International Journal of Data Warehousing and Mining
Volume 19 • Issue 1

An Integration Model on Brainstorming and Extenics for Intelligent Innovation in Big Data Environment

Xingsen Li, Guangdong University of Technology, China
Haibin Pi, Guangdong University of Technology, China
Junwen Sun, Guangdong University of Technology, China
Hao Lan Zhang, NIT, Zhejiang University, China*
Zhencheng Liang, Guangdong University of Technology, China

ABSTRACT

Brainstorming is a widely used problem-solving method that generates a large number of innovative ideas by guiding and stimulating intuitive and divergent thinking. However, in practice, the method is limited by the human brain's capacity or special capabilities, especially by the experience and knowledge they possess. How does our brain create ideas like storming? Based on the new discipline of Extenics, the authors propose a new model that explores the process of how ideas are created in our brain, with the goal of helping people think multi-dimensionally and getting more ideas. With the support of information technology and artificial intelligence, we can systematically collect more information and knowledge than ever before to form a basic-element information base and build human-computer interaction models, to make up for the lack of information and knowledge in the human brain. In addition, the authors provide a methodology to help people think positively in a multidimensional way based on the guidance of Extenics in the brainstorming process.

KEYWORDS

Basic-Element Theory, Big Data, Brainstorming Method, Extenics, Extension Innovation Method, Human-Computer Interaction, Problem Solving

1. AN INTEGRATION MODEL ON BRAINSTORMING AND EXTENICS FOR INTELLIGENT INNOVATION IN BIG DATA ENVIRONMENT

Brainstorming (BS), also known as intellectual stimulation, is a method of stimulating creative thinking proposed by Alex F. Osborne, an American creativity theorist and businessman, in 1938 (Shui, 2003). Now it has been widely used in creative thinking activities to generate new possible solutions to problems and has become an effective method for developing creativity, mainly on intuitive and divergent thinking (Al-Samarraie & Hurmuzan, 2018; Osborn, 1987). To ensure a successful

DOI: 10.4018/IJDWM.332413
*Corresponding Author

brainstorming process, a highly active mind and unrestricted free association and discussion are all essential ingredients. However, at its foundation, brainstorming relies heavily on human brain capabilities, particularly on the experience and knowledge they possess. Today's Internet environment provides us good opportunities for innovation (Zhuang et al., 2017; Li et al., 2015). There is an increasing amount of information and knowledge on the Internet that can be used by brainstorming methods to overcome the shortcomings of the human brain.

Extenics is a new discipline that is used to obtain systematic creativity by studying the extension and transformation of things in formal models. It has been widely used to solve contradictory problems based on the theory of extension sets, basic-element theory, and extension transformation methods since 1983 (Yang & Cai, 2013; Yang, 2019; Yang & Cai, 2007). Its fundamental role is to inspire thinking and improve the efficiency of the actual innovation process (Li et al., 2016). The extension innovation method is a formal and quantifiable method to generate ideas for solving various contradictory problems with the basic theory of modeling, expanding, reasoning, and transformation in Extenics (Yang & Li, 2012).

While innovation is playing an increasingly important role in research and business (Chen & Lv, 2018), the brainstorming method is being used more and more. However, some shortcomings of the method have been found in practice. To overcome them, various brainstorming techniques have been proposed to facilitate and enhance creativity during idea generation sessions. Also, many other improvement solutions have been proposed, such as the use of computers for anonymous brainstorming to remove the bias caused by subjective factors (Maaravi, 2021).

At present, researchers aim to use various improvement plans to reduce understanding difficulties and inconsistencies caused by subjective factors in the brainstorming process. The description method of thinking and things in Extenics can objectify and model subjective evaluations and explore the correlation between things by establishing a basic element model. Existing research lacks a combination of Extenics and brainstorming, as well as mutually supportive methods. In this paper, we introduce the Extenics theory to the brainstorming process to reduce over reliance on personal ability and experience. Moreover, by combining the extension innovation method, we managed to support idea generation in a systematic way and thus optimize the brainstorming method.

The rest of our paper is organized as follows. The second section of this paper provides a literature review on innovation and brainstorming in the big data environment. The third section analyzes the attributes, shortcomings, and the general application process of the brainstorming method. The fourth section introduces Extenics theory and the application of the extension innovation method. Then we propose the basic idea of integrating Extenics with brainstorming methods. We also design the general application process and the human-computer interaction model of the new brainstorming method with the support of information technology and artificial intelligence. The fifth section verifies the effectiveness of the new method through use cases. Finally, the last section concludes the paper and discusses future research directions.

2. LITERATURE REVIEW

The innovation and problem-solving abilities in the context of big data and artificial intelligence are key to addressing complex conflicts. Liao et al. (2023) proposed that the demand for financial human resources in the intelligent era is reflected in three characteristics: having good intelligence literacy, being able to effectively collaborate with humans, and possessing creative learning ability. And talent cultivation has gone from a single major to cross integration in the knowledge system (Liao et al., 2023). Ding (2023) emphasized that the development of computers and the Internet extends from individual and individual technologies to the integration of individual computers and the Internet. The iterative development of the Internet and artificial intelligence is causing profound social changes, especially in the field of education, which requires education to face the challenges of technological modernization.

Creative thinking is proposed to solve divergent problems in the innovation process. Ding and Luo (2022) pointed out that the characteristics of creative thinking include both the universal characteristics of general thinking and its unique characteristics. The essence of creative thinking determines that it can become the driving force for pioneering innovation in different historical periods and scenarios (Ding & Luo, 2022). The results of Dou et al. (2022) show that there is a positive correlation between the fluency of creative thinking and experimental design thinking, but variable thinking and reflective thinking in experimental design thinking are negatively related to creative thinking. Yu et al. (2022) describe the process of creation as a dialectical unity of logic and non-logic. Creative education should return to the process of learning, enabling students to have a deeper understanding of creation and exploration, and emphasizing the importance of the endogenous motivation of the subject (Yu et al., 2022).

The research of Ye and Fang (2022) aims to provide problem-solving methods and paths by creating learning contexts and problem-driven approaches, ultimately achieving practical problem solving and cultivating creative thinking. Yao (2022) proposed that to fully utilize the subjective initiative of the educated, it is necessary to seek truth from facts and attach importance to the cultivation of the interests, needs, and motivations of the learning object. Zhang et al. (2022) studied the impact of emotions on creative thinking. Under the overall processing mode, compared to sadness emotions, happy and angry emotions are more likely to promote divergent thinking. While pleasant emotions can promote convergent thinking more than anger and sadness. The research results of Avci and Durak (2023) indicate that extrinsic motivation is a direct antecedent variable for creative thinking dispositions and creative thinking skills, while learning and performance-approach goal orientation is an indirect antecedent variable. Innovation search and inquisitive and opportunity-oriented dimensions are determinants of engagement. Beda and Smith (2022) discussed the theoretical background of forgetting in memory and creative cognition research related to the forgetting fixation theory.

