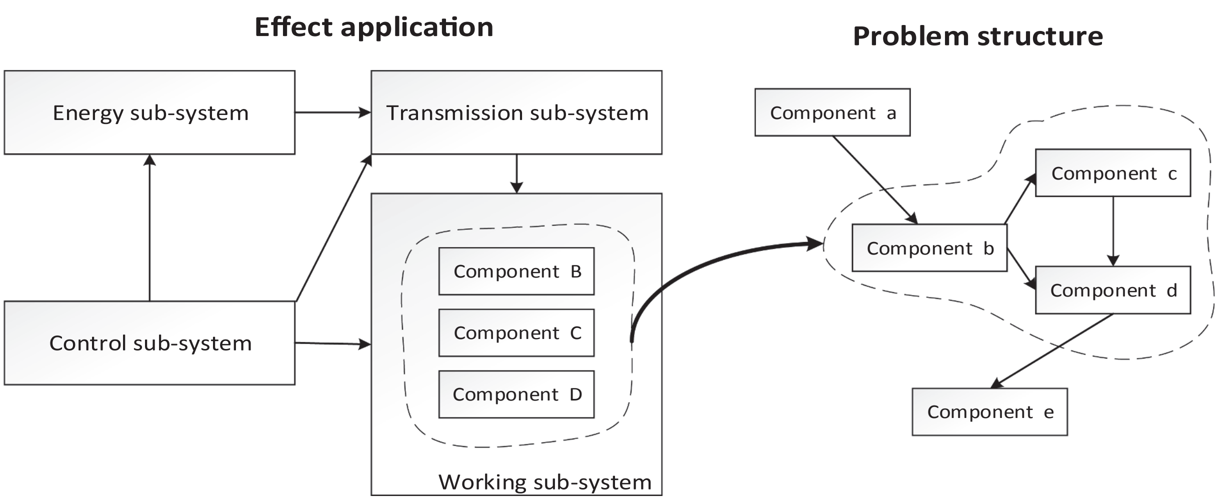


Fig. 5. Analogy example of product.

3.5. Design evaluation

Solutions can be evaluated based on the cost, design quality and development cycle. The evidence theory can consider multiple information sources (Tao et al., 2017) and expert group opinions. The concept scoring matrix (Ulrich, 2003) and spider web diagram (Kralisch et al., 2018) also provide evaluation methods. But a common problem of the above methods is the lack of pertinence to RI. We use an evaluation method (Liu et al., 2019) based on a large number of recognized RI examples.

The working process of the proposed method is as follows. (1) Product design schemes are divided into four sub-systems. A design process can cause sub-systems to change in the expected or unwelcoming direction. This will produce eight technical attributes as shown in Table 4. Through the regression analysis of 65 recognized RI cases, it is found that only three technical attributes have impact on RI (Liu et al., 2019). (2) Technical differences are divided into four levels: physical principle, working principle, embodiment and technical details. Their corresponding scale factors are assumed as 10:6:3:1 based on reference (Shah, Smith, & Vargas-Hernandez, 2003). When there is no difference between the existing product and proposed design scheme at a certain level, the value is "0″. When the design scheme has worse attributes than the existing product, it is necessary to determine at which level this negative change comes from. This will produce four values "−10, −6, −3, −1". Expected attribute of control sub-system (CE) is valued as "−6" meaning the control sub-system with the negative change at the level of working principle. For example, an existing product is wired in control, the new scheme is the wireless remote control. The wireless control is vulnerable to external interference, and users may not accept the change of reliability reduction. (3) according to comparisons between the existing product and design scheme, unknown variables (Liu et al., 2019) can be determined using Eq. (6). According to Eq. (6), following

Table 4
Technical attributes.

No.	Abbreviation	Meaning	Impact on RI
1	WE	Expected attributes of working sub-system	Yes
2	WU	Unwelcoming attributes of working sub-system	No
3	EE	Expected attributes of energy sub-system	Yes
4	EU	Unwelcoming attributes of energy sub-system	No
5	TE	Expected attributes of transmission sub-system	No
6	TU	Unwelcoming attributes of transmission sub-system	No
7	CE	Expected attributes of control sub-system	Yes
8	CU	Unwelcoming attributes of control sub-system	No

solutions can be found. When z is positive, the denominator approaches 1. The RI value is closed to 1, and the design scheme is an RI. When z is negative, the absolute value of denominator is much greater than 1. The RI value is closed to 0, and the design scheme is a general improvement.

$$RI \quad value = \frac{1}{|1 - e^{-z}|} \tag{6}$$

where $z = -106.065 + 18.621 \times WE + 10.129 \times CE + 3.502 \times EE$

Therefore, an entire process of RI for product design consists of seven steps as shown in Fig. 6. Through the market research and user feedback, design constraints and benchmarks are analyzed. The function and interaction analysis matrix are formed for the product function analysis. A problem network is built to search the key problem using the problem importance degree equation. The L-T chart and FOWA method are introduced to obtain appropriate effects. A special analogy mechanism is formed to obtain the preliminary structure at the level of functions. Eq. (6) is proposed to determine whether a design scheme belongs to RI. Product physical parameters, materials and processing methods are decided in the detailed design stage. A physical model can be developed to test the design solution if necessary.

