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Element Variation Innovation Thinking: A Method of Simplifying and Reorganizing TRIZ

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Abstract. The industrial environment is undergoing the fourth revolution. TRIZ as an effective innovation method possesses an entire system consists of multiple powerful tools like inventive principles and standard solutions to solve technical problems. Since they were invented, many researchers have attempted to further develop them, pointing out some difficulties in applying these tools in a simple way and the need to modify these powerful tools. In line with it, this study introduced Element Variation Innovation Thinking (EVIT), a novelty innovation method, to simplify and reorganize the application system of TRIZ. The variation rules are formed into 9 variation method groups by clustering the existed innovation methods such as the 40 inventive principles in TRIZ. 9 element groups are introduced based on the innovative work practice of Feng's group. By the intervention of variation method groups, the element groups are converted to form new solutions. To illustrate the proposed method and validate its utility, this study selects the field of coal-bed methane (CBM) extraction technology as a use case.

Keywords: TRIZ, Element Variation Innovation Thinking, element group, variation method group.

1 Introduction

The industrial environment is undergoing the fourth revolution [1]. To effectively solve engineering and scientific challenges on demand, some conceptual design tools as TRIZ [2], SIT [3], and USIT [4] have been introduced. Genrich Altshuller founded the Theory of Inventive Problem Solving (TRIZ) technique in 1956. It rests on the study of resourceful principles used in patents to obtain solution inspirations [5]. There are four specific approaches to a solution that can be selected through the TRIZ method according to the level of involvement of the problem, which involve 39 engineering parameters and 40 inventive principles [6]. Systematic Inventive Thinking (SIT) was introduced by Genady Filkovsky and his two students Roni Horowitz and Jacob Goldenberg with the aim of simplifying TRIZ so that it could be accepted by more people and allow users to pay more attention to the issues involved

[3]. Five innovation strategies are included in SIT. Unified Structured Inventive Thinking (USIT) was originally developed by Ed. Sickafus [7] at the Ford Motor Company in the 1990s based on TRIZ and SIT. Nakagawa [8] further developed the system of USIT and proposed five categories of solution generation methods containing 32 sub-methods, called the “USIT Operators”, which were reorganized from 40 innovative principles in TRIZ.

TRIZ, SIT and USIT have proven themselves as powerful tools for solving practical engineering problems. Apart from that, Morphological analysis (MA) was introduced by Zwicky [9]. The core of MA is that the research object is resolved into several fundamental dimensions, which depict the object from a detailed and inclusive perspective. Each dimension can then be divided into several values to depict the characteristics of the entire system [10]. In virtue of morphological analysis (MA), we analyzed the inner mechanisms of different innovation methods through the innovative work practice of Feng’s group and found that innovation solutions consist of innovation dimensions and corresponding elements, which possess the ability of variation. The variation rules are formed into 9 variation method groups by clustering the existed innovation methods such as the 40 inventive principles in TRIZ. 9 element groups are introduced based on the data analysis results and author’s experience. By the intervention of variation method groups, the element groups are converted to form new solutions.

With the purpose of simplifying and developing TRIZ, this article introduces a method called Element Variation Innovation Thinking (EVIT) which can be considered as a simplification and development of 76 standard solutions and 40 inventive principles in TRIZ and other innovation methods. In this innovation method, “element” means the innovative elements in various innovation groups while “variation” has the meaning of inventive principles for varying “elements”. EVIT consists of three parts: element group, variation method group, and the innovation coupling paths between element groups and variation method groups. The basic scheme of problem solving in EVIT is a six-box scheme covering three phases, which has been represented in a data diagram. The input and output of each diagram could be described by the information of patents, product manuals, or other scientific literature. EVIT has been successfully applied into chemical industry, mechanical engineering and coalbed methane mining technology. This study selects coalbed methane (CBM) extraction technology as a case to illustrate the system of EVIT.

This article is composed of 5 parts after the introduction. The second part is dedicated to the components of EVIT and cites the relevant valuable contributions on our study. It is in the third part that the overall structure of problem solving in EVIT is presented. The fourth part is dedicated to the case study with “coalbed methane (CBM) extraction technology”, followed by discussions, conclusions, acknowledgments, references and appendix.