Some researchers also focus on the research and interpretation of the process of creative thinking. Lansing-Stoeffler and Daley (2023) proposed four skills and three characteristics of creative thinking to reveal the relationship between creative thinking and innovation. The four skills include conventional thinking, diverse thinking, unconventional thinking, and evaluating and improving ideas. The three characteristics include openness to experience, tolerance for ambiguity, and risk tolerance (Lansing-Stoeffler & Daley, 2023). Xu et al. (2022) have transformed creative thinking into three stages—the display of perception, the attention of perception, and the explanation of perception—providing theoretical support for the normalization of creative thinking. The display stage corresponds to the preparation stage of creative thinking, the attention stage corresponds to the brewing and production stage, and the explanation stage corresponds to the verification stage (Xu et al., 2022).

Afterwards, brainstorming was introduced for rapid problem-solving. Song (2022) studied product technology problems based on computer-aided technology and used brainstorming methods to most effectively assist product design. Dostatni et al. (2022) use brainstorming, stimulation, reverse brainstorming, word games, and other methods to solve problems related to ecological design, ecological innovation, and inventory. Galardi et al. (2022) elaborated on innovative business concepts through brainstorming and business model canvas tools and examined the data through SWOT and cross case analysis. Morioka (2022) has proposed a thinking tool that identifies sustainable innovation opportunities through a structured brainstorming process, while providing a systematic business perspective and a strong multi-stakeholder orientation.

3. ANALYSIS ON THE BRAINSTORMING METHOD

3.1 Principles of Brainstorming

Brainstorming, which is known as an intellectual stimulation method or a free-thinking method, includes free talk and free meeting. It can be divided into direct brainstorming method (usually referred to as brainstorming method) and questioning brainstorming method (also known as anti-brainstorming method). The association reaction, enthusiasm infection, competitive consciousness, and personal desire in the process create a series of internal excitation mechanisms (Maaravi et al., 2021). The brainstorming method has been studied and developed by scholars in various countries. Therefore, it has formed a multi-style group of methods and techniques that are widely used in business and teaching (Wu, 2004). The brainstorming method encourages the participants to express their ideas freely so that each participating member can put forward ideas and creativity in a suitable place and a relaxing environment. This will help them to inspire each other, motivate each other, and associate with each other, so that the participants can generate resonance and chain reaction of thinking. Thus, by breaking through various thinking barriers and psychological constraints, more ideas, creativity, and suggestions will be induced (Guest et al., 2017). In essence, people are expected to overcome their thinking stereotypes in which the focus of attention is on the imagination, association, intuition, inspiration, and other non-logical thinking processes based on existing experience, information, and knowledge. Better ideas usually emerge later in brainstorming sessions and the quality of ideas improves as the number of unique ideas increases (Danes et al., 2020). In a word, we need to follow the following basic principles of brainstorming: the principle of free thinking, the principle of delayed decision-making, the principle of quality by quantity, and the principle of comprehensive improvement with the proper sequential order.

3.2 General Process of Brainstorming Method

According to the stimulating mechanism of brainstorming, association is the basic process of generating new ideas. In the process of collective discussion, each new idea can initiate a chain of associations, and thus elicit a series of new ideas. It provides more possibilities for solving problems creatively. In terms of enthusiasm infection, without any restrictions, everyone can speak freely, influence and infect each other, which can give full play to creative thinking ability to the greatest extent. With a sense of competition, everyone competes to speak, constantly feeds the thinking machine and strives to have unique opinions and novel ideas. In the process of collective discussion and problem-solving, it is very important that the individual's desire is free from any interference; everyone speaks freely and puts forward a large number of new ideas (Shui, 2003; Al-Samarraie & Hurmuzan, 2018; Osborn, 1987).

Brainstorming can be conducted in three stages, namely the preparation stage, the brainstorming stage, and the evaluation and selection stage. In the preparation stage, the problem should be clearly described and subtly designed: it should be open enough to prompt the participants to generate new and innovative thinking but not too open to keep people on track with their goal. An external environment suitable for boosting creativity and focusing attention is also necessary (Maaravi et al., 2021).

In the brainstorming stage, the reasons and topics for brainstorming are explained. Also, the basic principles of discussion and the order in which the group members will speak are accepted. What comes next is free speech, which encourages the participants to think creatively. In the meantime, a recorder records the inspiration and ideas stimulated by the participants. At the end, the meeting is concluded.

In the evaluation and selection stage, the meeting records are first organized and presented to all participants. Then, the participants evaluate each creative idea in terms of effectiveness and feasibility. Finally, they select the most suitable solution (Osborn, 1987).

As shown, brainstorming is a simple process without too many restrictions. The method involves a group of people exploring specific topics and issues together. The joint exploration can make the process much more exciting and dynamic (Maaravi et al., 2021). As a result, when properly performed, the brainstorming method can overcome the limitations that might exist due to an individual's incomplete knowledge and improve the understanding of innovation (Chen & Ren, 2013).

3.3 Shortcomings of Brainstorming Method

There are still many problems that need to be solved in brainstorming. Firstly, the brainstorming process lacks an effective intelligent method to support it, which makes divergent thinking lack a systematic guidance and only allows us to solve relatively simple problems. It just stimulates the original talents of the participants and most of the ideas generated are not pioneering ideas (Windon, 2020).

Secondly, the success of brainstorming depends on the ability and experience of the individuals. However, the professional backgrounds of group members are often too far apart to possibly elicit enlightening thoughts (Litchfield et al., 2011). Besides, the knowledge and abilities of the participants and facilitators also have great impacts on the quality and efficiency of their brainstorming (Liu & Li, 2010).

Thirdly, brainstorming requires participants to use divergent thinking as much as possible to encourage random and unconventional ideas. A widely accepted conceptualization assumption is that the quality of ideas improves as the number of unique ideas increases. However, observational studies through many brainstorming sessions have shown that the order in which ideas are presented can have an impact on the outcome of the brainstorming method (Danes et al., 2020). Also, some psychological studies have shown that group-think can blind us from connections we might find on our own or discourage us from expressing different ideas; therefore, teamwork can reduce our ingenuity and creativity (Stroebe et al., 2010).

