Technical Knowledge Consolidation using Theory of Inventive Problem Solving

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Abstract: Technical knowledge is a valuable asset for construction companies. The diversity and accumulation of such knowledge on an organizational level contribute to company profitability and growth. This paper discusses a new approach for extracting, consolidating, and then retrieving technical construction knowledge that builds on the contradiction resolution concepts of the theory of inventive problem solving. The approach was used to extract knowledge from a number of lessons learned describing technical construction problems encountered by a major construction company. The approach depends on finding the similarities between technical solutions of problems that belong to different technological domains. These similarities represent the essence of these solutions and are represented using domain-independent terms so that they can be applied to new problems. The outcomes of the knowledge extraction and accumulation process are discussed in the paper to address the feasibility of the proposed approach and its potential benefits and limitations.

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Introduction

Construction projects are unique and, therefore, field problems associated with them may have few similarities. Construction projects usually involve many disciplines and require integration of knowledge from civil, mechanical, electrical, and other engineering domains. Therefore, the technical knowledge required for delivering construction projects effectively is quite diverse. The accumulation and preservation of such knowledge plays a vital part in the company's success.

Several approaches are followed in the literature for knowledge acquisition, consolidation, and representation in the construction domain. The most basic approach is documenting innovative construction methods and publishing these documentations so that they become available to the construction community. Numerous examples of this approach are found in the literature including: Elazouni (1997), Abd el-Razek and Basha (2001), Gambatese and James (2001), and Bernold et al. (2001).

A second approach makes use of multimedia technology to provide a more automated way for acquisition, storage, retrieval, and manipulation of constructability lessons learned. This approach provides better accessibility to a wider range of documents, images, and videos of construction solutions. Examples of this approach can be found in the work of Vanegas (1993), McCullouch and Patty (1993), and Williams (1994).

The above two approaches provide the details of a construction method to the user in a raw form with different degrees of browsing and searching abilities. It is up to the user to relate the description of the method to the new problem he/she is trying to solve. This approach is not limited to a particular domain of problems. However, the extraction of reusable knowledge from such documentations is left to the end user.

A third approach focuses on automating the knowledge acquisition, representation, and retrieval process by applying artificial intelligence techniques like expert systems (ESs), artificial neural networks (ANNs), or case-based reasoning (CBR). Examples of these applications are found in the work of Mohan (1990), Chao and Skibniewski (1995), and Arditi and Tokdemir (1999). The knowledge stored in these applications is usually structured to allow reusability in an electronic form. Extrapolating for solving problems from the same domain but outside the knowledge base (i.e., rule base of an ES, case-base of a CBR system, or training set of ANN) is usually difficult.

The theory of inventive problem solving (TRIZ) (Altshuller 2000) utilizes a special approach for consolidating and preserving high-level knowledge. The theory extracts knowledge from different technological fields and consolidates them in a set of tools that should apply to many engineering domains. This unique approach can be useful in preserving technical knowledge used for solving problems in construction. The generic nature of TRIZ tools allows them to adapt to construction. However, the use of these tools requires a considerable amount of training and often yields generic solutions that require further manipulation to make them practical.

This paper discusses an approach for representing and navigating construction knowledge by emulating the process used by

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Altshuller in the development of TRIZ. It focuses mainly on the following objectives:

1. To test the practicability of the TRIZ approach in representing technical construction problems and
2. To develop a prototype framework for consolidating technical knowledge used for solving construction problems to enable preserving construction companies' know how in an abstract form.

In the study described in this paper, the proposed approach is used to extract knowledge from lessons learned in construction and to consolidate these lessons in a manner that makes them usable by others. A knowledge representation schema is formulated based on the concepts of TRIZ. A number of lessons learned summaries are analyzed according to this schema and stored electronically. The outcomes of the knowledge extraction and accumulation process are then analyzed and discussed to assess the feasibility of the objectives mentioned above.

Table 1. Levels of Inventions (Savransky 2000)

Level	Description	Percentage
1	Regular: Includes solutions for routine design problems using methods well known within the specialty or within a company.	32
2	Improvement: Includes an improvement to earlier known prototype using uncommon methods from the same engineering field and some creative effort.	45
3	Invention inside paradigm: Essential improvement and radical change of the earlier known prototype by utilizing knowledge from other disciplines.	18
4	Breakthrough outside paradigm: Radical change of the prototype using a new idea that has practically nothing in common with the prototype.	4
5	Discovery: Pioneer invention of a radically new technique based on major discovery in some basic or new science.	Less than 1

Relevance to Industry Practitioners and Researchers

This study presents a new approach for dealing with innovative solutions produced by construction contractors based on their experience with various projects and construction problems. For years, contractors have cited the importance of lessons learned from previous projects. However, the usability of these lessons was always a problem due to difficulties associated with accessing the knowledge embedded in them. The approach described in this paper offers a new view for dealing with this issue. It should be of interest to industry practitioners as it provides a generic way to consolidate the knowledge embedded in their lessons learned. It also gives researchers a new perspective in dealing with knowledge extraction and representation that may produce new research initiatives for better utilization and maintenance of contractor "know how."

