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Developing a knowledge management system for improved value engineering practices in the construction industry

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ABSTRACT

This paper has developed a value engineering knowledge management system (VE-KMS), which applies the theory of inventive problem-solving and integrates its creativity tools into the creativity phase of the VE process and thus makes the creativity phase more systematic, more organized and more problem-focused. This attempt will significantly enhance the creativity power of the VE team beyond their collective capability and consequently enhance the efficiency and effectiveness of the VE exercise. The data of a number of sample VE exercises has been extracted and stored in the database to test the validity of the information schema of the VE-KMS, and the domain knowledge is condensed and coded into a broad scope of ten disciplines to increase the utility of the VE-KMS. Furthermore, a transport interchange project is used to demonstrate the application of the VE-KMS.

1. Introduction

Value engineering (VE) is a management tool to achieve essential functions of a product, service or project with the lowest cost. VE has become a standard practice for many government agencies and private engineering firms and contractors since its first adoption in the 1950s. It has been widely practiced in the construction industry and become an integral part in the development of many civil infrastructure projects.

VE has been practiced for half a century in the construction industry with an aim to produce innovative ideas and solutions for enhanced project value. Surprisingly, little research has been done on how to reutilize the ideas and solutions generated in previous VE studies for future projects and share the VE knowledge in the entire company or the whole industry. The construction industry is still practicing VE in the same fashion as it was 50 years ago. Each VE study starts from scratch and its success solely relies on the VE team members' experience and competence. Past experience has shown that the VE study has led to cost savings of 5–10% for a wide range of construction projects. However, there is no significant result from the VE study in a number of other construction projects. This may be one of the reasons that the overall public opinion on VE is controversial as shown in the Engineering News Record's website poll, in which about half of the respondents think VE is a valuable constructability tool whereas around 43% of the respondents consider it as a marketing ploy.

There is a need to improve the efficiency of the VE practice for better outcomes. One approach is to develop a knowledge management system (KMS) to support the knowledge creation process, code and retain ideas from historical VE studies, and share this valuable information. This KMS will avoid reinvent the wheel and reduce redundant work in future VE studies. In addition, innovative problem-solving tools can be built in the KMS to further enhance the efficiency and effectiveness of the VE study. The writers have thus conducted a research and consequently developed a VE knowledge management system (VE-KMS) for VE knowledge acquisition, representation, and retrieval. In this system, the theory of inventive problem solving (TRIZ) is applied to the creativity phase of VE to make it more systematic and more organized and to enable the VE team to control the creativity process.

TRIZ is a methodology and tool set for generating innovative ideas and solutions for problem solving [1]. It is believed that the incorporation of TRIZ tools in the VE process will significantly enhance the creative power of the VE team beyond their collective knowledge and imagination power, and improve the efficiency and effectiveness of the VE study in generating innovative and practical ideas and solutions to the problems of a project under consideration.

2. Knowledge management in the construction industry

There are two categories of knowledge, explicit and tacit [22]. In the construction industry, explicit knowledge refers to documented information such as project information, design drawings and specifications, cost reports, risk analysis results, and other information being collected, stored, and archived in paper or electronic format. Tacit knowledge is the experience and expertise kept in the construction professional's mind, company culture, lessons learned, know-how, and other elusive yet valuable information [17].

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Knowledge will not bring any value unless it is used actively. A KMS is useful in actively using existing knowledge (whether explicit or tacit) to create value. Knowledge management is a process to create, secure, capture, coordinate, combine, retrieve, and distribute knowledge [17]. The effective application of existing knowledge can create innovation, and improve business performance and client satisfaction whereas the failure to capture and reuse the knowledge kept in previously accomplished projects will increase the likelihood of reinventing the wheel and consequently lead to the waste of resources and the loss of profits [13,14].

Knowledge management is particularly important in the construction industry. First, the construction industry is extremely competitive due to tight construction schedule, low profit margins, and the complexity, diversity and non-standard production of construction projects. Effective knowledge management will facilitate the generation of new technologies and processes, which will improve the industry's productivity, profitability and competitiveness [6,23]. This is confirmed by Carrillo and Chinowsky [4] in their survey on contractors in the United Kingdom, which indicated that the application of a KMS had resulted in new technologies and processes. Second, the construction industry is a project-based industry, much more fragmental than many other industries. The formation of a project team (including engineering, procurement and construction professionals) is temporary and project specific. Without a KMS, it is difficult to reuse a professional's knowledge if he/she leaves the company or if he/she is not a team member of a new project even if he/she still in the company.

3. Theory of inventive problem solving

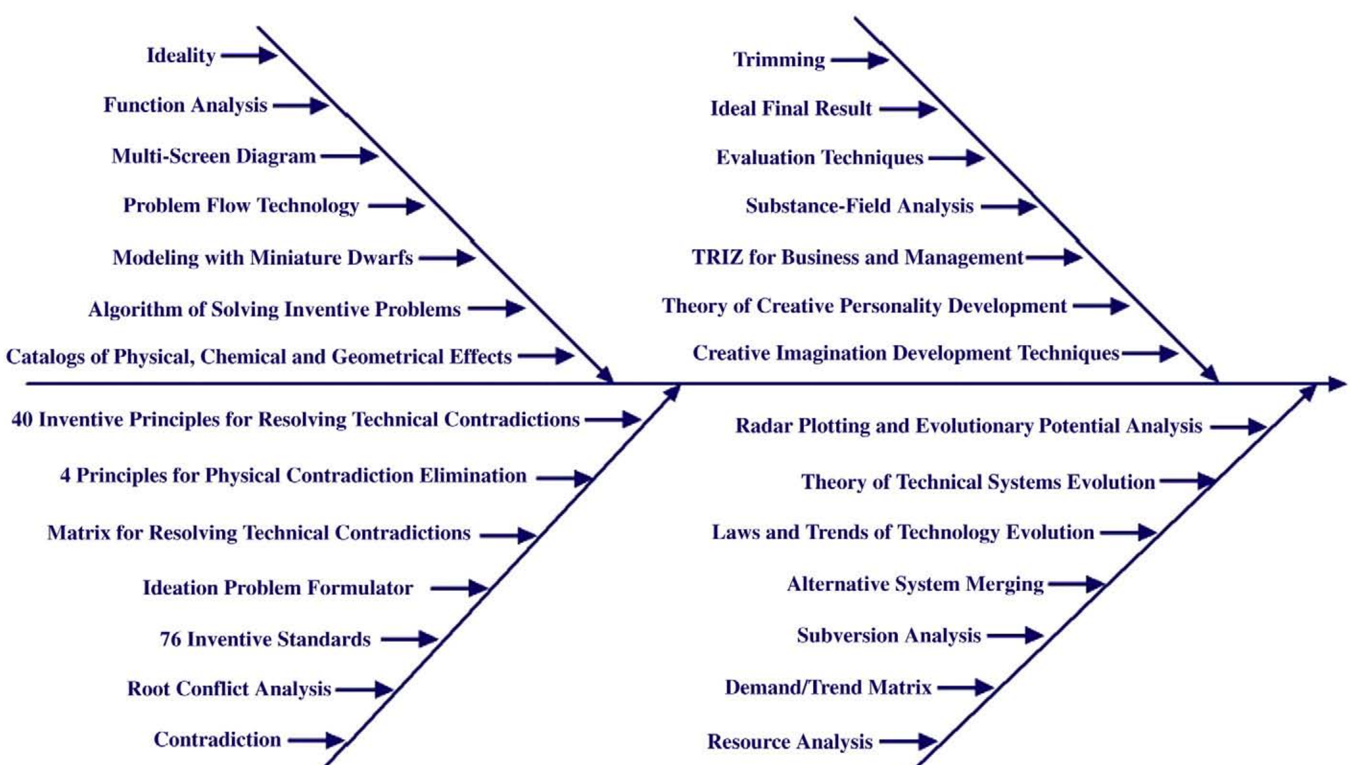
3.1. TRIZ concepts and tools

TRIZ is a romanized acronym of Russian "Theory of Inventive Problem Solving", which is a body of knowledge for inventive problem-solving that has been developed by TRIZ researchers through abstracting and generalizing the world's most genius innovation principles after examining over 2.5 million international patents. TRIZ researchers hold that (1) the advancement of inventions obeys certain universal principles of creation, (2) all innovations across industries and sciences follow a handful number of inventive principles, (3) technology evolves according to certain trends, (4) the idealization of a solution is a process to destroy conflicts and trade-offs or to transform harmful elements of a system into useful resources [7]. As a result, TRIZ researchers have developed a group of interrelated concepts and knowledge management tools in an attempt to assist inventors in finding ideal solutions in a relatively simple and predictable way.

