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Research Article

A Novel Development of TRIZ-Analogic Construction Interface Problem Identification and Solutions Framework

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One of the critical factors of project success is the interface management. Past project interface management mainly relies on knowledge and experience of the project managers. The existing studies of project interface management also mainly focused on the definition and the classification of project interfaces. There is no workable and flexible framework for construction interface problem identification and solutions. This study conducted an analogic study of contradiction matrix at Theory of Inventive Problem Solving (TRIZ) to develop such a framework. This research collected around six hundred interface management cases from civil works and building projects. For comparison, this research defined an experimental group (TRIZ case) and a control group (experience-oriented solution case) based on the concept of clinical experiments in medical science to evaluate and improve the rationality of the matrix. Subsequently, based upon the theory of information retrieval (IR), this research conducted statistical evaluation and TRIZ features remedies to develop generalized construction interface problem identification and solutions. For solving project management interface problems, the TRIZ-analogic construction interface problem identification and solutions framework provides a systematic approach to develop more robust solutions for interface problems in construction engineering rather than just simply relying on intuitive experience.

1. Introduction

The most diverse, complex, and difficult problem to be solved in the construction industry is interface management. It is also the most commonly encountered problem in practice. In the complex and highly-risky environment of a construction project, if an effective decision cannot be made at the planning and design phase, disagreements, conflicts, disputes, change orders, and claims can occur at the construction phase [1]. The in-depth study of Waring and Gibb [2] on the failure of curtain walls indicates that more than 60% of malfunctions are caused by interfaces. Interfaces are generally defined as the interdependence between people, organizations, phases, physical entities, systems, and even concepts [3, 4]. Using the multiple regression models, Huang [5] categorized the interface problem into six categories and found that significant interface problem factors are the experience and coordination. Because of the complexity of interfaces, interface management is conducted to carefully integrate people, organizations, units, and subprojects with the anticipated methods [6, 7]. Also, lack of common values results in a limited understanding of how behaviors of one discipline impact on the related disciplines will lead to tons of interface conflicts, which ultimately affect project effectiveness [8]. The traditional construction industry generally relies on the work experience of project participants to solve interface problems, including owners, designers, construction contractors, subcontractors, maintenance contractors, and material suppliers. Archibald [9] stated that interface management is planned and controlled by project managers; nevertheless, the detailed work amongst these interface incidents is often judged and assessed according to the experience of engineers. The systematic approach to interface problems is seldom involved. In summary, the traditional interface problem solving is subjective, experience counted, and not a systematic framework to identify interface problems and comprehensively propose appropriate solutions.

This study refers to the contradiction matrix established in the theory of inventive problem solving (TRIZ) [10], which properly solves the above-mentioned problems. The engineering features of the original contradiction matrix are first converted into interface-related features through model transformation and validation, which creates a systematic framework to identify interface problems and provide generalized reference solutions for the practical implementation on the construction management interface problems. The remainder of this study is organized in the following. Section 2 reviews the related research in regard to the interface problems in the construction projects. Section 3 provides the descriptions of contradiction matrix, organization management, and information retrieval used for model transformation and validation. Section 4 introduces the process of TRIZ-analogic construction interface problem identification and solutions framework. Section 5 introduces the operational procedures to solve practical construction interface problems based upon the proposed framework. Lastly, Section 6 offers a conclusion and explores future developments.

2. Literature Survey

During the lifecycle of construction projects, the interface conflicts always exist amongst things and people. A lot of researches have been proposed to solve interface problems using digital information systems and information models. Bernold [11] combined the digital space model with the construction equipment using the digital space design data to help solve the construction interface problems with spatial conflicts. CladdISS proposed by Pavitt and Gibb [12] was applied to solve interface problems among layers of interface-related issues. Siao and Lin [13] used multilevel interface matrix approach to provide an effective interface management tool for the construction phase. Senthilkumar et al. [14] proposed a methodology for an interface management system with the integration of design structure matrix (DSM) and constructed Web systems to improve interface management efficiencies during the design stage. Recently Lin [15] proposed the use of Building Information Model (BIM) to retain interface information, which is beneficial to interface update and transmission as well as the improvement of the construction process. Similarly, Gou [16] and Senthilkumar et al. [14] developed computer-aided design systems to manage interface conflicts in construction projects. Furthermore, Chua and Godinot [17] used the work breakdown system (WBS) matrix concept to facilitate the presentation and management of the interface. It is expected to gradually eliminate the shadow areas of related subitems among interfaces. Nevertheless, until now, there is no specification and systemization regarding the identification and solutions of interface problems. Classical approaches heavily rely on the engineering experience. McCarney and Gibb [18] focused on organizational interface management and studied and analyzed various processes and human factors that impact the efficiency of conflict resolution. Mousli and Sayegh [19] took the case study of design and construction interface in the Arab construction industry and indicated that most of the interface problems are due to the lack of coordination and communication between the contracting parties. Keerthanaa & Shanmugapriya [20] categorized the interface problems and summarized practical experience-oriented solutions. In practical architecture, engineering, and construction collaboration, exchange requirements are one of the important conflict resolution techniques to ensure the completeness and accuracy for a construction project [21]. In summary, although some methods and information technology approaches were proposed for solving the interface problems, few researches are conducted regarding the systematic framework of the conflict identification and solutions for the generalized construction management interfaces. Table 1 summarizes the feature of relevant studies on construction interface problems and TRIZ-based problem-solving applications.

In view of the diversity of interface problems and the unavailability of generalized interface problem identification and solution framework, this study refers to the contradiction matrix in TRIZ theory and transforms its original inventive thinking on "physical object interface" into the discussion of identification and thinking of solutions for the "human (organization) interface" based upon the concept of organizational behavior. Based upon the theory of information retrieval, this research conducts data collection, discussion, statistical evaluation, and remedy to develop a novel and generalized construction interface problem identification and solutions framework. This framework assists supervisors to extensively discuss and explore possible solutions for the construction interface problems. This framework owns a high level of flexibility to support practical solutions for interface problems through systematic induction and inference. By defining appropriate interface-related features based upon the physical characteristics of interface problems, the proposed framework is able to work accordingly to explore feasible solutions for real construction interface problems even under diverse conditions.

3. Framework Architecture and Methods

The overall process of this study is shown in Figure 1, including three main steps: (1) initial TRIZ contradiction matrix transformation, (2) experimental design and data collection, and (3) statistical validation and revision. Original TRIZ contradiction matrix works for "physical object interface." When the matrix is used for solving the construction interface problems, it is necessary to tune up the matrix features to suit the characteristics of construction interface management. One main function of the theory of organizational management is to study and resolve the conflict and negotiation amongst the individuals, groups, and organizations. This study follows the theory of organizational management to do the first transformation from the original TRIZ contradiction matrix into the construction interface-related matrix.