2 Components of Element Variation Innovation Thinking (EVIT)

2.1 Element Group

One or a series of technologies or products could be considered as a technical system, which is composed of different components. These components can be divided into several categories according to the roles they play in the system, the disciplines they belong to or common laws. These categories are defined as element groups. On the basis of summarizing and analyzing a large number of innovation cases such as the technological field in coalbed methane extraction, 3D printing and rapid prototyping, fluid transfer equipment and etc., the element groups can be divided into 9 categories, including space dimension, environment dimension, structure dimension, function dimension, mechanism dimension,

material dimension, dynamic system dimension, time series dimension and human-machine relationship dimension, following the core ideology of MA. By utilizing the 9 element groups, most technology and product systems could be described. The definition of each element group is listed as Table 1.

Table 1. The definition of each element group in EVIT

No.	Element group	Definition
1	Space dimension	The appearance and characteristics of a system (machine, product or engineering, etc.) in space, including but not limited to direction, position, shape, volume and area, etc.
2	Environment dimension	The environmental appearance and characteristics of a system (machine, product or engineering, etc.), including environmental conditions such as temperature, humidity, light and sound, etc., suspended matter such as harmful and beneficial components, etc., and environmental parameters such as field.
3	Structure dimension	The structural appearance and characteristics of a system (machine, product or engineering, etc.), including the components and the relationship between components.
4	Function dimension	The functional appearance and characteristics of a system (machine, product or engineering, etc.), including the ability of the system to solve specific problems and possess specific effects.
5	Mechanism dimension	The mechanism appearance and characteristics of a system (machine, product, or engineering, etc.), including the basic principles of the physical, chemical, and biological characteristics of the system's functions.
6	Material dimension	The material appearance and characteristics of the system (machine, product or engineering, etc.), including all attributes of the attributed material, mainly including material composition and phase state, etc.
7	Dynamic system dimension	The power system's appearance and characteristics of the system (machine, product or engineering, etc.), including the energy of the system from the power source to the transmission mode and energy storage mode.
8	Time sequence dimension	The time series' appearance and characteristics of the system (machine, product or engineering, etc.), including the processes related to the time sequence in the system, including the operating sequence, process sequence and time sequence, etc.
9	Human-machine relationship dimension	The appearance and characteristics of the human-machine relationship of the system (machine, product or engineering, etc.), including the interaction between the human and the operating object, tool, and environment in the system.

2.2 Variation Method Group

The continuous advancement of science and technology makes the element groups continue to change under a certain law. As TRIZ 40 inventive principles, SIT methods and USIT Operators aim to indicate the law of development and change in technology and product innovation, we summarized and analyzed the common characteristics of these methods in solving innovative problems. In this study, we call the law of development and change as variation method groups. The definition of each variation method group is described as Table 2.

Table 2. The definition of each variation method group

No.	Variation method group	Definition
1	Decomposition and removal	The system is deconstructed into the smallest unit, and the system's structure is changed to optimize system performance through removal, extraction, segmentation, and separation.
2	Combination and integration	Combination refers to the integration of elements with the same performance or different properties. Integration refers to the use of a certain method to change the original dispersed state of independent elements and make them form an interconnected and organic whole.

Table 2. Cont.

No.	Variation method group	Definition
3	Local optimization	The emphasis is placed on optimization and adjustment of the system rather than essential transformation, and the partial optimization of the system is achieved through parameter adjustment, performance improvement or other optimization techniques.
4	Substitution	Taking the space dimension, environment dimension, structure dimension, function dimension, mechanism dimension, material dimension, dynamic system dimension, time sequence dimension, and human-machine relationship dimension of the system as the research objects, the element groups are changed and replaced.
5	Dynamics	Give the ability to dynamically change the elements of innovation.
6	Self-service	By changing the relationship of the components in the system (relative position, volume, quality, mode of action, etc.) or adding new components, the system can achieve self-service, self-protection and self-maintenance under specific conditions.
7	Friendliness	Change the relationship between the dimensional elements and the environment so that the innovative dimensional elements involved in the system occupy the least resources, minimize the harm to people and the environment. Meanwhile, the comprehensive utilization of the resources, and harmony and friendliness between human, machine, environment and management are realized.
8	Flexibility	Smooth the system's appearance, shell, function, phase, function, speed, position and other elements.
9	Intelligence	The specific application of intelligence in the converge of modern communication and information technology, computer network technology, intelligent control technology, etc.

