KSCE Journal of Civil Engineering (2016) 20(6):2143-2153

DOI 10.1007/s12205-016-0346-3

Construction Management

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Developing a General Model for Construction Problem Solving for an Engineering Consulting Firm

Pei-Lun Chang* and Wen-der Yu**

Received April 29, 2015/Revised August 11, 2015/Accepted September 30, 2015/Published Online February 15, 2016

Abstract

This paper presents the development of a lessons-learned-based general construction problem-solving model, namely GCPM, within an engineering consulting firm to assist construction engineers in finding the preliminary solution for a construction problem. The proposed GCPM is developed using an induction method based on 631 historical lesson-learned files collected from a leading engineering consulting firm in Taiwan. Elements of the Construction Project Management Body of Knowledge (CPMBOK) of the Project Management Institute (PMI), Theory of Inventive Problem Solving (TRIZ) and Data Mining (DM), are adopted so that the Management Parameters (MPs) and Problem-Solving Principles (PSPs) are defined and derived. Finally, a Construction Problem-Solving Matrix (CPSM) is obtained comprising of two types of MPs and a set of 76 PSPs. After tested with 54 real world cases, the proposed GCPM is verified to achieve 96.5% overall successful application rate. It is concluded that the proposed GCPM provides a promising tool for construction engineers of engineering consultants to direct appropriate problem-solving principles regardless of the complexity and diversity of construction problems.

Keywords: *knowledge management, problem solving, construction engineering, lesson-learned files*

1. Introduction

In resolving various daily construction problems, construction engineers usually rely on their previous knowledge and experience for creating solutions. By using a Knowledge Management System (KMS), the lesson-learning processes and experiences can be documented and reused. Because engineering consultants is a knowledge-intensive industry, constant creation and accumulation of new Lesson-learned Files (LLFs) are required to facilitate the resolution of problems encountered during an engineer's daily tasks. Using the community of practice (CoP) model for problem-solving is widely adopted in many commercial KMS applications as well as the important internet portals, such as Yahoo scholar, Google, and other community portals and Web sites. The application of CoP to solving construction problems has also been found in many major engineering consulting firms both in Taiwan, Korea, and many other countries.

A specialized KMS dedicated to resolving emergent construction problems, namely "Knowledge Management-enabled construction problem solver (KM-CPS)," (Yu *et al.*, 2013) was established by Taiwan's top ranking engineering consulting firm, CECI Engineering Consultants, Inc. (http://www.ceci.com.tw/english/), namely CECI hereafter in this paper, in 2004. With a systematic lesson-learning module, the "KM-CPS" system has accumulated a large number of LLFs for use by engineers in solving future problems. The problem-solving process of CoP in a KMS can be described as follows: first, a problem is raised and posted in the CoP by the engineer (namely *Questioner*) who confronts the construction problem; then, responses are provided from the domain experts (namely *Responders*); after the suggested solution has been adopted and the problem has been solved, the *Questioner* is required to document the solution into a template document called Lesson-Learned File (LLF). Generally, a LLF comprises at least three components: (1) problem description; (2) solution process; and (3) result evaluation.

As construction projects proceed, engineers frequently encounter various engineering problems during work, and the engineers are regularly required to solve new engineering problems based on their past problem-solving experience no matter the problems were ever encountered or not. Carrillo *et al.* (2013) investigated the main reasons for adopting knowledge management by 41 British construction firms and found two most common reasons were: (1) obtaining lessons learned for future use in similar projects; (2) avoiding mistakes and repeating successes. Other researchers also pointed out that the increasing need of knowledge learning for resolving new problems encountered in more and more complex projects caused by changing issues in the market, e.g., sustainability, eco-construction, and green building (Edum-Fotwe and McCaffer, 2000; Hwang and Ng, 2013). However, such lessons learned are not always used to the best

*Engineer, CECI Engineering Inc., Taipei, Taiwan, R.O.C. (E-mail: peilun@ceci.com.tw)
**Professor, Chung Hua University, Hsinchu, Taiwan, R.O.C. (Corresponding Author, E-mail: wenderyu@chu.edu.tw)

advantage to improve future projects; there is a disjoint in the effort spent obtaining lessons learned and their dissemination and use (Paranagamage *et al.*, 2012). In particular, the content, format and retrieval methods used can create problems for end users in project teams (Carrillo *et al.*, 2013). From such perspectives, summarizing or extracting reusable principles from previous problem-solving experiences can be more beneficial and reusable than just providing historical LLFs. Furthermore, these reusable principles could also mediate the long-term impact caused by organizational experience losses resulting from retirement or resignation of senior engineers.

The reusable problem-solving principles adopted by construction engineers are very similar to the Altshuller's theory of inventive problem-solving (TRIZ) (Altsuller, 2002), a method of solving technological contradictions. TRIZ has been applied successfully to various fields including architecture design and construction engineering (Cheng *et al.*, 2006; Ding and Ma, 2014; Mohamed and AbouRizk, 2005a). Although TRIZ has been applied successfully to various fields, Yeh *et al*. (2010) found that the Engineering Parameters (EPs) and Inventive Principles (IPs) in TRIZ are more suitable for solving technical or technological contradictions than for general application in solving construction engineering problems. Construction problems are generally solved using management measures and techniques, implying that a problem-solving theory suitable for construction specific problems needs to be developed.

This paper presents a new model that summarizes construction problem-solving principles from historical lessons-learned to provide a General Construction Problem-solving Model (GCPM) that is reusable and suitable for an engineering consulting firm. The rest of this paper is organized as follows: relevant literature of problem domain and related fields are reviewed first; it is followed by the detailed description of model development and versification of the proposed GCPM; then two application examples of the proposed GCPM are demonstrated; finally conclusions and recommendations are addressed at the end of the paper.

2. Review of Relevant Works

2.1 Construction Problem Solving and Lessons Learned

Problem-solving is the most significant issue for many construction engineering disciplines. Planning, design, construction, and even project management are integrally related to problem-solving activities. Li and Love found construction problems pose several characteristics (Li and Love, 1998): ill-structured nature, inadequate vocabulary, minimal generalization and conceptualization value, temporary multi-organization, uniqueness of problems, and difficulty to reach the optimal solution. They also addressed the importance of integrating cognitivism and decision support system for developing model of construction problem solving and mechanisms for automatically acquiring experiential knowledge from past construction problem solving examples (Li and Love, 1998). Based on the framework proposed by Li and Love, Tam *et al.* (2006) proposed a Non-Structural Fuzzy Decision Support System (NSFDSS) for construction problem solving. Although NSFDSS has improved the efficiency of decision making with traditional Analytical Hierarchy Process (AHP), no lessons-learned were adopted; *i.e.*, no previous lessons can be consulted while developing the solution for the new problem.