4. Case study

4.1. Applications of the proposed method

In order to verify the ESM in improvement of the RI possibility, the proposed method was applied in the design of some electromechanical products. Table 5 lists design schemes developed using the proposed method. The evaluation was acted to compare the new design and existing products according to criteria introduced in Section 3.5. Except for No.4 and No.8 products, all the design schemes meet criteria of RI. In the next section, the design process of a wind turbine using the proposed ESM is described in detail.

Table 5
Summary of application results.

No.	Product Name	WE	EE	CE	RI
1	Wind turbine	1	6	10	Yes
2	New energy vehicle charging pile	3	1	6	Yes
3	Steel pipe cutting machine	6	1	3	Yes
4	Manual dispensing machine	3	0	0	No
5	Drilling blowout preventer	6	0	0	Yes
6	Tumble dryer	6	1	3	Yes
7	Tire breaker	6	3	3	Yes
8	Insecticidal lamp	3	6	1	No

4.2. RI for a wind turbine

RI development of the wind turbine is implemented following the proposed process in 7 steps.

(1) Problem identification. Wind energy is a kind of clean and renewable energy that has attracted more and more attentions in the world (Leung & Yang, 2012). The Chinese national energy administration has issued policies to promote the wind power. The installed wind power stations have surged. Comparing with the traditional power generation, one of the problems using the

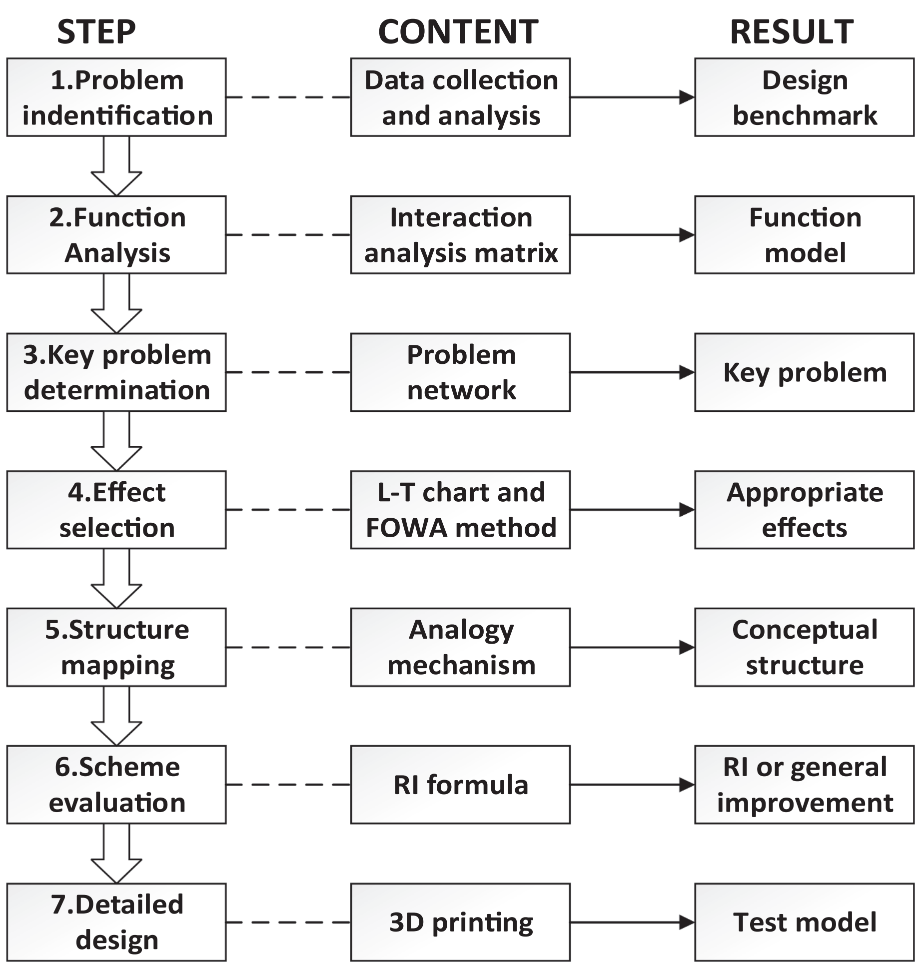


Fig. 6. Proposed 7 steps of RI for the product design.

