Resource-Constrained Innovation Method for Sustainability: Application of Morphological Analysis and TRIZ Inventive Principles

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Abstract: Extensive research on resource-constrained innovation has been conducted by scholars and practitioners in recent years. An interesting research avenue is how firms explore the process of the new product development (NPD) and the ideas generation to foster resource-constrained innovation. However, despite the importance of product development and creative ideas under the resource-constraints contexts, innovation methods for applying to the resource-constrained innovation and designers have received comparatively less attention. As a remedy, this paper proposes a resource-constrained innovation method (RCIM) to generate ideas for the NPD. The RCIM is mainly divided into four sections: Developing the resource-constrained innovation approaches, developing the resource-constrained innovation dimensions, generating the creative ideas and evaluating the creative ideas. First, the resource-constrained innovation algorithms are developed based on success factors, characteristics, and attributes of resource-constrained innovation and the TRIZ (ТеорияРешения Изобретательских Задач in Russian; Theory of Inventive Problem Solving in English) inventive principles via the systematic literature review (SLR). Second, the innovation dimensions are categorized to structure a target technology by means of the morphological analysis (MA) and the Derwent manual codes (DMCs) mapping based on collected patents. Third, the creative ideas are generated for the NPD by combining the innovation dimensions with the resource-constrained innovation approaches. Finally, the creative ideas are evaluated by the frugal criteria. The RCIM will stimulate designers’ creativity for achieving sustainability and innovation within constraint-based scenarios, MA and TRIZ.

Keywords: resource-constrained innovation; innovation method; sustainability; innovation approaches; innovation dimensions; morphological analysis; TRIZ

1. Introduction

The world is seeing resource shortages, overproduction, environmental damage, and a plethora of other negative consequences as a result of the conventional approaches to product and service innovation, and people put those down to the fact that most developed countries have failed to embrace a resource-constrained method in the past [1]. Resource-constrained innovation is the ability of a product, service, practice or process to ‘do better with fewer resources for more people’, i.e., to create significantly more value while minimizing the use of resources [2]. It is characterized by: Sustainable [3], resource-constrained [4,5], scarcity-induced or minimalist [6,7], reuse of existing components and ease of use [8]. These characteristics indicate that resource-constrained innovation
focuses not only on the emerging markets and the bottom of the pyramid (BOP) markets [9–11], but also on the small and medium-sized enterprises (SMEs), even on the large companies [12], and on areas in which it is either not profitable, or profits cannot be appropriated freely by the innovating company. Resource-constrained innovation can be a firm driver of progress in achieving sustainability [1].

Scholars have so far generally concentrated on the geographic relevance and business propositions of resource-constrained innovation. The broader question about actual the new product development (NPD) under extreme resource-constraints has received comparatively less attention. The NPD refers to the innovation process of production technology, the core task of which is to formulate the corresponding systematic solutions to the innovation ideas [13–15]. Different from the traditional NPD, which is built on assumptions of affluence and abundance [16], the NPD of the resource-constrained innovation involves sustainability and scarcity [4]. A more fundamental NPD effort may be necessary to develop truly effective cost-innovative methods and product designs [17]. How to explore the process of NPD and design product architecture to foster resource-constrained innovation is an interesting research avenue [12]. Companies find it increasingly challenging to develop successful new products, and the generation of new ideas is one of the important initial tasks in the NPD process. The idea generation, however, is the first and foremost stage of the NPD and innovation [18,19]. This front end of innovation is of particular importance as it determines a firm’s potential to find promising new product ideas and ways of producing this product at reasonable costs [20,21]. For the resource-constrained context, creativity seems to be more important than the status of characteristics of resource-constrained innovation, and contributes to problem-solving in environments with constraints or resource scarcity [22].

Nevertheless, despite the importance of the NPD and the creative ideas under the resource-constraints contexts, innovative methods for applying to resource-constrained innovation and designers have received comparatively less attention. In the process of NPD for the resource-constrained innovation, a minimalist and good-enough innovation method is necessary. Because the mainstream innovation methods advocate the over-engineered, fully functioning, overall performance-optimized, premium and high-priced products [23]. However, the characteristics of resource-constrained innovation are savings in resource, time and cost, which are different from those of mainstream innovations; therefore, the characteristics need to be understood from novel perspectives [24]. Low-cost manufacturing, simple design and basic functionality are keys to serving low-income customers [6]. Hence, there is still much to uncover regarding how to create innovative products and services in the resource-constrained context.

As a remedy, this paper proposes an innovative method to generate ideas for resource-constrained innovation. Since the existing approaches focus on case studies, regionalism and business models, it must be further coupled with innovative methods or supported by concrete data. In addition, the idea generation process that uses this method is proposed to assist designers and engineers in performing technology development and product design. More specifically, this research aims to create a resource-constrained innovation method (RCIM) that hybridize the morphological analysis (MA) and TRIZ (Теория Решения Изобретательских Задач Russian; Theory of Inventive Problem Solving in English). The RCIM is a heuristic process model and attempts to demonstrate the key role of innovation methods in the process of NPD for ensuring ideas differentiation and facilitating creativity. In doing so, the authors hope to offer a complete model of idea generation of resource-constrained innovation, and thereby to help both academics and organizations to understand, to research, and to manage better this fuzzy and important phase of the innovation process. The RCIM is illustrated by a design case of Chinese coal-bed methane (CBM) extraction technology. In this way, our study makes an important contribution to the emerging body of literature on resource-constrained innovation. Moreover, the results have important implications for how the technology strategy and design choices can be tailored to enhance the disruptive potential for resource-constrained innovation.

The remainder of the paper is organized as follows. We review the related literature in Section 2. With the background, a research framework and an overall detailed process to develop the RCIM will
be explained in Section 3. To illustrate the feasibility of the proposed RCIM, a case study of Chinese CBM extraction technology is conducted in Section 4. Finally, Section 5 discusses and summarizes the paper, and illustrates its contribution and directions for future research.

2. Literature Review

The resource scarcity does not only affect innovation, but also starves certain users of much-needed products at the BOP markets. Innovators facing the resource constraints are more likely to find the creative analogies and combinations that would otherwise be hidden under a glut of resource [25]. Resource-constrained innovations have been recognized and described that innovation developed in the emerging markets in a context characterized by the lower power of purchase, the lower understanding of technology, and the lower investment resources [26]. Therefore, some concepts, such as the frugal innovation [6], the disruptive innovation [8], the grassroots innovation [27], and the reverse innovation [26] according to the characteristics of resource-constrained innovation. Nevertheless, how to generate creative ideas to the NPD for resource-constrained innovation that meets the savings of resource, time and cost, there is still a lack of innovation methods for this phenomenon.

