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► **To cite this version:**

Lijie Feng, Yuxiang Niu, Jinfeng Wang, Yinuo Chen, Zhenfeng Liu, et al.. Element Variation Innovation Thinking: A Method of Simplifying and Reorganizing TRIZ. TRIZ Future conference, Sep 2021, Bolzano, Italy. pp.301-314, 10.1007/978-3-030-86614-3_24 . hal-04067830

HAL Id: hal-04067830

<https://inria.hal.science/hal-04067830>

Submitted on 13 Apr 2023

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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,

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

81 **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.

82 **2.2 Variation Method Group**

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

89 **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.

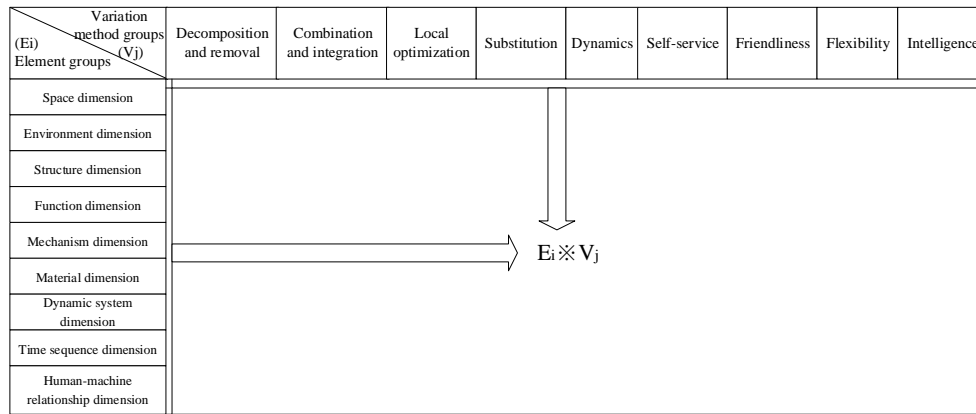
Table 2. Cont.

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.

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

104 2.3 The Innovation Coupling Paths between Element Groups and Variation Method Groups

105 The concept of coupling originated from physics, and its connotation is a sign that two or more unre-
106 lated systems or forms of motion establish a relationship to influence each other until they are united.
107 The process of element transformation and integration is actually the process of combining product
108 elements and other information with processing techniques. Therefore, the meaning of innovation cou-
109 pling in EVIT is defined as the process of combining element groups and variation method groups
110 according to certain rules. This process is not a static single intersection and combination between ele-
111 ment groups and variation method groups, but the process of mutual penetration and interaction be-
112 tween element groups and variation method groups, finally deriving a systematic technological innova-
113 tion path map. The coupling relationship map between element groups and variation method groups is
114 depicted as Fig. 1, which is also named as EVIT inventive principle map.



115

116

Fig. 1. EVIT inventive principle map

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

118

119

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

120

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.

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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.

126

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

127

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

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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.

134

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

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

138

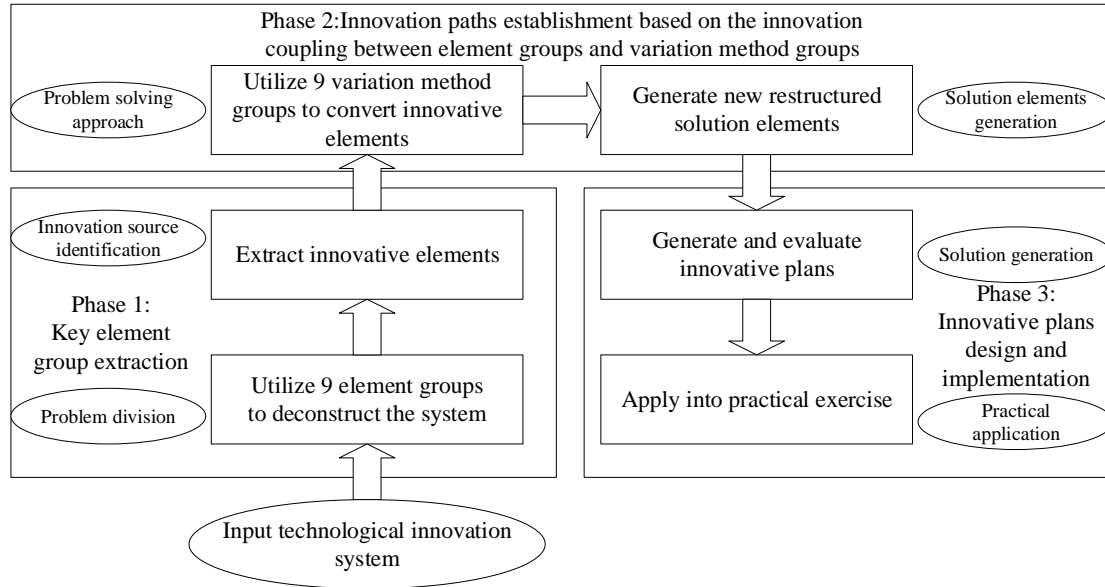
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In summary, the coupling of each type of element group and each variation method group may form one or more innovative ideas, thereby constructing a systematic innovation plan in a certain industry

140 field to reveal potential technological innovation opportunities and guide enterprises Plan the innova-
 141 tion strategy in a targeted manner.