Table 1: Relevant studies on construction interface problems and TRIZ-based problem-solving applications.

Author	Problem/Improvement	Method
Bernold (2002)	Construction interface spatial conflicts	Digital space model
Gou (2002)	Manage interface conflicts	Computer-aided design systems
Pavitt and Gibb (2003)	Interface problems among layers of interface-related issues	Proposed CladdISS (Digital system)
Chua and Godinot (2006)	Shadow areas of related subitems among interfaces	Work breakdown system matrix
Senthilkumar et al. (2010)	Interface management efficiency during the design stage	Proposed design structure matrix
Venkatachalam et al. (2010)	Manage interface conflicts	Computer-aided design systems
Siao and Lin (2012)	Interface management for the construction phase	Multilevel interface matrix
Lin (2015)	Retain interface information and beneficial to interface update and transmission	Building information model
Mann and Catháin (2009)	Generate innovative construction solutions to reduce risks for the complicated design of the external elevation of buildings	TRIZ-based method
Mao et al. (2009)	Incorporated the TRIZ theory and tools into the traditional value engineering process	TRIZ-based method
Zhang et al. (2009)	Applied TRIZ methodology to develop a VE knowledge management system (VE-KMS)	TRIZ-based method
Cheng et al. (2012)	Utilized the contradiction matrix to find the improving and worsening features of the design cases	TRIZ-based method
Moon et al. (2016)	Established a methodology to provide design alternatives for temporary construction in VE by integrating the problem-solving principles of TRIZ	TRIZ-based method
Nassar and AbouRizk (2016)	Presented techniques for resolving project performance contradictions based on TRIZ	TRIZ-based method
Lee et al. (2020)	Integrated TRIZ to develop an advanced composite material-based concrete formwork	TRIZ-based method

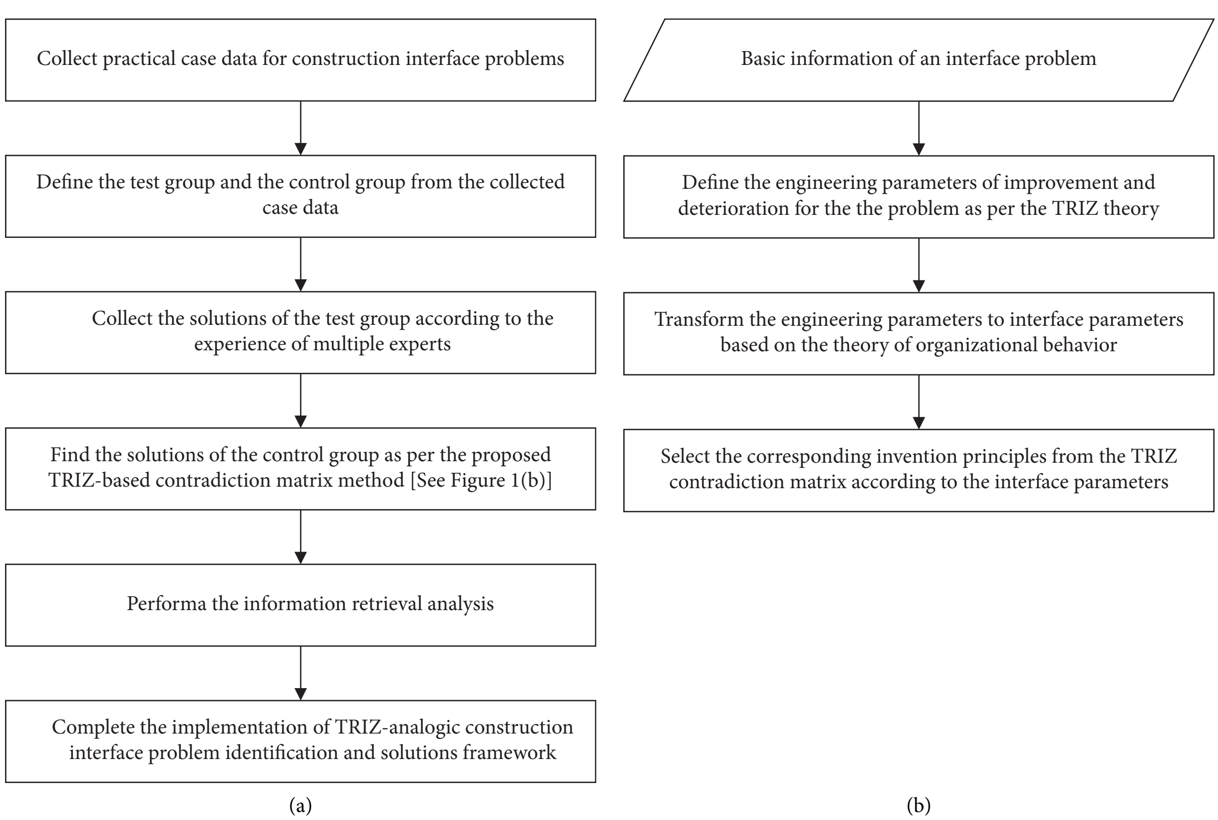

Figure 1: Research method diagram. (a) Primary procedure. (b) Application process of the TRIZ contradiction matrix.

Furthermore, the matrix is sequentially revised based upon data collection, analysis, and validation for practical cases. For comparison, this research defined an experimental group (TRIZ case) and a control group (experience-oriented solution case) based on the concept of double-blind clinical experiments in medical science to evaluate and improve the rationality of the matrix. Furthermore, this research utilizes the concept of information retrieval (IR) for statistical validation on the experimental group and control group data based upon IR performance indices: recall and precision. According to the IR performance data, this study kept investigating and modifying the matrix to ensure its suitability and comprehensiveness. The concept of the contradiction matrix, organization management, and information retrieval used in this study for model transformation and validation are briefly described as follows.