From the perspective of sustainability, the NPD and creative ideas under resource-constrained innovation cannot depend on the traditional innovation methods which advocate the over-engineered, fully functioning, overall performance-optimized products by replacing or adding components to solve technology problems [20,23]. Since Osborn’s brainstorming [28], many traditional innovation methods have been employed to support innovations [29]. The existing innovation methods, such as brainstorming [28], MA [30], checklists, axiomatic design (AD) [31], TRIZ [32], structured inventive thinking (SIT), unified structured inventive thinking (USIT) [33,34], are introduced to primarily target the traditional and mainstream innovations. Among them, MA and TRIZ are the most popular innovation methods.

However, from the resource-constrained perspective, the MA is characterized by structuring a system into independent partial systems and quickly finding answers by combining the different solutions of these subsystems. However, the MA is a method to structure a problem rather than solve it [35]. While the TRIZ focus on finding fundamental contradictions within a system, representing the core problems, and solving them by applying the accumulated experiential knowledge of previous inventors [36]. On the one hand, the basic idea of MA is that a subject is broken down into several dimensions, through which the subject can be described as comprehensively and detailed as possible [30,35,37]. The strength of this method lies in its ability to model the complex problems in a non-quantitative manner. A general form of MA is developed as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes and is applied to diverse fields. On the other hand, originated from the former Soviet Union and developed in Europe and America, TRIZ won undivided admiration in Motorola, Chrysler, Ford, GE and Samsung, etc. TRIZ was developed by Genrich S. Altshuller, who found that scientific literature lacked a method for inventing new solutions [32]. Previous studies have demonstrated that innovative methods were rarely applied alone; the hybrid method could improve the accuracy of innovation [38]. Our research mainly makes MA and TRIZ inventive principles complement each other and constructs the RCIM.

3. Proposed Method for Resource-Constrained Innovation

3.1. Research Concept

The mainstream innovation methods are not suitable for resource-constrained innovation because they advocate over-engineered, fully functioning, overall performance-optimized, premium and high-priced products [23]. We propose a novel innovation method based on a structured perspective of MA and TRIZ to help designers in the process of product development under the resource-constrained contexts. The proposed resource-constrained innovation method (RCIM) is the step-by-step processes
for a non-typical problem, which is considered as an epitome of the whole resource-constrained innovation process. Unlike some of the literature where grassroots innovation is based on learning by doing and improvising by trials [39], we consider that the RCIM must be taken into account the following issues:

- A method to lay emphasis on the savings of resource, time and cost in the process of product development under resource-constraints context and sustainability;
- A method to focus on generating creative ideas for NPD;
- A method to put emphasis on problem-solving of resource-constrained innovation by integrating the advantages of TRIZ and MA;
- A structured method to develop innovation dimensions from existing patent documents and deduce creative ideas by means of resource-constrained innovation approaches.

3.2. Research Framework

The detailed process for developing the RCIM is shown in Figure 1, and the framework is mainly composed of three modules. To begin with, before the main modules start, literature documents on resource-constrained innovation are retrieved from journal databases, and patents are collected from patent databases. In the first module, the resource-constrained innovation approaches are developed to deduce creative ideas based on success factors, characteristics, attributes and ways of resource-constrained innovation and TRIZ inventive principles. In the second module, the innovation dimensions are categorized to structure the targeting technology by means of MA and technology map based on collected patents. In the third module, the creative ideas are generated for NPD by combining innovation dimensions with the resource-constrained innovation approaches. In this module, a resource-constrained innovation matrix is designed for problem-solving of resource-constrained innovation by taking advantage of matrix thinking. Finally, after the main modules, the creative ideas are evaluated by three criteria, such as substantial cost reduction, a concentration on core functionalities, and an optimized performance level [23].

**Figure 1.** Research framework. DMC, Derwent manual code; DII, Derwent innovations index; TRIZ, ТеорияРешения Изобретательских Задачи Russian, Theory of Inventive Problem Solving in English.
3.2.1. Module 1: Developing the Resource-Constrained Innovation Approaches

The resource-constrained innovation approach is a set of innovation tools to analyze non-typical problem situations of resource-constraints and to provide effective solutions by using TRIZ inventive principles. To develop the resource-constrained innovation approaches, Module 1 contains the following detailed steps, as shown in Figure 2.

First, we collected literature on resource-constrained innovation via systematic literature review (SLR) [40,41]. We refer to [10,12,24,42,43], and created a search strategy where “resource-constrained innovation” or “frugal innovation” or “frugal engineering” or “Gandhian innovation” or “Jugaad” as main search keywords. At least one of these keywords was retrieved in “title, keywords or abstract” in the following databases: Web of Science, ScienceDirect, IEEE Explore, EBSCO, Taylor & Francis, Wiley, SpringerLink, Emerald, and SSRN. We only collected papers that were written in English, and were either journal articles, conference papers, or working papers. The search was conducted in December 2018. Then, 468 documents were searched from above nine databases. Then we obtained 468 documents and read 468 authors or titles to remove 180 duplicates that appear in different databases. Second, we analyzed 288 remaining documents. We read abstracts and exclude 141 articles where the keywords are considered in the non-innovation or non-management domain. Besides, we found an additional 22 articles that are cited in the reviewed literature and supplement them. We ended up with 169 articles on resource-constrained innovation. Third, we read and searched for abstracts, keywords, definitions, and conclusions of 169 articles and get words, phrases, sentences, etc., associated with the resource-constrained innovation. We were particularly interested in how resource-constrained innovation was successfully implemented. Then we obtained a total of 56 items for factors and
characteristics used in 169 articles, as summarized in the third column of Appendix A Table A1. Forth, we searched for synonyms of 56 items via WordNet that uses sets of synonyms, and provided many types of relationships among concepts [19]. We classified similar words or phrases according to semantic similarity. Then, the resource-constrained ways and attributes were summarized by using categories, as shown in the second column of Appendix A Table A1. Finally, we invite two experts in the field of innovation methods. They matched the resource-constrained ways and attributes to TRIZ inventive principles. Then we proposed eight resource-constrained innovation approaches that are defined, as shown in Table 1. Each approach contained several TRIZ inventive principles and the resource-constrained principles.