Electronic brainstorming (EBS) and other proposed methods have been studied, such as using computers for anonymous brainstorming to address the confound of subjective factors (Maaravi et al., 2021). EBS can be useful for enhancing the creativity of some students with high level of openness (Pi et al., 2022). Some researchers have proposed a hybrid structure (Ostrowski et al., 2022), constructive criticism (Curhan et al., 2021), or other innovative methods to overcome the weaknesses of brainstorming, such as strengthen the integration and application of innovation methods (Gallupe et al., 1991) and provide some structure to brainstorming sessions by asking a series of questions or requiring participants to engage in specific activities in order to make the sessions more productive (Gobble & Anne, 2014).

Usually, brainstorm optimization is not able to thoroughly explore the search space, and its diversity is reduced as well. It needs a mechanism to escape from sub-optimal solutions. The combination of chaotic maps, opposition-based learning, and disruption operator improves the exploration ability of brainstorm optimization by increasing the diversity of the population for a given problem (Zhang et al., 2015). To break the barriers of inertia and limited knowledge, some scholars propose to combine TRIZ and brainstorming method to support problem solving and obtain the ideal solutions (Litchfield et al., 2011; Guo et al., 2014).

4. MODEL AND PROCESS OF AN INTELLIGENT BRAINSTORMING METHOD COMBINED WITH EXTENICS

4.1 Overview of Theory and Methods on Extenics

Extenics, which is a new inter-discipline based on mathematics, philosophy, and information science, was founded by Professor Cai Wen. It studies the possibility of the expansion of things and the methods to solve contradictory and paradoxical problems systematically and intelligently with formal models. Extenics includes extension sets theory, basic-element theory, extension logic, and the extension innovation method (Yang & Cai, 2013; Yang, 2019; Cai & Shi, 2006; Cai & Yang, 2013).

The basic-element theory defines the basic elements for problem modeling of "Matter-element" (all physical and non-physical existence), "Affair-element" (events or actions), and "Relation-element" (the relationship between things or affairs) to model problems and describes its related information. A one-dimensional basic-element is an ordered triad consisting of an object, attribute, and its value, denoted as $M = (O,c,v)$, where M represents the Matter-element, c is the attribute of M, and v is the corresponding value of attribute c of element M. The Affair element is denoted as $A = (E,c,v)$ and the relation element is denoted as $R = (N,c,v)$, respectively. The use of basic-element theory for modeling problems can guide us to extend information and think in higher dimensions in a systematic and unified structure (Chen & Ren, 2013). The basic-element structure is shown in Figure 1, where

O denotes an object, usually represented by the name of the object; $c_1, c_2, \ldots, c_n$ denote the attributes of object O, represented by attribute classification or subject-object representation; and $v_1, v_2, \ldots, v_n$ denote the corresponding n attribute values of object O. In the classification representation, values can be measurable values or a unified discretization representation of subjective evaluation, while in the subject-object representation values are the corresponding object.

Things change over time, so we usually use dynamic matter with multiple attributes to represent information about the matter-element, as follows.

$$M(t) = \begin{bmatrix} O_m(t), & c_{m1}, & v_{m1}(t) \\ & c_{m2}, & v_{m2}(t) \\ & \vdots & \vdots \\ & c_{mn}, & v_{mn}(t) \end{bmatrix} = \left(O_m(t), C_m, V_m(t)\right) \tag{1}$$

The basic-element theory makes divergent thinking to become structured and aids us to think in all possible directions, such as an object has multiple attributes, an attribute has multiple values, a value may map multiple attributes, and an attribute may map multiple objects.

The basic expansion methods include conjugate analysis, divergence analysis, correlation analysis, implication analysis, and expandability analysis (Li et al., 2016). The elements of extensible thinking are summarized in Table 1.

In the network environment, a large amount of information and knowledge have become important resources for innovation. Basic-element modeling can be carried out depending on the conditions and objectives of practical problems, and basic-element base can be further constructed with support of data mining technology.

Figure 1. The basic-element theory-based information structure

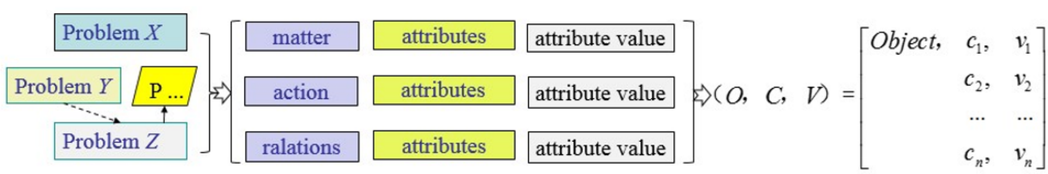


Table 1. The performance comparison of the state-of-the-art approaches on the SMR dataset

Model	Accuracy
Three paths for problem solving	Transformation on conditions, transformation on target, transformation both on target and condition
Five expansion methods	extensions of divergence trees, correlation networks, implication systems, decomposition and integration chains and conjugate analysis on attributes of matter
Five basic transformation methods	Substitution transformation, addition/deletion transformation, increase/decrease transformation, subdivision transformation, replication transformation
Three types of objects for transformation	elements, criteria, and domains (universe in Set theory)
Four operations	and, or, product, inverse

4.2 Extension Innovation Method

The extension innovation method is an operable idea generation method based on the basic theory of Extenics (Yang, 2019; Yang & Li, 2012). It can be used in processes of idea generation and solving contradictory problems in many fields (Yang & Luo, 2016). For example, the use of Extenics and TRIZ theory in the design of cell phone chargers (Guo et al., 2021), and the study of technological innovation process for the mechanical innovative design of petroleum machinery (Zhang & Yang, 2013). Its fundamental role is to inspire people to think and improve innovation efficiency (Li et al., 2016).

The application of the extension innovation method in practice involves four steps: modeling, expansion, transformation, and selection. It first calculates the compatibility of the problem using the correlation function, and next performs expansion analysis, conjugate analysis, and extension transformations on the problem; then, it evaluates the superiorities of the solutions obtained from last step, and finally selects the best feasible solution to the problem (Li et al., 2016). The general steps are as follows (Yang, 2019; Yang & Cai, 2016):

(1) Modeling. Formalize the conditions and targets of the contradictory problem in form of basic-elements and identify the core conflict attributes and factors.
(2) Expansion. Extend the targets and conditions separately to find the extended extension set of basic-elements by correlation analysis, conjugate analysis, extensible analysis, and implication analysis.