As schematically illustrated in Fig. 1, TRIZ contains a number of concepts and tools that provide systematic approaches and generic principles to formulate and analyze problems, generate creative ideas, and forecast the evolution trend of a system or project. One great advantage of TRIZ is that it can overcome psychological inertia, which represents the barriers against personal creativity and problem-solving ability. TRIZ allows problem solvers to generate creative ideas and solutions beyond their own knowledge, experience and expertise [8].

3.2. General problem-solving model of TRIZ

TRIZ tools follow the general problem-solving model as demonstrated in Fig. 2. Instead of directly seeking for solutions to solve the current problem, TRIZ first identifies the current problem in the system. Then, this particular problem is abstracted into one of the three types of standard problems: (1) a technical contradiction, (2) a physical contradiction, and (3) a substance-field model. Next, a couple of standard solutions may be found for this particular problem by examining all the standard solutions provided by TRIZ for that type of standard problems. For example, there are seven standard solutions to solve a substance-field problem [20], 40 inventive principles to solve the technical contradiction problem, and four separation principles to



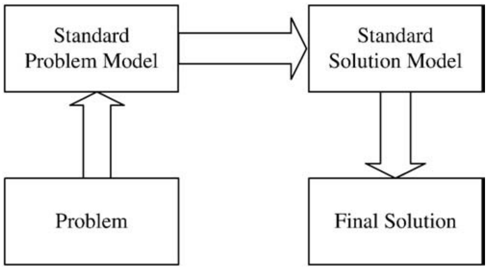


Fig. 2. General problem-solving model of TRIZ.

solve the physical contradiction problem. After that, the standard solutions are evaluated against the nine technological evolution trends to further enhance the ideality of the standard solutions. Finally, the problem solver will come out with a solution that is practical to the particular problem based on his/her experience and expertise.

The biggest challenge lies in the transformation of the generic principles/solutions of TRIZ into domain-specific solutions. As Mohamed [21] stated, those generic principles/solutions only indicate the directions where the most effective solutions could possibly exist, but the success to find a practical solution mainly depends on the ability of the problem solver. This difficulty explains one of the writers' motivations to conduct this research. By capturing the innovative ideas/solutions to various problems in previous VE studies in a knowledge database, the writers hope to facilitate VE team members to efficiently and effectively find out practical solutions.

4. Improving the value engineering process

4.1. Value engineering process

VE is a structured problem solving process based on function analysis to improve the value of a system. Value is defined by a ratio of function to cost and consequently it can be increased by either improving the function or reducing the cost. The VE study is normally conducted by a team of members of multi-disciplinary experience and expertise. First, the VE team establishes the functional relationships in a system through a "how–why" questioning technique. Then, the VE team develops a matrix of the various functions of the system against their associated costs. The value of the system is maximized by an optimal tradeoff between the functions and their associated costs. In the context of construction, the objective of the VE study is to achieve the necessary functions with the lowest project life cycle cost. This may be done through the use of new material, creative design, simplified construction process, innovative construction method, reduced construction cost and time, improved construction quality and safety, and minimal environmental impacts.

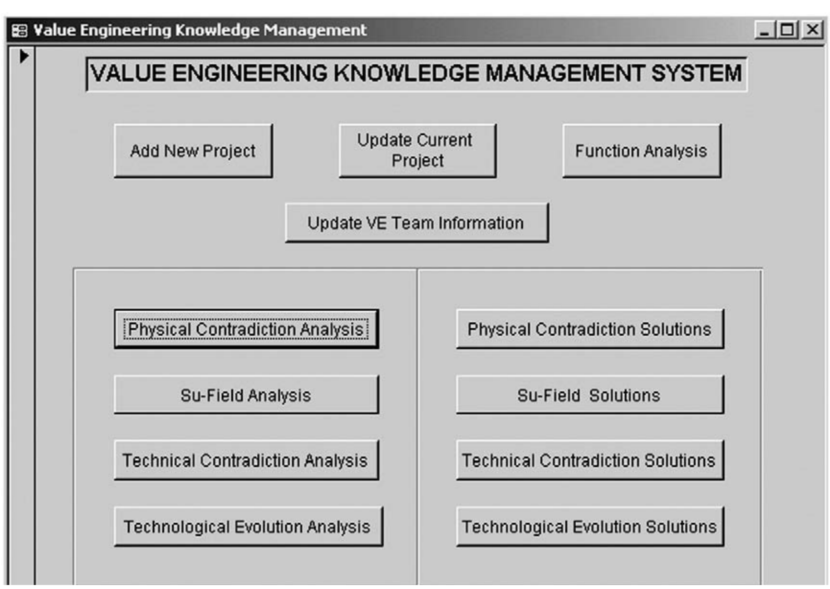
A VE study includes three sessions, pre-workshop, workshop and post-workshop. Each session in turn has some phases. For example, the workshop session includes three phases: information and function analysis phase, creativity phase and evaluation phase. It is generally recognized that the creative phase of the workshop is the most critical phase that determines the success or failure of a VE study because it is in this phase that creativity techniques are applied to generate innovative ideas for enhanced project functions and reduced project costs.

4.2. Shortcomings of traditional value engineering studies

A traditional VE study mainly relies on free-thinking techniques (e.g., the brainstorming technique) to generate creative ideas and solutions, and it usually starts from scratch without adequately utilizing the knowledge and results generated from previous VE studies partly because the lack of a KMS. Obviously, the chance of generating an innovative solution is limited by the current VE team members' experience, knowledge and creativity. Furthermore, in a traditional VE study, little effort is made to understand the essential problems of a project. Therefore, there is no guidance on the direction in which the search for effective and robust solutions is efficient. To overcome these shortcomings, it is proposed in this paper to incorporate the TRIZ tools in the creativity phase of the VE study to make this phase more systematic and more organized and enables the VE team to control the creativity process. This attempt will significantly enhance the creative power of the VE team beyond their collective knowledge and imagination power, which is confirmed by Clarke [5], Hannan [12] and Sawaguchi [26] who believe that TRIZ has the potential to generate more innovative ideas and enhance the efficiency and effectiveness of the VE study.

4.3. Value engineering knowledge management system

As shown in Fig. 3, the VE-KMS is developed by integrating TRIZ tools into the creativity phase of the VE process. The TRIZ tools incorporated in



the VE-KMS include (1) technical contradiction analysis, (2) physical contradiction analysis, (3) substance-field analysis, and (4) technological evolution analysis.

The VE-KMS enables VE team members to capture, extract, and convert their engineering experience, expertise, innovative ideas and solutions into explicit knowledge, store it in the database of the system in the process of a VE study, and to continuously consolidate and update the knowledge database over time. VE team members can use this platform to retrieve previous innovative solutions, which may either be reutilized as direct solutions for a new project or provide more discipline-related insights for the generation of new ideas to solve the problems of the new project. Alternatively, VE team members may choose to generate innovative solutions themselves by systematically applying the TRIZ tools. Essentially, the two approaches share the same logic of TRIZ's general problem-solving methodology as shown in Fig. 2.