3.1. TRIZ and Contradiction Matrix. TRIZ is a systematic innovative theory presented by Altshuller and Shapiro [10] based upon the extraction of invention principles from more than 200,000 patents. Altshuller and Shapiro [10] also found that some fundamental principles had appeared repeatedly in inventions from different industries, and the most creative patents had been embedded with solutions to satisfy contradictory requirements [22]. Kaplan proposed that the inventive problem can be organized, classified, and resolved in sequence just as engineering problems [23]. TRIZ includes a set of tools and techniques, including a contradiction matrix and 40 inventive principles. The original TRIZ contradiction matrix provides generic solutions of innovative problems. One main function of invention is to resolve the conflict between objects. Over decades, TRIZ proposes a contradiction matrix, in which 40 principles and 39 features are covered, to systematically resolve the conflict between two subsystems in a system. The main objective of the contradiction matrix was to simplify the process of selecting the most appropriate principle to resolve a specific contradiction by selecting appropriate positively and negatively affected features based upon the characteristics of real problems. After finding the certain invention principles, the tailored solutions can be generated according to these invention principles and the properties of real problems. Jiang et al. [24] presented the evolution route of a product service systems (PSS) based on TRIZ theory to reduce the material flow and to enhance the environmental friendliness. In the field of deep-rock mechanic, Li et al. [25] applied the TRIZ method to improve the rock coring technique regarding the coring structure, contact medium of barrel and core, and motion control method. In addition to the engineering innovation application, Souchkov [26] published the TRIZ contradiction matrix for business and management. The roadmap of business innovation with TRIZ is similar to the classical approach; however, it places more emphasis on the business innovation, such as flow analysis, line of business systems evolution, and the like. Recently, Berdyugina and Cavallucci [27] have developed an automatic contradiction retrieval approach to analyze unstructured texts of patent contents and to build a real-time contradiction matrix for a technical field based on natural language processing (NLP). Because the patent classification and information retrieval often suffer from poor accuracy in data extraction, Guarino et al. [28] further developed a TRIZ-dedicated extraction tool using a deep neural network summarization to update TRIZ matrix and to create a whole new matrix based on patents independent from inventive principles. Guarino el al. [29] also presented a patent analysis algorithm with deep learning (called as SummaTRIZ) to extract the contradictions solved by existing patents. The performance of SummaTRIZ was experimentally evaluated on a real data set through classical measures in the field of information retrieval.

TRIZ has been applied to different fields of “innovation” and “problem-solving methods” to solve or optimize the existing and potential problems. Ilevbare et al. [30] explored the conventional TRIZ literature to identify the benefits associated with TRIZ knowledge and the challenges associated with its application based on practical practice. Four broad application areas of TRIZ were considered in their survey, including technical problem solving, innovation, technology strategy, and business management. In addition, the existing work also showed the use of TRIZ in the domain of business and services. Ben Moussa et al. [31] reviewed the practice of the TRIZ in green supply chain problems and identified potential challenges for the use of classical TRIZ contradictions. Fiorineschi et al. [32] collected the literature contributions and focused on the application of TRIZ on the conceptual design of products in industry. Abramov et al. [33] indicated that based upon the survey of customer satisfaction, the success rate of TRIZ is about 48%. Spreafico and Russon [34] summarized the distribution of TRIZ-based applications all over the world, as shown in Figure 2. Among them, the use percentage of civil engineering is 8%. Mann and Catháin [35] proposed that the TRIZ method is able to generate innovative construction solutions to reduce risks for the complicated design of the external elevation of buildings. Cheng et al. [36] utilized the contradiction matrix to find the improving and worsening features of the design cases. Mao et al. [37] incorporated the TRIZ theory and tools into the traditional value engineering (VE) process for enhanced efficiency and effectiveness in creating innovative ideas. Zhang et al. [38] applied TRIZ methodology to develop a VE knowledge management system (VE-KMS), which enables the VE team to control the creativity process systematically. Their case studies demonstrated the usefulness and applicability of the VE-KMS in the construction industry. Recently, the TRIZ theory were also adopted in the innovation of construction technologies [39]. Moon et al. [40] established a methodology to provide design alternatives for temporary construction in VE by integrating the problem-solving principles of TRIZ. Lee et al. [41] integrated TRIZ and quality function deployment to develop an advanced composite material-based concrete formwork with improved constructability. Such TRIZ-related methods escape from traditional processes-based approaches and generate innovative solutions based on global human intelligence, generally from the public patent databases.

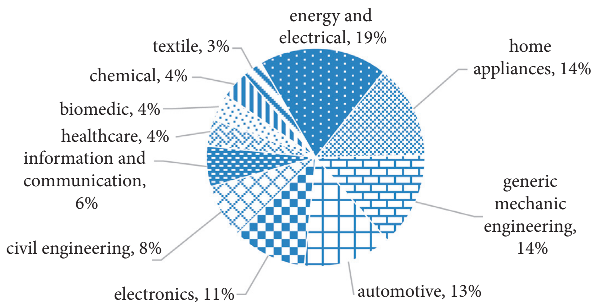

Figure 2: Use of TRIZ worldwide (data source: Spreafico and Russon [34]).

Although TRIZ method has maturely developed and utilized, few studies have applied TRIZ framework for the construction management interface. Nassar and AbouRizk [42] presented techniques for resolving project performance contradictions (TRAC) based on TRIZ for the construction performance problems.

As stated above, this research refers to the contradictory matrix structure in TRIZ and attempts to combine the original innovative thinking on the conflict of "object interface" with the concept of organizational behavior and to transform it into the identification and solution framework for the "human (or organizational) interface." The core of innovative thinking is similar to the solution generation of construction interface problems and the aim is on the identification and improvement of system interfaces. The primary conflict factors of construction interface problems are the participants (including organizations, groups, and members); thus, how to convert the engineering features into human features and create a suitable contradiction matrix are key factors. This study follows the theory of organizational management to perform the first transformation, and then, the matrix is sequentially improved based upon practical cases through data collection, validation, and calibration.

3.2. Organizational Behaviors. The construction management interface problems mainly come from the conflicts amongst the participants and the derived issues. The model of organizational behaviors proposed by Robbins and Judge [43] indicated that three levels of variables such as inputs, processes, and outcomes, as well as three levels of analysis such as the conflict and negotiation amongst the individuals, groups, and organizations. Katz and Kahn [44] pointed out that people must overcome the intersection of different actions through methods such as coordination. The concept of ergonomics is proposed to be integrated into project management, strategic planning, and personnel management [45]. Several relevant studies on the construction management also reached the similar conclusion [46].

In general, chaos, disputes, and conflicts may occur among the participating members at a construction organization because the organizational objectives, cultures, and qualities may be different. The study of organizational behavior proposed by Robbins and Judge [43] investigated the impact of individuals, groups, and structures on the internal behavior of the organization, so as to apply the knowledge to improve the effectiveness of the organization. As stated above, the original TRIZ focuses on "physical object interface" and interface management on "human (organization) interface." Therefore, this research conducted the first transformation from original contradiction matrix to interface-related matrix by following the organizational behavior theory by Robbins and Judge [43]. The original 39 features of the contradiction matrix are transformed to be human-related features to create a preliminary structure of the contradiction matrix for the construction management interface problems. Specifically speaking, this research applies the organizational behavior philosophy that concentrates on "human-to-human" issues to modify the TRIZ contradiction matrix and to develop an initial TRIZ-analogic Construction Interface Problem Identification and Solutions Framework.