Suppose B is a basic element, (O,c,v) is an object, c denotes a set of attributes of object O, and v denotes the corresponding values of c. The conjugate analysis can be shown as follows:

$$B = \left(O,c,v\right) \mapsto \left\{\left(O,c_1,v\right),\left(O,c_2,v\right),\ldots,\left(O,c_n,v\right)\right\} \tag{2}$$

$$B = \left(O,c,v\right) \mapsto \left\{\left(O_1,c,v\right),\left(O_2,c,v\right),\ldots,\left(O_n,c,v\right)\right\} \tag{3}$$

The implication analysis is denoted as:

$$B \Rightarrow \left\{B_1,B_2,\ldots B_n\right\} \Rightarrow \left\{\left\{B_{11},B_{12},\ldots,B_{1m}\right\},\left\{B_{21},B_{22},\ldots,B_{2m}\right\},\ldots\left\{B_{n1},B_{n2},\ldots,B_{nm}\right\}\right\} \tag{4}$$

The extensible analysis is denoted as:

$$B = B_1 \oplus B_2 = \begin{bmatrix} O_1 \oplus O_2, c_1, v_1 \oplus c_1\left(O_2\right) \\ c_2, c_2\left(O_1\right) \oplus v_2 \end{bmatrix} \tag{5}$$

$$B = \left(O,c,c\left(O\right)\right) = \left\{\left(O_1,c,c\left(O_1\right)\right),\left(O_2,c,c\left(O_2\right)\right),\ldots,\left(O_n,c,c\left(O_n\right)\right)\right\} \tag{6}$$

(3) Transformation. Transform the basic-elements related to the original targets and conditions from elements, criteria, and domain, respectively into multi-possibility through five basic transformations and four operations. The five basic transformations include *substitution, addition* and *deletion, increase* and *decrease, subdivision,* and *replication*. The four operations are *and, or, product,* and *inverse*.

Suppose $\tau \in \{M, A, R, k, U\}$, M,A,R denotes the matter element, affair element, and relation element, respectively; k denotes criteria, and U denotes domain or universe. T is the transformation operation.

Then, five basic transformations are denoted as follows:

$$T_{substitution}`` = \Gamma'$$
$$T_{addition}`` = \Gamma \oplus \Gamma_1$$
$$T_{increase}`` = \alpha\Gamma$$
$$T_{subdivision}`` = \{\Gamma_1, \Gamma_2, ..., \Gamma_n\}, (\Gamma_1 \oplus \Gamma_2 \oplus ... \oplus \Gamma_n = \Gamma)$$
$$T_{replication}`` = \{\Gamma, \Gamma^*\}, (\Gamma \approx \Gamma^*)$$

(4) Evaluation. Evaluate the solutions obtained from the transformation, calculate the superiority of each solution by superiority evaluation method (Yang, 2019), then the decision makers select the best solutions.

Suppose the set of solutions is $Z = \{Z_1, Z_2, ..., Z_m\}$, the set of evaluation conditions is $M = \{M_1, M_2, ..., M_n\}$, and weight coefficients are $\alpha = (\alpha_1, \alpha_2, ..., \alpha_n)$. We used dependent function (Yang, 2019) to obtain dependent degree $K_i(Z_j)$ of Z_j about evaluation condition M_i. then dependent degree of each solution about evaluation condition M_i is $K_i = (K_i(Z_1), K_i(Z_2), ..., K_i(Z_m)), i = 1,2,...,n$

Then all the dependent degrees are normalized as k_{ij}. The normalized dependent degree of solution Z_j about each evaluation condition is $K(Z_j) = (k_{1j}, k_{2j}, ..., k_{mj}), j = 1,2,...,m$

The comprehensive dependent degree of solution Z_j is $C\left(Z_j\right) = \alpha \cdot K\left(Z_j\right) = \sum_{i=1}^{n} \alpha_i k_{ij}, j = 1, 2, ..., m$

If $C\left(Z_0\right) = \max_{j=1,2,...,m} \left\{C\left(Z_j\right)\right\}$ is the best.

4.3 A Hybrid Model of Brainstorming and the Extension Innovation Method

To explore the process of how ideas are generated in the brain, help people think in multiple dimensions, and put forward more ideas systematically, we propose an intelligent hybrid model integrating brainstorming, the extension innovation method, and information technology to improve the system ness of ideas. We define the problem from the conditions and objectives and divide all participants into several groups based on Table 1. The detailed steps are as follows:

Step 1: Problem analysis. Analyze the problem from the perspectives of conditions and objectives based on the background and other relevant information, and divide the participating members into two groups: group 1 analyzing conditions is called group L, and group 2 analyzing objectives is called group G. Propose the hypothesis on why the existing conditions cannot achieve the objective, list what sufficient conditions are needed to achieve the objective, and determine whether the objective to be achieved is the original intent we truly want to accomplish? If not, what is the ultimate objective? Are there any other more concise ways to achieve the final objective?

Step 2: Basic-element analysis. Based on condition and objective analysis, merge group G and group L together and then redistribute them into matter-element analysis group GL1, affair-element analysis group GL2, and relation-element analysis group GL3. Each group uses methods such as divergence analysis, correlation analysis, conjugation analysis, and implication analysis to list as many objects, attributes, and values related to the topics of the group as possible. Support the team to think in a higher dimension to get more objects, attributes, and their value.

Step 3: Information gathering. Collect the information obtained by each group in Step 2, use the human-computer interaction model to search for more information on the Internet or the software of

basic-element base, and obtain a multi-dimensional information database in basic-element format. The information about objectives and conditions is relatively systematic and nearly all-round.
Step 4: Extension transformation. The participants are divided into five groups—A, B, C, D, E—based on the five basic methods of extension transformation: substitution, increasing/decreasing, expansion/contraction, decomposition, and duplication. Each group generates new ideas using the assigned basic transformation method and then switches to a different basic transformation method, then the process is repeated so that eventually each group iterates through all those five methods. We then record all the ideas, describe our conditions and objectives from almost all directions, and improve the dimension of creating innovative ideas as much as possible.
Step 5: Scheme sifting. Combined with the superiority evolution method, we can score and select ideas based on the technical requirements, economic requirements, social requirements, and other required measurement indicators. Then, high-scoring ideas can be carried out and finally chosen.