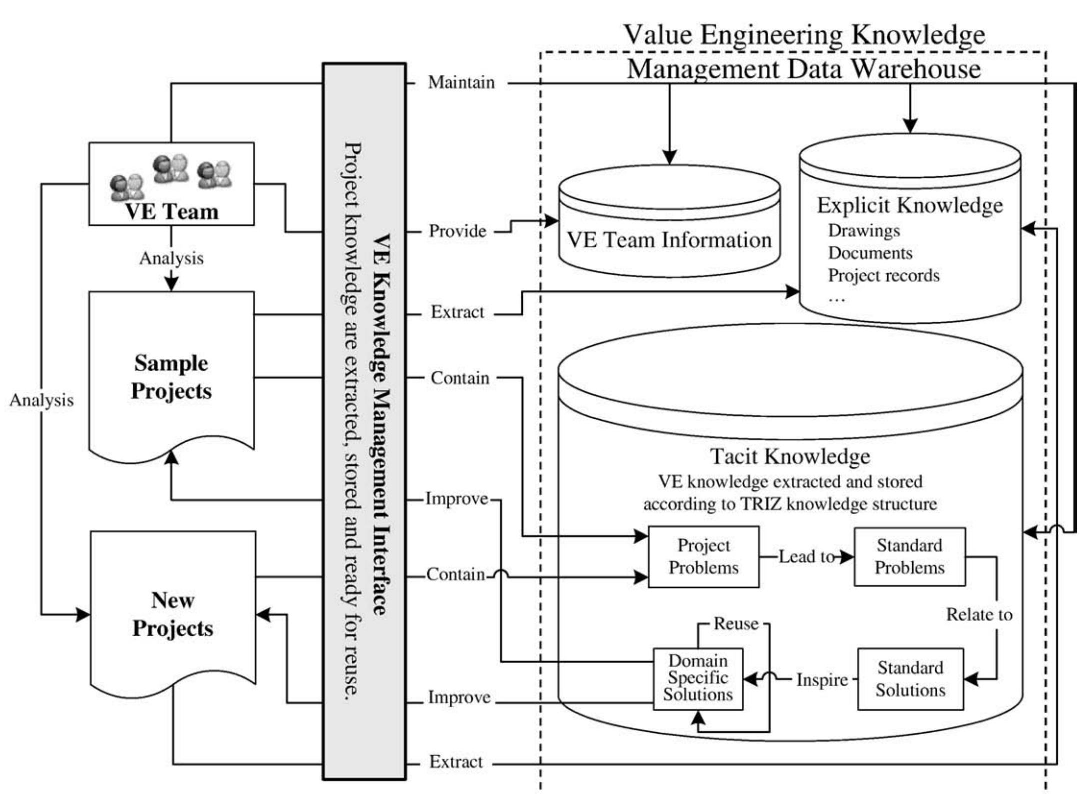
4.4. Knowledge sharing among value engineering team members

An anonymous reviewer of this paper commented that in his/her academic/consulting experience, he/she found that (1) the information phase is also very important as he/she see VE as a jigsaw puzzle where each project team members are holding a few different pieces and (2) unless VE team members are willing to share their knowledge, otherwise it is not possible to have a complete picture of the project, which in turn affects values. The writers concur with this reviewer that knowledge sharing is critical to knowledge creation and consequent value creation. In this regard, Fong [9] reviewed key literature on team processes and knowledge creation, and discussed issues in knowledge creation in multidisciplinary project teams through an empirical study of the processes and their dynamic interrelationships. Chu [10] conducted an exploratory study of knowledge sharing in contracting companies from a sociotechnical perspective, investigated the main barriers, and identified the critical factors for effective knowledge sharing in contracting companies. Fong et al. [11] conducted a case study to explore the nature, processes, and issues associated with fostering a dynamic knowledge creation capability within value management teams. They concluded that: (1) the dynamic knowledge creating process is embedded in and influenced by managing team constellation, creating shared awareness, developing shared understanding, and producing aligned action; (2) open dialogue and discussion among participants are the catalysts that can speed up this process; and (3) the use of facilitators skilled at extracting knowledge can further enhance this process.

5. Architecture of the VE-KMS

5.1. Previous construction knowledge management systems

Many researchers have conducted studies on knowledge management in the construction industry. These studies provide insights on the development of the VE-KMS. For example, Assaf et al. [2] developed a computerized system for the application of the VE Methodology. Mohamed [21] developed a TRIZ-based framework for systematic improvement of construction systems. Fong [9] developed a conceptual model of the knowledge creation process and discussed knowledge creation within the context of multidisciplinary project teams. Mann and Hey [19] proposed a knowledge management schema based on TRIZ concepts to store and access design solutions according to design conflicts solved and principles applied. Soibelman et al. [27] developed a data mining system to collect and store frequently used design review comments, personal experiences and lessons learned on projects. Tserng and Lin [28] proposed a construction activity-based knowledge management concept and system for general contractors. Pulaski and Horman [24] proposed to organize constructability information in accordance with the timing and levels of details required to assist a project team to identify and resolve constructability issues at appropriate time. Zanni and Rousselot [30] studied how to use TRIZ to formalize innovative designs. Fong et al. [11] explored the nature, processes, and issues



associated with fostering a dynamic knowledge creation capability within VE teams.

5.2. Architecture of the VE-KMS

The architecture of the VE-KMS is presented in Fig. 4. The major component of this architecture is the data warehouse, which contains three types of information: VE team information, project explicit knowledge and project tacit knowledge. VE team information includes VE team members' contact information, expertise, and their specific contributions to particular projects. This information will help VE team members seek for support directly from these experts in case the knowledge expressed in the database is not sufficient to solve the current problems. Project explicit knowledge covers project drawings, specifications, records, and other related documentation. This information gives the background of the project so that VE team members can better understand the project and its associated problems for which the solutions are being sought. It also enables VE team members to quickly find relevant experience and lessons from previous projects. Project tacit knowledge consists of know-how, expert suggestions and innovations originated from the current VE study.

5.3. Knowledge extraction and coding in the database

Extracting construction knowledge from a subject matter or a discipline expert is the most challenging step in developing a knowledge base [15]. Without having the core knowledge of construction practices captured and stored in an orderly and retrievable format, it will be time-consuming to find useful information and difficult to apply it in solving problems encountered in new projects. This is partly because every construction project has its uniqueness due largely to the variation of scope of work, specification, geographic location, and disciplinary requirements.