Table 1. Definition of resource-constrained innovation approaches.

| Resource-Constrained Innovation Approaches | TRIZ Inventive Principles | Resource-Constrained Principles |
|-------------------------------------------|---------------------------|--------------------------------|
| Decomposition and removal approach        | Segmentation              |                                 |
|                                           | Taking out                |                                 |
|                                           | Universality              |                                 |
| Partial optimization approach             | Local quality             | Local optimization principle     |
|                                           | Asymmetry                 | which is defined to overcome a   |
|                                           | Partial or excessive      | system’s weak links and optimize |
|                                           | actions                   | the system state by improving    |
|                                           |                          | local components.               |
| Permutation and combination approach      | Merging                   | Cheaper substitution principle  |
|                                           | Nested doll               | is defined to reduce time,      |
|                                           | Preliminary anti-action   | materials and human effort by   |
|                                           | Intermediary              | replacing with cheaper labour,  |
|                                           |                          | materials and local services.   |
| Substitution and changing approach        | Copying                   | Theory substitution principle   |
|                                           | Cheap short-living objects|
|                                           | Mechanics substitution    | is defined to optimize system    |
|                                           | Porous materials          | efficiency by use of interchange|
|                                           | Color changes             | of the light field, sound field,|
|                                           | Parameter changes         | force field, electric field,    |
|                                           | Phase transitions         | magnetic field or mechanic field.|
|                                           | Thermal expansion         |                                 |
|                                           | Strong oxidants           |                                 |
|                                           | Inert atmosphere          |                                 |
|                                           | Composite materials       |                                 |
| Dynamic approach                          | Dynamics                  | Re-use principle which is defined|
|                                           | Another dimension         | to make full use of waste       |
|                                           | Periodic action           | materials and energy or parts   |
|                                           | Continuity of useful      | to provide service for the system|
|                                           | action                    | itself so as to maximize the    |
|                                           | Skipping                  | use of system resources.        |
| Self-service and balance approach         | Anti-weight               |                                 |
|                                           | Turn Lemons into Lemonade |
|                                           | Feedback                  |                                 |
|                                           | Self-service              |                                 |
|                                           | Discarding and recovering |                                 |
| Friendliness and coordination approach    | Spheroidality-curvature   | Consistency principle which is   |
|                                           | Homogeneity               | defined to combine systematic    |
|                                           |                          | characteristics, allocate system |
|                                           |                          | resources to maintain            |
|                                           |                          | consistency and achieve best    |
|                                           |                          | system efficiency.              |
| Intellectualization approach              |                          | Self-Analysis principle is defined|
|                                           |                          | to load data processing software|
|                                           |                          | into the system so that it can   |
|                                           |                          | automatically analyze and        |
|                                           |                          | process data to improve its      |
|                                           |                          | decision-making speed.          |
|                                           |                          | Sharing principle is defined to  |
|                                           |                          | share R&D knowledge or           |
|                                           |                          | information among innovators to   |
|                                           |                          | control costs and accelerate     |
|                                           |                          | product design cycle.            |

Note: The definition of TRIZ inventive principles are in The TRIZ Journal.

3.2.2. Module 2: Developing the Resource-Constrained Innovation Dimensions

This paper aims to explore the process of NPD and design product architecture to foster resource-constrained innovation under emerging markets or sustainability. Developing the resource-constrained innovation dimensions mainly consists of three phases: Patents collection, data analysis, and define dimensions. The detailed steps for developing the resource-constrained innovation dimensions are shown in Figure 3.
First, it was necessary to investigate just what technology is suitable for resource-constrained innovation. We invited both technical experts and patent examiner to select a target technology. They provided professional consultation of patent retrieval and analysis for the target technology. Second, according to experts’ opinion, we created a search strategy that is either topic, title, or keywords search from a patent database, such as Derwent innovations index (DII). DII collects a large number of the patents from more than 40 patent organizations all over the world. Patents are rewritten into English for facilitating to classify patent information. Derwent selects their contents from the whole of patent documents and splits them up into chemical, mechanical and electric patents. We exported full records from all patent documents in DII. Full records include patent number, title, abstract, inventors, International Patent Classification (IPC), Derwent Manual Code (DMC), etc.

In DII, all of patents were assigned a so-called Derwent class (a rough one letter, two-digit code). Different areas of technology are then further classified, and patents get indexed deeper with what is known as DMC. DMCs are applied to the inventive/significant features of an invention. The codes are assigned by analysts who have specialist knowledge in each of technology areas with which they are concerned. DMCs are superior to the International Patent Classification (IPC) in several ways, which are the best known and most widely spread classification of patents. DMCs are more clearly worded (they call a mobile phone a mobile phone), they are much more up to date with respect to the latest technology (e.g., many fields to do with automotive electrics), and they are much more detailed in many areas [44]. Third, DMCs are extracted from full records of the collected patent documents. Derwent Data Analyzer (DDA), a patent analysis tool, is used for DMCs extraction, grouping and cleansing. DMCs are arranged in accordance with occurrence frequency preferentially. Frequency is an indicator that reflects the major innovation elements of the target technology. The occurrence frequency of DMCs is the number of times a DMC appears in all patents. Then, unrelated DMCs are eliminated according to technical experts’ opinion. Forth, a DMCs co-occurrence matrix is constructed by use of DDA. If two DMCs appear in the same patent, then the two DMCs have a relationship of co-occurrence.