On the basis of a large number of case studies, the variation method groups can be divided into 9 categories, including decomposition and removal, combination and integration, local optimization, substitution, dynamics, self-service, friendliness, flexibility and intelligence. The relationship between EVIT and TRIZ 40 inventive principles is described in Appendix A. It means TRIZ 40 inventive principles could be expressed in EVIT framework, which is showed in the table A1. The horizontal axis means variation method groups while the vertical axis is presented as element groups. According to the cross influence between element groups and variation method groups, TRIZ 40 inventive principles could be explained in an unified way. One thing should be mentioned, considering the target field features and the characteristics of the developing era, we introduced a new inventive principle called “intelligence” for making the innovation process more efficient and significant., which is not contained in classical TRIZ. Thus, in Appendix A, the relationship between “intelligence” with TRIZ inventive principles is not listed.

2.3 The Innovation Coupling Paths between Element Groups and Variation Method Groups

The concept of coupling originated from physics, and its connotation is a sign that two or more unrelated systems or forms of motion establish a relationship to influence each other until they are united. The process of element transformation and integration is actually the process of combining product elements and other information with processing techniques. Therefore, the meaning of innovation coupling in EVIT is defined as the process of combining element groups and variation method groups according to certain rules. This process is not a static single intersection and combination between element groups and variation method groups, but the process of mutual penetration and interaction between element groups and variation method groups, finally deriving a systematic technological innovation path map. The coupling relationship map between element groups and variation method groups is depicted as Fig. 1, which is also named as EVIT inventive principle map.

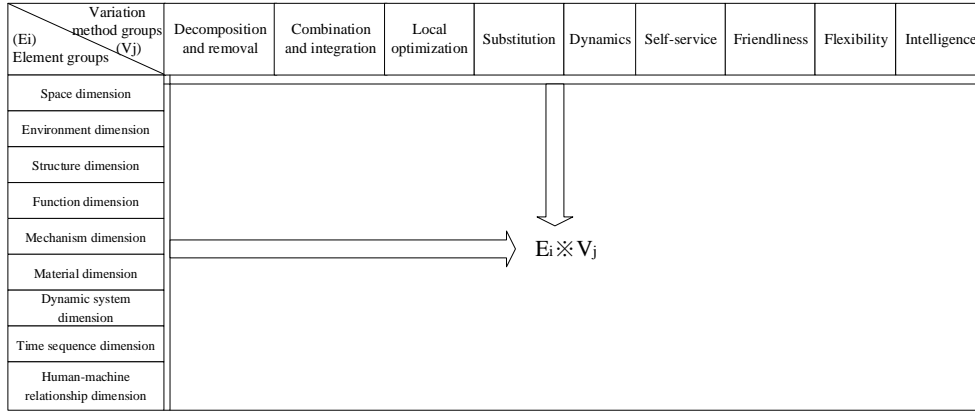


Fig. 1. EVIT inventive principle map

The process of obtaining the technological innovation path N through EVIT inventive principle map can be expressed as follow.

$$N = E_i \times V_j \quad (1)$$

In Equation (1), $E_i (1 \leq i \leq 9)$ represents element groups. $V_j (1 \leq j \leq 9)$ represents variation method groups. The sign of \times represents the concept of the coupling between element groups and variation method groups.

When applying this method to a specific field, one or more element groups can be arbitrarily selected to couple with different variation method groups to obtain technological innovation paths. The equation can be adjusted as follow.

$$N = E_m \times V_n \quad (2)$$

In Equation (2), m is a set. $m \subseteq \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$ Also, n is a set. $n \subseteq \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$

In Equation (2), the number of m set is $a (a \leq 9)$, the number of n set is $b (b \leq 9)$, then the number of subsets after removing the empty set from the m set is $(2^a - 1)$, and each subset represents several element groups in one or a fixed combination. In the same way, the number of subsets of the n set excluding the empty set is $(2^b - 1)$, and each subset represents one or a fixed combination of several variation method groups. Therefore, C_N , the number of technological innovation paths, can be obtained by applying coupling when target for specific fields. The equation (3) is listed as follow.

$$C_N = C_9^a \times C_9^b = (2^a - 1) \times (2^b - 1) \quad (3)$$

For example, if a is 3 which means there are 3 element groups and b is 3 which means there are 3 variation method groups, the number of technological innovation paths would be 49.

$$((2^3 - 1) \times (2^3 - 1))$$

In summary, the coupling of each type of element group and each variation method group may form one or more innovative ideas, thereby constructing a systematic innovation plan in a certain industry

field to reveal potential technological innovation opportunities and guide enterprises Plan the innovation strategy in a targeted manner.