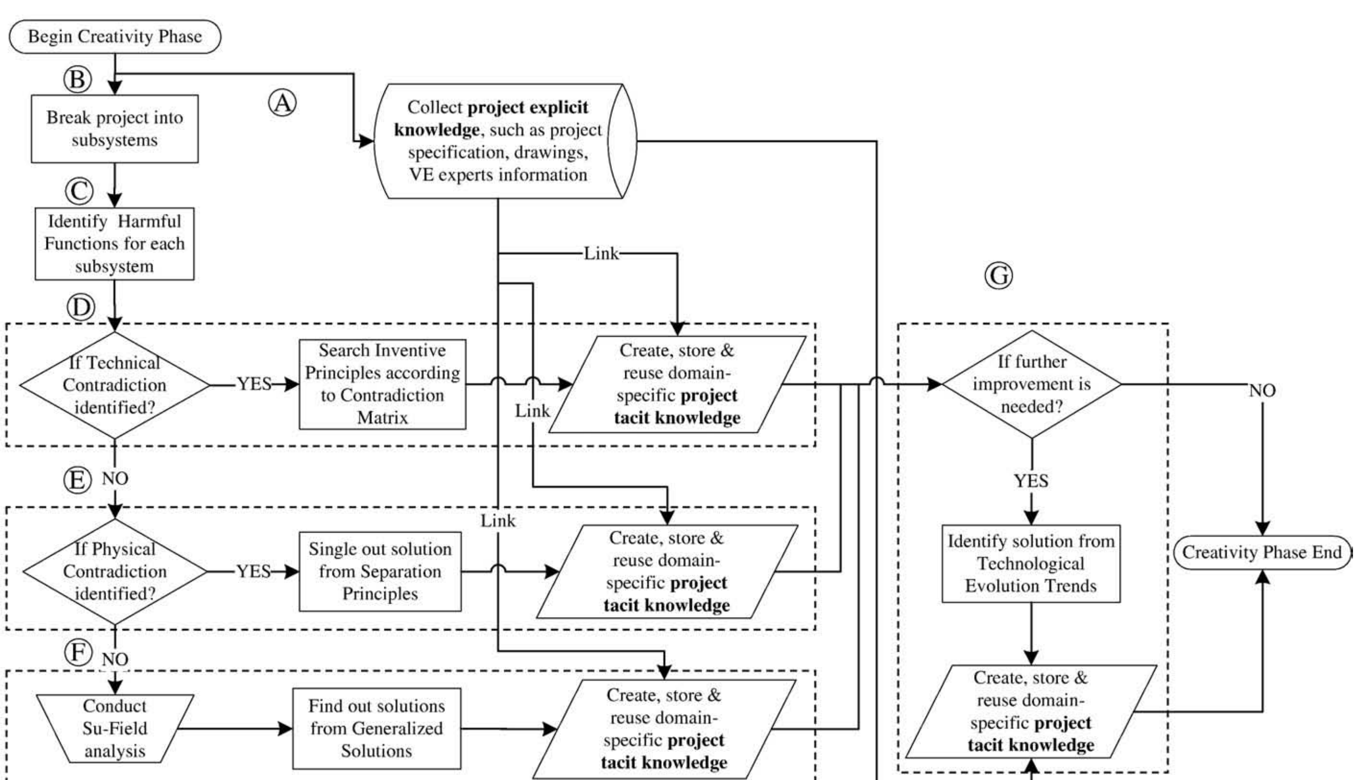
The knowledge obtained from the VE study is extracted and stored in the central database according to the knowledge classification based on four TRIZ tools: (1) nine laws and trends of technology evolution, (2) 40 inventive principles for resolving technical contradictions, (3) four inventive principles for physical contradiction elimination, and (4) 76 inventive standards for substance-field analysis. This means that the knowledge obtained from a VE exercise and the resultant solutions are consolidated and stored in the database according to the TRIZ tools to which the knowledge and solutions mainly belong. In addition, the knowledge and solutions are coded by the disciplines of the project components (e.g., structural, mechanical, plumbing, and electrical components), which can be used to narrow down the search for useful knowledge in future VE studies.

6. Procedures of the improved value engineering creativity phase

As discussed in previous sections, TRIZ concepts and tools are incorporated into the VE-KMS to enhance the creativity phase of the VE process. The procedures to conduct this improved creativity phase are shown in Fig. 5 and the details are discussed in the following.

6.1. Step A: collect project explicit knowledge and VE team information

This step collects and stores the project explicit knowledge and VE team information currently available. The project explicit knowledge is linked to the project discipline-specific solutions obtained from the VE study in the database at the end of the creativity phase. Meanwhile, VE members' contact information and their expertise are attached to their project-specific solutions so that these experts can be easily identified and reached when their knowledge and expertise are needed in the future.



6.2. Step B: break project into subsystems

According to TRIZ, a project consists of a group of subsystems that provide various functions. This step decomposes a project into subsystems down to a level at which project functions can be sufficiently identified and properly analyzed. This can be done based on a hierarchical analysis. For example, a building project could be either broken down based on the disciplines of its components or based on their physical nature (e.g., foundation, floor, wall, and roof). This step facilitates the categorization of various solutions into specific domains to make the knowledge retrieving process more efficient and effective.

6.3. Step C: identify harmful functions in each subsystem

Function analysis in TRIZ is a modification of original function analysis in VE, utilizing the same basic approach to modeling a system in terms of components and functions they deliver [31]. However, "function" in TRIZ has a different definition from that in VE. In TRIZ, function is defined as an effect of a physical interaction between two system components whereas in VE it is regarded as an action performed by a system component. This action is expressed in a two-word abridgment, in which an active verb describes what action is being done and a measurable noun indicates what the action is being done to. Due to this difference, in TRIZ there are the terms of "useful functions" and "harmful functions" while in VE there are the terms of "necessary functions" and "unnecessary functions".

Function analysis of TRIZ has algorithms for ranking functions and formulating problems in the patterns required by other TRIZ problem solving tools. Harmful functions in each subsystem are first identified and then ranked in accordance with the VE team's level of intolerance. The intolerance level may be from 1 to 10, with 10 representing the most intolerable level. This ranking directs the attention and focus of the VE team on the most intolerable harmful functions. As to be discussed in steps D to F, TRIZ tools will be deployed to generate technical solutions to remove the harmful functions or minimize them to a level below a threshold intolerance level, say 7. Different technical solutions will incur different costs. The solutions that have the highest benefit/cost ratios will be selected. Here the benefit means the intolerance level reduced by a particular solution.

6.4. Step D: identify and solve technical contradictions

A technical contradiction represents the conflict between two parameters of a system/subsystem. This contradiction occurs when improving one parameter of a system/subsystem worsens another parameter. This means the measure taken to remove/minimize one harmful function will worsen another useful function. Two examples are: (1) a vehicle has higher horsepower but uses more fuel and (2) an electric vehicle can go long distances between recharging but the battery weight gets too high to move at all. A conventional approach to solve this dilemma is to seek a compromise between the two parameters. However, this is not an ideal solution. To find better solutions, TIRZ has identified 39 engineering parameters and 40 inventive principles, based on which a 39×39 contradiction matrix is developed. In this matrix, the 39 parameters are listed on the horizontal axis in a worsening feature and on the vertical axis in an improving feature, and some of the 40 inventive principles are located at the cross point of the column and row. These inventive principles solve the contradiction represented by the parameters on the corresponding vertical and horizontal axis. Specifically, the corresponding principles improve the parameter on the vertical axis without worsening its counterpart on the horizontal axis. For a particular system/subsystem, once a pair of contradicted parameters is identified, the corresponding inventive principles can be obtained from the contra-

6.5. Step E: identify and solve physical contradictions

A physical contradiction results from incompatible requirements on the same parameter of a system/subsystem, i.e., this parameter is required to be modified in two opposite directions to remove or minimize a harmful function. Two examples are: (1) a highway should be wide for easy traffic flow but narrow for low impact on communities and (2) a frame should be heavy for structural safety but be light for cost and ease of assembly. Physical contradictions do not occur as frequently as technical contradictions. Although a physical contradiction sometimes can be converted to a technical contradiction, it is differentiated as a separate stream for better knowledge management. TRIZ provides four general separation principles to solve physical contradictions: (1) separation in time, (2) separation in space, (3) separation between the whole system and its parts, and (4) separation based on different conditions. These principles guide the directions in finding a solution to a physical contradiction.