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**Figure 3.** Detailed steps for developing the resource-constrained innovation dimensions.

| Process                                      | Description                                                                 |
|----------------------------------------------|-----------------------------------------------------------------------------|
| Selecting a target technology                | Deciding what technology is suitable for resource-constrained innovation     |
| Collecting patent documents in DII           | Inviting technical experts and patent examiner                              |
| Extracting and cleaning DMCs                 | Creating a search strategy by opinion                                        |
| Constructing a technology map                | Exporting full records from all patent documents in DII                     |
| Clustering technology morphology             | Extracting DMCs from full records                                           |
| Matching innovation dimensions with          | Arranging DMCs by occurrence frequency                                      |
| target technology morphologies                | Eliminating unrelated DMCs to the target technology                          |
|                                              | Constructing a DMCs co-occurrence matrix                                    |
|                                              | Generating a DMCs co-occurrence network                                     |
|                                              | Clustering theme-related technological fields by degree centrality measure   |
|                                              | Defining technology morphologies and shapes                                  |
|                                              | Defining resource-constrained innovation dimensions by experts’ participation|
|                                              | Developing a morphology matrix that consists of dimensions and sub-dimensions|

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The co-occurrence represents the important relationship among these innovation elements in each patent. Then a technology map based on the DMCs co-occurrence matrix is constructed by using social network analysis in a software Ucinet that is a software package for the analysis of social network data. Ucinet comes with a Netdraw network visualization tool. Fifth, the technology map is a symbolic representation of technological fields that are associated with relevant themes. Technological fields are positioned on the map so that similar fields are situated nearby.

These technological fields contribute significantly to divide innovation dimensions. Then, several technology morphologies and shapes are clustered by means of degree centrality measure in Netdraw software. Moreover, the target technology morphologies and shapes are defined by the use of MA. The idea of MA is to break the subject down into a number of fundamental dimensions that describe the subject as completely as necessary [35]. MA begins by identifying and defining the dimensions of the problem complex to be investigated, and assigning each parameter a range of relevant “values” or conditions [37]. In this sense, MA provides a strong advantage in structuring and analyzing technological, organizational and social problems by breaking the subject down into a number of fundamental dimensions [35,45]. In the existing literature, Yoon and Park (2007) described a morphology matrix of a patent as four dimensions: Material, forming process, bonding process and form [46]. Yoon and Park (2005) exemplified a morphology matrix of a specific patent as five dimensions: Process, Energy, Structure, Function and Material [47]. Duczynski (2017) summarize security and law enforcement capabilities into seven dimensions: Decision-making, leadership, Resources, Ethos and professional practice, Capability objectives, Interactions and relationships, Security and law enforcement architecture [48]. Therefore, in the last step, we suggest a morphology matrix that consists of several dimensions through the above-mentioned co-occurrence, clustering, network analysis, MA, and experts’ participation. The use of DMC-based MA generates a large number of dimensions and shapes compared to traditional MA. Then, we match the resource-constrained innovation dimensions with the target technology morphologies. The various shapes of each morphology are categorized as sub-dimensions of each resource-constrained innovation dimensions.

3.2.3. Module 3: Generating Creative Ideas

We create an innovative matrix to solve how to generate creative ideas for new product development for the resource-constrained innovation. We can learn matrix thinking mode in TRIZ contradiction matrix and MA [30,37]. For any object to be innovated, the resource-constrained innovation problems or demands can be solved or satisfied by means of combining corresponding innovation dimensions and suitable resource-constrained innovation approaches to get a resource-constrained innovation solution. The resource-constrained innovation problem’s analytical framework is shown in Figure 4. In the resource-constrained innovation matrix, the vertical coordinate represents the innovation dimension, and the resource-constrained innovation approach is in the horizontal coordinate. The intersections in the matrix between the innovation dimension and approach are creative ideas. In the face of inventive problems of resource-constrained innovation, innovators choose innovation dimensions and sub-dimensions of target technology firstly. Then innovators select the resource-constrained innovation approaches to solve the resource-constrained innovation’s inventive problems. Detailed solving procedures of resource-constrained innovation are discussed as follows. First, a core technology problem of the resource-constrained innovation needs is defined. The innovation needs can be a technology or product. For example, if a firm wants to develop a new technology under resource-constraints contexts or emerging markets, the core problem should be a technology conflict that cannot satisfy the savings of resource, time and cost. Second, the resource-constrained innovation dimensions and sub-dimensions are chosen after defining the core technology problem. In the case of choosing dimensions, domain experts’ participation is necessary to decompose the constituents of the target technology, thus, can be used for dimensions of morphology. Third, after identifying dimensions, one should combine each dimension with the eight resource-constrained innovation approaches, respectively, and generate creative ideas. The creative ideas are the foundation of next-step solution analysis, such as NPD
and patent application. If creative ideas cannot be reached via the above process, innovators can re-define innovation dimensions from a different perspective and re-start the introduction of creative ideas. Module 3 is to have comprehensive thinking of the resource-constrained innovation problems from a systematic perspective. It enables a problem solver of resource-constrained innovation to get deeper into the problem and better understand a process to match the resource-constrained innovation approaches to innovation dimensions of the matrix.

Figure 4. The resource-constrained innovation problem’s analytical framework. After the abovementioned three modules, the creative ideas are evaluated by three criteria, such as substantial cost reduction, concentration on core functionalities, and optimized performance level [23]. First, concerning criterion 1, the resource-constrained innovations have a significantly lower purchase price or lower total cost of ownership from a customer perspective. Second, the criterion 2 is not a way to reduce costs. Concentrating on core functionalities can also have the purpose of making a product easy to use, of saving resources, of having a lower impact on the environment, and of meeting a specific lifestyle or consumer behavior. Third, in view of criterion 3, the resource-constrained innovations must meet the performance level that is needed for its actual purpose and the local conditions, covering the performance of all functionalities and engineering characteristics, such as speed, power, durability, and accuracy. Agarwal and Brem (2017) also acknowledged that higher focus is required on exploring the principles of resource-constrained innovation for designing a solution with minimal use of resources to attain core functionalities and optimal performance [49].

4. Illustrative Example: Idea Generation for CBM Extraction Technology in China

4.1. Background

To illustrate the process of executing and utilizing the proposed RCIM, we will provide a case of Chinese coal-bed methane (CBM) extraction technology. China is rich in coal resources and has become the largest coal producer and consumer in the world [50]. In the process of coal mining, gas accidents, which are usually caused by gas explosions and outbursts, are still threatening miners’ lives [51,52]. The CBM extraction technology is the main measure affecting safety production and reducing greenhouse gas emissions in coal mines. Therefore, the research and application of CBM extraction technology is a key technical problem in a Chinese coal mine. The successful creation, development, and commercialization of a resource-constrained innovation require proximity to the local markets throughout the value chain, team formulation, and marketing [49]. Chinese CBM extraction technology is a prime example of how the RCIM can play a significant role in generating creative ideas for resource-constrained innovation. We follow Weyrauch and Herstatt (2016) [23], and use three criteria to determine that Chinese CBM extraction technology can be developed by the RCIM.