142 3 The Overall Structure of Problem Solving in EVIT

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



144

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

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

162 4 Case Study

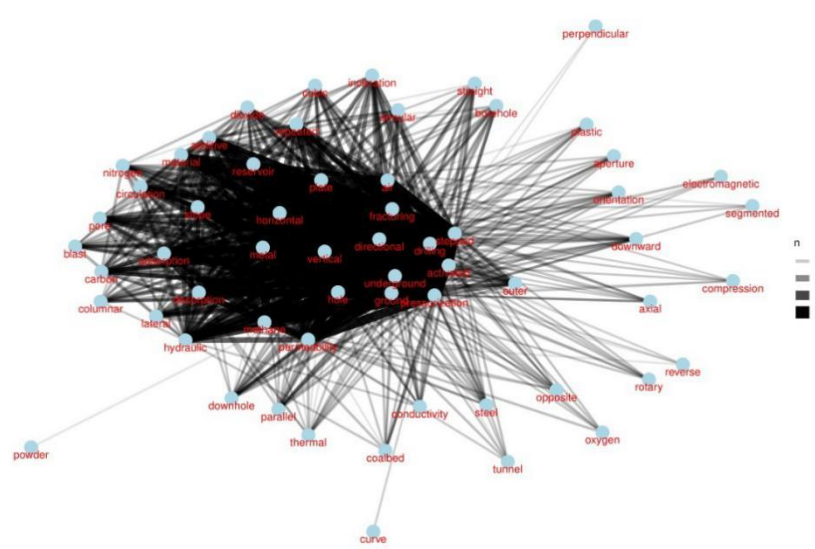
163 CBM is an efficient, clean and environmentally friendly new energy and has become one of the
 164 emerging industries with huge development potential in the energy industry, identifying possible tech-

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

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

182 **4.1 Phase 1: Key Element Group Extraction**

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



195

196 **Fig. 3.** Co-occurrence network: semantic distances between keywords in CBM extraction technology197 According to clustering results, 3 key element groups and corresponding keywords could be classi-
198 fied as Table 3.

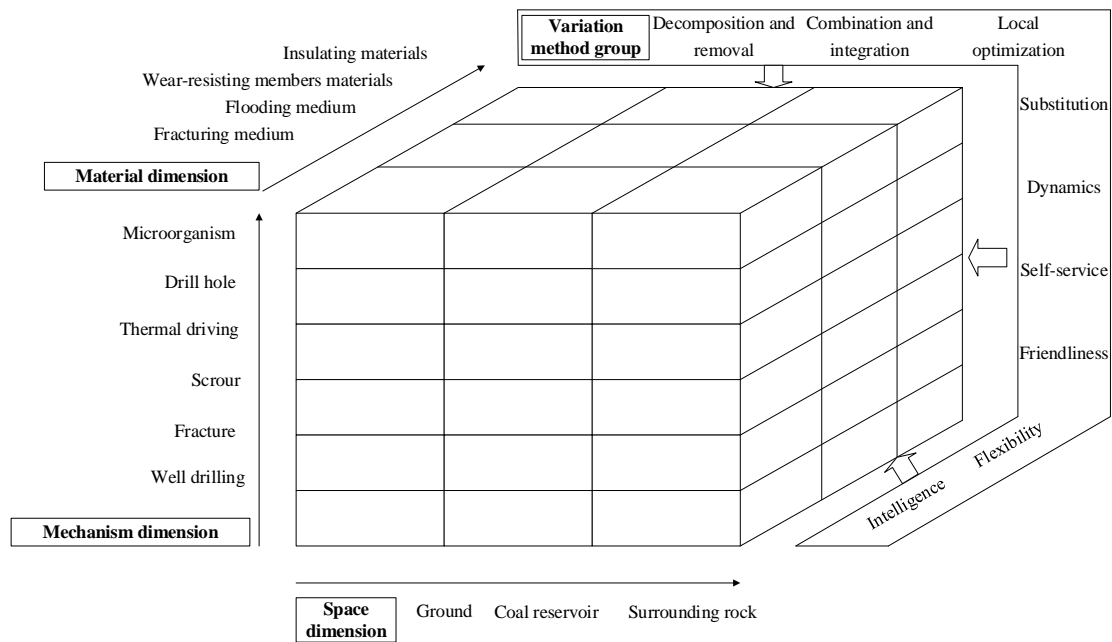
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Table 3. Extracted key element groups

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

200 4.2 Phase 2: Innovation Paths Establishment Based on the Coupling between Element Groups 201 and Variation Method Groups

202 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
203 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.
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Fig. 4. Innovation paths establishment based on the coupling between element groups and variation method groups

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4.3 Phase 3: Innovative Plans Design and Implementation

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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 acupuncture points 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.

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5 Discussions

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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

232 dimension. After determining the structure of the technology opportunity, the variation method group
233 of local optimization plays a role in varying the specific details. Similarly, the second technology op-
234 portunity indicates the innovative plan occurs in coal reservoir and surrounding rock. The target mech-
235 anisms are selected as drill hole and scour. With the guide of variation method groups of local opti-
236 mization and friendliness, the opportunity is derived by changing the structure and relationship between
237 each innovative element in the element group framework. In the application of EVIT, the variation
238 method groups are selected based on the inner characteristics of each innovative element, which re-
239 quires the analysis of conventional CBM extraction methods. This study doesn't cover all the technol-
240 ogy opportunities, but list part of the opportunities to prove the effectiveness of the EVIT application.

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

252 **6 Conclusions**

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

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

274 mechanism and generating conceptual technical solutions for problem solving. Besides, a more intelli-
275 gent and comprehensive evaluation system could be developed to improve the quality of technology
276 opportunities.

277

278 **Acknowledgement.** This work is supported by Innovation Method Fund of China with grant number
279 2019IM020200. The statement made herein are solely the responsibility of the authors.

280 **Appendix 1**281 **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 dimension		9 Preliminary anti-action	35 Parameter changes	38 Strong oxidants, 39 Inert atmosphere	21 Skipping			36 Phase transitions	
Structure dimension	2 Taking out	7 Nested doll, 17 Another dimension,	16 Partial or excessive actions			37 Thermal expansion	33 Homogeneity	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"		

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