$$\tilde{B} = (\tilde{b}_{ij})_{5\times5} = \begin{bmatrix} (0.6,0.7,0.8) & (0.5,0.7,0.8) & (0.5,0.6,0.8) & (0.5,0.5,0.5) & (0.1,0.2,0.4) \\ (0.5,0.5,0.5) & (0.3,0.4,0.6) & (0.2,0.3,0.5) & (0.2,0.3,0.4) & (0.1,0.2,0.3) \\ (0.7,0.8,0.9) & (0.6,0.8,0.9) & (0.6,0.7,0.9) & (0.5,0.6,0.8) & (0.5,0.5,0.5) \\ (0.6,0.7,0.8) & (0.5,0.7,0.8) & (0.5,0.5,0.5) & (0.2,0.4,0.6) & (0.2,0.4,0.5) \\ (0.4,0.6,0.7) & (0.5,0.5,0.5) & (0.2,0.3,0.5) & (0.2,0.3,0.4) & (0.1,0.3,0.4) \end{bmatrix}$$

wind power is the limitation of meteorological conditions. Wind turbines (Nikolić et al., 2016) require appropriate wind speed and wind direction. Urban areas with the power shortage may not have sufficient wind energy resources (Padmanabhan, 2013). The design task was to improve an existing wind turbine product to achieve RI for the wind power generation. Fig. 7(a) shows the mainstream product.

(2) Function analysis. The function of wind turbines is the conversion of energy forms from the wind power to electric energy. Based on the interactive analysis, a complete function model was formed as shown in Fig. 7(b).

(3) Key problem determination. Through the function analysis, it is found that main problems of the existing wind turbine are lack of the suitable installation location, insufficient electric energy output and noise. On the basis of further analysis of causes of these problems, a problem network was formed by using the problem decomposition as shown in Fig. 8. Based on D_i listed in Table 6, the key problem was determined as Pb2.11.

(4) Effect selection. The physical quantity extracted from the key problem is velocity. By looking at the L-T chart, it was found that velocity is alone in cell L^1T^{-1} without other physical quantities. Results are shown in Table 7 by searching for velocity related effects. The FOWA method was used to rank five effects (n = 5). The triangular fuzzy array required in the ranking process is a result provided by three designers who have more than three years of design experience, (a, b) = (0.3, 0.8) in this case. Weighted vector $\omega = (0, 0.2, 0.4, 0.4, 0)^T$ was obtained using Eqs. (2) and (3). Decision risk $\lambda = 0.5$ was set to obtain expected value $\tilde{A}^{(0.5)}$ according to Eq. (4). A sorting vector $\omega' = (0.238, 0.136, 0.283, 0.201, 0.142)^T$ was obtained using a normalization process. Ranking results of the five effects are No.3, No.1, No.4, No.5, No.2 as follows.

$$\tilde{A} = (\tilde{a}_{ij})_{5\times5} = \begin{bmatrix} (0.5,0.5,0.5) & (0.6,0.7,0.8) & (0.1,0.2,0.4) & (0.5,0.6,0.8) & (0.5,0.7,0.8) \\ (0.2,0.3,0.4) & (0.5,0.5,0.5) & (0.1,0.2,0.3) & (0.2,0.3,0.5) & (0.3,0.4,0.6) \\ (0.6,0.8,0.9) & (0.7,0.8,0.9) & (0.5,0.5,0.5) & (0.5,0.6,0.8) & (0.6,0.7,0.9) \\ (0.2,0.4,0.5) & (0.5,0.7,0.8) & (0.2,0.4,0.6) & (0.5,0.5,0.5) & (0.6,0.7,0.8) \\ (0.2,0.3,0.5) & (0.4,0.6,0.7) & (0.1,0.3,0.4) & (0.2,0.3,0.4) & (0.5,0.5,0.5) \end{bmatrix}$$