6.6. Step F: conduct substance-field analysis

The components of a technical system perform various functions (as mentioned earlier, a function in TRIZ refers to the interaction between two components). There are mainly five types of interactions (useful, harmful, excessive, insufficient, and transformation) among which useful and harmful interactions are the common ones [25]. In substance-field analysis, an interaction is graphically represented by a triangular model after abstractizing the two components and their interaction. As shown in Fig. 6(a), the substance-field model includes two substances (i.e., an object S_1 and a tool S_2) and a field. The field is a kind of energy that acts on the tool to modify its interaction with the object. The field can be mechanical, acoustic, thermal, chemical, electric, magnetic, or electromagnetic. If the field is generated by a hidden substance, the triangle could be simplified into a dumbbell shape with the field indicated on top of the arrow and the interaction indicated underneath the arrow, as shown in Fig. 6(b). A complex system can be modeled using multiple connected substance-field models. In general, there are four basic types of substance-field models [32]: (1) an effective complete system, (2) an incomplete system that requires completion or a new system, (3) a complete system that requires improvement to create or enhance certain useful interaction, and (4) a complete system that requires the elimination of some harmful or excessive interaction.

Once substance-field models are developed, it is possible to identify the system's problems generically through further analysis. Substance-field analysis is often used when a harmful function cannot be explained by a technical or physical contradiction. The objective of such an analysis is to maintain/strengthen useful functions and eliminate/minimize harmful functions. It first checks whether any of the three elements (tool, object and field) of a substance-field model is missing or whether there are undesired interactions in the system. Then, it points out the direction for improving the system. TRIZ recommends 76 inventive standards (typical patterns) for solving problems associated with substance-field models. To facilitate substance-field analysis and increase efficiency, Mao et al. [20] have condensed the 76 inventive standards into seven general ones: (1) completing an incomplete substance-field model, (2) modifying the tool to eliminate or reduce the harmful function, (3) modifying the object to be insensitive or less sensitive to the harmful function, (4) changing the existing field to reduce or eliminate the harmful function, (5) eliminating, neutralizing, or isolating the harmful function using another counteractive

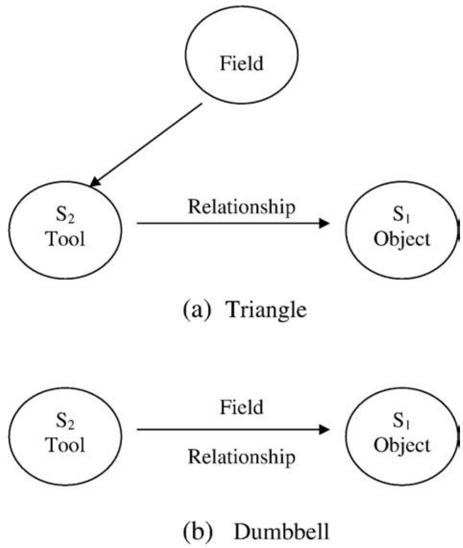


Fig. 6. Basic substance-field model.

6.7. Step G: improve the project according to technological evolution trends

TRIZ holds that a technical system develops according to objective laws that have been used in different fields in various formats for a long time. Consequently, TRIZ condenses these laws into nine evolution patterns: (1) life cycle of birth, growth, maturity and death, (2) systems evolving toward ideality, (3) uneven evolution of system components, (4) increasing dynamism, (5) increasing controllability, (6) increasing complexity, followed by simplicity through integration, (7) matching and mismatching of parts, (8) transition from macrosystems to microsystems, and (9) decreasing human interaction and increasing automation. The nine evolution patterns allow VE team members to transform a subjective system improvement process into a search for the steps to fill the gap between the existing system and the desired system.

7. Data warehouse development

7.1. Entity relationship diagram

The development of a valid information schema is critical for successful knowledge management. The information schema addresses how the comprehensive information repository is organized and formalized on the storage medium for effective and efficient knowledge development [29]. The entity relationship diagram (ERD) is a simple semantic network model for designing a database. The ERD should be designed in accordance with some understandable classification or framework of information [16]. The ERD for the database (developed in Microsoft Access) of the VE-KMS is shown in Fig. 7. Enclosed by the dash line, the entities and relationships are grouped into five blocks corresponding to the five primary components of the VE-KMS: (1) project information collection and function analysis, (2) technological evolution analysis, (3) physical contradiction analysis, (4) technical contradiction analysis, and (5) substance-field analysis. The project information collection and function analysis component decomposes a project into subsystems and identifies their harmful functions. The other four components collect the creative ideas and solutions according to the specific TRIZ tools involved. The creative ideas and solutions

7.2. Coding of domain knowledge in the database

The strength and utility of a KMS depend largely on the quality and scope of the domain knowledge coded into the knowledge base [18]. Reflecting the importance of the domain knowledge, all tables of the database that store practical solutions resulted from VE studies have two common fields, the VE initiator and the domain. The VE initiator documents the name and relevant information of the person who assumes a leadership role in the development of an innovative idea or solution. The domain documents the discipline of the idea or solution. The construction knowledge is categorized into ten disciplines: civil, structural, architectural, piping, mechanical, process, electrical, instrumentation, chemical, and material. The two fields allow a knowledge search to be done by the domain, initiator or the combination of both.

7.3. Some sample interfaces of the database

A few sample database interfaces are provided here to help readers better understand the VE-KMS. Fig. 8 shows the interface that records the information of a project, its subsystems, and the harmful functions of each subsystem. The solutions to these harmful functions that have been generated from individual TRIZ tools are documented using separate interfaces. For example, as demonstrated in Fig. 9, this interface collects the solutions and other supporting knowledge from the substance-field analysis. The database also enables the VE team to use a query to retrieve existing knowledge and solutions to previous problems. As shown in Fig. 10, previous solutions to physical contradictions using the principle "separation based on different conditions" can be retrieved by querying on this principle. The attached document assists the VE team in gaining more information and deeper understanding of a solution. The name of the VE initiator allows the VE team to contact the corresponding expert when needed. Furthermore, the dropdown list of the "Discipline" narrows down the search and only the solutions within a particular domain will be provided.

8. Case study

A transport interchange project is used to demonstrate the application of the proposed VE-KMS. Because of space limitation, only the part of the VE study related to the protection of the existing pipelines underneath the soil of the project area is presented in the following sections.

8.1. Background of the interchange project

The City of Edmonton, Canada has experienced a significant increase of population with the rapid economic growth in recent years. This causes severe congestion during the rush hour in the intersection of the Calgary Trail and the 23rd Avenue and raises serious safety concern. To solve these problems, the City of Edmonton decides to build a grade separated interchange as shown in Fig. 11. This interchange project would allow easy access to surrounding commercial and residential areas and create a free flow condition on the Gateway Boulevard and the connecting main provincial highway #2.

One existing pipeline corridor crossing the project area poses a challenge to the interchange project. This pipeline corridor contains 12 high-pressure gas lines ranging from 50 to 600 mm in diameter, which had been installed between the early 1950's and through the 1980's. There is no detailed information on the precise condition of their coating systems. Most of the pipelines have bends, which likely were made with some sort of fittings. These fittings represent the weak points in the pipelines. Furthermore, the soil overburden