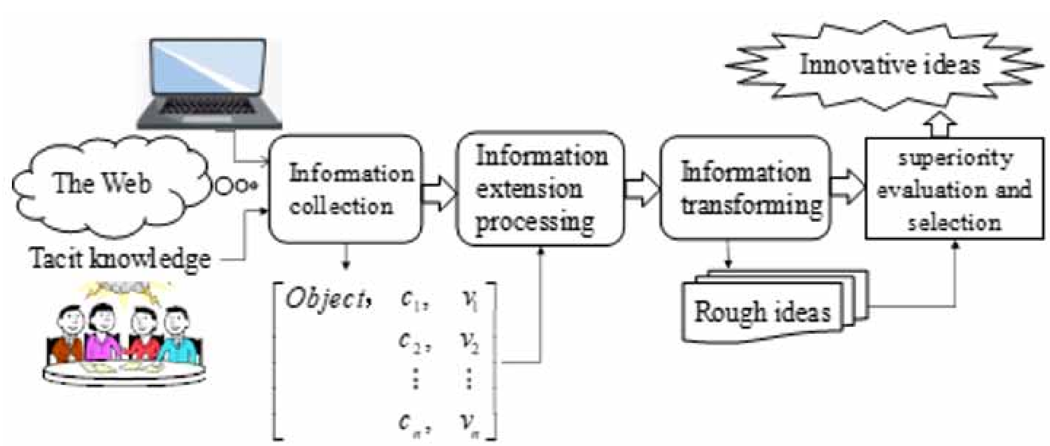
In addition to using the method of expansion and transformation to create new ideas, each group can also use the questioning brainstorming method in brainstorming to further challenge the ideas and improve their quality. This is a special procedure to evaluate the feasibility of an idea or scheme drawn from the above process and to form a list of practically feasible final ideas for solving the problems discussed. It is also necessary to absorb experts' opinions because this enables us to make more accurate judgments on the implementation of the assumption. Based on Extenics, the questioning brainstorming method can effectively realize the objective and continuous latent analysis of the problems discussed.

4.4 Human-Computer Interaction Methods to Aid Brainstorming

As mentioned above, to overcome the limitations of an individual's or team's knowledge background and experience, we developed a software to collect a large amount of data and information from the knowledge graphs and constructed a basic-element base using Internet resources (Yu & Li, 2015; Li & Liu, 2011). It can break through the team's original knowledge limitations and provide materials for innovation. Therefore, it makes the "innovation process" observable and the limitations of personal knowledge can be resolved to a certain extent by a human-computer interaction model based on Extenics.

With the human-computer interaction model, the process of acquiring new ideas can be divided into the four steps (Figure 2).

Figure 2. Main steps for acquiring new ideas by human-computer interaction



Step 1. Collect information and knowledge

With the development of information technology, the Internet together with big data and AI technology are changing the world, bringing new opportunities for innovation (Yang & Li, 2012; Yu et al., 2017). Behind the heterogeneous, rapidly evolving, and sparse big data, there exists almost all the raw materials required for the brainstorming of ideas. Mining knowledge from big data to promote innovation will be an inevitable trend in the future (Xu et al., 2017). In the age of data explosion, to answer the question of how to systematically and intelligently collect and process the information and knowledge for brainstorming, we will need the help of data technology in the form of collecting information and tacit knowledge related to innovation objectives and its conditions from the web by web crawling and web mining.

Step 2. Information extension processing

With the information technologies in Step 1, the required information and knowledge have been obtained. Then, Extenics is used to expand the information, study the expression and storage mode of ontology, realize the intelligent collection and storage of information and knowledge required for innovation, establish the basic element database, and continuously expand the innovative base for applications. Describe the information and knowledge as matter-element, affair-element, or relation-element and save them in a table or database. Then, build an extension information cube by conjugate analysis.

Step 3. Obtain possible rough ideas through transformation

Combine the acquired multiple knowledge with people's empirical knowledge and find the deep knowledge and laws behind the multiple knowledge by means of intelligent knowledge management (Guest et al., 2017). Apply the five basic transformation methods to transform the information cube in the basic element matrix to get possible ideas.

Step 4. Select the best ideas

From all the possible ideas above, novel ideas are selected based on AHP method or dependency function (Yang, 2019), using both quantitative and qualitative evaluation criteria.

Quantitative evaluation analysis generally needs to analyze the quantitative attributes, quantitative relations, and quantitative changes of new ideas based on certain domain knowledge. This, being used in conjunction with qualitative evaluation, can help us gain a thorough understanding of each idea and improve the performance of the evaluation and selection of novel ideas.

5. CASE ANALYSIS

5.1 A Classic Problem of Power Supply Affected by Snow

Background: In 2016, winter storm Jonas blanketed the northeast of the United States in over three feet of snow and caused 55 deaths. Snow, ice, and toppled trees shorted out power lines and caused a large-scale power outage, which severely disrupted communications, water, and transportation. This is not a rare case; every year, snowstorms sweep across the United States, inflict huge damage to electric power delivery system, and consume a lot of manpower and resources. Many people have tried to solve this problem, but they have all failed. So, the manager held a brainstorming meeting with experts from different professional backgrounds, trying to apply the brainstorming method to solve the problem.

Brainstorming: At the beginning of the meeting, the participants were asked to abide by the four basic principles of brainstorming. Then, the discussion started. Some people proposed to design a special wire snow blower; some thought of using electric heaters to melt ice and snow; some suggested using oscillation technology to clear snow; others suggested using large snow brooms carried by a helicopter to sweep the snow off the wires. Although everyone thought the idea of sweeping the snow with a helicopter was funny, no one criticized it in the meeting. On the contrary, when an engineer heard this idea, his brain was suddenly shocked, and a simpler, more feasible, and more efficient method of clearing snow emerged. He thought that, after a heavy snow, they could send a helicopter to fly low over the snow-covered electric wires so that the fast-spinning blades could swirl the snow off the wires. After he put forward his new idea of blowing the snow off with a helicopter, this immediately sparked creativity in other participants. There were seven or eight more ideas about using a plane to remove snow.

Result: After the meeting, the company organized experts to classify the ideas. Experts believed that it is technically feasible to design a special snow blower, using electric heating or electromagnetic oscillation, to remove snow on the wires, but they all require large development costs and long development cycle times, so it is difficult to see immediate results. However, the several ideas inspired by sweeping snow with a helicopter are bold new plans; there could be simpler and more efficient alternatives. After trials, it turned out that using a helicopter to blow the snow off really worked. A long-standing problem was finally solved after a brainstorming session.

5.2 Apply the New Brainstorming Method With the Extension Innovation Method

Although the application of traditional brainstorming methods to solve the problem of snow on electric wires is classic, we are wondering if there exist other, better solutions. Therefore, we applied the new brainstorming method with extension innovation method. Detailed steps are shown below: Problem analysis. We first define a set of analysis conditions, which is called group L, and another set of analysis targets, which is called group G. The target and conditional basic-element obtained by group G and group L are as follows:

$$\mathrm{P} = G * L$$

$$G = \begin{bmatrix} \text{Keep} & \text{Dominating object} & M_1 \\ & \text{Acting object,} & \text{any} \\ & \text{season} & \text{winter} \\ & \text{efficient} & \text{high} \\ & \text{cost} & \text{low} \end{bmatrix}$$

$$L = \begin{bmatrix} \text{Remove} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{tool} & \text{shovel} \\ & \text{efficient} & \text{low} \end{bmatrix}$$