$$\tilde{A}^{(0.5)} = \begin{bmatrix} \tilde{a}_{11}^{(0.5)} = 0.500 & \tilde{a}_{12}^{(0.5)} = 0.700 & \tilde{a}_{13}^{(0.5)} = 0.225 & \tilde{a}_{14}^{(0.5)} = 0.625 & \tilde{a}_{15}^{(0.5)} = 0.675 \\ \tilde{a}_{21}^{(0.5)} = 0.300 & \tilde{a}_{22}^{(0.5)} = 0.500 & \tilde{a}_{23}^{(0.5)} = 0.200 & \tilde{a}_{24}^{(0.5)} = 0.325 & \tilde{a}_{25}^{(0.5)} = 0.425 \\ \tilde{a}_{31}^{(0.5)} = 0.775 & \tilde{a}_{32}^{(0.5)} = 0.800 & \tilde{a}_{33}^{(0.5)} = 0.500 & \tilde{a}_{34}^{(0.5)} = 0.600 & \tilde{a}_{35}^{(0.5)} = 0.725 \\ \tilde{a}_{41}^{(0.5)} = 0.375 & \tilde{a}_{42}^{(0.5)} = 0.675 & \tilde{a}_{43}^{(0.5)} = 0.400 & \tilde{a}_{44}^{(0.5)} = 0.500 & \tilde{a}_{45}^{(0.5)} = 0.700 \\ \tilde{a}_{51}^{(0.5)} = 0.325 & \tilde{a}_{52}^{(0.5)} = 0.575 & \tilde{a}_{53}^{(0.5)} = 0.275 & \tilde{a}_{54}^{(0.5)} = 0.300 & \tilde{a}_{55}^{(0.5)} = 0.500 \end{bmatrix}$$

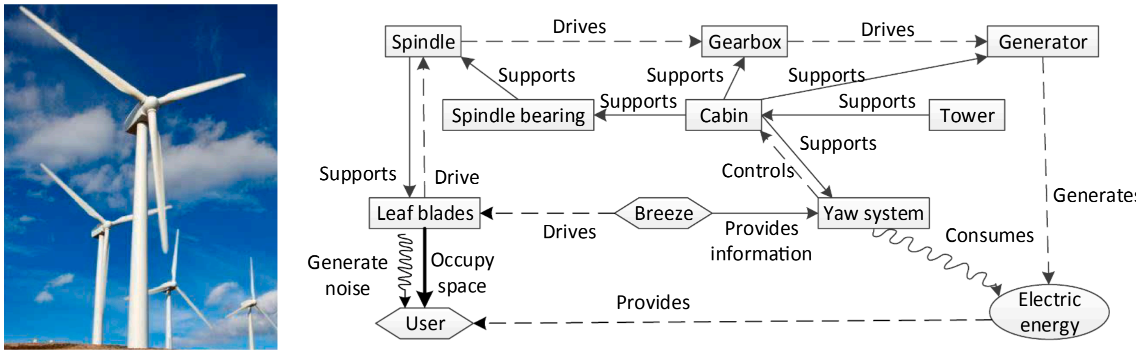
$$\tilde{D} = (\tilde{d}_i)_{5\times1} = \begin{bmatrix} (0.5,0.58,0.68) \\ (0.22,0.32,0.48) \\ (0.56,0.68,0.86) \\ (0.38,0.5,0.6) \\ (0.26,0.34,0.46) \end{bmatrix} \tilde{D}^{(0.5)} = \begin{pmatrix} 0.585 \\ 0.335 \\ 0.695 \\ 0.495 \\ 0.350 \end{pmatrix}$$

(5) Structure mapping. The application of No.3 effect is a Venturi tube. Its structure is the analog object of design scheme 1 as shown in Fig. 9. The wind collector is designed as a horn. The side with a large opening can collect a large amount of wind energy resources. After passing through the horn shaped wind collector, the wind speed is magnified due to reduction of the cross-section area. The magnified wind drives blades of the generator in the pipeline to rotate, thus converting the wind energy into electric energy. In order to fully use the wind energy, multiple wind collectors can be installed along the tower body, but this will lead to the increase of volume. According to No.7 inventive principle "Nested doll", multiple wind collectors are nested together.

The application of No.1 effect is a chimney. Its structure is the analog object of design scheme 2 as shown in Fig. 10. Through the solar collector plate, the air in the tower can be heated up and the density is reduced after absorbing sunlight, forming a density difference with the external environment, thus forming a pressure difference and a strong updraft, so as to drive the turbine generator set in the center of the chimney to generate electricity. In addition, in the process of resource analysis, it was found that when the generator is working, it generates a lot of heat. Generally, this part of heat is harmful to the system and needs to be emitted. According to inventive principle No.22 "Blessing in disguise", a heat conducting pipe is installed to collect heat to increase the intensity of the chimney effect as shown in Fig. 10(b).

The application of No.4 effect is a variable-wing aircraft. Its structure is the analog object of design scheme 3 as shown in Fig. 11. The bracket is equipped with a variable direction induced draft fan and a wind direction sensor. The sensor collects the natural wind data and transmits them to a single chip microcomputer installed at the bottom. The blade of the variable direction of the induced draft fan is controlled by the single chip microcomputer to rotate around the shaft, so as to maintain the most suitable air inlet angle at any time. In the process of structure mapping, Effects No.5 and No.2 failed to form a feasible scheme.