Lessons-learned was referred as experience that has gone through in the past; the lessons learned through experience can help identify problem solving models for recent events and link them with previous events (Salmon and Siegel, 2001). While solving the problems encountered in a construction organization, the solutions usually generated by knowledge creation activities of the staffs, based on the Nonaka's theory of Knowledge Creation Spiral (Nonaka, 1994). Knowledge Management Systems (KMSs) provide an effective means for recording the problem-solving process. Such records are structured and stored so that they can be reused in solving similar problems in the future. Yu *et al.* (2013) proposed a KM-CPS (KM-enabled Construction Problem Solver) based on the KMS of a consulting firm. In the KM-CPS, an emergent construction problem encountered by the engineer is posed in a specialized Community of Practice (CoP), namely "SOS" (implying "Emergent Assistance Seeking"). With such a specialized CoP, all experts (senior engineers and managers) of the firm can respond with their solutions to the CoP promptly. After the problem is resolved, the *Questioner* who raised the problem in SOS is required to document the solution process and its effectiveness into a Lesson-Learned File (LLF). Anyone refers to the LLF can easily evaluate its applicability. Yu *et al.* (2013) showed that KM-CPS shortened the average time required to solve a problem from 4.64 days to 2.68 days, with 42.22% of time benefit.

Based on KM-CPS, Yu *et al.* (2010) proposed a Proactive Problem Solving (PPS) with the LLFs accumulated by the KMS of the firm and a text mining algorithm. The PPS was proved to be able to further shorten the average time required for solving a problem from 2.68 days to 6.67 hours. Wu *et al.* (2012) enhanced PPS with an Integrated Proactive Knowledge Management Model (IPKMM). With IPKMM, the database of LLFs is expanded to include knowledge corpuses automatically generated by a text mining method.

A different approach for lesson learning was proposed by Carrillo *et al.* (2013) to eliminate the gap between the commercial KMS and the practical requirements of the medium-sized enterprise (SME) construction firms. In their approach, a Project Learning Roadmap was developed including five needs identification elements: process and tools, content and format, information repository, communication, and dissemination. Carrillo *et al.* (2013) addressed that the SME construction firms need a cheaper, faster, and simpler approach of lesson learning rather than the traditional Decision Support Systems (DSSs) or the commercial KMSs.

2.2 TRIZ-based Problem Solving

TRIZ (an acronym for the Russian term *Theoria Resheneyva*

Isobretatelskehuh Zadach) is a method using innovative thinking to solve technological contradiction problems that has been successfully applied in numerous fields (Mann, 2001; Terninko 2001; Retseptor, 2002). TRIZ was developed by Genrich Altshuller and his colleagues in the former USSR starting in 1946, and is now being developed and practiced all over the world (The TRIZ Journal, 2015). Altshuller believed that traditional process for increasing creativity suffers a major flaw that their usefulness decreases as the complexity of the problem increases. He determined to improve the inventive process, which led to the creation of TRIZ after studying more than 400,000 patents (Terninko *et al*., 1998). The TRIZ method has been widely applied to various fields and experienced great successes, including business, social science, architecture, food science, software engineering, microelectronics, quality management, public health, chemistry, biological engineering, operation and service management, education, financial management, marketing, construction engineering, chemical engineering, customer relation management, etc. (The TRIZ Journal, 2015).

A very relevant research was conducted by Mohamed and AbouRizk to develop a knowledge representation schema for construction problem solutions (lessons-learned) (Mohamed and AbouRizk, 2005b) based on TRIZ. Their schema consists of three major components: (1) the main functions/effects of the solution; (2) the contradiction set of the encountered problem; (3) the resolution principle that best represents the solution. Mohamed and AbouRizk also developed a computer system to implement the proposed schema. Their method provides a framework for efficient knowledge representation for construction lessons-learned. One drawback of the schema is that only the principles but no details of problem-solving lessons are stored, which may cause difficulty of users to reapply the lessons-learned. Zhang *et al.* applied TRIZ to generate innovative ideas in the idea-generation stage of the five-step job plan for Value Engineering (VE) (Zhang *et al.*, 2009). Their research explores the capability of TRIZ in systematic generation of VE alternatives given the objective of improving function and reducing cost for the defined VE problem. Such an application is highly related to the present research that aims at resolving a defined problem with previously developed model, except that this study emphasizes on the special characteristics of construction problems and develops its own models rather than adopting the models of the original TRIZ.

Although some technological applications were reported in the construction area, former research has found that TRIZ failed to achieve widespread applications in solving general management-type construction problems (Yeh *et al*., 2010). It indicates that a construction-specific model for problem solving is desirable.

2.3 Project Management Body of Knowledge (PMBOK)

In searching for the characterizing Management Parameters (MPs) and the Problem-Solving Principles (PSPs) for general construction problems, three widespread international standards for construction project management were reviewed including the Project Management Body of Knowledge (PMBOK) of Project Management Institute (PMI) (PMI, 2008), the IPMA Competence Baseline (ICB) (IPMA, 2006) of the International Project Management Association (IPMA), and the CIOB Education Framework of the Chartered Institute of Building (CIOB) (CIOB, 2005). Among those, the Construction Extension of the Project Management Body of Knowledge (CPMBOK) (PMI, 2007) is finally selected as a primary reference for identification of the MPs and PSPs in this research due to its popularity in the international construction community. PMBOK is an officially recognized standard by the Project Management Institute (http://www.pmi.org), which documents the established norms, methods, processes, and practices in project management specialized fields (PMI, 2008). The project management processes identified by PMBOK can be categorized into the following five process groups (PMI, 2008).

Based on PMBOK, Project Management Institute (PMI) published its Construction Extension of Project Management Body of Knowledge (CPMBOK) (PMI, 2007) with supplementary knowledge areas and the relevant processes. The CPMBOK is not only a body of knowledge more suitable for managing construction projects but also becoming a common language adopted worldwide to define the required knowledge fields, process groups, operational processes, and useful tools and techniques for construction project management. The CPMBOK adds four additional knowledge areas exclusive to construction projects in addition to the original ten major knowledge fields of PMBOK, including safety management, environment management, financial management, and claims management.

Chou and Yang (2012) examines the relationships among the four key project success factors by assessing the efficacy of management techniques, tools, and skills for implementing infrastructure and building construction. They identified six project success indicators: Completed on time, Completed within budget, Meeting quality requirement, Meeting design requirement, Overall stakeholders' satisfaction, and Reoccurring business. Their study also suggested the most relevant techniques and tools of PMBOK for achieving project success based on the results of a questionnaire to construction practitioners in Taiwan.