We then split the team into matter-element analysis group GL1, affair-element analysis group GL2, and relation-element analysis group GL3. Some of the obtained matter-elements are as follows:

$$M_1 = \begin{bmatrix} \text{Wires,} & \text{condition} & \text{normal} \\ & \text{position} & \text{between 2 poles} \\ & \text{place} & \text{in the field} \end{bmatrix}$$

$$M_2 = \begin{bmatrix} \text{Accumulated snow} & \text{state} & \text{soft solid} \\ & \text{temperature} & \leq 2 \\ & \text{position} & \text{on } M_3 \end{bmatrix}$$

$$M_3 = \begin{bmatrix} \text{Electric wire} & \text{structure type} & \text{cable line} \\ & \text{transmission type} & \text{alternating current} \\ & \text{material} & \text{composite material} \\ & \text{withstand the maximum tension} & x \text{ N} \\ & \text{installation method} & \text{overhead} \\ & \text{support tool} & M_4 \\ & \text{support point} & y \text{ m/piece} \end{bmatrix}$$

$$M_4 = \begin{bmatrix} \text{Telephone pole} & \text{interval} & \text{200 meters} \\ & \text{high} & \text{10 m} \\ & \text{material} & \text{cement} \end{bmatrix}$$

$$M_5 = \begin{bmatrix} \text{Electricity} & \text{transfering object} & M_3 \\ & \text{voltage} & \left\langle 35, 220 \right\rangle \text{kv} \\ & \text{current} & \text{small} \\ & \text{thermal effect,} & \text{small} \\ & \text{magnetic effect,} & \text{weak} \end{bmatrix}$$

Some of the obtained affair-elements are as follows:

$$A_1 = \begin{bmatrix} \text{Remove} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{place} & \text{electric wire} \\ & \text{method,} & \text{manual} \\ & \text{tool,} & \text{shovel} \end{bmatrix}$$

$$A_2 = \begin{bmatrix} \text{Improve} & \text{Dominating object} & \text{temperature} \\ & \text{Receiving object} & M_2 \\ & \text{place} & M_3 \\ & \text{method,} & N_1, N_2 \cdots N_i \end{bmatrix}$$

$$A_3 = \begin{bmatrix} \text{Crush} & \text{Receiving object} & M_3 \\ & \text{Acting object} & M_2 \\ & \text{way} & \text{weight} \\ & \text{condition,} & \text{gravity} \geq \text{2000N} \end{bmatrix}$$

Some of the obtained relation-elements are as follows:

$$R_1 = \begin{bmatrix} \text{Attachment relationship} & \text{antecedent} & M_2 \\ & \text{consequent} & M_3 \\ & \text{degree,} & \text{serious} \end{bmatrix}$$

$$R_2 = \begin{bmatrix} \text{Supporting relationship} & \text{antecedent} & M_3 \\ & \text{consequent} & M_4 \\ & \text{degree,} & \text{fixed} \end{bmatrix}$$

The results of the matter-element analysis are as follows:

$$M_2 \begin{cases} M_{21} = \begin{bmatrix} \text{Snow} & \text{phase transition} & \text{from solid into liquid} \\ & \text{temperature} & \left\langle 0,100 \right\rangle {}^\circ C \\ & \text{speed} & \text{slow} \end{bmatrix} \\ M_{22} = \begin{bmatrix} \text{Snow} & \text{state} & \text{dispersed} \\ & \text{speed of the wind,} & \geq \ x'\text{km/s} \\ & \text{humidity} & \leq \text{~y } \% \end{bmatrix} \end{cases}$$

$$M_3 4 \begin{cases} M_{31} = \begin{bmatrix} \text{Electric wire} & \text{structure type} & \text{cable line} \\ & \text{transmission type} & \text{alternating current} \\ & \text{material} & \text{composite material} \\ & \text{the maximum tension} & \text{2000N} \\ & \text{installation method} & \text{underground} \end{bmatrix} \\ M_{32} = \begin{bmatrix} \text{Electric wire} & \text{structure type} & \text{cable line} \\ & \text{transmission type} & \text{alternating current} \\ & \text{material} & \text{elastic material} \\ & \text{the maximum tension} & \text{6000N} \\ & \text{installation method} & \text{overhead} \\ & \text{support method} & \text{telephone pole} \\ & \text{intervals} & \text{200 m} \end{bmatrix} \\ M_{33} = \begin{bmatrix} \text{Electric wire} & \text{structure type} & \text{cable line} \\ & \text{transmission type} & \text{alternating current} \\ & \text{material} & \text{composite material} \\ & \text{the maximum tension} & \text{4000N} \\ & \text{installation method} & \text{overhead} \\ & \text{support method} & \text{telephone pole} \\ & \text{intervals} & \text{100 m} \end{bmatrix} \\ M_{34} = \begin{bmatrix} \text{Electric wire} & \text{structure type} & \text{cable line} \\ & \text{transmission type} & \text{alternating current} \\ & \text{material} & \text{thermostatic material} \\ & \text{the maximum tension} & \text{2000N} \\ & \text{installation method} & \text{overhead} \\ & \text{support method} & \text{telephone pole} \\ & \text{intervals} & \text{150m} \end{bmatrix} \end{cases}$$

$$M_4 4 \begin{cases} M_{41} = \begin{bmatrix} \text{Telephone pole} & \text{interval} & \text{100 meters} \\ & \text{high} & \text{10 m} \\ & \text{function,} & \text{snow removal} \end{bmatrix} \\ M_{42} = \begin{bmatrix} \text{Telephone pole} & \text{interval} & \text{150 meters} \\ & \text{high} & \text{10 m} \\ & \text{function} & \text{turn the wire} \end{bmatrix} \end{cases}$$

$$M_5 4 \begin{cases} M_{51} = \begin{bmatrix} \text{Electricity} & \text{Transfering object} & \text{electric wire} \\ & \text{voltage} & \langle 35,220 \rangle \text{kv} \\ & \text{current} & \text{small} \\ & \text{thermal effect,} & \text{high} \\ & \text{magnetic effect,} & \text{powerful} \end{bmatrix} \end{cases}$$