3 The Overall Structure of Problem Solving in EVIT

The overall structure of problem solving in EVIT consists of six steps, which is presented in Fig. 2.

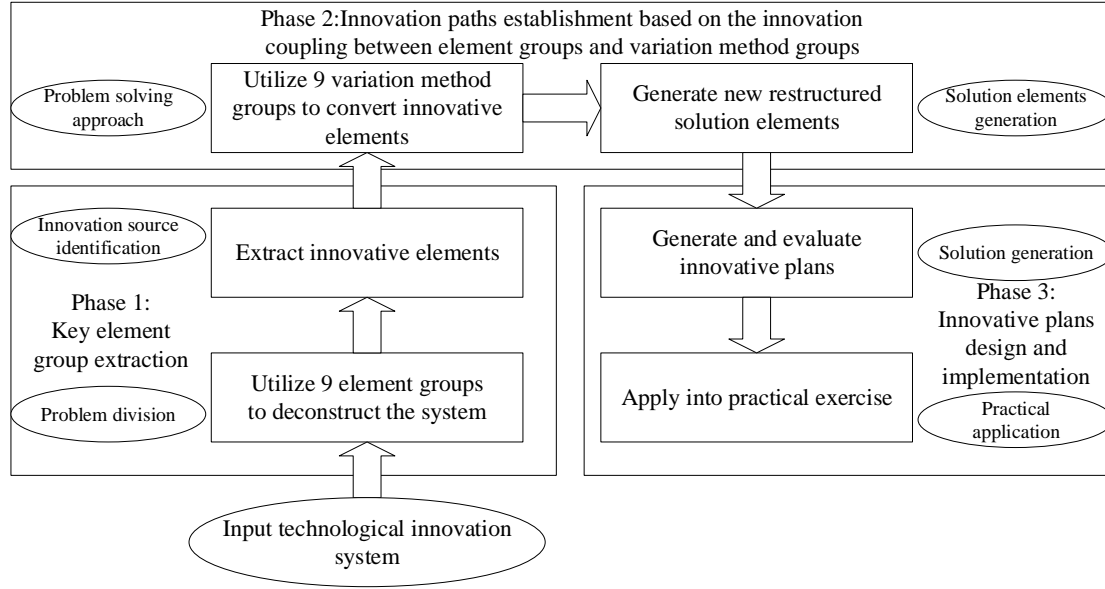


Fig. 2. The overall structure of problem solving in EVIT

The basic scheme of problem solving in EVIT is a six-box scheme covering three phases, which has been represented in a data diagram. The input and output of each diagram could be described by the information of patents, product manuals, or other scientific literature. In Phase 1, there are two steps to extract key element groups. First, problem division means 9 element groups are utilized as navigation to deconstruct the technological system in a structural and systematic way. Second, the basic innovative elements of the technical system are extracted with the aid of multiple tools such as patent mining, knowledge mining, expert interviews, group discussions, functional analysis, knowledge cross-border transfer and other methods. In Phase 2, two steps witness the process of constructing innovation paths based on the coupling between element groups and variation method groups. Third, 9 variation method groups are dedicated to transform and innovate the acquired innovative elements to generate new solution elements. Fourth, 9 variation method groups are further utilized to reorganize and reconstruct innovative elements to generate numerous new restructured solution elements. Phase 3 consists of two steps with the aim of designing feasible innovative plans. Fifth, all of the generated numerous innovative solutions are evaluated and selected, and technically and economically infeasible solutions are excluded. Finally, a satisfactory technical solution is selected for implementation and the effect of innovation is tested to iteratively improve the technical innovation solution.

4 Case Study

CBM is an efficient, clean and environmentally friendly new energy and has become one of the emerging industries with huge development potential in the energy industry, identifying possible tech-

nological opportunities in CBM extraction is greatly significant for the industry, the nation, and all of society in that it can reduce air pollution and harness mine gas hazards [11]. CBM development and treatment is a comprehensive problem with complex structure and multiple dimensions. It is difficult to solve the problems in CBM treatment from only one dimension or one way. In view of this, EVIT is utilized to conduct in-depth analysis of the structure and internal mechanism of CBM extraction technology from multiple dimensions.