Dogbegah *et al.* (2011) argued that project management competencies have been evolving eccentrically on issues that affect project performance. They identified six new project management competency areas based on the analysis of the results from a structured survey questionnaire to 100 project managers. Six new knowledge areas are: Knowledge management, Conflict and dispute management, Ethical management, Stakeholder management, Information technology management, Materials resources management and Plant and equipment resources management.

2.4 Data Mining (DM)

As the advent of the Internet and the maturity of database technology, data acquisition has become very handy. With the automatic and globalized searching tools, the data explosion problem has become a crucial issue for contemporary data managers (Han and Kamber, 2001). DM is also referred to as Knowledge Discovery in Database (KDD) (Fayyad and Uthurusamy, 1996). The purpose of DM is to extract previously unknown or hidden knowledge rules, constraints, and regularity information from databases with a large volume of historical transactions that could have application value in the future. Construction problems are industry-specific, which require the collection and analysis of the domain knowledge for effective solutions. Using DM to identify specific and common rules and principles from past or historical experiences and cases provides a means to rank the solution principles and provide them in order of priority, which can improve the problem-solving efficiency. Moreover, the significance of association rules identified by DM techniques also provide an alternative method to verify the appropriateness of problem-solving principles identified.

3. Research Methodology

This research adopts similar approach that was employed by Altshuller in constructing TRIZ theory. The essential issue for establishing GCPM is the acquisition of construction-specific experience and knowledge for problem solving. In this regard, the historic LLFs of previous problem-solving cases are adopted as the knowledge source from the KMS of a local Leading Engineering Consulting Firm (CECI). The collected LLFs are then characterized with a set of vocabulary elicited from CPMBOK for describing the problem characteristics and the problem-solving techniques. In order to verify the appropriateness of the quoted vocabulary (for characterizing parameters and problem-solving principles of the problems), domain experts with abundant experience and expertise in solving related construction problems are consulted to establish a Construction Problem-solving Matrix (CPSM). After revision and verification with domain experts, a DM technique is employed to identify the association rules from historic LLFs. The results are used to rank the priority of problem-solving principles in the CPSM. Finally, the General Construction Problem-solving Model (GCPM) is proposed to equip the construction engineers with a means to locate reference solution principles while they are confronting emergent construction problems. In order to verify the validity and applicability of the proposed GCPM, a set of new real world construction problems encountered by engineers in the field are employed for model testing. The testing results are then discussed in depth to conclude the findings of the study. Detailed procedure of the proposed methodology is described in details in the following sub-sections.

3.1 Lessons-Learned Acquisition

A top-ranking engineering consulting firm, CECI Engineering Consultants, Inc., in Taiwan has been selected as the industrial partner to collect historic lessons-learned for the development of GCPM. There were several reasons why a single industrial partner was selected for study instead of comprehensive survey industry-wide: (1) not all companies retain or maintain LLFs for their previous projects—it is impossible to collect statistically sufficient LLFs to represent the industry-wide practice; (2) LLFs are usually treated as trade secrets or competitive know-hows—the firms are usually reluctant to disclose such information; (3) essence of construction problem solving—there exists a common practice for solving similar problems, the experienced engineers solve similar construction problems with similar approaches. Moreover, the selected industrial partner is a major consulting firm in Taiwan that performs diversity of construction projects covering almost all areas in the construction both in Taiwan and overseas.

A wide range of 908 representative problem-solving LLFs were collected from 2004 to 2010. The vocabulary of CPMBOK is employed in order to characterize the LLFs generally. By reviewing the content of the collected LLFs, it was found that some cases are related to schedule delays (Time Management) but the problem description was focused on how to resolve the dispute between the project participants; it is then reclassified to the category of Claim Management. Such situations are commonly found in the collected cases, indicating that a more specific classification system is needed to replace the original 13 knowledge areas of CPMBOK. Moreover, it was also found that some LLFs dealt with emergent problems such as computer operation system crash-down, emergent request for the required administrative procedure to release a classified information, etc. Such kinds of problems are beyond the scope of the study and should be excluded from the data pool.

In order to improve the quality of the collected data, the study established the following criteria for expelling the unqualified cases: (1) incomplete data—e.g., incomplete solution description or that were not evaluated by the solution adopters; (2) non-engineering relevant problems—e.g., computer related or administrative problems; (3) non-urgent problems—e.g., word processing or software usage problems; (4) lowly evaluated cases—e.g., scored below 2 (40%) in terms of Likert 5-point scale; and (5) low data reusability rates—cases rated by the manager of the relevant department to be low reusability. After screening with the above criteria, 277 cases were excluded from the study, leaving 631 cases for in-depth analysis in the research.

3.2 GCPM Model Development and Verification

The model development procedure is depicted in Fig. 1 and consisting of 10 steps: (1) Lesson-Learned File (LLF) collection—collecting 908 LLFs from the study case firm; (2) LLF selection—selecting 631 LLFs from the original 908 according to the screening criteria; (3) Problem and solution modeling—classifying problem domains with the First Management Parameter (MP-1) and analyzing problem time-phase in the project lifecycle with the Second Management Parameter (MP-2), and then determining the problem-solving tools with the Problem-Solving Principle (PSP); (4) Development of the Construction Problem-Solving Matrix (CPSM)—relating the associations between management parameters (MPs) with the problem-solving principles

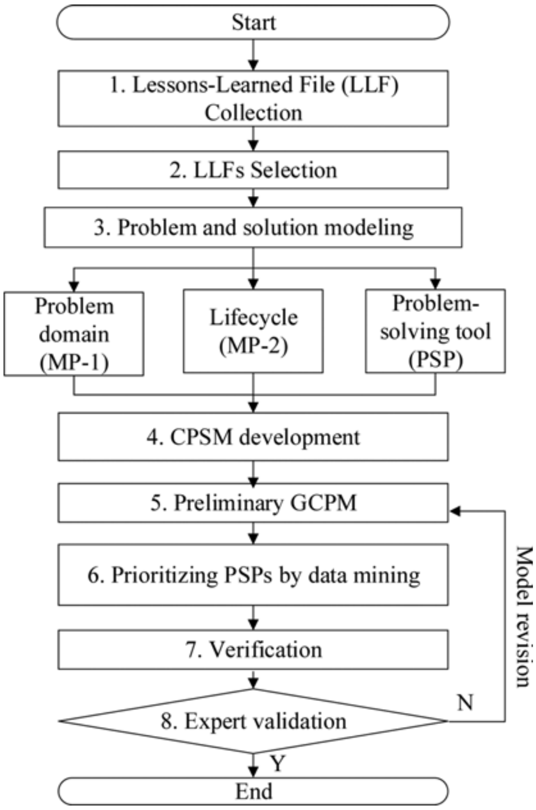

Fig. 1. Procedure for Model Development of GCPM

(PSPs); (5) Development of preliminary model of GCPM—the GCPM model is established and revision by the domain experts; (6) Determining the PSP priority in CPSM with data mining technique—the association rule is adopted to prioritize the PSP in the CPSM; (7) Verifying the proposed GCPM with real world construction problems—totally 54 real world cases are collected from newly encountered SOS problems; and (8) Expert validation—a highly qualified senior domain expert is invited to carefully review the results of testing to determine the applicability of the proposed GCPM and provide revision comments.