3.3. Information Retrieval (IR). This study adopted a sequential improvement process, including data collection, data validation, and features calibration. One crucial step is the data validation based upon the comparison between an experimental group and a control group. As stated above, the experimental group contains TRIZ-oriented case data, and the control group covers experience-oriented case data. Hopefully, TRIZ-oriented case data are similar to experience-oriented case data if the interface-related contradiction matrix works. To validate the similarity between these two group data, information retrieval (IR) was adopted. IR is the activity of obtaining information resources that are relevant to an information need from a collection of those resources. To validate the performance of IR, the two indicators, precision and recall, have been extensively used as the main evaluation indicators [47]. The generalized construction management interface problem identification and solution framework in this study can be deemed as an IR system for construction management interface problems. Therefore, this study used the two popular IR indicators to conduct data evaluation on the control group and the experimental group in order to ensure the suitability of the proposed framework and the possible subsequent investigation and revision.

Precision and recall are performance measures used in the fields of IR, statistics, and machine learning [48]. They are used to measure the quality of implementation results of systems. The value of the two indicators is ranging between 0% and 100%. The higher the precision and recall is, the better the system implementation. The original definitions of the two indicators are as shown in Equations (1) and (2). The precision refers to how many of the returned documents are correct during the IR process, which indicates how much confidence we have in making correct predictions. The recall refers to how many of the positives the system returns, which indicates the comprehensiveness of the retrieved data.

$$\text{Precision} = \frac{\#\,(\text{relevant items retrieved})}{\#\,(\text{retrieved items})} = P\,(\text{relevant}|\text{retrieved}), \tag{1}$$

$$\text{Recall} = \frac{\#\,(\text{relevant items retrieved})}{\#\,(\text{relevant items})} = P\,(\text{retrieved}|\text{relevant}). \tag{2}$$

Based on the concept of double-blind clinical experiments in medical science, this research designed two data groups: the experimental group and control group. Both data are surveyed for the same interface problem through the questionnaires at different construction stages. The experimental group conducted the investigation on the TRIZ contradiction matrix after transformation and carried out the identification of interface problems using the positively and negatively affected features to find the general solutions. The control group directly collected the interface problems and the commonly used solutions with practical experience. The precision and recall can be obtained through the revised formulas given in Equations (3) and (4). Numerator item refers to the matched number between the experimental and control group for the same interface problems. Especially, the higher the precision of the interface management contradiction matrix, the higher the degree of conformity of the practical solutions obtained through the interface management contradiction matrix are. That means that the interface management contradiction matrix is more suitable for the practical interface problems.

On the basis of the test of several information systems conducted by Loh et al. [49] and Arora et al. [50], the surveys showed that different information retrieval systems have different recall and precision values. Moreover, these two IR performance indices often have mutual negative-affected influence on each other. The higher the precision is, the lower the recall will be and vice versa. Because of that, break even logic is generally used to balance both indices. TRIZ-analogic construction interface problem identification and solutions framework proposed by this study is the first trial in the field of construction interface management. As stated above, the customer satisfaction of TRIZ is around 50%. It may be reasonable to define the basic threshold as 50% for the precision and recall. A higher threshold, say 60%, is used in this study. Based upon the continuous evaluation of the IR performance indices, sequential modification and improvement of interface-related contradiction matrix are conducted. A feasible contradiction matrix developed for the construction interface management can then be the core of the generalized framework of construction interface problem identification and solutions.

$$\text{Precision} = \frac{\text{the number of correct answers}}{\text{the number of answers in the experimental group}}, \tag{3}$$

$$\text{Recall} = \frac{\text{the number of correct answers}}{\text{the number of answers in the control group}}. \tag{4}$$

4. Framework Creation and Revision

4.1. Initial Feature Transformation of Contradiction Matrix. Original TRIZ focuses on "physical object interface" and interface management focuses on "human (organization) interface." When applying this framework for the engineering management interface problems, the first task is to deal with the improving and worsening features as well as solution principles in the matrix to suit for the interface activities. This research followed the study of organizational behaviors by Robbins and Judge [43] to conduct the initial transformation between object interface and human interface. The original features of TRIZ contradiction matrix are redefined and transformed into interface management features, as shown in Table 2. Note that the original features of TRIZ contradiction matrix can be classified into six groups: geometric type, resource types, physical type, capacity type, operation type, and harmful type. By following the principle of organizational behaviors and contrasting the object interface and human interface, these six categories are first transformed into organizational structures, organizational resources, characteristics of the organization, capabilities of the organization, implementation management and control, and negative impacts on the organization correspondingly. After the initial transformation of the features at the contradiction matrix, the matrix has been revised in accordance with data collection, analysis, and validation for practical cases to enhance the stability and feasibility of the proposed framework.

The original 40 invention principles of the TRIZ contradiction matrix also need to conduct the transformation from object interfaces to human interfaces. Taking the invention principle 1 as an example, TRIZ defines the principle as "segmentation." When applying it in the interface management, the segmentation action can be transformed into grouping and disassembling of WBS. Based upon such logic and brainstorming from experts, the original 40 invention principles are converted into the appropriate principles for interface management. After the contradiction matrix of the management interface is initially created, this study evaluated the consistency of empirical solutions and the TRIZ-based

Table 2: Initial definition of 39 features used by interface-related contradiction matrix.

Organizational structure (geometric type)	3. The structural integration scope of field personnel's vertical units of the organization 4. The structural integration scope of office staff's vertical units of the organization 5. The structural integration scope of field personnel's parallel units of the organization 6. The structural integration scope of office staff's parallel units of the organization 7. The structural integration scope of field personnel's cross-units of the organization 8. The structural integration scope of office staff's cross-units of the organization 12. The structural integration scope	Organizational resources (resource type)	19. The cost and salary of field personnel of the organization 20. The cost and salary of office staff of the organization 22. Waste of asset 23. Waste of manpower 24. Loss of information 25. Time consumption 26. Amount of manpower
Characteristics of the organization (physical type)	1. The load and influence of field personnel of the organization 2. The load and influence of office staff of the organization 9. Speed or rate 10. Strength 11. Tension and pressure 17. Organizational atmosphere 18. Organizational mission 21. Dynamic force/power	Capabilities of the organization (capacity type)	13. Stability of staff organization 14. Ambition 15. Work continuity of field personnel of the organization 16. Work continuity of office staff of the organization 27. Level of royalty 32. Easy management 34. Easy enhancement 35. Suitability/adaptability 39. Productivity
Implement management and control (operation type)	28. Check precision 29. Implement precision 33. Use convenience 36. Difficulties in implementation 37. Control complexity 38. Self-management capability	Negative impact (harmful type)	30. Harmful impact on the organization (negative impact from external to internal) 31. Harmful factors generated by the organization (negative effects from internal to external)

systematic solutions to improve the proposed framework continuously for achieving a best workability.