The results of affair-element analysis are as follows:

$$A_1 4 \begin{cases} A_{11} = \begin{bmatrix} \text{Remove} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{place} & M_3 \\ & \text{way,} & \text{remote control} \\ & \text{tool,} & \text{wire snowplow} \end{bmatrix} \\ A_{12} = \begin{bmatrix} \text{Remove} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{place} & M_3 \\ & \text{way,} & \text{wing wind} \\ & \text{tool,} & \text{helicopter} \end{bmatrix} \\ 4 \begin{cases} A_{121} = \begin{bmatrix} \text{Remove} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{place} & M_3 \\ & \text{way,} & \text{wing wind} \\ & \text{tool,} & \text{smart drone} \end{bmatrix} \end{cases} \\ A_{13} = \begin{bmatrix} \text{Melt} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{place} & M_3 \\ & \text{way,} & \text{increase temperature} \end{bmatrix} \\ A_{14} = \begin{bmatrix} \text{Melt} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{place} & M_3 \\ & \text{way,} & \text{spray snow melt agent} \end{bmatrix} \\ A_{15} = \begin{bmatrix} \text{Peck,} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{birds} \\ & \text{place} & M_3 \\ & \text{way,} & \text{spray birdseed on snow} \end{bmatrix} \end{cases}$$

$$A_2 4 \begin{cases} A_{21} = \begin{bmatrix} \text{Improve} & \text{Receiving object} & M_2 \\ & \text{Dominating object} & \text{temperature} \\ & \text{place} & M_3 \\ & \text{way,} & \text{temperature conduction} \end{bmatrix} \\ 4 \begin{cases} A_{211} = \begin{bmatrix} \text{Improve} & \text{Receiving object} & M_2 \\ & \text{Dominating object} & \text{temperature} \\ & \text{place} & M_3 \\ & \text{way,} & \text{radiant heat} \end{bmatrix} \\ A_{212} = \begin{bmatrix} \text{Improve} & \text{Receiving object} & M_2 \\ & \text{Dominating object} & \text{temperature} \\ & \text{place} & M_3 \\ & \text{way,} & \text{electromagnetic induction heater} \end{bmatrix} \\ 4 \begin{cases} A_{2121} = \begin{bmatrix} \text{Improve} & \text{Receiving object} & M_2 \\ & \text{Dominating object} & \text{temperature} \\ & \text{place} & M_3 \\ & \text{way,} & \text{electromagnetic induction heater} \\ & \text{tool,} & \text{ferrite ring} \end{bmatrix} \end{cases} \\ A_{213} = \begin{bmatrix} \text{Improve} & \text{Receiving object} & M_2 \\ & \text{Dominating object} & \text{temperature} \\ & \text{place} & M_3 \\ & \text{way,} & \text{pyroelectric phenomenon} \end{bmatrix} \end{cases} \end{cases}$$

$$A_3 4 \begin{cases} A_{31} = \begin{bmatrix} \text{Crush} & \text{Accepted object} & M_3 \\ & \text{Acting object} & M_2 \\ & \text{way} & \text{weight} \\ & \text{condition,} & \text{gravity} \leq 2000\text{N} \\ & \text{degree,} & \text{normal} \end{bmatrix} \end{cases}$$

The results of relation-element analysis are as follows:

$$R_1 4 \begin{cases} R_{11} = \begin{bmatrix} \text{Attachment relationship} & \text{antecedent} & M_2 \\ & \text{consequent} & M_3 \\ & \text{degree,} & \text{separate} \end{bmatrix} \\ R_{12} = \begin{bmatrix} \text{Conduction relationship} & \text{antecedent} & M_2 \\ & \text{consequent} & M_3 \\ & \text{conduct content,} & \text{temperature} \\ & \text{way,} & \text{attach} \\ & \text{degree,} & X_n \end{bmatrix} \end{cases}$$

Step 3: Collect the information obtained by each group in Step 2, use the human-computer interaction model to search for more information on the Internet. For example, according to the online search results, some effects that can be used to increase the temperature are conduction, convection, radiation, electromagnetic induction, pyroelectric medium, thermionic, discharge, material absorption of radiation, pyroelectric effect, object compression, nuclear reaction, etc. When the Curie point of a ferrite ring is near to 0°C, the magnetic effect will start to generate heat if the temperature is below 0°C, and stop heating when the temperature is above 0°C. So, this could be a perfect match to our needs; it will heat but only on snowy days.

Step 4: Extension transformation. The participants are divided into five groups A, B, C, D, E, such as substitution, increasing/decreasing, expansion/contraction, decomposition, and duplication. Each group generates new ideas based on a basic transformation method, and the group then try all the other different basic transformation methods, recording all the ideas.

The possible solutions obtained are as follows:

$$T_{22}M_2 = \begin{bmatrix} \text{Snow} & \text{state} & \text{dispersed} \\ & \text{speed of the winds} & \geq x'\text{km/s} \\ & \text{humidity} & \leq \text{y } \% \end{bmatrix} = M_{22}$$

$$T_{A11}A_1 = \begin{bmatrix} \text{Remove} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{place} & M_3 \\ & \text{way,} & \text{remote control} \\ & \text{tool,} & \text{wire snowplow} \end{bmatrix} = A_{11}$$

$$T_{A14}A_1 = \begin{bmatrix} \text{Melt} & \text{Dominating object} & M_2 \\ & \text{Acting object} & \text{workers} \\ & \text{place} & M_3 \\ & \text{way,} & \text{spray snow melt agent} \end{bmatrix} = \text{A}_{14}$$

$$T_{A31}A_3 = \begin{bmatrix} \text{Crush} & \text{Accepted object} & M_3 \\ & \text{Acting object} & M_2 \\ & \text{way} & \text{weight} \\ & \text{condition,} & \text{gravity} \leq 2000\text{N} \\ & \text{degree,} & \text{normal} \end{bmatrix} = A_{31}$$

$$T_{\text{R}11}R_1 = \begin{bmatrix} \text{Attachment relationship} & \text{antecedent} & M_2 \\ & \text{consequent} & M_3 \\ & \text{degree,} & \text{separate} \end{bmatrix} = R_{11}$$

After the 'and' operation again, we can get: $T = T_{22} \wedge T_{A11} \wedge T_{A14} \wedge T_{A31} \wedge T_{R11}$

Solution 1: Use bonuses to encourage residents near utility poles to use remote-controlled snowplows to remove snow, or to spray viscous deicing agents to melt the snow, so that the snow will not crush the utility poles and achieve the goal. The extension model is: $D_0^1 = M_{22} \wedge A_{11} \wedge A_{14} \wedge A_{31} \wedge R_{11}$

In the same way (detailed steps of extension transformation are omitted to conserve space), dozens of other possible solutions are obtained. For example, using drones to cruise and sweep snow, and using wind created by drone propellers to remove snow on power lines as solution 2, with the extension model being: $D_0^2 = M_{22} \wedge A_{121} \wedge A_{31} \wedge R_{11}$. Use the wind created by aircraft to remove the snow on the wires and bury the overhead wires below ground to solve the snow problem as solution 3, with the extension model being: $D_0^3 = M_{31} \wedge A_{31} \wedge R_{11}$. Replace the material used in electric wires with elastic material to increase the wires' tensile strength as solution 4, with the extension model being: $D_0^4 = M_{32} \wedge M_{41} \wedge A_{31}$. Set up more utility poles so that the wires can get more points of support as solution 5, with the extension model being: $D_0^5 = M_{33} \wedge M_{41} \wedge A_{31} \wedge R_2$. Install ferrite rings with a Curie point near 0°C on the wires to increase the electromagnetic induced heat, increase the wire temperature, and thus melt the snow on the wire through heat conduction as solution 6, with the extension model being: $D_0^6 = M_{21} \wedge M_3 \wedge M_{42} \wedge M_{51} \wedge A_{2121} \wedge R_{12}$.