Firstly, criterion 1 for resource-constrained innovation is substantial cost reduction. This criterion must always be met from a customer perspective. China is a developing country and an emerging market. Chinese coal mines have high production costs and frequent gas accidents for the following reasons. Coal-beds in most Chinese coal mines have local characteristics, such as micro porosity [53], low gas permeability [54], and high gas adsorption. However, conventional CBM extraction technologies have many limitations, such as high rock-drivage costs and high drilling requirements, consequently leading
It is necessary to adjust CBM extraction technology to localization and emerging market in terms of cost savings and security. Concerning criterion 1, the resource-constrained innovations of Chinese CBM extraction technology should meet a significantly lower purchase price or lower total cost of ownership for the emerging market.

Secondly, criterion 2 for resource-constrained innovation is the concentration on core functionalities. Historically, CBM problems lead to high intensity research efforts, large expenditures, determined attempts to control gas, and extensive drainage time [55,56]. Especially Chinese unsuccessful CBM extraction technology is attributed to the lack of sufficient training and support, experienced operators and adequate maintenance provision [55]. Concentrating on core functionalities can also have the purpose of making a product or service easy to use [57], of saving resources and of saving time.

Thirdly, criterion 3 for resource-constrained innovation is optimized performance level. Coal resources are widely distributed and deeply mined in China [55,58]; the differentiation of CBM extraction technology is huge. It needs to respond to customer’s requirements quickly. Concerning criterion 3, the resource-constrained innovations of Chinese CBM extraction technology should meet the performance level that is needed for its actual purpose and the local conditions, covering the performance of all functionalities and engineering characteristics.

In view of this, we will apply the proposed RCIM to develop CBM extraction technologies for preventing gas outbursts in Chinese coal mines. Before data collection, three researchers in the field of CBM and one patent examiner from the patent examination department are invited. Three CBM researchers come from China University of Mining and Technology (CUMT) and Henan Coal Society (HCS). One patent examiner comes from the Intellectual Property Office of China (SIPO). The above four experts provide professional consultation of patent retrieval and analysis for this research.

4.2. Patents Data Collection and Preprocessing

In the data collection phase, according to experts’ opinion, we create a search strategy “TS=(coalbed OR coal-bed OR coal bed) AND TS=(gas OR methane) AND TS=(extraction OR drainage OR mining OR exploitation OR control)” in DII databases from 1963 to 2018. The search was conducted in February 2019. Then we collected 1588 patent documents and exported full records that were downloaded on February 22, 2019 (contact the author at zfliu@shmtu.edu.cn for getting data set). In the data preprocessing phase, DMCs are extracted from 1588 patent documents. Most patents contained more than one DMC, such as patent US20180087368A1 which contained seven DMCs, as follows: H01-B03B3, H01-C01, H01-C10, H01-D04, H01-D12, Q49-A, and Q49-V35. With the splitting, cleansing and grouping of 1588 patents, 1037 independent DMCs were arranged in accordance with occurrence frequency. We invited three CBM experts who analyzed 1037 DMCs, one by one, and eliminated 910 unrelated DMCs. For example, they suggested eliminating general terms so that Q49-V28 is expressed as “Coal”, A12-W10 as “Mining, oil wells”, and X25-D02 as “Mining (Covers rock or ground testing)”, etc. In addition, we removed some drilling and measuring equipment, such as Q49-C05, Q49-H, X27-A03, H01-C11, H01-D12, and H01-C06, etc. After patents preprocessing, cleaning and consolidation, we finally achieved 127 DMCs covering “CBM extraction technology”. Then, 127 DMCs are constructed into a 127 × 127 co-occurrence matrix, as shown in Table 2. The cater-corner represent occurrence frequencies of single DMC, and the rest of intersections express the number of patents where two DMCs appear together.

4.3. Technology Map Construction and Clustering

After data preprocessing, a DMC co-occurrence network is generated based on the co-occurrence matrix by using the Netdraw network visualization tool, as shown in Figure 5. The network shows all 127 DMCs by means of degree centrality measure that represents technological distances and groups of technologies in each of the technological areas. Label and color related settings are adjusted to produce a reasonably clear map and facilitate its examination. The technology map suggests three broad technology morphologies of the CBM extraction technology. The left side of the map represents
extraction modes which contain ten shapes, such as drilling, fracturing or fracking, water flooding, vibrations, thermal or heating, using bacteria, blasting, pressure and separation, chemical methods, and cutting. The right part of the map is materials of displacing CBM, such as steam, noble gas, CO₂, N₂, bacteria or microorganisms, and other drilling fluids. The upper portion of the map is primarily concerned with locations of CBM extraction. In Figure 5. The red ellipses in the technology map indicate ten shapes of technology morphology for CBM extraction modes (represented by a red rectangle). The purple ellipses in the technology map indicate five shapes of technology morphology for CBM extraction materials (represented by a purple rectangle). The locations of CBM extraction are framed by a blue rectangle. Because the automated method has a limitation in that it may fail to reflect the intrinsic features of technology, this process must be supported by domain experts. In this regard, the technology map can help experts define the morphology of technology [47].

|               | H01-B03B3 | H01-C03 | H01-D03 | X25-E03 | H01-D13 | X25-L01A |
|---------------|-----------|---------|---------|---------|---------|---------|
| H01-B03B3     | 127       | 7       | 23      | 3       | 1       | 0       |
| H01-C03       | 7         | 87      | 10      | 1       | 0       | 0       |
| H01-D03       | 23        | 10      | 63      | 1       | 0       | 0       |

Table 2. 127 × 127 DMCs co-occurrence matrix of Chinese coal-bed methane (CBM) extraction technology.

Figure 5. DMC mapping and clustering.

4.4. Defining the Resource-Constrained Innovation Dimensions

Next, we invite three CBM experts in the field of CBM extraction to define innovation dimensions that are matched with CBM extraction technology morphologies. The innovation dimensions are
developed by text analysis from the DMCs on existing technology and by experts’ participation [19,59]. This research suggests that the CBM extraction technology is multi-dimensional with three perspectives: Mechanism, material and space. As shown in Figure 6.