(6) Scheme evaluation. As shown in Table 8, three design schemes are compared with the existing product. The final scheme is formed by combining advantages of the above three schemes. A specific structure is formed as shown in Fig. 12(a). New working principle is adopted in the energy system. The existing product only relies on the wind energy, the new design also uses solar energy to assist the power generation. There are differences in the



(a) (b)

Fig. 7. (a) Existing wind turbine, (b) Function model of the wind turbine.

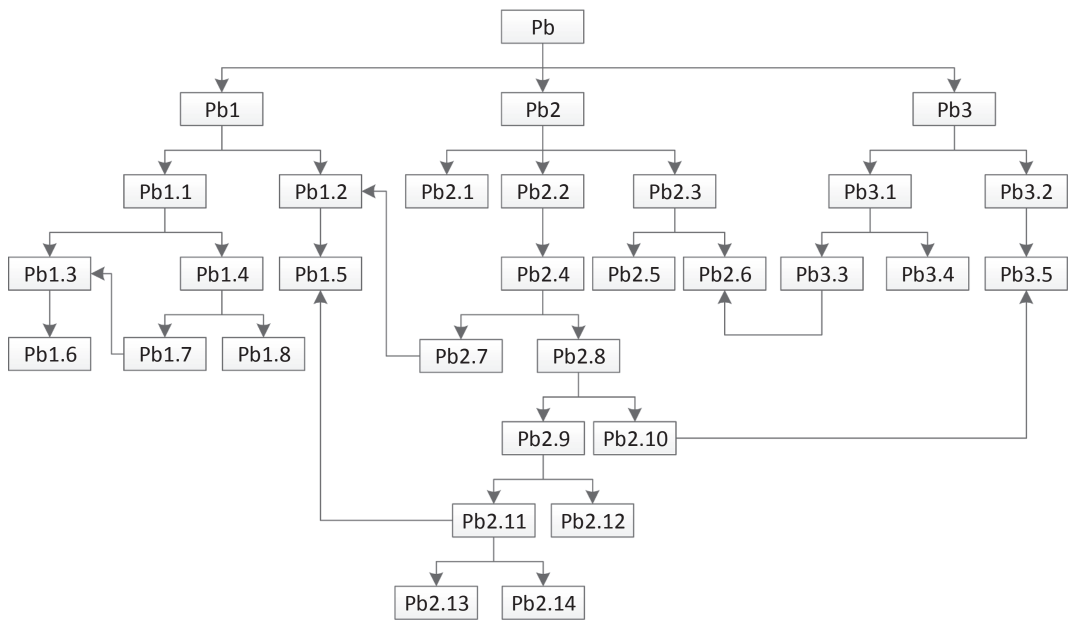


Fig. 8. Problem network of the wind turbine.

Table 6
Problem summary.

Pb	Problem description	D_i	Pb	Problem description	D_i
1	Lack of suitable installation location	3.74	2.6	Long mechanical transmission route	4.69
1.1	Take up too much space	4.12	2.7	Short driving force arm	5.39
1.2	Insufficient free space	4.12	2.8	Small resultant force	5.83
1.3	Large fan leaf length	4.69	2.9	Small thrust	7.07
1.4	Large tower height	4.69	2.10	Large resistance	6.16
1.5	Dense buildings	4.12	2.11	Small rotational speed	7.81
1.6	Large windward area required	4.58	2.12	Fan leaf shape is unreasonable	6.78
1.7	Prevent fan leaf from touching the ground	4.90	2.13	Unable to adapt to the wind direction quickly	7.68
1.8	High wind speed at high altitude	4.58	2.14	In a windless zone	7.68
2	Insufficient electric energy output	5.10	3	Make a lot of noise	3.31
2.1	Lack of auxiliary energy	3.74	3.1	Mechanical noise	3.74
2.2	Unable to start normally	4.12	3.2	Air noise	3.00
2.3	Great energy loss	4.69	3.3	Noise of transmission structure	3.74
2.4	Insufficient drive torque	5.20	3.4	Generator noise	3.32
2.5	Lost heat not collected	4.36	3.5	Fan leaf friction air	3.74

Table 7
Search results.

No.	Physical quantity	Category	Name	Content	Example
1	Velocity (L^1T^{-1})	Physical effect	Chimney effect	The air inside the building rises or falls along a space with a vertical slope, resulting in an increase in air convection speed	Chimney
2	Velocity (L^1T^{-1})	Physical effect	Wing in ground effect	When a moving object runs close to the ground, the aerodynamic impact of the ground on the object.	Ground-effect vehicle
3	Velocity (L^1T^{-1})	Physical effect	Venturi effect	When a restricted flow passes through a reduced overflow section, the fluid increases in velocity, and its velocity is inversely proportional to the overflow section.	Venturi tube
4	Velocity (L^1T^{-1})	Biological effect	Pigeon change wings	Pigeons can adjust their wing shape with the wind direction to achieve higher flying speed.	Variable-wing aircraft
5	Velocity (L^1T^{-1})	biological effect	Shark skin	The rough V-shaped folds on the surface of the shark's skin can greatly reduce the friction of the water flow, allowing the water flow around the body to flow more efficiently, and the sharks can swim quickly.	Swimsuit