Following describes the detailed development process of GCPM:

1. Classification of problem classes

Originally, the 631 selected LLFs were classified using the 13 project management knowledge areas suggested by CPMBOK, and found severe overlaps problems exist in such a classification. It implies that the selected classification system is unable to characterize the domain problem effectively. An improvement problem modeling method is employed based on characteristic keywords of the problem: at first, the problems classified in the 13 knowledge areas of PMBOK (PMI, 2013) were reviewed and further categorized into 39 sub-areas; then, the similar sub-areas are grouped and aggregated to yield 11 characterization problem classes, including: (A) Cost estimation; (B) Insurance/Bond; (C) Contract; (D) Safety; (E) Cost control; (F) Tendering/Documentation; (G) Dispute; (H) Quality/Technical; (I) SPEC/Standards; (J) Schedule; (K) Resources/Materials. The 11 characterization problem classes are defined as “Management Parameter I (MP-1)”. The “Expert Judgment” technique suggested by PMBOK is adopted as the primary method for problem classification of MP-1. That is, the MP-1’s associated with the 631 LLFs were first selected by the research team and then verified by domain expert during verification stage.

2. Analysis of problem occurrence stage (time phase) in project lifecycle

The occurrence stage in the project lifecycle has an obvious impact on the solution adopted. For example, a quality problem discovered in the design stage will trigger a design modification and specification revision; however, it needs costly rework and may result in a dispute after construction work has proceeded. As a result, the second management parameter (MP-2) for characterizing a construction problem is to describe the occurrence stage of a construction problem.

Project lifecycle analysis primarily involves analyzing the time phase at which urgent construction problems occur. This research adopts the five process groups of CPMBOK as a standard for project lifecycle analysis: initiating, planning, executing, monitoring and controlling, and closing process groups. Each of the selected LLFs are analyzed and labeled with an associate process group. Since all of the collected LLFs have been labeled with the five lifecycle stages when they were documented, the classification of MP-2 is quite straight forward.

After analyzing and summarizing the 631 LLFs, it is observed that no urgent problems occurred in the initiating process group, 363 cases (58%) occurred in the planning process group, 82 cases (13%) in the executing process group, 26 cases (4%) in the monitoring and controlling process group, and 160 (25%) cases in the closing process group. The data indicates that urgent problems in CECI occur primarily during the planning (58%) and the closing (25%) processes. This may be due to the nature of an engineering consultant where the design and planning play the major role in their business activities.

3. Determination of Solution Principles (Tools and Techniques)

After characterizing the construction problems, the next step is to determine the problem-solving principle (PSP) adopted in the historical LLF. This is a challenging task, since the summarized solution for the quoted construction problem has been documented by the questioner of the problem and articulated in his own language. Different responders may describe the same solution in different way. In order to reach a common language for defining problem-solving principle, this study adopts the tools/techniques of the processes in CPMBOK as a standard to define the adopted PSP in the selected LLFs.

While determining the PSP’s of each historical LLF, the “Expert Judgment” technique is adopted again. That is, the PSP’s associated with each of the 631 LLFs were first determined by the research team and then verified by the original questioner who documented the LLF. After carefully reviewing all 631 LLFs, it is found that most problem-solving principles (PSPs) can be determined with tools/techniques of the relevant processes in CPMBOK, while 26 LLFs (4.12%) cannot be properly assigned. Among those, the PSPs of 21 LLFs can be defined with the suggested tools/techniques in the other process groups of CPMBOK, while the rest 5 LLFs cannot be interpreted appropriately. As a result, 5 additional PSPs are added.

4. Developing Construction Problem-Solving Matrix (CPSM)

After determining the relationships among MP-1, MP-2, and PSPs, a CPSM can be constructed to serve as a look-up table for directing applicable problem-solving principles (PSPs) given a set of preconditions (MP-1 and MP-2).

5. Establishing preliminary model of GCPM

An integrated construction problem-solving procedure is established combining MP-1, MP-2, PSPs, and CPSM. Such a procedure along with the associated management parameters and problem-solving principles constitute the preliminary model of the proposed GCPM. The problem-solving process of the proposed GCPM is briefly described as follows: "when a problem is posted, it is first classified based on the type of problem to identify the first management parameter (MP-1)—problem class (PC); next, the problem is classified according to the associated process group (PG) where it belongs to identify the second management parameter (MP-2)—PG; finally, the identified PC (MP-1) and PG (MP-2) are used to query the CPSM and obtain the recommended PSPs within the matrix. Detailed descriptions of PSP can be referenced to the associated historical LLF."

6. Prioritizing PSPs with data mining

After constructing the preliminary GCPM, a DM technique is employed to analyze the support, confidence, and importance of each managing parameter and solution principle to prioritize the applicable PSPs in CPSM. The primary objective for employing DM is to determine the existence of interesting patterns, which can be very time-consuming if it is done by human manually.

This research adopts "association rule" technique to mine the nine attributes and identify the association among the attributes. After performing DM, this study identified nine interesting patterns. The examples from the DM are:

- When a problem with "bid invitation or submission procedure and documentation" occurs in the planning process, the "sample, form, standard" technique is frequently used as a solution, with support = 0.3%, confidence of 100%, and importance = 0.142;
- When a problem with "engineering insurance and guarantee" occurs in the planning process, the "planning meeting and analysis" tool is frequently used as a solution, with support = 0.16%, confidence of 100%, and importance = 0.093; and
- When a problem with "cost control" occurs in the executing process, the "expert judgment (added)" tool is frequently used as a solution, with support = 1.70 %, confidence of 40.70%, and importance = 0.212.

7. Model verification

Eleven experts from different specialized domains are involved to verify the proposed GCPM. The backgrounds of the eleven domain experts are shown in Table 1. The average practical experience for the eleven domain experts is 15 years. During model verification, the eleven domain experts were invited to assess the correctness and appropriateness of the classification works for the historical LLFs both on the MP-1's and PSP's according to their specialized areas. When an inappropriate classification was found, a more appropriate classification is suggested by the domain expert for the associated LLF.