![Diagram](image-url)

**Figure 6.** Linking innovation dimensions and DMCs of CBM extraction technology.

- The mechanism dimension focuses on basic physical, chemical or biological effects that release pressure and gas in the coal-bed.
- The material dimension includes solid states, liquid states and gas states.
- The space dimension focuses on the location sub-dimension that represents the location from where the CBM extraction technology is carried out. The locations, including ground, coal reservoir, surrounding rock and tunnel above/below the coal-bed.

Figure 6 shows the list of DMCs and sub-dimensions for three innovation dimensions. The sub-dimensions are represented by numerical symbols in Figure 5. Each sub-dimension includes one or more DMCs.

4.5. Generating Creative Ideas for CBM Extraction Technology

After defining the target technology’s innovation dimensions and identifying sub-dimensions for each dimension. The heterogeneity combination of innovation dimensions and approaches significantly affects the result of the creative ideas generation. The recombination of multiple innovation dimensions similar to MA is hard to apply to ideas extension, which is achieved through differentiation and heterogeneity. While differentiation is related to the extension of sub-dimensions, and heterogeneity is concerned with the upgrading and conversion of dimensions through the resource-constrained innovation approaches. To address this defect, this research also provides multipath procedures for the creative ideas generation, as shown in Figure 7. Thus, the creative ideas for CBM extraction technology proliferate.

![Diagram](image-url)

**Figure 7.** Multipath procedures for the creative ideas generation of CBM extraction technology.
Figure 7 shows that after innovation dimensions for CBM extraction technology are identified, the sub-dimensions of each innovation dimension are first combined internally. For example, Patent No. CN102022134B shows a combination of three mechanism sub-dimensions: Drilling, fracking and vibrations. Patent No. CN106121604B indicates a technique to remove CBM using two hybrid material sub-dimensions: CO₂ and modified water. If combinations between sub-dimensions can generate ideas that are absent from the existing patents database, these are selected as new ideas. If not, users can identify and investigate the total set of possible relationships or “configurations” contained in the CBM extraction technology by using MA, as shown in Figure 8a. Similarly, if combinations between dimensions can generate ideas that are absent from the existing patents database, these are also selected as creative ideas. If not, users can obtain upgraded sub-dimensions by making use of the resource-constrained innovation approaches and repeat the first procedure. The process of upgrading sub-dimensions and re-generating creative ideas are as shown in Figure 8b. The detailed steps from original ideas to updated ideas for CBM extraction technology are shown in Figure 9. First, we choose the CBM extraction technology and define the core problem. Then we analyze the problem is analyzed and determine the innovation dimensions. We obtain several original ideas of CBM extraction technology by using MA, as shown in Figure 9. Next, we choose one original idea that is very difficult to satisfy the requirement and continue to define the core problem of this original idea. Finally, we repeat the above steps until obtaining updating ideas via the resource-constrained innovation approaches.

Figure 8. Generating creative ideas for CBM extraction technology. (a): Original Ideas, (b): Updated Ideas.
The CBM extraction technology

Defining the core problem

Determining the innovation dimension

Original ideas using resource-constrained innovation approaches

Choosing ideas for updating

Defining the core problem

Updated ideas using resource-constrained innovation approaches

Figure 9. Detailed steps from original ideas to updated ideas for CBM extraction technology.

Figures 8 and 9 delineate examples of differentiation and heterogeneity for the CBM extraction technology development. This research shows updated ideas compared to original ideas by using the resource-constrained innovation approaches, as shown in Table 3.

Table 3. Updated ideas vs. original ideas for CBM extraction technology.

| Example | Updated Ideas | Resource-Constrained Approaches | Original Ideas |
|---------|---------------|--------------------------------|----------------|
| (1)     | substitute Me_D with Me_C + S_C | Dynamic, Substitution, Removal | Me_D + Ma_W + S_C |
| (2)     | combine Me_F with Me_U + mix environment-friendly Maq in Ma_F + S_C | Combination, Friendliness | Me_F + Ma_F + S_C |
|         | simultaneous Me_F in adjacent Wells + Ma_F + S_C | Self-service | |
| (3)     | Me_D with remote intelligent monitoring system + Ma_W + S_C | Intellectualization | Me_D + Ma_W + S_C |
|         | Me_D horizontal Wells in S_C and Me_D vertical Wells from S_C + Ma_W + S_C | Partial optimization, Combination | |
| (4)     | Me_F material is partially optimized to liquid N_2 + S_C | Partial optimization | Me_R + Ma_N + S_C |

4.6. Validation in China

Whether the applicability of the suggested RCIM conforms to resource-constrained innovation needs to be validated. This section mainly explains the updated ideas in Table 3 and evaluates these ideas by the resource-constrained criteria. We take (1) for example and explain it in detail under emerging markets. In China, current technologies for extracting CBM during coal excavation are drilling through the coal reservoir to decompression [54,55,60]. Due to the relatively large area, a large number of drilling holes are needed to guarantee the effects, thus, enlarging construction period, cost, project quantity and workload [52]. It needs to adjust technologies to localization and meet the savings of resource, time and cost. Figure 10 shows the analysis process of Example (1).
Figure 10. The analysis process of Example (1).

The core problem is that the coal reservoirs have a large area, but need a huge number of voids to release CBM. It involves a coal reservoir (SC) sub-dimension in space dimension. Three original ideas are generated by combining SC with the resource-constrained innovation approaches.

- Using multiple small-sized drills to work at the same time. We combine the SC with the decomposition and removal approach. Thus, the segmentation principle divides an object into independent parts and makes it easy to disassemble. We can decompose the large-diameter drilling equipment into multiple small-sized drills to work at the same time. The small-sized drills mean compact and portable, easy to maintenance and replacement, ease to transportation [61]. This original idea is already a resource-constrained end-solution for Chinese CBM extraction technology. Using multiple small-sized drills can largely shorten the construction period and cut cost compared with the large-diameter drilling equipment. Resource-constrained innovation has been achieved. There is no analysis on developing the small-sized drilling equipment in this article.

- Applying chemical, physical or biological reactions to make the coal-bed internal self-cracking. We combine SC with the substitution and changing approach. Thus, the theory substitution principle makes the coal-bed internal self-cracking by use of force field, electric field, magnetic field or mechanic field. These reactions change the pressure of coal-bed and release the gas. However, there is no existing technology to decompose CBM chemically or biologically. Resource-constrained innovation has not been achieved.