Since the proposed method is executed based on the patent documents in CBM extraction technical fields, structured data must be extracted to explore their inner logic and law. WIPO PatentScope is selected as the data source, which records many countries' patents, including China, the Russian Federation, the United States, etc. The PatentScope database provides access to international Patent Cooperation Treaty (PCT) applications in full-text format on the day of publication, as well as the patent documents of participating national and regional patent offices. Thus, numerous patent documents from worldwide patent databases can be collected in WIPO PatentScope, and valuable information can be derived automatically. The time window was set from 2009 to 2018, and 1385 patent documents were collected by searching the keyword "coalbed extraction" in the WIPO PatentScope database with cross-lingual expansion. With the aid of experts' knowledge, 100 high relevant patent documents were screened as the innovative source.

4.1 Phase 1: Key Element Group Extraction

In Phase 1, 9 element groups are utilized to deconstruct the CBM extraction technology field. It means the overall features of the field could be described through the framework consisting of 9 element groups. Then, to extract the innovative elements, computerized program was conducted to preprocess the unstructured patent documents by Python. Word segmentation is executed to divide the patent documents into single words and function words and stop words are removed to eliminate unnecessary impact. TF-IDF, a term weighting scheme, was utilized to extract keywords of each patent documents. It was believed the keywords possessed the capability of representing the valuable information of patent documents. 2930 keywords were originally derived and then 168 keywords were extracted from those to express the most valuable information. In this study, Word2Vec algorithm was utilized to deal with the ambiguous relation of the keywords from different patent documents. All of keywords are transformed into a keyword vector and then clustered into 40 groups. The relationship between different keywords was depicted in Fig. 3.

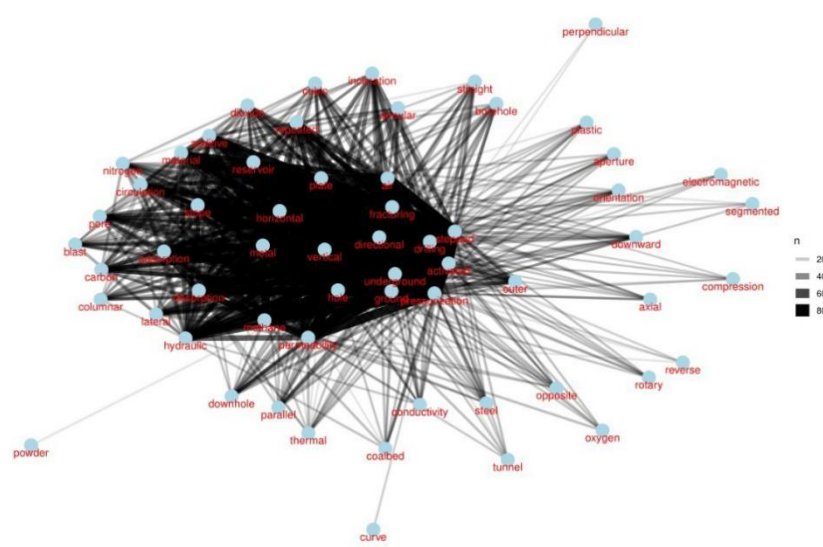


Fig. 3. Co-occurrence network: semantic distances between keywords in CBM extraction technology

According to clustering results, 3 key element groups and corresponding keywords could be classified as Table 3.

Table 3. Extracted key element groups

Keywords	Key element groups
ground, coal reservoir, surrounding rock	Space dimension
well drilling, fracture, scour, thermal driving, drill hole, microorganism	Mechanism dimension
fracturing medium, flooding medium, wear-resisting members materials, insulating materials	Material dimension

4.2 Phase 2: Innovation Paths Establishment Based on the Coupling between Element Groups and Variation Method Groups

Based on the classification of innovative elements, each element group is mapped to a spatial coordinate system, where the X-axis is the space dimension, the Y-axis is the material dimension, and the Z-axis is the mechanism dimension. Then the variation method groups and the element groups are coupled to form innovation paths of CBM extraction. The process is depicted in Fig. 4.