63 newly posted construction problems were selected from the KMS of CECI for model testing. According to the screen criteria described in Section 3.1, six unqualified cases were excluded. The remaining 57 cases (90.5%) are used as verification cases. Each case was analyzed for problem classification and problem occurrence time, with the following results after the problems were classified: (1) three cases (5.3%) are classified as "A. Engineering Estimates or Appraisals" problems; (2) two case (3.5%) is classified as "C. Engineering Contracts" problems; (3) three cases (5.3%) are classified as "D. Safety Management" problems; (4) 28 cases (49.1%) are classified as "H. Quality and Technology" problems; (5) 14 cases (24.6%) are classified as "I. Norms/Standards" problems; (6) one case (1.8%) is classified as "J. Progress Planning and Control" problems; and (7) six cases (10.5%) are classified as "K. Construction Resources/Material" problems.

The solution descriptions for 34 of the verification cases (applicability rate of 59.6%) completely align, rated as "5" in Litkert's 5-point scale by 12 domain experts of CECI, with the

Table 1. Backgrounds of the Eleven Domain Experts

No.	Specialized domain	Position	Years of Experience
1	Construction management and structural engineering	Associate manager	17
2	Construction management	Associate manager	13
3	Railway engineering and construction management	Senior engineer	13
4	Construction management and construction materials	Senior engineer	9
5	Construction management	Engineer	6
6	Geotechnical engineering	Project engineer	18
7	Geotechnical engineering	Project manager	20
8	Hydraulic and environmental engineering	Associate manager	22
9	Hydraulic and environmental engineering	Senior engineer	19
10	Electric and mechanic engineering	Associate manager	18
11	Spatial and geological information	Senior engineer	11
Average years of experience			15

Table 2. Statistics of LLFs in Terms of Problem Class (PC) Categories

Code	Problem Class (PC)	Description	# of LLFs
A	Engineering Estimates or Appraisals	Problems related to estimating the price and cost of engineering	16
B	Engineering Insurance and Guarantees	Problems related to engineering insurance and risk	3
C	Engineering Contracts	Problems related to engineering contracts	28
D	Safety Management	Problems related to safety management when agreements are honored for engineering	14
E	Cost Control	Problems related to engineering cost control and management	27
F	Bid Invitation or Submission Procedure and Documentation	Problems related to procedures for inviting or submitting bids and relevant documents	3
G	Dispute Settlement	Problems related to disputes and arbitration over honoring agreements	30
H	Quality and Technology	Problems related to engineering quality, including technological problems	251
I	Norms/Standards	Problems related to construction norms and standards	146
J	Progress Planning and Control	Problems related to engineering progress planning and control	15
K	Construction Resources/Material	Problems related to construction resources and materials, including construction tools	98

PSPs identified in the matrix. The solution descriptions for 36.8% (21 cases) of the verification cases partially match, rated as "3~4" in Litkert's 5-point scale, by the domain experts, with the recommended PSPs, as some PSPs had not been created in the matrix because they were not found in past cases. Only two of the verification cases were unsuitable, rated less than "2" in Litkert's 5-point scale, for the matrix because solution descriptions are incompatible with those identified in the CPSM for the model, comprising 4% of all cases. Overall, 52 of the 54 cases are compatible with the PSPs recommended in the matrix, indicating that this verification has a suitability rate of 96.5%.

8. Expert validation

A senior domain expert was invited to assist with the verification of the proposed model. This expert possesses over 13 years of practical experience in construction management and railway engineering, and hold a position in the Taiwan branch of the PMI International Project Management Association, which explains he proficiency in PMBOK. The expert has participated in KMS problem-solving activities and has an extensive understanding of CECI Engineering Inc.'s KMS operations.

The expert scores the verification cases in this study between 1~5 based on his degree of agreement. Excluding four cases that received a score of 2 (indicating disagreement), the remaining 50 cases all received scores of 5, thereby obtaining an average score of 4.8. The expert agreed that the model was suitable for 50 of the problem-solving cases, for an overall agreement of 92.6%; the expert disagreed with the model's suitability for four cases, for an overall disagreement of 7.4%. The cases where the expert disagreed were discussed further with the expert during expert interviews after the questionnaire was received. The expert explained that the reason why these four cases received a score of 2 was because the PSPs should be (but were not) included in the CPSM. Furthermore, the problem-types for these four cases are extremely common. Therefore the expert suggested that these PSPs be added to the matrix and that a mechanism for updating and expansion should be developed.

3.3 Revised GCPM Model

After validation by the domain expert, the preliminary GCPM model is revised. The major components of GCPM are described in the following:

A. MP1: Problem Classification (PC)

The PC items include: (A) Engineering Estimates or Appraisals; (B) Engineering Insurance and Guarantees; (C) Engineering Contracts; (D) Safety Management; I Cost Control; (F) Bid Invitation or Submission Procedure and Documentation; (G) Dispute Settlement; (H) Quality and Technology; (I) Norms/Standards; (J) Progress Planning and Control; (K) Construction Resources/Material. Table 2 shows each PC category.

B. MP2: Process Group (PG)

The PGs include the following groups: (1) initiating; (2) planning; (3) executing; (4) monitoring and controlling; and (5) closing. Following the expert-assisted verification of the 631 cases analyzed and summarized by this study, one case of an urgent problem (0.1%) occurred in the initiating PG, 342 cases (54%) in the planning PG, 101 cases (15.9%) in the executing PG, 26 cases (4%) in the monitoring and controlling PG, and 165 (26%) cases in the closing PG. These research results indicate that the urgent or emergency construction engineering problems for this study primarily occur during the planning, executing, and the closing PG. Table 3 shows the PG categories.

C. Problem-Solving Principle (PSP)

After expert-assisted verification of the 631 cases researched

Table 3. Statistics of LLFs in Terms of Problem Group (PG) Categories

Code	Problem Group (PG)	# of LLFs
a	Initiating	1
b	Planning	342
c	Executing	101
d	Monitoring and Controlling	26
e	Closing	165

Table 4. Problem-solving Principles (PSPs) and the Associated Categories

Code	PG	PSP	# of PSPs
a	Initiating	a-1expert judgment	1
b	Planning	b-1 document check; b-2 feasibility analysis; b-3 bottom-up estimating; b-4 contract;b-5 contractual legal precedent; b-6 cost-benefit analysis; b-7 cost pooling; b-8 other safety planning tools; b-9 consultation (added); b-10 legal feasibility analysis (added); b-11 quality cost; b-12 risk information quality assessment; b-13 risk probability and conflict assessment; b-14 expert judgment; b-15 project requirement investigation; b-16 product analysis; b-17 planning meeting and analysis; b-18 precedence diagramming methods (PDM); b-19 communication techniques; b-20 communication requirement analysis; b-21 information gathering techniques; b-22 sample, form, standard; b-23 benchmarking; b-24 standard form; b-25 environmental test and simulation; b-26 analogous estimation method	26
c	Executing	c-1 safety-hazard risk analysis; c-2 safety planning tools and techniques; c-3 quality control tools and techniques; c-4 quality planning tools and techniques; c-5 quality management investigation; c-6 process analysis; c-7 safety control execution tools and techniques; c-8 environment control execution tools and techniques; c-9 expert judgment (added); c-10 communication skills; c-11 information collection and selection or extraction system; c-12 Internet (added); c-13sample, form, standard (added); c-14 customer evaluation system; c-15 selection or screening system; c-16 modification tools and methods (added)	16
d	Monitoring and Controlling	d-1mutually acknowledged modification; d-2 contract modification control system; d-3 safety-hazard risk analysis; d-4 cost modification control system; d-5 consultation (added); d-6 settle claims with insurance company (added); d-7 quality assurance tools and techniques; d-8 process statistical analysis and report methods; d-9 process comparison; d-10 risk reassessment	28
e	Closing	e-1 claim assessment or expert report; e-2 consultation; e-3 expert judgment (added); e-4 develop project completion checklist; 3-5 accounting/finance system	5