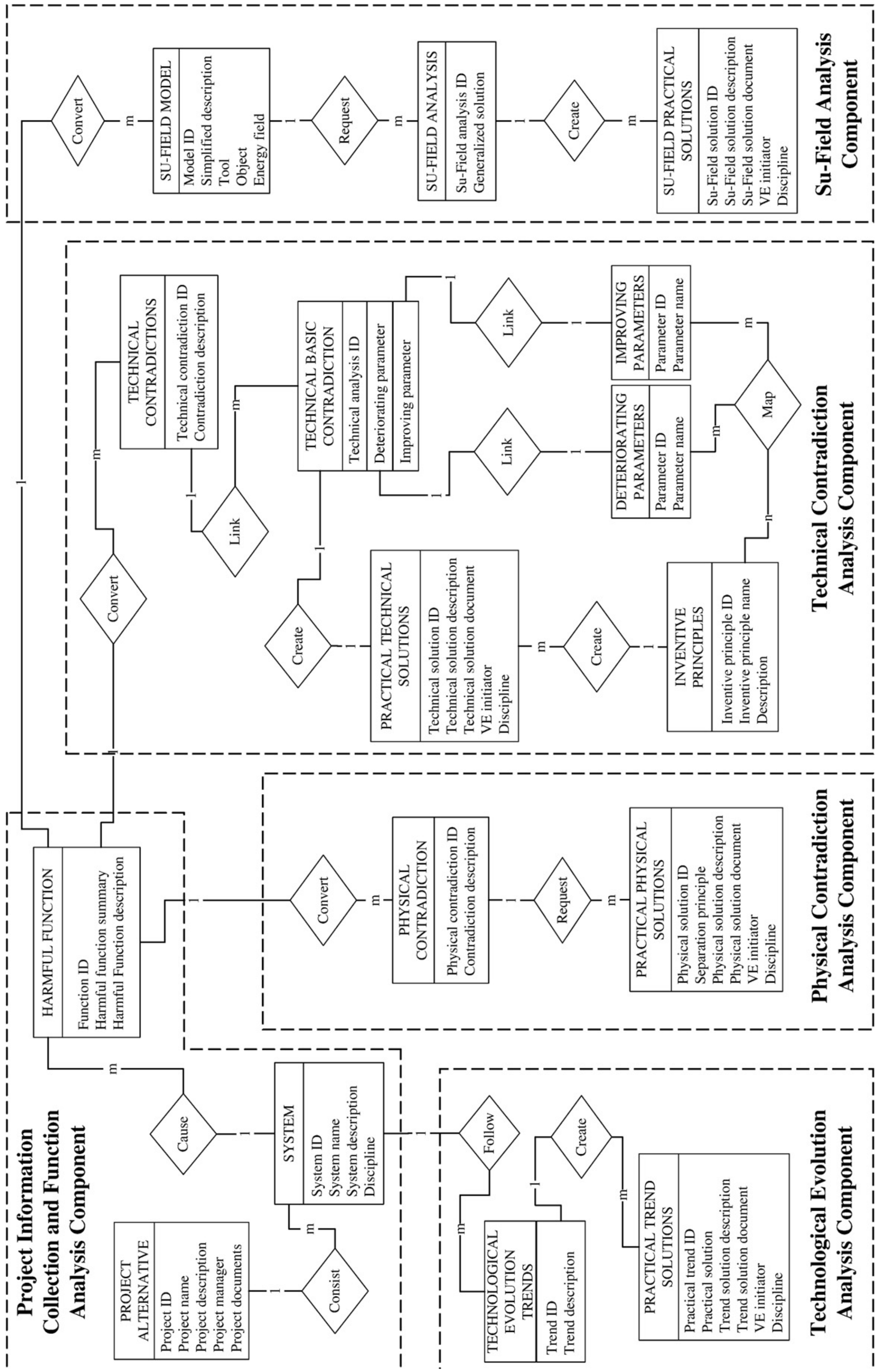


Fig. 7. Entity relationship diagram.

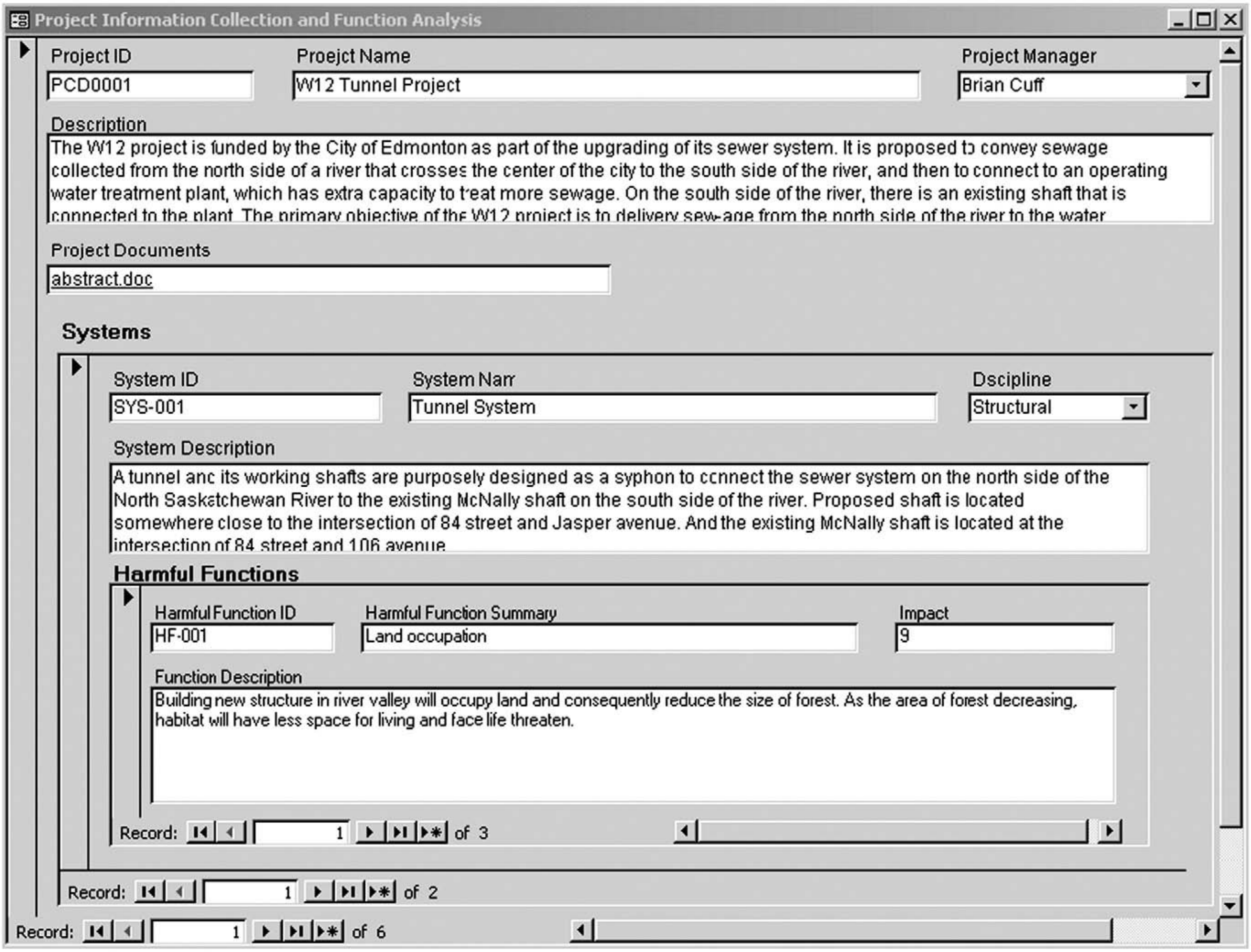
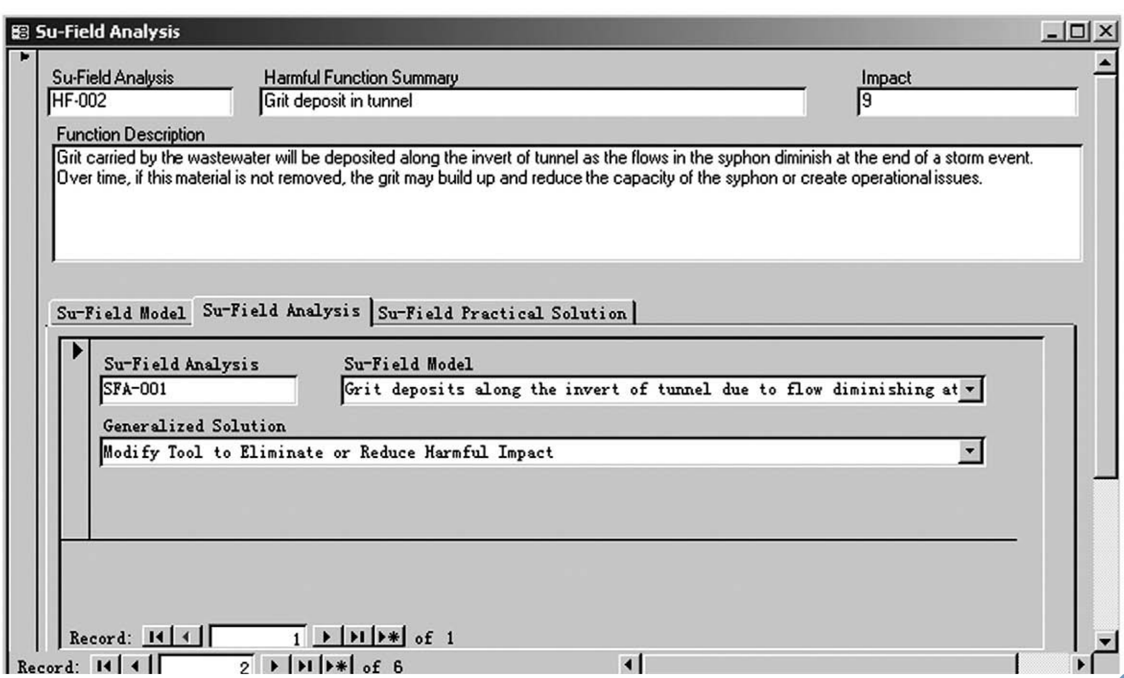