4.2. Contradiction Matrix Revision for Interface Management. To improve and verify the suitability of the transformed contradiction matrix in Section 3.1, this study followed the concept of clinical experiments in medical science: blind test. A questionnaire for control groups (as shown in Table 3) was first designed to extensively collect case data for construction management interface problems and relevant empirical solutions through interviews with experts and literature investigation. Subsequently, the TRIZ-analogic approach was conducted for an experimental group. The investigation approach is described as follows:

4.2.1. Collection of Control Group Cases. In order to help the experts to focus on the interface management features, this questionnaire includes seven aspects: (1) activity, (2) task, (3) potential interface problems, (4) potential causes, (5) interface participants, (6) descriptions, and (7) recommended corrective actions. The definition of activity and task follows the principle of WBS [51]. WBS is an important tool of the project management. The upper level of the WBS usually reflects the major deliverable work areas of the project, and it is decomposed into logical work groups, depending on the project type involved. The lower WBS elements provide detail for support of project management processes, such as scheduling, cost estimating, resource allocation, and risk assessment [52]. An example is given in Table 3 based upon the above-mentioned questionnaire. In this example, one contractor reported that the grouting construction cannot be conducted due to insufficient construction time for hydropower piping construction during the grouting construction. After the on-site investigation, it was found that the actual reason for this case is the water and electricity subcontractor reduced manpower resources to control the cost and that caused the task to fail to be completed as scheduled. Because of that, the subsequent grouting operation cannot be conducted, which may lead to delay of the overall construction schedule. The authors further interviewed with experts regarding this interface contradiction and proposed solutions based on the experience feedback in the aspects such as timeline, implementation, status, and resources, as shown in Table 3. In order to acquire high-quality support, 20 specialists with average work experiences of 24.5 years were interviewed for the data collection. Table 4 shows the profiles of the experts.

Table 3: Interview with experts and cases for interface problems.

Item no.	Activity	Task	Potential interface problems	Potential causes	Interface participants						Description	Recommended corrective action		
					Business owner	Contractor	Design unit	Supervising unit	Subcontractor A	Subcontractor B				
No.	Building construction	Floor	The grouting construction cannot be conducted due to insufficient construction time for hydropower piping construction	Manpower insufficient	X	X	X	X	○	○	Description of the contradiction: while simplifying manpower, it should avoid affecting the construction schedule	I	Timeline The entire system and timeline of the conducting event is a major relation	To convene a meeting to discuss enhancement the improvement plan with related subcontractors
												II	Implementation Under the entire system structure, the way of performing the operations	To adjust the practical route and overlap the construction flow, so that the workers can enter the site early for work
												III	Organization Organizational type of the system operation	
												IV	Change status Change the operation, direction, space, or environmental status of the current system	To flexibly change the grouting operation and label the completed pipes with colors to clarify the grouting area
											Problem attribute: construction stage on the site	V	Management integration Management and handling method in the system	To provide incentive bonuses to encourage workers to participate more actively
												VI	Resources (people) System operations in handling human resources	
												VII	Performance Performance in regards to the system and handling methods	

Table 4: Experts profiles.

No.	Title	Work experience (yrs)	No.	Title	Work experience (yrs)
1	Project manager	30	11	Senior engineer	13
2	Project manager	23	12	Senior engineer	30
3	Project manager	27	13	Senior engineer	30
4	On-site manager	30	14	Senior engineer	31
5	Deputy of on-site director	15	15	Senior engineer	32
6	Assistant president	25	16	Chief engineer	40
7	Safety & hygiene officer	20	17	Planning engineer	23
8	Senior engineer	11	18	CEO of construction company	30
9	Senior engineer	12	19	CEO of construction company	28
10	Senior engineer	12	20	Electromechanical manager	28

4.2.2. System Operation of Experimental Group. Based upon the interface information from the collected cases, this study then conducted the system operation for the experimental group. By following the initial definition of 39 features of interface-related contradiction matrix depicted in Table 2, for each interface problems, the improving and worsening features are selected and defined based upon the interface problem characteristics. After the improving feature on the vertical axis of the matrix and the worsening feature on the horizontal axis are defined, the principle for solving the interface problem is recommended from the contradiction matrix table.

The key procedures for the operation of the experimental group are to determine the contradiction situation of interface management. It is necessary to reveal the root cause of the interface problem and to understand the interface management features for improvement as well as degeneration prevention. Subsequently, the recommended interface solution that meets the situation can be acquired. As for finding the root cause of the interface problem, it can use the approach of asking several questions regarding the interface problem to approach the core of the problem and to improve the core contradiction of the problem substantially.

In the aforementioned interface case, the apparent cause of the problem is the insufficient construction time for hydropower piping construction (Why 1). The reason for the observed problem is the shortage of manpower of the other subcontractor (Why 2). The reason for the shortage of manpower is that subcontractors cut down manpower with the consideration of cost reduction (Why 3). Based upon such a drill-in survey, it is realized that the cost should be well managed, and thus, the interface feature No. 22 (i.e., Waste of the costs) is selected. Correspondingly, the impact on the construction schedule should be avoided when manpower is reassigned, and hence, the interface feature No. 25 (i.e., Time consumption) is selected. The general rules for solving the problem can be found in Table 5.