- Conducting large-area continuous operating to replace drilling holes. We combine SC with a dynamic approach. Thus, the continuity of useful action principle advocates to work continuously and eliminate all idle or intermittent actions. We can carry on continuous operating to replace independent, one by one and intermittent drilling work. Conducting large-area continuous operating can fulfill one-time and continuous work by utilizing existing cutting equipment [62]. Savings of time and cost have achieved resource-constrained innovation. This original idea should be further discussed in the stage of updating ideas.
Since using multiple small-sized drills is already a resource-constrained end-solution for Chinese CBM extraction technology, we analyze the next stage that begins with conducting large-area continuous operating. However, existing drilling technologies are very difficult to satisfy the requirement of "large-area and continuous" operating [54,55,60]. Therefore, we define the core problem that drilling holes are very difficult to satisfy the requirement of “large-area and continuous” operating. Two updating ideas are generated by better use of the resource-constrained innovation approaches.

- Increasing the drill diameter to enlarge the drilling area. We use the partial optimization approach. Thus, the local optimization principle overcomes the drilling equipment is weak and optimize them by increasing the drill diameter. Moreover, the super-large-diameter drilling equipment enlarges the drilling area. However, it may easily result in coal-bed collapse and lead to fatal gas accidents [52]. Resource-constrained innovation cannot be achieved this way.
- Replacing drilling with cutting. We use the substitution and changing approach. The mechanics substitution principle changes operating mode for coal-bed from static to movable fields or from unstructured fields to those having structure. Thus, we can change the direction of voids from vertical to horizontal. The drilling is vertical, but the cutting is horizontal. The horizontal cutting can largely increase the operating area at one go-off, decrease project quantity and reduce construction cost. A new cutting system which is combined with existing cutting equipment of coal-bed will save the cost and time. Resource-constrained innovation can be achieved this way.

In fact, the suggested RCIM has successfully been validated by the application case of resource-constrained innovation in Chinese CBM extraction technology. Moreover, the updated idea of replacing drilling with cutting has been applied three patents for invention. The first patent disclosed a pressure relief and outburst elimination method for a coal mine by liner cutting of micro-releasing layer [63]. The second patent discloses a system and method for coal mine pressure relief outburst elimination of circulating type micro liberated seam linear cutting and CBM exploitation [64]. Moreover, the third patent discloses a coal mine pressure relief and outburst elimination and CBM exploitation system and method for reciprocating linear cutting micro-liberation layer [65].

5. Discussion and Conclusions

This research attempted to establish a concept of the resource-constrained innovation method and problem-solving process, based on a systematic literature review, text mining, patent analysis, social network analysis, MA and TRIZ inventive principles. Although extensive research on resource-constrained innovation has been conducted by scholars and practitioners, the broader question about actual NPD and idea generation under extreme resource-constraints or sustainability has received comparatively less attention. Furthermore, the existing research on generating ideas for resource-constrained innovation is limited in the traditional innovation methods. As a result, the solution process of resource-constrained innovation is over-engineered and non-repeatable. In response to this limitation, this research proposed the RCIM that lays emphasis on the savings of resource, time and cost in the process of the idea generation under extreme resource-constraints or sustainability. The proposed method has three contributions.

Firstly, based on the SLR and text analysis of the existing literature, this article focuses on developing the resource-constrained innovation approaches that are defining by the TRIZ inventive principles. The innovation approaches are a set of innovation tools to analyze the non-typical problem situations of the resource-constraints and to provide effective solutions by using the TRIZ inventive principles. This is different from previous literature that concentrated mainly on the characteristics, success factors, and ways [12,23,24,43,66]. Furthermore, eight resource-constrained innovation approaches are consistent with some common understanding of resource-constrained innovation [1,8,39,67,68], and strongly support that the most promising research area for the emerging and developing countries is the frugal approach to innovation [43,61,69–71].
Secondly, the innovation dimensions are developed to foster resource-constrained innovation under resource-constraints contexts based on text analysis, social network analysis and MA of patents and DMCs. We construct the technology map that consists of several dimensions through the above-mentioned co-occurrence, clustering, network analysis and MA. The use of DMC-based MA generates a large number of dimensions and sub-dimensions of the target technology compared to the traditional MA. However, the construction of the innovation dimensions in this paper is different from the previous literature on MA [45–47,59,72]. Since the recombination of multiple innovation dimensions similar to MA are hard to apply to the creative ideas extension, which is achieved through differentiation and heterogeneity. This research places emphasis on the upgrading, extension and conversion of sub-dimensions through the resource-constrained innovation approaches. Thus, the creative ideas for the target technology of the resource-constrained innovation proliferate.

Thirdly, the proposed RCIM is the step-by-step processes for the non-typical problem, which is considered as the epitome of the whole resource-constrained innovation process. This process is not only different from the mainstream methods that advocate the over-engineered, fully functioning, overall performance-optimized, premium and high-priced products [23], but also distinct with the learning by doing and improvising by trials that are put forward in the existing literature on resource-constrained innovation [39]. Moreover, it is successfully validated by an application case of resource-constrained innovation on Chinese CBM extraction technology.

The proposed RCIM can be extended to the following applications. On the one hand, it is able to act as a tool for forecasting and planning technology or product that satisfies the resource-scarce emerging markets. It will be useful for researchers and policymakers who belong to the department of R&D organization to discover R&D areas for developing potential the resource-constrained or the sustainable technology to satisfy the local needs. In particular, the creative ideas generated by the RCIM can contribute to the industrial distribution of government and the patent strategy of the research agency. On the other hand, from the viewpoint of individual firms that include the SMEs and the multinational corporations (MNCs), the SMEs are short of R&D engineers and funds, while the MNCs are facing increasingly shorter innovation cycles. They begin to consider developing an innovative method to easily operate and provide direct guidance for achieving resource-constrained innovation and sustainability. These applications deepen our understanding of how innovators or designers can produce the novel ideas to drive innovation in conditions where resources are becoming increasingly constrained and widely sacrificed and where products are friendly and affordable to the customers.

Nonetheless, this study has several limitations. Firstly, eight resource-constrained innovation approaches represent the rule adopted in the process of resource-constrained innovation. They are not all validated in the illustrative example. More resource-constrained cases are worth studying in the future. Secondly, developing innovation dimensions based on DMCs requires much cleaning and analyzing task. Future research should focus on quantitative text mining or specific technology dictionaries to provide more scientific value for dimension building.