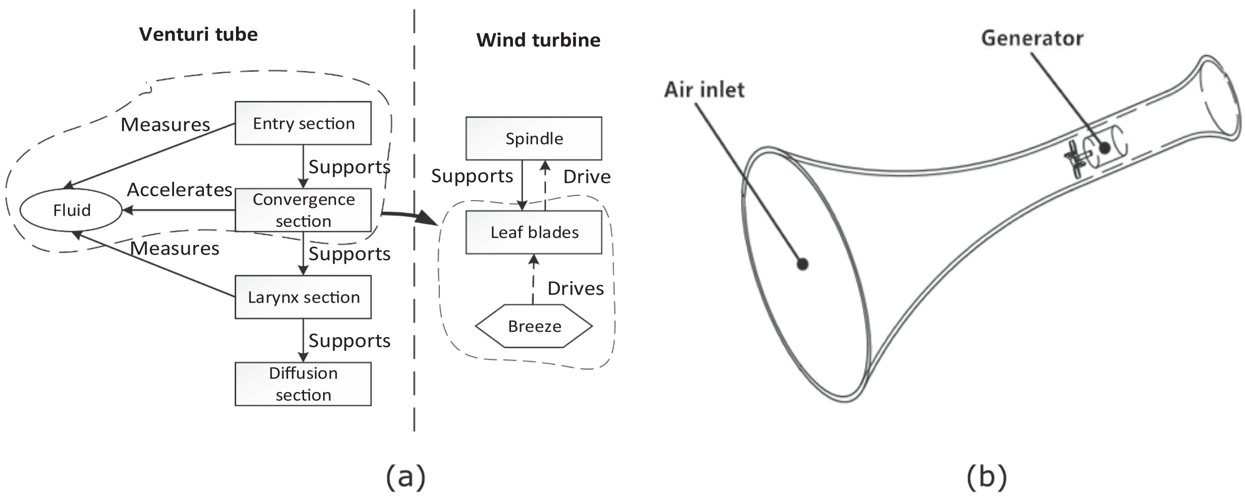


Fig. 9. (a) Analogy by Venturi tube, (b) Design scheme 1.

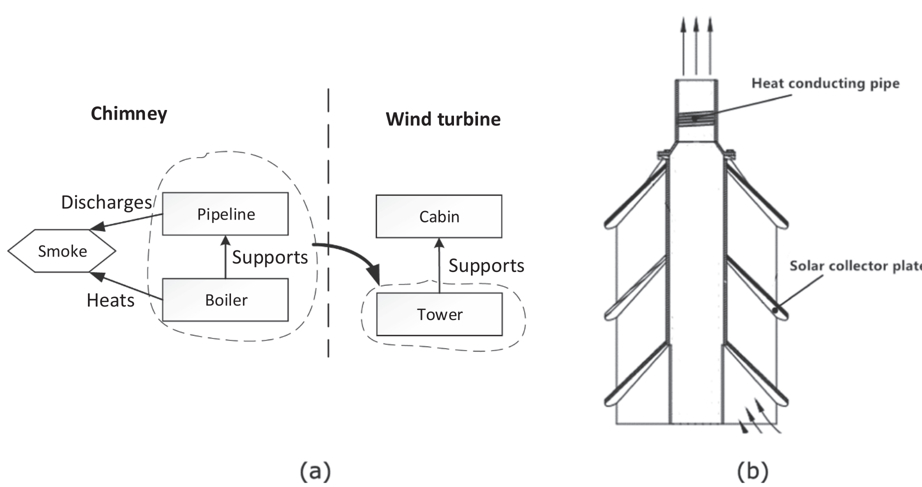


Fig. 10. (a) Analogy by chimney, (b) Design scheme 2.

level of physical principles in the control system. Blades of the existing product can only adjust the angle horizontally and the speed is slow. The new design can adjust the angle of the induced draft fan at any time by virtue of the wind direction sensor, so as to improve the utilization of the wind energy. The working system uses small-sized fan blades for a difference in the embodiment level. It reduces the wind speed required to start the power generation and the space required for installation. There are differences only in the technical detail level in the transmission system. It can be determined that technical attributes of the new design are EE = 6, CE = 10, WE = 3. Using Eq. (6), RI value = 1 is obtained, which means that the new design belongs to RI.

(7) Detailed design. Using the 3D printing technology, the design model was made as shown in Fig. 12(b). After testing, the final design solves the problem of the existing product for the power generation, and achieves the required design goal.