4.3. Evaluation for the Contradiction Matrix of Interface Management. In order to verify and improve the suitability of the aforementioned interface-oriented transformation of contradiction matrix, this research adopted the theory of information retrieval (IR) to study the quality of interface feature transformation and to continuously conduct improvement. As stated above, the two IR performance indices, precision and recall, are used to analyze the similarity between the control group and the experimental group so as to improve the quality and applicability of the proposed framework if necessary. When calculating the precision and recall, it is required to calculate the matched number between the experimental and the control group for an interface problem. The contradiction matrix is composed of forty principles and thirty-nine features. Their relationships are many to many. The principles can be regarded as the function of features. The similarities among the principles are measured based upon the distances between features behind the principles. Nevertheless, TRIZ features are regarded as categorical values. Commonly used numerical clustering method, K-mean, cannot be directly applied. This study separately conducted the cluster analysis on the improving features and the worsening features through K-mode clustering method [53]. The dissimilarity measure between two principles can be defined by the total mismatches among the corresponding categorical features of the two principles. The smaller the number of mismatches, the more similar the two principles are. Based upon the clustering results of the two groups, the study recombined them into seven subgroups, in which they are similar functions in terms of features (as shown in Table 6). When calculating the precision and recall for each case, if the results of the control group and the experimental group are in the same subgroups, they match each other.

This study collected 589 practical cases of interface management among the entire construction lifecycle for the purpose of comprehension. The phases of collected cases and the corresponding coverage are listed as follows: the planning and design phase (11.2%), the construction phase (70.6%), and the operation and maintenance phase (18.2%), respectively. Also, the fields of collected cases cover civil engineering (8.8%), architecture (26.7%), electromechanical (25.6%), decoration (17.5%), equipment (19.0%), and landscape construction (2.4%). The relevant graphical results are shown in Figure 3.

On the basis of the above-mentioned 7 cluster groups, this study compared and evaluated the matched number between the control group and the experimental group. An illustrated example is shown in Table 7. The solution principles for the control group are 10, 17, 19, and 35, and they belong to subgroups 1 and 2. The solution principles for the experimental group are 10, 19, 35, and 38, and they also belong to subgroups 1 and 2. Because both of the solution principles locate in the same subgroup, they are considered as a total match. After the analysis of the collected 589 practical cases, the precision is 66%, and the recall is 42%. As stated in Section 3.3, the acceptable precision and recall is 60% or above, which indicates that the initial framework needs to be further adjusted.

Table 5: Cases of system operations for interface problems.

Item no.	Activity	Task	Potential interface problems	Potential causes	Interface participants: Business owner	Contractor	Design unit	Supervising unit	Subcontractor A	Subcontractor B	Description	Recommended corrective action		
No.	Building construction	Floor	The grouting construction cannot be conducted due to insufficient construction time for hydropower piping construction	Manpower insufficient	X	X	X	X	○	○	Description of the contradiction: while simplifying manpower, it should avoid affecting the construction schedule	I	Timeline The entire system and timeline of the conducting event is a major relation	To convene a meeting to discuss enhancement the improvement plan with related subcontractors
												II	Implementation Under the entire system structure, the way of performing the operations	To adjust the practical route and overlap the construction flow, so that the workers can enter the site early for work
												III	Organization Organizational type of the system operation	
												IV	Change status Change the operation, direction, space, or environmental status of the current system	To flexibly change the grouting operation and label the completed pipes with colors to clarify the grouting area
											Problem attribute: construction stage on the site	V	Management integration Management and handling method in the system	To provide incentive bonuses to encourage workers to participate more actively
												VI	Resources (people) System operations in handling human resources	
												VII	Performance Performance in regards to the system and handling methods	

Table 6: The invention principle and cluster groups for the contradiction matrix of interface management.

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
(i) Group and disassembling WBS (1)	(i) Unbalanced adjustment, increased subversion (4)	(i) Integration, cooperation, heterogeneous complement (5)	(i) Diversified operations and multiple functions (6)	(i) Initiate external management and make adjustments in advance (9)	(i) Implement quickly (21)	(i) Feedback, rotation (23)
(ii) Transform (2)	(ii) Change to a new status, environment (17)	(ii) Duplication and flexible organization, overlapped manpower (7)	(ii) Preventive measures, lesson learned (11)			(ii) Homogeneity (33)
(iii) Partial integration (3)	(iii) Self-assistance, self-sustain (25)	(iii) External manpower resource (8)	(iii) Change the function without changing the organization (12)			
(iv) Management and preparation in advance (10)	(iv) Change direction, status (36)	(iv) Multiaspect management (14)	(iv) Turn the resistance into the helping force (22)			
(v) Reverse and counter process (13)	(v) Provide power resource (38)	(v) Continuous and effective implementation (20)	(v) Intermediary, mediator (24)			
(vi) Flexibility (15)	(vi) Strengthen and motivate internal functions (37)		(vi) Flat organization (30)			
(vii) Reduce or increase management (16)			(vii) Multiaspect organization (31)			
(viii) Stimulation and inspiration (18)			(viii) Cold treatment (39)			
(ix) Cycle and build a loop (19)						
(x) Duplicate (26)						
(xi) Dispose after usage, ordered operation, temporary tasks (27)						
(xii) Substitution (28)						
(xiii) Soft appeal, buffer (29)						
(xiv) Color management, classification management, benchmark management (32)						
(xv) Continue after rest (34)						
(xvi) Change condition or participant (35)						
(xvii) Composite organization (40)						

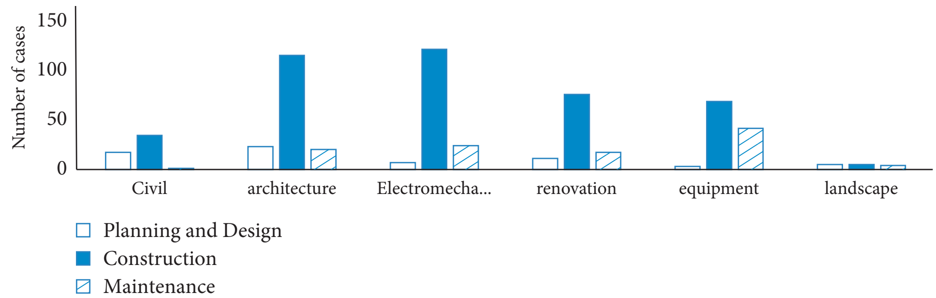

Figure 3: Statistics of the test cases.

Table 7: Comparison and evaluation of the experimental group and control group.

Item no.	I control group: Interface problems	I control group: Experience solutions 40 invention principles (control group) — 7 cluster grouping	I control group: Control group answers	II experimental group: 39 interface management features — Improving feature	II experimental group: 39 interface management features — Worsening feature	II experimental group: 40 invention principles (experimental group) — 7 cluster grouping	II experimental group: Experimental group answers	III information retrieval: Precision	III information retrieval: Recall
No.	Accident of excavation construction	10 17 19 35 1 2 1 1	1, 2	21	15	10 19 35 38 1 1 1 2	1, 2	100%	100%

4.4. Refinement of the Contradiction Matrix of Interface Management. After the interview and the discussion with many experienced engineering experts, the basic reasons for low precision and recall are the ambiguous cognition for the definition and operation of the 39 interface features. The 39 features were gradually modified based on the aforementioned process. After the two-cycle refinement, the final precision and recalls were up to 80% and 62%, respectively (as shown in Figure 4). For the further statistical analysis of the entire cases on the basis of recall, the number of cases with 100% precision occupied 71%, and the precision of 50% and above are 93% (as shown in Figure 5). As shown in Section 3.1, the customer satisfaction rate of TRIZ is around half. This means that the TRIZ-analogic construction interface problem identification and solutions framework proposed by this study is able to provide satisfactory solutions in practice.