Item			MP2: PG				
		Code	a	b	c	d	e
	Code	Item / Category	Initiating	Planning	Executing	Monitoring and Controlling	Closing
MP1: PC	A	Engineering Estimates or Appraisals		b-3,b-14,b-26(b-21)		d-2,d-15,d-24,(d-27)	e-2
	B	Engineering Insurance and Guarantees		b-17		d-6	e-3
	C	Engineering Contracts		b-5,b-9,b-14		d-1,d-5,d-9,d-15, d-18,d-22,d-23	e-1,e-2, e-3,e-4
	D	Safety Management		b-14,b-16,b-22	c-1,c-2	d-3,d-15,d-24, d-28	
	E	Cost Control		b-2,b-3,b-7,b-14, b-24,b-26	c-9	d-1,d-4,d-13, d-15, d-16,d-22, d-23	e-5
	F	Bid Invitation or Submission Procedure and Documentation		b-22			
	G	Dispute Settlement		b-4,b-5,b-9,b-14	c-8, c-10	d-1,d-11,d-15, d-17, d-19,d-22, d-24,d-28	e-2,e-3
	H	Quality and Technology		b-1,b-6,b-8,b-11, b-12,b-13,b-14, b-16,b-21,b-22, b-23,b-25,b-26, (b-15),(b-20)	c-1,c-3, c-5,c-6, c-7,c-9, c-11, c-12, c-16	d-5,d-7,d-8,d-10,d-12 d-14,d-15, d-20, d-21,d-22, d-23, d-24,d-25, d-28	
	I	Norms/Standards	a-1	b-3,b-8,b-10,b-14, b-16,b-19,b-20, b-22,b-23	c-2,c-3,c-4,c-5, c-9,c-11, c-12,c-13	d-5,d-23,d-28,d-12	e-3
	J	Progress Planning and Control		b-9,b-14,b-18		d-11,d-15,d-22, d-26,d-27	e-2
	K	Construction Resources/Material		b-3,b-14,b-15, b-16,b-21,b-22	c-3,c-9, c-12, c-14c-15,c-16	d-3,d-15,d-21, d-22,d-23	

Fig. 2. Construction Problem-Solving Matrix (CPSM)

and analyzed by this study, the cases used a total of 76 PSPs. The PSP categories are shown in Table 4.

D. Construction Problem-Solving Matrix (CPSM)

The 631 cases are classified based on 11 problem-types and their PGs and PSPs are used to develop a CPSM. In the future, users can identify PSPs corresponding to the two MPs of PC and PG for their construction engineering problem and follow the recommended PSP to solve the problem. Fig. 2 shows the proposed CPSM.

4. Application Demonstration

Two cases are used to demonstrate the applicability of the proposed GCPM in solving real world construction problems. To use the model, the problem must be classified and the process group confirmed to obtain the PC and PG and use these parameters to search or query the CPSM. In this way, several PSPs can be obtained. These PSPs are the problem-solving methods in similar past cases. Users can consult detailed descriptions in the historical LLFs for solving the problem.

4.1 Application Case I—Contract Requirement

1. Problem Description—"For weak electronic device installation works, is it required for a contractor to assign a full-time engineer to supervise the task?"
2. LLF Solution—"(1) If weak electronic device installation work does not comply with the scope of Construction Industry Regulation (CIR), then it is not restricted by CIR, however, the contract stipulates an onsite responsible agency (or project manager); (2) Such a work should comply with Communication Construction Regulation (CCR) and should assign a full-time professional engineers based on Stipulation or Clause I; (3) Additional legal requirements from the proprietor should be outlined separately in the contract and it should be budgeted accordingly."
3. Application of GCPM (see Fig. 2) to Identify PSPs—(1) This problem is classified under "C. Engineering Contracts," (PC) and occurs in the "monitoring and controlling process" (PG); (2) The final solution descriptions are "d-15 expert judgment" and "d-23 sample, form, standard (added)"; (3) This study uses the two MPs for the case, "C. Engineering Contracts" (PC) and the "monitoring and controlling" (PG), to determine that the PSPs in the matrix are "d-15 expert judgment" and "d-23 sample, form, standard (added)"; (4) Associated LLF can be consulted for a description of "d-15 expert judgment" and "d-23 sample, form, standard (added)" to solve the problem.

4.2 Application Case II—Construction Resources/Material

1. Problem Description—"Please help provide the construction method and unit price information regarding the surface processing work of exposed concrete."
2. LLF Solution—"It is suggested to contact Engineering Consultant "A" directly. The unit price for a water mold is generally based on work complexity and work volume (fewer volume implies higher price). Specialized or professional vendors provide design drawings and cost estimates, see the attached. (attachment provided, including the correspondence information of Engineering Consultant "A")"
3. Application of CPSM to Identify PSPs—(1) This problem is classified under "K. Construction Resources/Material," (PC) and occurs in the "planning process" (PG); (2) The final solution description is "b-14 expert judgment"; (3) This study uses the two MPs for this case, "K. Construction Resources/Material" (PC) and "planning" (PG), to determine that the PSP in the matrix is "b-14 expert judgment"; (4) Appendix A should be consulted for a description of "b-14 expert judgment" to solve problems.

5. Discussions

5.1 Adoption of GCPM

The proposed GCPM was developed based on the historical LLFs collected from the KMS of the top-ranked engineering consulting firm, CECI, in Taiwan. As the specialized domains of CECI cover almost all areas of engineering consulting, including: Site investigations and surveying, Highways and freeways, Railways and high speed rail, Rapid transit systems, Airport works, Harbor works, Bridges and structures, Architecture design, Urban planning and land development, Environmental engineering, Tunnels & geotechnical engineering, Electrical & mechanical engineering, Information network applications, Hydraulic/water resources engineering, Information technology and systems, Traffic control and management, BOT general consultant services, Construction supervision and management, and Material testing. Interested adopters from the above engineering consulting areas may find GCPM applicable. Users from the other areas can develop their own GCPM by following the methodology presented in this paper. Moreover, the generality of proposed GCPM will be improved if the updating procedure of Fig. 3 (described in Section 5.3) is continuously exercised.