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Appendix A

Table A1. Success factors, attributes and approaches of resource-constrained innovation.

| Resource-Constrained Innovation Approaches | Resource-Constrained Ways and Attributes | Success Factors and Characteristics Used in Literature |
|-------------------------------------------|----------------------------------------|------------------------------------------------------|
| Decomposition and removal approach        | Minimizing                              | Keep it simple, cut corners [57]. Minimize the use of material and financial resources in the complete value chain [5]. Reducing the complexity, lean, minimize the use of extensive resources [73]. Minimize inessential costs, low input of resources [74]. Highly scalable products which have reduced functionalities, while reducing costs [75]. Avoiding obesity [76]. Simplification, minimalist features and functional requirements [1]. Cost innovation [17]. Cost engineering, the reduction of raw materials costs, as well as conversion and logistics in getting products into retail channels [77–79]. Good enough, limited features [67]. Bare essentials, eliminate unessential functions, reduce the complexity, tailored for less, provide insights into required features and functions, functional requirements of the user [76]. Core product modification [80]. Decomposition of multipurpose machines by using established technology [81]. Eliminating unessential functions [74]. Provide the essential functions people need [82,83]. Strip the products down to their bare essentials rather than add ever more bells and whistles [84]. Unnecessary frills stripped out [85]. Basic no-frills product to minimize unnecessary feature, swarms of low-cost simple products perform complex tasks in unison, small and compact products comprised of cheap parts [74]. |
| Concentration on core functionalities       | Modularity                              | Create families of parts that share common characteristics, reduce development costs for future generation of products and provide the innovator with speed to customize products [43,61,86–90]. Manufacturing processes, process parameters, labor, supply-chain logistics and other relevant manufacturing variables that could be optimized for achieving lower costs [8]. Where expensive capital-intensive processes can be streamlined [17]. Rigorous design procedure [91]. Developing markets, emerging markets, exploration of local needs, end to end localization, core value identification, proximity to the local markets [67]. Provides information on local operational conditions and infrastructure [90]. Use of local resources [1]. |
| Functional and focused on essentials       | Architectural innovation                | Mix and match [67]. Recombination of established technologies into a new product [81,91]. Reconfiguration of an established system to link together existing components in a new way without changing core technology or know-how [61,89]. Combining existing materials at hand, leveraging existing innovation processes, using existing resources, use of limited raw materials [68,92,93]. Leveraging existing products, inputs and services [1]. Proven technologies from other industry domains [39]. |
| Compact design with no frills structure    | Bricolage                               | Within-industry analogues, cross-industry analogues, biotic analogies [96], transferring solutions from nature, transferring solution from one industry domain to the other field of physical, chemistry and biology. Making do with resources at hand, easily available physical materials, non-material resources [79]. Do not have sophisticated technological features [74]: Using homegrown or self-created technologies [97]. Meeting the desired objective with a good-enough, economical means [98,99]. Substitute cheaper materials for the expensive [17]. Use of cutting edge technology [8]. Careful consideration of the materials [78,79]. Reduces material use [4]. |
| Partial optimization approach              | Location                                | Keep it simple, cut corners [57]. Minimize the use of material and financial resources in the complete value chain [5]. Reducing the complexity, lean, minimize the use of extensive resources [73]. Minimize inessential costs, low input of resources [74]. Highly scalable products which have reduced functionalities, while reducing costs [75]. Avoiding obesity [76]. Simplification, minimalist features and functional requirements [1]. Cost innovation [17]. Cost engineering, the reduction of raw materials costs, as well as conversion and logistics in getting products into retail channels [77–79]. Good enough, limited features [67]. Bare essentials, eliminate unessential functions, reduce the complexity, tailored for less, provide insights into required features and functions, functional requirements of the user [76]. Core product modification [80]. Decomposition of multipurpose machines by using established technology [81]. Eliminating unessential functions [74]. Provide the essential functions people need [82,83]. Strip the products down to their bare essentials rather than add ever more bells and whistles [84]. Unnecessary frills stripped out [85]. Basic no-frills product to minimize unnecessary feature, swarms of low-cost simple products perform complex tasks in unison, small and compact products comprised of cheap parts [74]. |
| Permutation and combination approach       | Architectural innovation                | Mix and match [67]. Recombination of established technologies into a new product [81,91]. Reconfiguration of an established system to link together existing components in a new way without changing core technology or know-how [61,89]. Combining existing materials at hand, leveraging existing innovation processes, using existing resources, use of limited raw materials [68,92,93]. Leveraging existing products, inputs and services [1]. Proven technologies from other industry domains [39]. |
| Substitution and changing approach         | Bricolage                               | Within-industry analogues, cross-industry analogues, biotic analogies [96], transferring solutions from nature, transferring solution from one industry domain to the other field of physical, chemistry and biology. Making do with resources at hand, easily available physical materials, non-material resources [79]. Do not have sophisticated technological features [74]: Using homegrown or self-created technologies [97]. Meeting the desired objective with a good-enough, economical means [98,99]. Substitute cheaper materials for the expensive [17]. Use of cutting edge technology [8]. Careful consideration of the materials [78,79]. Reduces material use [4]. |
| Dynamic approach                           | Re-use of existing components           | Upcycling, remanufacturing, organic materials [91]. Reduce use of limited raw materials, reuse of existing components [8]. |
| Self-service and balance approach          | Easy to repair and service              | Products can be repaired and maintained at the local level [61]. Light and highly manufacturable, as well as robust and low maintenance [99]. Provide ways for customers to eliminate the need for expensive personal service without forgoing the value of the service [68]. |
| Friendliness and coordination approach     | User-friendly and easy to use           | Lightweight. Portable for varying transportation options [1]. Human centric design [1]. Pleasing to the eye, easy to use, highly portable, and adaptable to an ever-growing range of accessories [76,79]. User-centric innovation; Eco-friendly [103]. Sustainable [23]. Green technologies: Powered by renewable resources [1]. Affordability and sustainability [101]. Draw sparingly on raw materials and minimize environmental impact [102]. Low carbon footprint [74,103]. Tailor made [47,97]. Reducing the use of scarce resources [9]. Factor of safety [94]. |
| Intellectualization approach               | Mobile enabled solutions                | Connectivity anytime, anywhere [1]. |
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