Through the aforementioned refinement steps, the original TRIZ contradiction matrix features and invention principles are transformed into the contradiction matrix used for identifying and solving the construction interface problems. They had reached the level of stable operation and practical application through the operations, analysis, and continuous refinement using large amounts of practical cases under the support of experienced engineers and managers. The identification and solution framework of the generalized construction interface management has the same structure as the typical TRIZ; however, the original physical features and invention principles are modified so that the features and the solution principles are suitable for

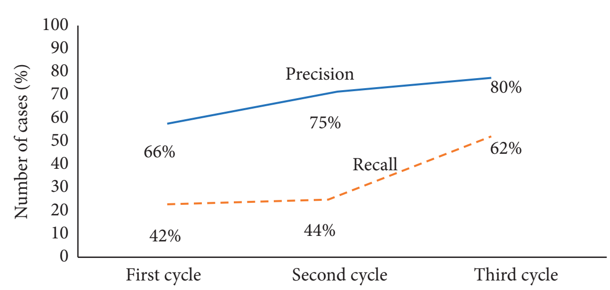

Figure 4: System optimization and enhancement trends.

the construction interface problems, as shown in Tables 8 and 9, respectively.

5. Operations of Triz-Analogic Interface Problem Identification and Solutions Framework

The procedure of the proposed TRIZ-analogic construction interface problem identification and solutions framework is given as follows, which is similar to the operation of a typical TRIZ contradiction matrix. First of all, the interface problem is defined and described, possibly with the aid of WBS. If there are several interface problems, they shall be discussed separately. After clarifying the core of the interface problem, the next step is to define the suitable improving features, which are helpful to correctly identify the interface problem, selected from the 39 interface management features, given in Table 8. Subsequently,

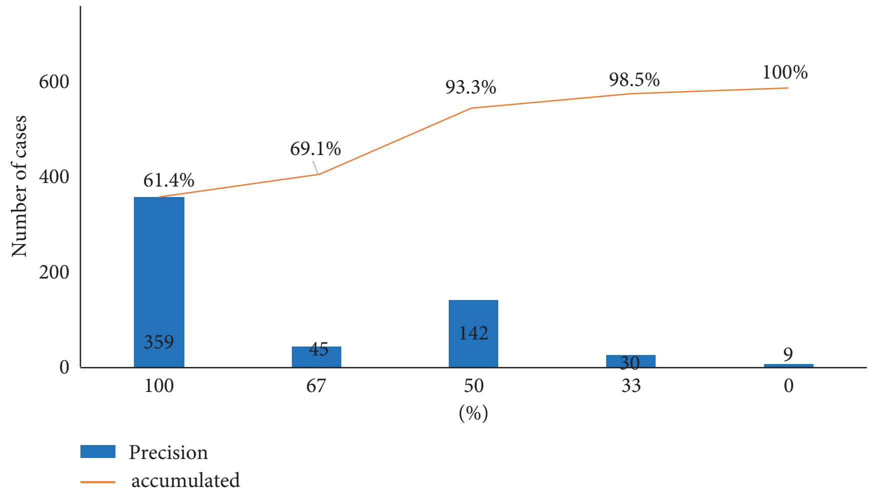

Figure 5: Precision distribution after system revision.

Table 8: Adjustment table of interface management features.

No.	Engineering feature	Management feature	No.	Engineering feature	Management feature
1	The weight of moving objects	Field personnel's capabilities	21	Dynamic force, power	Management efficiency of the organization team
2	The weight of fixed objects	Office staff's capabilities	22	Waste of energy	Waste of cost
3	The length of moving objects	Field personnel's internal management capabilities	23	Waste of resources	Waste of manpower dispatch
4	The length of fixed objects	Office staff's internal management capabilities	24	Waste of information	Loss of information
5	Area of moving objects	Field personnel's ability of managing parallel units	25	Waste of time	Time consuming
6	Area of fixed object	Office staff's ability of managing parallel units	26	Amount of materials	Structure of human resources
7	Volume of moving objects	Field personnel's ability of managing other units	27	Reliability	Comprehensiveness of achievements
8	Volume of fixed objects	Office staff's ability of managing other units	28	Precision of measurement	Target quality
9	Speed	Operational efficiency of the organization	29	Precision of manufacturing	Target precision
10	Power	Management capabilities of the organization team	30	Harmful impact on objects	Affected by errors during implementation
11	Tension, pressure	Pressure resistance capabilities of the organization team	31	Harmful factors generated by objects	Errors generated during implementation
12	Shape	Form of the organization team	32	Easy manufacturability	System is easy for implementation
13	Object stability	Operational stability of the organization team	33	Usage convenience	Convenience of implementation
14	Strength	Demonstration of organization team's capabilities	34	Easy repairability	Convenience of modification
15	Durability of moving objects	Demonstration of field personnel's ability	35	Suitability/adaptability	Smoothness of the manage mechanism
16	Durability of stationary objects	Demonstration of office staff's ability	36	Device complexity	The impact of organization complexity
17	Temperature	Centripetal degree of the organization team	37	Control complexity	Difficulty of management and control
18	Brightness	Achievement of the organization team	38	Degree of automation	Achievement rate of self-management
19	Energy consumption of moving objects	Costs of field personnel	39	Production ability	Production amount
20	Energy consumption of fixed objects	Costs of office staff			

Table 9: Modification table of interface problem solution principles.