5.2 Model Assumptions

There were two assumptions while GCPM was developed, including: (1) the assessments of the domain experts are correct; and (2) the interviewees are honest while they are answering questions. Since the inquired domain experts are volunteers as interviewees and all experts are required to participate in problem solving of the SOS cases of CECI's KMS, the honesty of domain interviewees should be assured. Moreover, the domain experts are selected according to their expertise regarding to the problem domains of the SOS cases (see Table 1). The judgments

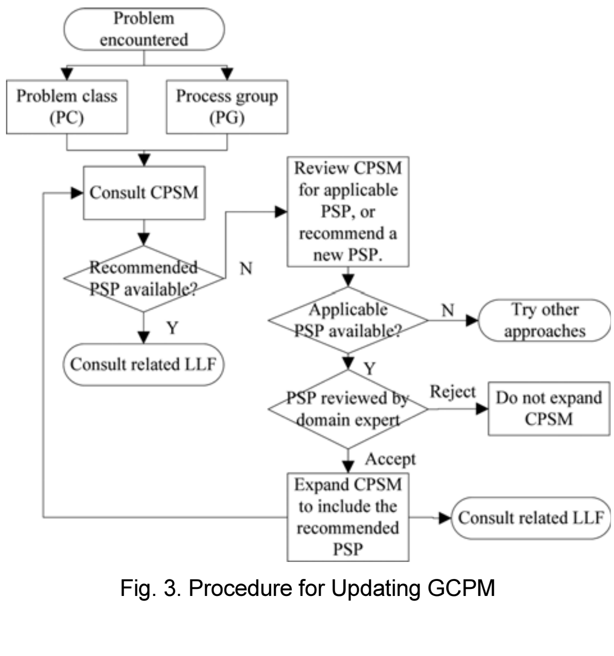

Fig. 3. Procedure for Updating GCPM

made by the selected domain experts are conceived the best attainable results for the study. As a result, the two assumptions made for the research are believed to be true.

5.3 Model Limitations

There are also three limitations for the proposed GCPM: (1) only problem-solving principles (PSPs) are provided for the encountered problems; (2) the available PSPs are limited to the existing LLFs; (3) problem-solving effectiveness may be restricted by the problem domain. The first limitation is due to the solutions provided by GCPM are in form of abstract principles, no detailed solution is provided to the questioner. Even though, questioner can refer to the related LLF for detailed descriptions of the solution adopted to solve the historical case. It should be noted that the solution recorded in the historical LLF may not be directly applicable to the current problem case.

The second limitation is due to that the PSPs in GCPM were summarized from the historical LLFs. Problems that have never been not encountered would not be resolved and recorded in the LLFs. As a result, they may not be resolved by GCPM. To break this limitation, a model updating procedure is suggested for GCPM as shown in Fig. 3. The model updating procedure is described as follows: when a problem is encountered, its Problem Class (PC) and Process Group (PG) are identified first; then, the CPSM is consulted to find out the recommended PSPs. If the any recommended PSP is available, the related LLF is retrieved for reference of final solution development; otherwise all PSPs in the CPSM are reviewed to select an appropriate existing PSP, or a new PSP is recommended if possible. If no applicable PSP is available, try other approaches other than GCPM; otherwise, the recommended PSP along with the associated PC and PG are sent to a domain expert for review. If the recommended PSP is accepted by the domain expert, the CPSM is expanded to include the new PSP; otherwise, the CPSM remains unexpanded.

The third limitation of the proposed GCPM is also related to its theoretical basis—historical LLFs. Since the CPSM of the GCPM is constructed with on the historical LLFs, different problem domains may result in slightly different CPSM. In this study, a wide range of LLFs of the top-ranked engineering consulting were utilized. Such a selection could relieve the limitation significantly. However, difference in problem domains will result in different LLFs and thus the different CPSM.

6. Conclusions

Construction engineers and managers are faced with emergent problem in their daily works. Efficient and effective resolution of emergent problems plays a key role to a successful construction project. Previous researchers have developed Knowledge Management System (KMS), Community of Practice (CoP), and historical Lessons-Learned File (LLF) to help construction engineers and project managers in finding problem solutions. The CoPs approach needs to wait for the solution-knower to reply; while KMS and LLF require accessibility to computer and information systems. Such requirements are not feasible or practical for the construction engineers and managers in solving the emergent problems encountered on construction site.

This paper presents a general construction Problem-Solving Model (GCPM) that bases on the management parameters (MPs) and Problem-solving Principles (PSPs) adopted from the construction extension of project management body of knowledge (CPMBOK). 631 historical lessons-learned files acquired from previous problem-solving cases are utilized to construct the Construction Problem-solving Matrix (CPSM) that associates the MPs with relevant PSPs. 54 real world cases are tested with the proposed GCPM to find applicable PSPs; among those, 96% are solvable by the PSPs recommended by GCPM. It is concluded that the proposed GCPM provides the construction engineers and managers a useful tool for finding the direction of problem solution. Such a tool may save tremendous time and effort for the construction engineers and managers while they encounter the emergent construction problems.

Although the proposed model has been proved to be useful for practical use, limitations exist with the current version of GCPM due to its theoretical basis—the historical lessons-learned files. A model updating procedure is suggested for the continuous improvement of the proposed GCPM. Moreover, the acquired LLFs had significant influence on the resulted CPSM and thus the effectiveness of problem solving. We suggest using the current version of GCPM as a starting point to develop a more comprehensive GCPM.

Acknowledgements

The valuable historical lessons-learned files utilized in this research were provided by CECI Engineering Consultants, Taipei, Taiwan. The verification of the proposed model in this research was assisted by senior managers and engineers of CECI Engineering Consultants, Taipei, Taiwan. Their helps are highly appreciated.

References

Altsuller, G. S. (2002). *40 Principles: TRIZ Keys to Technical Innovation*, Technical Innovation Center, Worcester, MA.

Carrillo, P., Ruikar, K., and Fuller, P. (2013). "When will we learn? Improving lessons learned practice in construction." *International Journal of Project Management*, Vol. 31, No. 4, pp. 567-578, DOI: 10.1016/j.ijproman.2012.10.005.

Cheng, S. T., Yu, W. D., Wu, C. M., and Chiu, R. S. (2006). "Analysis of construction inventive patents based on TRIZ." *Proceedings of the International Symposium on Automation & Robotics in Construction 2006 (ISARC 2006)*, SessionB3—Construction Planning & Management Methods, 2006, Tokyo, Japan, 134-139.