Step 5: In the evaluation and optimization process, after the extension evaluation, it is concluded that both solution 1 and 6 are feasible.

We tested our new brainstorm model with other topics and get a good result (involving 21 majors and 60 students in one week before training).

For the study, 120 students in 19 majors from Ningbo Institute of Technology Zhejiang University and students from Guangdong University of Technology were randomly selected as training group or control group. Then, we let them list all the answers to the same brainstorm topic. As is usually expected, the results are not significantly different. Then one week after training on extension brainstorm, the two groups were given two similar training topics again. The results show that the number of effective innovative ideas developed by trained students has a remarkable improvement. The statistical results are shown in Table 2.

D_{old} is defined as the number of effective innovative ideas before training, D_{new} is the number of effective innovative ideas for post-training extension, and the degree of lift is as follows:

Table 2. Comparison and analysis of training results

	Control Group			Training Group		
Topic ID	First test: Average per team	2nd test: Average per team	Extend of the progress	Before training	After training	Extend of progress
E1	6.23	7.31	17.34%	6.67	19.31	189.51%
E2	6.33	8.01	26.54%	6.47	18.72	189.34%
E3	6.87	6.79	-1.16%	6.82	22.86	235.19%
E4	6.73	7.41	10.10%	6.48	16.36	152.47%
E5	7.23	8.01	10.79%	7.13	18.82	163.95%
E6	6.89	7.98	15.82%	6.65	17.94	169.77%
Average			13.24%			183.37%

$$l = \frac{D_{new} - D_{old}}{D_{old}} \times 100\% \tag{7}$$

6. DISCUSSION

Based on Extenics, we presented a new hybrid model of intelligent extension brainstorming to help people think in multiple dimensions and come up with more ideas. Using this model, we can also generate alternative ideas ensuring sufficient coverage, lower the standards for participants, improve the lower limit of brainstorming, enlarge the creative breadth control ability of brainstorming, and improve its efficiency. It is worth noting that this method is more effective in dealing with complex problems because it is time consuming for simple problems, and the requirements of the meeting moderator have also been increased significantly.

7. CONCLUSION AND FUTURE WORK

A novel model has been proposed in this paper, which uses the basic-element of Extenics to describe the brainstorming process. The proposed new model allows users to generate more creative ideas based on the Extenics matrices representation process. It is particularly efficient in the big data environment where the basic-element information base can be maximized with abundant data sources extracted from the big data environment.

In the next stage, we will further simplify the steps and processes, while systematically expanding the dimensions of thinking as much as possible. With the help of electroencephalography (EEG) (Ein et al., 2021; Xu et al., 2019; Zhang et al., 2018) and MCGNet+ model (Li et al., 2022), we will propose a test method to explore the process of how ideas are created in the brain. The Extension innovation method makes up for the defects in brainstorming, such as the lack of scientific methods, poor average quality of personal ideas, and uncontrollability of results. We will further complete the model and try to cover as many directions of creativity as possible with the help of Extenics, guide participants to brainstorm in divergent directions, and avoid uncontrollable results caused by too many random factors.

In the future, with the support of information technology and artificial intelligence, we will systematically collect more information and knowledge, build the basic-element base on Extenics, and improve the classification and evaluation system. We are trying to use human-computer interaction models to help people discover more attributes and their values which will break through the limitations of limited information and knowledge in the human brain. We will maintain and use this new methodology to help people from different fields think positively in multiple dimensions during the brainstorming process.

8. ACKNOWLEDGMENT

The authors would like to thank Professor Chunyan Yang from GDUT and the reviewers for their suggestions. This work was partially supported by the National Natural Science Foundation of China Grant (No. 72071049), the Ningbo Natural Science Fund Plan (Grant No. 2022J164), the Humanity and Social Science Foundation of the Ministry of Education of China (21A13022003), and the Ningbo Public Welfare Science and Technology Plan (Grant No. 2021S093).

9. AVAILABILITY OF DATA AND MATERIALS

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

10. COMPETING INTERESTS

The authors declare that they have no competing interests.

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Xingsen Li graduated from School of Management, Graduate University of the Chinese Academy of Sciences and achieved his doctorate degree in management science and engineering in 2008. MSc degree in Mechanical Design and Theory, School of Mechanical Electronic Engineering, China University of Mining & Technology in 2000. B.S. in Vehicular Engineering, Energy Engineering Department, Zhejiang University in 1991. He has been the secretary-general of Extenics Specialized Committee, China Association of Artificial Intelligence, and director of China Creative Studies Institute. He has published four books and more than 120 papers in various Chinese journals and international journals/conferences proceedings, including ITQM best paper and ESI highly cited paper. He's won the 2017 Herbert Simon Award for outstanding contribution in information technology and decision-making, natural science awards of Zhejiang province, and teaching achievement prizes at Zhejiang University.

Haibin Pi received his Master of Engineering Management Professional Degree, specializing in Extenics, from Guangdong University of Technology, Guangzhou, Guangdong Province, China. His areas of research include an integration model on brainstorming and Extenics for intelligent innovation in big data environment.

Junwen Sun is with Guangdong University of Technology since 2022.

Hao Lan Zhang is currently with the Joint Center for SCDM, NIT, Zhejiang University and the board member of Jiangsu New Materials Co. He is the recipient of Natural Science Award of Zhejiang Province, Educational Science Research Award of Zhejiang Province, the 151 Talented Scholar of Zhejiang Province, 100 Talented Scheme of Suqian City in China, and National Intelligent Innovation Robotic Competion Award. I received my Ph.D. in Computer Science from Victoria University. He was a research fellow at RMIT University and sessional lecturer at Victoria University, Australia. He received a number of research awards and grants including National Nature Science Fund, National Overseas Scholars' Fund, Provincial Natural and Social Science Fund, Ministry of Education Social Science Fund, etc. He has been the editors of several journals including Web Intelligence, Mathematics, Journal of Internet Technology, etc.

Zhencheng Liang is a graduate student at the College of Mechanical and Electrical Engineering, Guangdong University of Technology, majoring in Industrial Engineering and Management, studying Extenics. He participates in projects like Intelligent Dust Removal in Coal Mine Using Extension Data Mining, The Operator of Extension Intelligence, and its Implementation.