Fig. 8. Database interface for project information collection and function analysis.



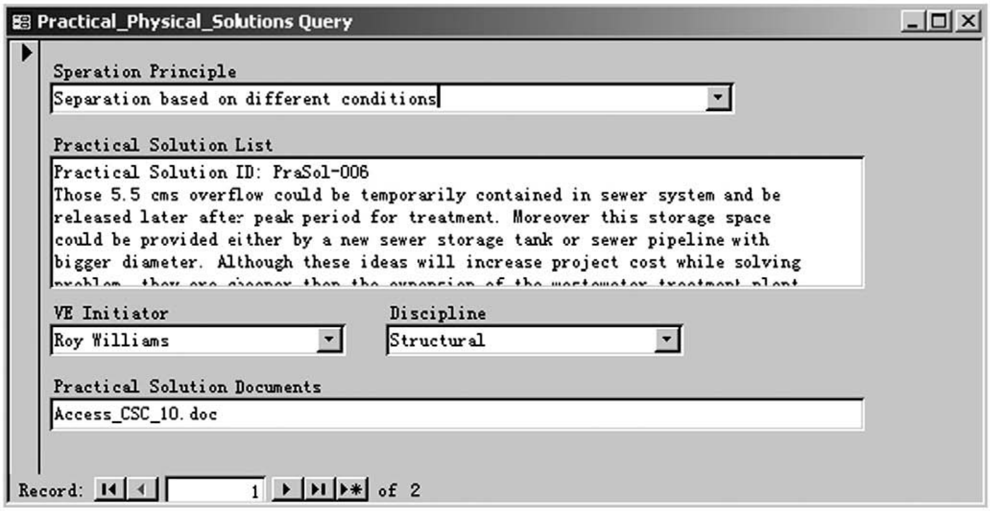


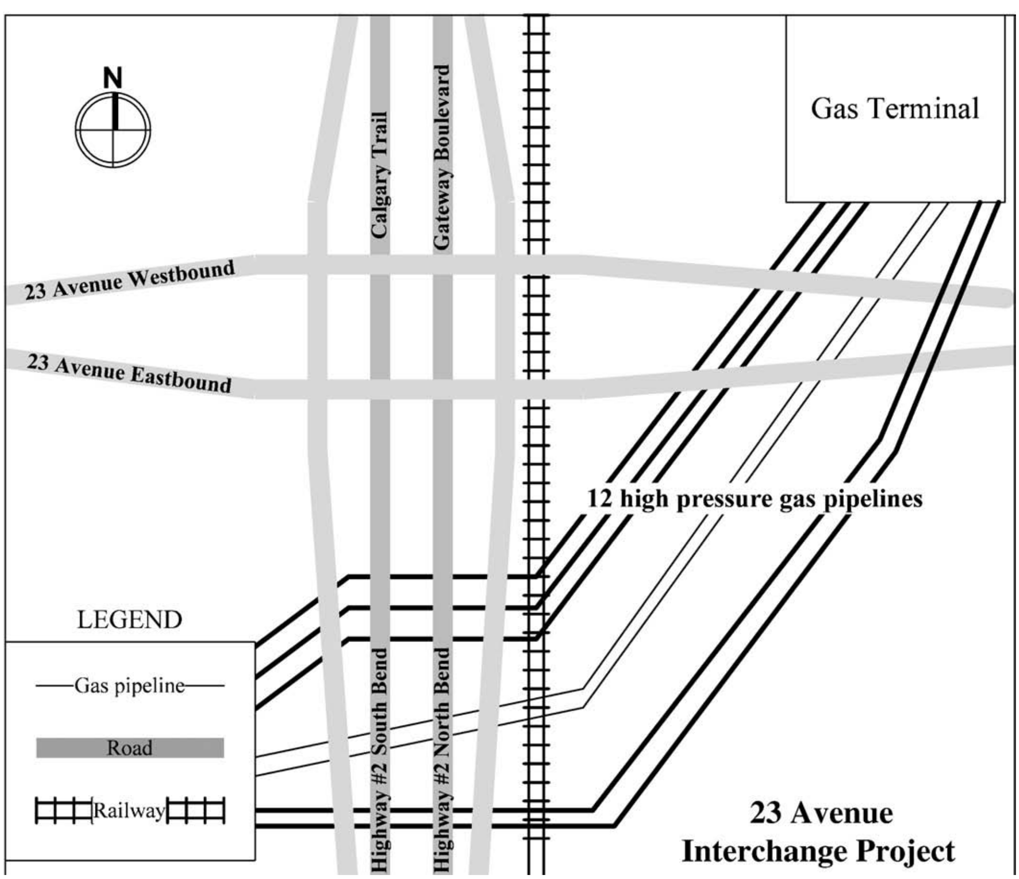
Fig. 10. Database interface for knowledge retrieval.

height ranging from 1 to 6.8 m above the existing grade. A differential settlement will take place near the interface between the soil under the ramp/retaining wall and that outside of the ramp/retaining wall. This differential settlement can cause significant stress along the pipelines [3]. The lack of detailed information on the existing pipelines and the stress of the pipelines caused by the differential settlement result in some design and construction problems. The following sections discuss how to apply the VE-KMS to find useful ideas and solutions to these problems.

8.2. Function analysis

The VE team has found that the interchange project presents the following harmful functions to the existing pipelines after a function analysis:

1. The pressure and differential settlements from the thick soil overburdens pose stress on the pipelines as the pipelines are buried under embankment fills with variable heights.



2. Differential settlement will take place near the interface between the soil under the ramp and that outside the ramp, resulting in significant stress on the pipelines.
3. Differential settlement may break pipelines at the bend areas because they were made with fittings, which are the weak points along the pipelines.
4. Traffic loads cause pressure on the pipelines where the overburden is shallow.
5. The retaining wall may damage the pipelines because of the differential settlement.
6. It is difficult to inspect the corrosion condition of the buried pipelines.
7. The future replacement of the pipelines using an open-cut method may severely interrupt the traffic flow in the interchange area.
8. Pipeline failures will interrupt gas transportation and it is difficult and time-consuming to repair buried pipelines.
9. Vibration compaction during ramp construction may damage the pipelines.