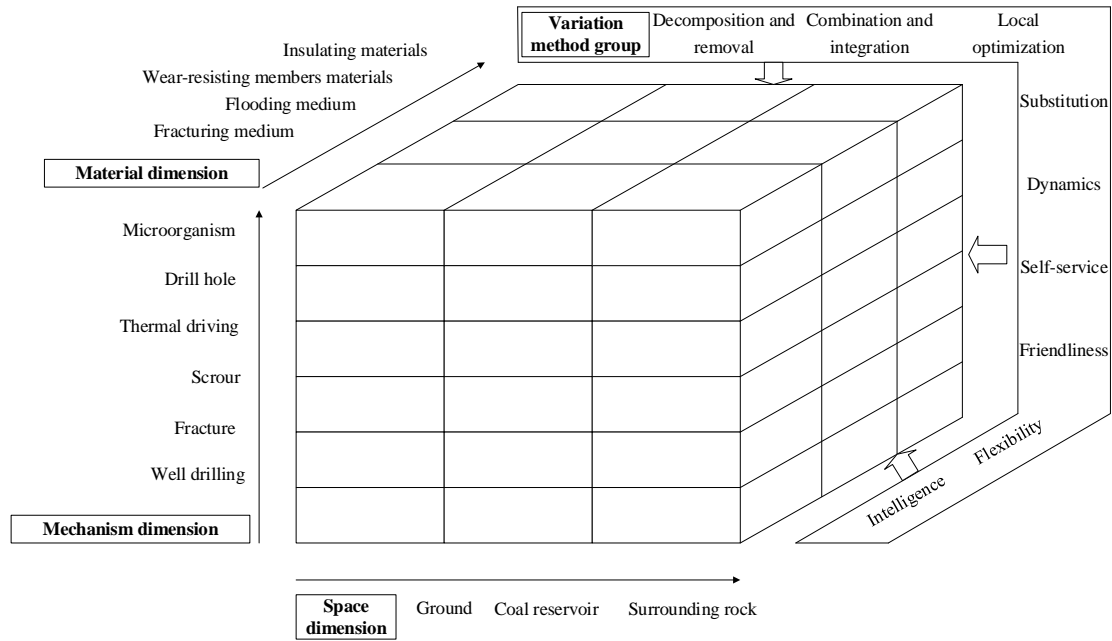


Fig. 4. Innovation paths establishment based on the coupling between element groups and variation method groups

4.3 Phase 3: Innovative Plans Design and Implementation

Based on the established innovation paths, we can obtain new ideas for depressurizing and eliminating outbursts in CBM extraction. Then combining the actual conditions of the current mine site and mining equipment, the equipment and methods of depressurizing and eliminating outbursts in CBM extraction are further improved by systematic design, resulting in the generation of targeted technical solutions. For example, through the coupling between space dimension, mechanism dimension, material dimension and the variation method group of local optimization, the technology opportunity could be described as follow: Due to the good sand carrying performance of liquid nitrogen and the obvious effect of increasing production, liquid nitrogen can be used as fracturing medium to unblock and support the formed fractures, optimize the fracture conductivity, and then increase gas production through repeated fracturing. Furthermore, another technology opportunity could be derived from the coupling between space dimension, mechanism dimension and the variation method group of local optimization and friendliness. The content of this opportunity is described as follow: The coal reservoir is drilled from the surrounding rock by rotary percussion method to increase the drilling speed and reduce the mining cost, and then use air scouring to release the pressure of the acupuncture points. Using the high-pressure air shock wave as the power source, it performs a nearly cylindrical rotating impact on the well wall to cut off the acupoints so that the coal around the well bore gradually breaks from the well wall, forming pressure and releasing space. Then, perform gas drainage in the coal seam according to the conventional method.

5 Discussions

This study introduced the components and the framework of EVIT, and analyzed patent information to resolve the technical problems in the field of CBM extraction by EVIT. In the first technology opportunity, we can know that the scheme is set in coal reservoir, which belongs to the space dimension. The related mechanism is fracture, paving the way for thinking about the fracturing medium in material

dimension. After determining the structure of the technology opportunity, the variation method group of local optimization plays a role in varying the specific details. Similarly, the second technology opportunity indicates the innovative plan occurs in coal reservoir and surrounding rock. The target mechanisms are selected as drill hole and scour. With the guide of variation method groups of local optimization and friendliness, the opportunity is derived by changing the structure and relationship between each innovative element in the element group framework. In the application of EVIT, the variation method groups are selected based on the inner characteristics of each innovative element, which requires the analysis of conventional CBM extraction methods. This study doesn't cover all the technology opportunities, but list part of the opportunities to prove the effectiveness of the EVIT application.