The quantitative analysis reduces the uncertainty in determining the

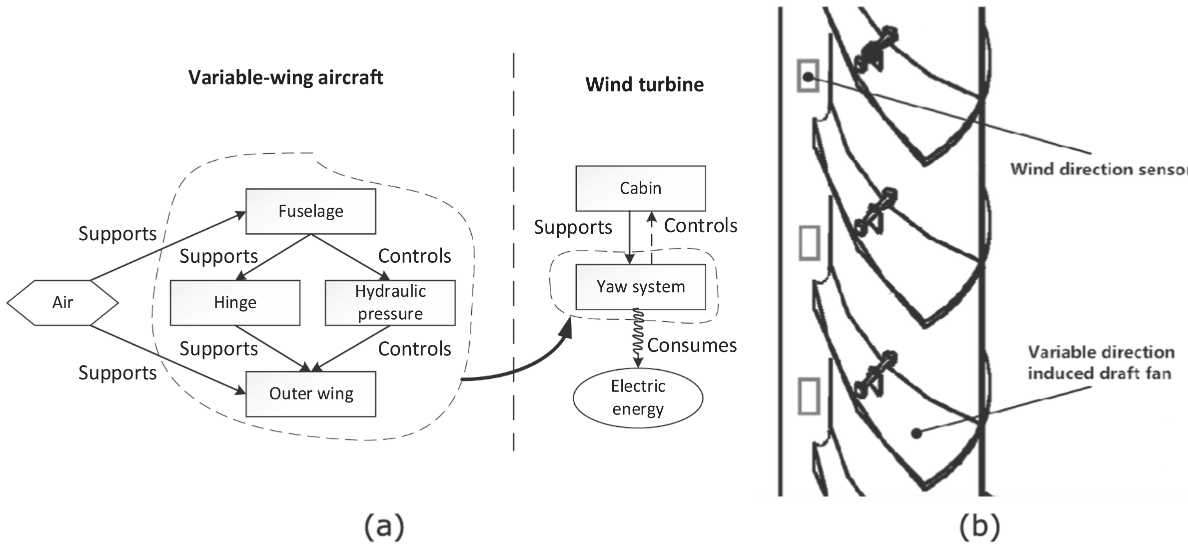


Fig. 11. (a) Analogy by variable-wing aircraft, (b) Design scheme 3.

Table 8
Design scheme comparisons.

Scheme System	Existing product	Design scheme 1	Design scheme 2	Design scheme 3
Working sub-system	Large-sized fan blades take up much space. (WE = 0)	Small-sized fan blades can start generating electricity at low wind speed. (WE = 3)	Small-sized fan blades can start generating electricity at low wind speed. (WE = 3)	Small-sized fan blades can start generating electricity at low wind speed. (WE = 3)
Transmission sub-system	The transmission process is long and wastes energy. (TE = 0)	Only the technical details are different. (TE = 1)	Only the technical details are different. (TE = 1)	Only the technical details are different. (TE = 1)
Energy sub-system	The speed and direction of natural wind are uncertain. (EE = 0)	Can increase the speed of natural wind. (EE = 3)	Using not only wind energy, but also solar-assisted power generation. (EE = 6)	Able to adapt to the direction of natural wind. (EE = 1)
Control sub-system	It can only rotate horizontally and is slow. (CE = 0)	Uncontrollable. (CE = −10)	Uncontrollable. (CE = −10)	Quickly adapt to the natural wind direction. (CE = 10)

key problem and effect selection. The L-T chart and effect table of ESM help the RI product development. Comparing with existing methods, our proposed method is easy in operation. However, ESM cannot completely get rid of the dependence on the experience. The problem network forming and scheme evaluation still need the participation of experts. The scale of the effect table is also limited, which may cause that search results cannot meet requirements. We believe that the user feedback will help to continuously improve the method along with the ESM application.

5. Conclusions

The design method plays an increasingly important role in radical innovation (RI) for product development. This paper proposed a systematic effect solving method (ESM) for RI. The application opportunity of effects was firstly decided by calculating the problem importance degree. An L-T chart was then introduced to expand the scope of effect selection, and the FOWA method was used to rank effects. After then, a preliminary structure of product design was obtained based on the analogy of function models. The design scheme was finally formed and evaluated using the proposed RI value equation.

The main contributions of this research include following three aspects. (1) The RI research is reviewed and summarized for advantages and limitations to propose the effect and L-T chart. The quantitative analysis solves three problems in the existing process of using effect including the key problem determination, effect selection and structure mapping. (2) A systematic and operable RI method of product design is proposed. ESM provides a new way to improve the possibility of RI products. (3) Different RI products are developed using the proposed ESM. The feasibility and effectiveness of the method are verified.