8.3. Knowledge creation, extraction and reutilization

Once the harmful functions are identified, the previously discussed procedures for the enhanced creativity phase are followed to generate ideas and solutions to overcome those harmful functions. The ideas and solutions generated from each TRIZ creativity tool are then abstracted and recorded in a table in the VE-KMS database. The TRIZ tool applied, its particular principle used, and the solutions generated from the TRIZ tool for each harmful function are listed in Table 1. It is seen from Table 1 that a harmful function may be solved using different TRIZ tools and different TRIZ tools may lead to similar solutions. In the following, one solution generated from each TRIZ tool is discussed to demonstrate how to apply the TRIZ tools to solve the harmful functions.

8.3.1. Substance-field analysis for harmful function #5—retaining wall may damage pipelines

The first step of the substance-field analysis is to create a substance-field model. This particular problem is modeled as the retaining wall (the tool) acting on the pipeline (the object) using a mechanical force (the field). On the one hand, the retaining wall provides support to the pipelines by holding fills. On the other hand, the retaining wall may damage the pipelines due to the differential settlement between the retaining wall and the pipelines. This is the harmful function to be removed. The second step is to identify a general principle to remove this harmful function. It is found that one of the seven general standards for solving substance-field models, “modifying the tool to eliminate or reduce the harmful function”, may be applicable. The third step is to develop a domain specific solution under the guidance of this selected general principle. Since the maximum ground settlement is about 64 mm, a hole made on the retaining wall that has a diameter of 128 mm or larger than the diameter of the pipelines will provide enough space to tolerate the settlement variance between the retaining wall and the pipelines. The void space between the pipeline and retaining wall may be stuffed with compressible materials. After the substance-field analysis, details will be captured in a subform of the VE-KMS database through the interface illustrated in Fig. 9. These details include (1) the substance-field model, (2) the harmful function, (3) the general standard used, (4) the actual solution, and (5) the problem discipline. For example, this actual solution is linked to the general standard #2 under the discipline of “Ci”.

8.3.2. Technical contradiction analysis for harmful function #2—differential settlement at ramp interface may cause stress on pipelines

The first step in the technical contradiction analysis is to identify the parameter that needs to be enhanced and the parameter that needs to be weakened. In this example, the length of the pipeline needs to be extended to cross the areas with different thicknesses of overburdens but the stress of the pipeline needs to be reduced. The variance of overburdens leads to differential soil settlements and consequently increases the pipeline stress at the transitional areas where the depth of the embankment changes. Obviously, the length of the pipeline and the stress of the pipeline constitute a technical contradiction. The second step is to search the contradiction matrix for possible inventive solutions. Two inventive principles, “segmentation” and “transformation of properties,” are identified to have the potential to solve the above contradiction. “Segmentation” may prompt the VE team to increase the degree of fragmentation to accommodate the differential settlement while “transformation of properties” may stimulate the team to change the degree of the pipeline's flexibility.

Table 1
Results summary of a value engineering study.

No.	Harmful function	TRIZ tool	Principle	Practical solution
1	Soil pressure and soil settlements produce stress on pipelines.	Su-field analysis	#2: Modifying tool to eliminate or reduce the harmful impact	1. Build an arch to cover pipes. 2. Install casing pipe on existing pipes.
		Technical contradiction analysis	#29: Pneumatic of hydraulic construction #35: Transformation of properties #22: Convert harm into benefit	1. Cover pipelines with lightweight materials, such as cellular concrete to reduce external pressure on pipe. 2. Increase embankment fills to optimal depth because soil pressure decreases when its depth increasing.
2	Differential settlement at ramp interface cause stress on pipelines.	Technical contradiction analysis	#35: Transformation of properties #1: Segmentation	Segment pipeline buried under different depths of soil with flexible joints, which compensate for expansion, bending and settlement of pipelines.
3	Differential settlement could break pipelines at bend areas	Su-field analysis	#2: Modifying tool to eliminate or reduce the harmful impact	Cover pipelines with lightweight materials, such as cellular concrete to reduce external pressure on pipe.
4	Traffic load causes pressure on pipelines	Su-field analysis	#4: Changing the existing field to reduce or eliminate harmful impact	Bury precast concrete slab in embankment to even pressure.
5	Retaining wall damages pipelines	Su-field analysis	#2: Modifying tool to eliminate or reduce the harmful impact	Increase the diameter of hole to tolerate settlement.
6	Difficult to inspect the corrosion condition of buried pipelines.	Technological trend analysis	#8: Decreased human interaction and increased automation	Monitoring corrosion status of inaccessible pipes using electrical polarization technique.
7	Find alternative to replace pipeline rather than using open-cut method	Technical contradiction analysis	#7: Nesting	Build new pipe within existing pipe.
8	Pipe reparation will stop gas transportation for a significant time.	Physical contradiction analysis	#1. Separation in space #2. Separation in time	Build spare pipe to provide temperate service when needed.

One solution possibly coming out from the two inventive principles is to use flexible joints to connect the segmented pipelines buried under different depths of soil. This is a practical solution as many manufacturers make flexible joints that can be used to compensate for expansion contraction, rotation, bending and settlement of pipelines.

8.3.3. Physical contradiction analysis for harmful function #8—pipeline repair may interrupt gas transportation

The purpose of solving this problem is to minimize the interruption to gas transportation in the maintenance and repair of pipelines. After evaluating the four separation principles for physical contradiction analysis, it is found that the principles of "separation in time" and "separation in space" may be applied to solve this problem. Based on the two principles, it is suggested that spare pipelines be built underneath the interchange area to backup the lost capacity when some existing pipelines are out of service. The number of spare pipelines may be determined through a probabilistic analysis.

8.3.4. Technological trend analysis for harmful function #6—it is difficult to inspect the corrosion condition of buried pipelines

Assessing the corrosion status of inaccessible underground coated pipelines has long been an issue. Buried pipelines are traditionally inspected by digging a test area over the pipeline, removing its coating, and visually inspecting the bare steel surface. This approach is expensive, destructive, and time consuming. One technological evolution trend is "system evolving towards ideality." This advises the VE team to seek for non-destructive solutions. One possible solution is to use the electrical polarization technique to assess the corrosion status of the buried pipelines.

9. Conclusions

VE has been practiced for half a century in the construction industry, which is still practicing VE in the same fashion as it was 50 years ago. The creative phase of the VE workshop determines the success or failure of a VE study. Traditionally, a VE study mainly relies on the brainstorming technique to generate ideas and solutions and it usually starts from scratch without adequately utilizing the knowledge generated from previous VE studies. There is no guidance on the direction in which the search for effective and robust ideas and solutions is efficient. There is a need to improve the efficiency of the VE practice for better outcomes. This paper proposes a value engineering knowledge management system (VE-KMS) to support the knowledge creation process, code and retain ideas from historical VE studies, and share this valuable information in the construction industry.

TRIZ is a methodology and tool set for generating innovative ideas and solutions for problem solving. These tools provide systematic approaches and generic principles to formulate and analyze problems, generate creative ideas, and forecast the evolution trend of a system or project. These include: (1) nine laws and trends of technology evolution, (2) 40 inventive principles for resolving technical contradictions, (3) four inventive principles for physical contradiction elimination, and (4) 76 inventive standards for substance-field analysis. The VE-KMS incorporates these TRIZ tools in the creativity phase to make it more systematic and more organized and to enable the VE team to control the creativity process. In addition, the VE-KMS allows automatic knowledge collection and consolidation while a VE study is ongoing and effective retrieval of existing knowledge from the database. It also facilitates cross-disciplinary knowledge transferring and sharing.

Utilization of the ideas and solutions from historical VE studies stored in the database will avoid reinventing the wheel and reduce redundant work in future VE studies. The incorporation of TRIZ imagination power, and improve the efficiency and effectiveness of the VE study in generating innovative and practical ideas and solutions. The case study of an interchange project has demonstrated the usefulness and applicability of the VE-KMS in the construction industry.

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