The simplicity of EVIT compared to TRIZ and other similar methods could be generalized in three aspects: core ideology, innovation process and innovation tools. First, the core ideology of EVIT is the innovation coupling paths between element groups and variation method groups, which provide the direction for developing technical solutions to problems. Second, the innovation process of EVIT starts from analyzing the demands of users, and then it comes to the establishment of innovation coupling paths between element groups and variation method groups, and the final step means generating specific innovative plans design. Compared to the Four-Box Scheme of Problem Solving in TRIZ, this framework is easier for engineers to understand and provides concrete ways of processing the information between the adjacent boxes. Third, compared to the multiple tools in TRIZ including 40 inventive principles, 76 standard solutions, 39 engineering parameters and etc., the innovation tools in EVIT are conciser and easier to be understood and applied into R&D projects.

6 Conclusions

In this study, we put forward a novelty innovation method called EVIT with the aim of simplifying and reorganizing TRIZ tools and other innovation methods. 9 element groups are generalized from different engineering & technology areas and 9 variation method groups are simplified and reorganized from 40 inventive principles and 76 standard solutions and other innovation methods. This study aims to summarize and analyze the TRIZ, SIT, USIT and MA to propose a systematic method which possess the potential to realize the unified expression of the above methods. However, there could be other element and variation method group to develop in the future researches. The proposed element and variation method group are defined with the aim of indicating the inner relationship between the above methods. The overall technological features are described with the aid of 9 element groups and the technical problems could be solved by the guide of 9 variation method groups. The process of coupling element groups and variation method groups is defined as innovation coupling. Then, the matching mechanism between element groups and variation method groups is defined in a mathematical form. In conclusion, EVIT could promote the process of generating various creative solutions effectively, meaning it is easy to understand and apply for experts and ordinary engineers. It has been successfully applied into chemical industry, mechanical engineering and CBM extraction technology.

However, this innovation method still has some limitations. First, the matching mechanism between element groups and variation method groups is still established in a semi-autonomous approach, which may decrease the efficiency of solving problem. Second, the comprehensive evaluation system of technical plans, which is located in the end of the application process, still have some room for improvement in the evaluation index setting and the process of calculating the index. The future studies could focus on the application of artificial intelligence to achieve the automation of constructing matching

mechanism and generating conceptual technical solutions for problem solving. Besides, a more intelligent and comprehensive evaluation system could be developed to improve the quality of technology opportunities.

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Appendix 1

Table A1. The relationship between EVIT and TRIZ 40 inventive principles

Variation method groups Element groups	Decomposition and removal	Combination and integration	Local optimization	Substitution	Dynamics	Self-service	Friendliness	Flexibility	Intelligence
Space dimension	1 Segmentation	32 Color changes, 8 Anti-weight							
Environment dimen- sion		9 Preliminary anti-action	35 Parameter changes	38 Strong oxidants, 39 Inert atmosphere	21 Skipping			36 Phase transi- tions	
Structure dimension	2 Taking out	7 Nested doll, 17 Another dimension,	16 Partial or excessive actions			37 Thermal expansion	33 Homog- eneity	14 Spheroidality- Curvature 30 Flexible shells and thin films	
Function dimension	5 Merging	5 Merging, 6 Universality, 34 Discarding and recovering	3 Local quality 4 Asymmetry	26 Copying	18 Mechanical vibration	25 Self- service, 13 The other way round	22 "Blessing in disguise" or "Turn Lemons into Lemonade"		

Table A1. Cont.

<div>Variation method group</div> <div>Element group</div>	Decomposition and removal	Combination and integration	Local optimization	Substitution	Dynamics	Self-service	Friendliness	Flexibility	Intelligence
Mechanism dimension				28 Mechanics substitution				29 Pneumatics and hydraulics	
Material dimension		31 Porous materials, 40 Composite materials		27 Cheap short-living objects					
Dynamic system dimension				24 Intermediary	19 Periodic action				
Time sequence dimension		10 Preliminary action, 11 Before-hand cushioning		21 Skipping	15 Dynamics	23 Feedback, 12 Equipotentiality		20 Continuity of useful action	
Human-machine relationship dimension									

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