Although the quantitative analysis of effect reduces the subjectivity of the design process, design experience is still required to decide the final solution. The application of ESM is still in its beginning stage. The law of physical quantities in the L-T chart has not been thoroughly understood, which needs further work with the help of professionals.

Our future work will further promote ESM for users to apply the effect in their design process. The work also includes reducing the dependence on TRIZ knowledge and improving certainty in the RI process of product design. A computer-aided innovation (CAI) system will be developed. We plan to use natural language processing (NLP) to automatically build a problem network of products. At the same time, an artificial neural network (ANN) will be introduced to the design evaluation. We will continuously improve the ESM with the support of increasing applications of RI cases.

CRediT authorship contribution statement

Kang Wang: Conceptualization, Methodology, Writing - original draft. **Runhua Tan:** Supervision, Funding acquisition. **Qingjin Peng:** Writing - review & editing. **Yindi Sun:** Visualization. **Haoyu Li:** Investigation. **Jianguang Sun:** Project administration.

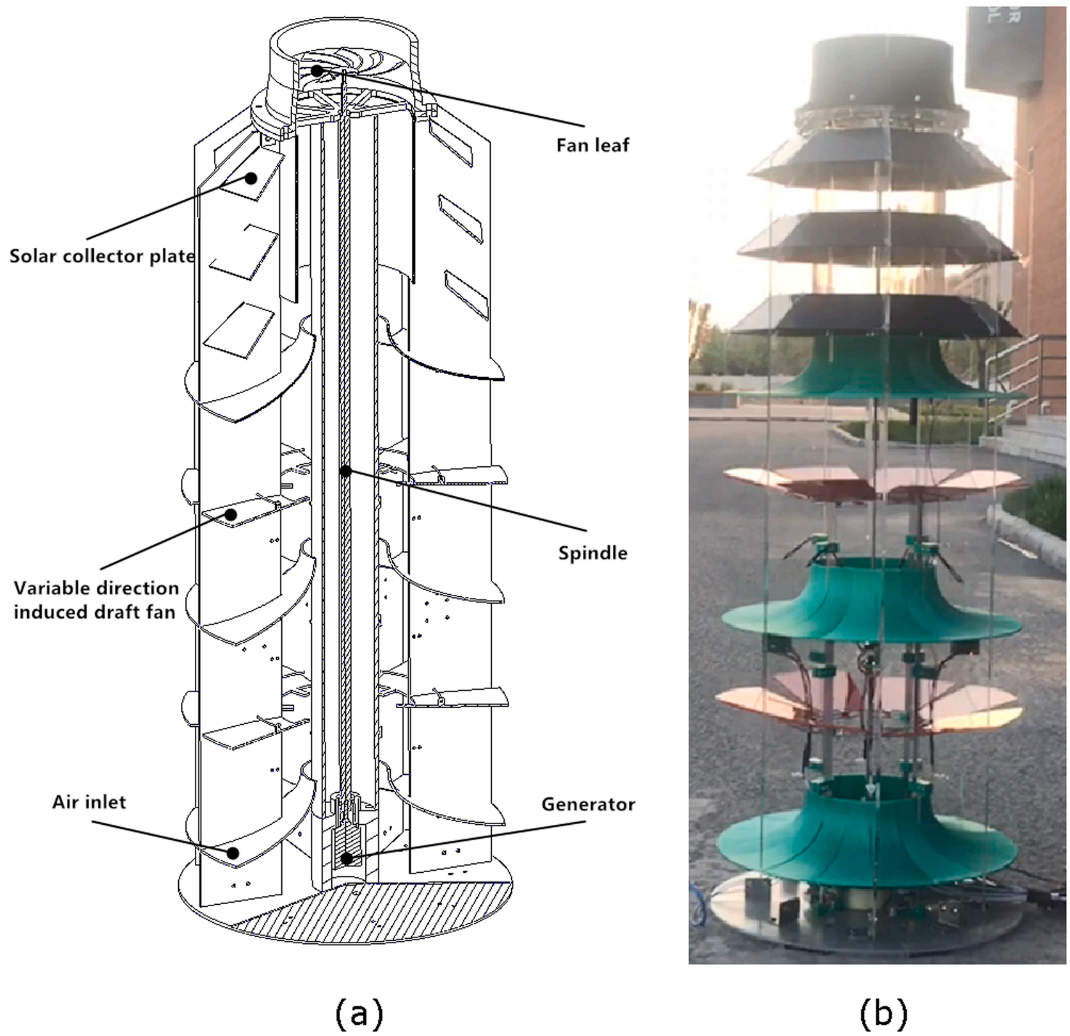


Fig. 12. Final design (a) Structure diagram, (b) Test model.

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