Chou, J. S. and Yang, J. G. (2012). "Project management knowledge and effects on construction project outcomes: An empirical study." *Project Management Journal*, Vol. 43, No. 5, pp. 47-67, DOI: 10.1002/pmj.21293.

CIOB (2005). *CIOB Education Framework*, Chartered Institute of

Building, UK.

Dogbegah, R., Owusu-Manu, D., and Omoteso, K. (2011). "A principal component analysis of project management competencies for the Ghanaian construction industry." *Australasian Journal of Construction Economics and Building*, Vol. 11, No. 1, pp. 26-40, DOI: 10.5130/ajceb.v11i1.1680.

Ding, Z. and Ma, J. (2014). "An exploration study of construction innovation principles: Comparative analysis of construction scaffold and template patents." In *Proceedings of the 17th International Symposium on Advancement of Construction Management and Real Estate* (pp. 843-850). Springer Berlin Heidelberg, DOI: 10.1007/978-3-642-35548-6_86.

Edum-Fotwe, F. T. and McCaffer, R. (2000). "Developing project management competency: Perspectives from the construction industry." *International Journal of Project Management*, Vol. 18, No. 2, pp. 111-124, DOI: 10.1016/S0263-7863(98)90075-8.

Fayyad, U. and Uthurusamy, R. (1996). Data mining and knowledge discovery in databases, *Commun. ACM*, Vol. 39, pp. 24-27, DOI: 10.1145/240455.240463.

Han, J. and Kamber, M. (2001). *Data Mining—Concepts and Techniques*, Morgan Kaufmann Publishers, San Diego, U.S.A., pp. 109.

Hwang, B. G. and Ng, W. J. (2013). "Project management knowledge and skills for green construction: Overcoming challenges." *International Journal of Project Management*, Vol. 31, No. 2, pp. 272-284, DOI: 10.1016/j.ijproman.2012.05.004.

IPMA (2006). *IPMA Competence Baseline*, Version 3.0, International Project Management Association, Nijkerk, Netherlands.

Li, H. and Love, P. E. D. (1998). "Developing a theory of construction problem solving." *Construction Management and Economics*, Vol. 16, No. 6, pp. 721-727, DOI: 10.1080/014461998372015.

Mann, D. (2001). "40 Inventive (Business) Principles with examples." *TRIZ Journal*, http://www.triz-journal.com, Oct 2001, visited 2014/08.

Mohamed, Y. and AbouRizk, S. (2005a). "Application of the theory of inventive problem solving in tunnel construction."*Journal of Construction Engineering and Management*, ASCE, Vol. 131, No. 10, pp. 1099-1108, DOI: 10.1061/(ASCE)0733-9364(2005)131:10(1099).

Mohamed, Y. and AbouRizk, S. (2005b). "Technical knowledge consolidation using theory of inventive problem solving." *Journal of Construction Engineering and Management*, ASCE, Vol. 131, No. 9, pp. 993-1001, DOI: 10.1061/(ASCE)0733-9364(2005)131:9(993).

Nonaka, I. (1994). "A dynamic theory of organizational knowledge creation." *Organization Science*, Vol. 5, No. 1, pp. 14-37, DOI: 10.1287/orsc.5.1.14.

Paranagamage, P., Carrillo, P., Ruikar, K., and Fuller, P. (2012). "Lessons learned practices in the UK construction sector: current practice and proposed improvements." *Engineering Project Organization Journal*, Vol. 2, No. 4, pp. 216-230, DOI: 10.1080/21573727.2012.681643.

PMI (2013). *A Guide to the Project Management Body of Knowledge*, 5th Edition, Project Management Institute, PA, USA.

PMI (2007). *Construction Extension to the PMBOK Guide*, 1st Edition, Project Management Institute, PA, USA.

Retseptor, G. (2002). "40 Inventive Principles in Microelectronics." *TRIZ Journal*, http://www.triz-journal.com, Feb 2002, visited 2014/08.

Salmon, D. A. and Siegel, A. W. (2001). "Religious and philosophical exemptions from vaccination requirements and lessons learned from conscientious objectors from conscription." *Public Health Reports*, Vol. 116, No. 4, pp. 289-295, DOI: 10.1093/phr/116.4.289.

Tam, C. M., Tong, T. K., and Chiu, G. W. (2006). "Comparing non-structural fuzzy decision support system and analytical hierarchy process in decision-making for construction problems." *European Journal of Operational Research*, Vol. 174, No. 2, pp. 1317-1324, DOI: 10.1016/j.ejor.2005.03.013.

Terninko, J. (2001). "40 Inventive principles with social examples." *TRIZ Journal*, http://www.triz-journal.com, Jun 2001, visited 2014/08.

Webb, S. P. (1998). *Knowledge Management: Linchpin of Change*, The Association for Information Management (ASLIB), London.

Wu, J. W., Tseng, J. C., Yu, W. D., Yang, J. B., Lee, S. M., and Tsai, W. N. (2012). "An integrated proactive knowledge management model for enhancing engineering services." *Automation in Construction*, Vol. 24, No. 1, pp. 81-88, DOI: 10.1016/j.autcon.2012.02.006.

Yeh, S. F., Chang, P. L., Yu, W. D., and Lee, S. M. (2010). "A pilot study on the application of TRIZ to problem-solving of engineering consultants." *Proceedings of the 1st International Conference on Value Engineering (ICVE 2010)*, Invited Lecture, IV4, Oct. 29, 2010, Taipei, Taiwan, 13 pp.

Yu, W. D., Lin, T. C., Liu, S. J., and Chang, P. L. (2013). "Is the knowledge management system truly cost effective? Case study of KM-Enabled engineering problem solving." *Journal of Construction Engineering and Management*, ASCE, Vol. 139, No. 2, pp. 216-224, DOI: 10.1061/(ASCE)CO.1943-7862.0000604

Yu, W. D., Yang, J. B., Tseng, J. C., Liu, S. J., and Wu, J. W. (2010). "Proactive problem-solver for construction." *Automation in Construction*, Vol. 19, No. 6, pp. 808-816, DOI: 10.1016/j.autcon.2010.05.003.

Zhang, X., Mao, X., and AbouRizk, S. M. (2009). "Developing a knowledge management system for improved value engineering practices in the construction." *Automation in Construction*, Vol. 18, No. 6, pp. 777-789, DOI: 10.1016/j.autcon.2009.03.004.

The TRIZ Journal (2015). *web site*: http://www.triz-journal.com, visited 2015/01.

Terninko, J., Zusman, A., and Zlotion, B. (1998). *Systematic Innovation-An Introduction to TRIZ*, CRC Press.

Altshuller, G. (1998). *40 principles: TRIZ keys to technical innovation*, L. Shulyak and S. Rodman, trans., Technical Innovation Centre, Worcester, Mass, USA.