No.	Engineering invention principles	Management invention principles	No.	Engineering invention principles	Management invention principles
1	Segmentation	Grouping, disassembling WBS	21	Quick action	Implement quickly
2	Separation	Transform	22	Turn harmful into beneficial	Turn the resistance into the helping force
3	Local characteristics	Local integration	23	Feedbacks	Feedback, rotation
4	Asymmetry	Unbalanced adjustment, increased subversion	24	Intermediary	Intermediary, mediator
5	Combination	Integration, cooperation, heterogeneous complement	25	Self-assistance	Self-assistance, self-sustain
6	Multifunction	Diversified operations and multiple functions	26	Duplication	Duplication
7	Nest structure	Duplication and flexible organization, overlapped manpower	27	Disposable	Dispose after usage, ordered operation, temporary tasks
8	Antigravity	External manpower resource	28	Mechanical system replacement	Substitution
9	Precounteraction	Initiate external management and make adjustments in advance	29	Use of gas or liquid	Soft appeal, buffer
10	Anticipation	Management and preparation in advance	30	Elastic shell and film	Flat organization
11	Premitigation	Preventive measures, lesson learned	31	Porous materials	Multiaspect organization
12	Equipotential energy	Change the function without changing the organization	32	Color change	Color, management
13	Reverse	Reverse and counter process	33	Homogeneity	Homogeneity
14	Curve level	Multiaspect management	34	Disappear and regeneration	Continue after rest
15	Dynamic	Flexibility	35	Change of parameters	Change condition or participant
16	Not sufficient or excessive effect	Reduce or increase management	36	Phase transition	Change direction, status
17	Transform into a new space	Change to a new status, environment	37	Thermal expansion	Strengthen and motivate internal functions
18	Mechanical vibration	Stimulation and inspiration	38	Use of strong oxidants	Provide power resource
19	Periodic action	Cycle, build a loop	39	Passive environment	Reduce the interactive association
20	Continuous and useful actions	Continuous and effective implementation	40	Composite materials	Composite organization

at this step, the worsening features that cause harmful results are defined. With these two features, the solution principles for interface problems, given in Table 9, can be obtained through TRIZ-analogic construction interface problem identification and solutions matrix. According to the solution principles, it is possible to develop suitable practical solutions for the construction interface problem under the guide of the principles mixed with the characteristics and conditions of the practical interface problem. The followings are four practical cases to illustrate the applications of the TRIZ-analogic construction interface problem identification and solutions framework. Relevant results are collected in Table 10.

The scenario of case one is that a contractor could not actually start to work according to the contract, and the construction duration reduced (as shown in Table 10). After the investigation, the actual situation is that it is necessary to accelerate the promotion of the project in order to meet the requirement of the tight construction period. In search of the problem solutions, it is necessary to prevent the schedule delay while reducing the impact of the management organization due to a manpower increase. After understanding the root cause of the aforementioned interface problem, the operational efficiency of the organization (the improving feature No. 9) and the impact of organization complexity (the worsening feature No. 36) are selected and defined based upon Table 9. Through the above-mentioned interface-related matrix, the recommendations extracted from the 40 interface solution principles are given as follows: (1) Principle 10: management and preparation in advance; (2) Principle 28: substitution; (3) Principle 4: unbalanced adjustment, increased subversion; and (4) Principle 34: continue after rest.

On the basis of the generalized interface problem-solving principles, the construction managers may develop several possible practical solutions for the interface problems: (1) to plan the process in advance, arrange the movement path, and coordinate the sequence according to principle 10; (2) to develop alternative solutions to increase work rates according to principle 28; and (3) to provide more resources, construction area or manpower to the critical path procedure according to principle 4.

Table 10: Operations for the interface management contradiction matrix: case 1–4.

No.	Life cycle phase	Interface problem	TRIZ-analogic construction interface problem identification and solutions framework: 39 interface management features — Improving feature	Worsening feature	40 solution principle	Practical problem solutions
1	Construction	A contractor could not actually start to work, and the construction duration reduced	Operational efficiency of the organization (9)	The impact of organization complexity (36)	10	Management and preparation in advance
					28	Substitution
					4	Unbalanced adjustment, increased subversion
					34	Continue after rest
2	Construction	Accident of excavation engineering	Management efficiency of the organization team (21)	Demonstration of field personnel's ability (15)	10	Construction environment and safety equipment, put efforts in safety education and hazard identification
					35	The temporary wooden support should be added for labor safety facilities
					19	The workers must be cautious at all time
					38	Provide a safe construction environment
3	Design	The business owner found that the budget items were inconsistent with the drawings of the contract	Target quality (28)	Form of the organization team (12)	6	The designers should have basic budgeting knowledge
					28	Acknowledge the error and make announcement after correction
					32	Include the deficiency in the key item of follow-up inspection to prevent recurrence
4	Operation	A dangerous bridge caused by erosion of foundation	Comprehensiveness of achievements (27)	Waste of cost (22)	10	Develop the management level of bridge risk
					11	Establish a mechanism for automatic bridge safety monitoring
					35	Create an early warning system

All of the above practical suggestions for the first interface problem are feasible. This indicates that TRIZ-analogic construction interface problem identification and solutions framework developed in this study may be suitable for practical applications. In order to demonstrate the comprehensiveness of the proposed framework, this study carried out the operations on three more cases at different lifecycle stages (refer to Table 10). The test results indicated that the practical solutions can be acquired under the guide of TRIZ-analogic construction interface problem identification and solutions framework. The practicability and the comprehensiveness of the framework developed by this research are further verified.

6. Conclusions and Future Development

The construction management interface problem frequently and randomly occurs. However, the previous researches have not developed reasonable identification logic for interface problems and the generalized solution principles for the interface problems. In view of this, this research referred to the innovative problem-solving method of the TRIZ contradiction matrix and proposed a TRIZ-analogic construction interface problem identification and solutions framework. There are several research outcomes in this study. First, a convenient and flexible implementation matrix form of construction interface problems solving are generated for real practice, not just to explore solutions based on experiences. This assists and inspires the project managers to think of potential solutions when encountering practical interface problems. Secondly, this study integrated the concept of double-blind clinical experiments in medical science and the theory of IR to develop a rigorous process, including transformation, validation, and revision. This process may provide fundamental architecture for the system conversion, which does not depend on intuition and experiences. Lastly, the proposed TRIZ-analogic framework is developed based upon real practice in construction engineering, which not only provides systematic interface identifications but also generates newly increased potential solutions different than traditional experience-oriented solutions.

Although the research on this innovative identification and solution framework for the interface problems has already achieved the preliminary but significant results, it is still necessary to refine the framework to be more applicable and effective. In the course of future research, it is recommended to persistently collect and accumulate cases of construction interface problems because the amount of cases plays a key role for the maturity of the system, just as the development of original TRIZ. Furthermore, the connection between the solution principles of the construction management interface problems and practical measures still relies on the practical experience and the brainstorming of engineers and project managers. If a solution database of practical interface problems can be established in the future, the interface problems and real solutions can be conducted in a more thoughtful and systematic way, so that the construction interface problems can be resolved in a more effective and diverse way.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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