Background

Theory of Inventive Problem Solving's Innovation Heuristics

Based on the study of a large number of engineering patents, Altshuller classified inventive problems into five levels according to the creativity level used in solving them: with level 1 pertaining to the lowest level of creativity and level 5 to the highest. The definitions of these levels and their percentages among the inventions he studied are shown in Table 1. Altshuller found that Levels 1, 2, and 3 represent the largest portion of patents while high level inventions of Levels 4 and 5 only correspond to about 5%. He also concluded that inventions of lower levels utilize the same principles and heuristics for solving problems that may appear under totally different technological classifications.

> "Analysis of thousands of authors' certificates [the Russian equivalent of patents] and patents demonstrates the existence of several common principles forming the basis for the majority of contemporary inventive ideas" (Altshuller 2000).

An example of these common principles is the replacement of straight beams for supporting mining tunnels with arched beams for better counteraction against pressure. The same transformation took place some years later in the construction of hydroelectric power stations where straight dams are replaced by arching ones. Excavator bucket (power shovel) manufacturing is a different industry; however, the same transformation principle is used. The shovel bucket's front edge was initially straight, then an arched bucket appeared (Altshuller 2000). Altshuller states that:

> "Knowledge of these principles, along with the knowledge of how to use them, creates the possibility for increasing the efficiency of creative work."

Based on these conclusions Altshuller and his co-workers formulated a number of tools to support TRIZ. These tools provide systematic analysis of inventive problems. The tools include "Contradiction matrix," "Substance-field analysis," "Physical contradiction principles," and "Evolution patterns." This study makes use of concepts used in the Contradiction matrix and therefore focuses only on that tool.

Structuring Construction Problem-Solving Knowledge Using Contradictions and Resolution Principles

According to TRIZ, the most effective solution of a problem is the one that overcomes some contradictions. Contradictions occur when improving one parameter or characteristic of a technique negatively affects other parameters of the technique. When a solver extracts a contradiction from the problem, it becomes easy to find a variety of creative and effective solutions for the problem. Usually a problem is not effectively solved if its contradictions are not overcome or substantially reduced. Altshuller and his co-workers distinguished three types of contradictions.

1. The first type is "Administrative contradictions" where something is required to make or receive some result but it is not known how to achieve the result. This type of contradiction has no heuristic value and does not show a direction to the answer. For example, management wants to increase quality of production and decrease cost of raw material.
2. The second type is "Technical contradiction" where an action has simultaneously useful and harmful effects on subcomponents of the system or on the system as a whole. For example, the erection of traditional formworks is necessary for completing concrete works but negatively affects the workspace required for other activities.
3. The third type is "Physical contradictions" where a given component should have Property "A" to deliver some func-

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Characteristic to be improved		Characteristic that is getting worse				
		27	28	29	30	31
	Engineering Parameters	Reliability	Accuracy of Measurement	Accuracy of Manufacturing	Harmful factors acting on object from outside	Harmful factors developed by an object
23	Loss of Substance			35, 10, 24, 31		
24	Loss of Information			Resolution principle numbers		
25	Waste of Time	10, 30, 4	24, 34, 28, 32	24, 26, 28, 18	35, 18, 34	35, 22, 18, 39
26	Amount of Substance			33, 30		
27	Reliability	Physical Contradiction		11, 32, 1		
28	Accuracy of Measure-ment		Physical Contradiction	-		

Resolution Principles	23) Feedback. 24) Intermediary. 25) Self-service.	26) Copying. 27) Inexpensive short-lived objects. 28) Mechanics substitution

Fig. 1. Sample components of theory of inventive problem solving's Contradiction matrix

tion and Property "non-A" or "anti-A" to satisfy the conditions of a problem or to prevent some harmful effects (Savransky 2000). For example, the cross-sectional area of a structural element needs to be large enough to withstand stresses while remaining sufficiently small to reduce element weight.

One of the tools provided in TRIZ is the "Contradiction matrix." The matrix is a decision table that provides directions to the most effective principle(s) that can be used for resolving a technical contradiction between two generic characteristics (also called technical parameters) in a system. The matrix developed by Altshuller (will be referred to as the standard contradiction matrix) includes 39 generic technical system characteristics and 40 inventive principles that were consistently used in a large number of patents. A sample of the different components of the matrix is shown in Fig. 1. When a problem solver uses the matrix to solve a new problem, the problem needs to be reformulated in terms of contradictions between generic characteristics of the system under analysis. For example, if a system for measuring the exact dimensions of a construction component causes a big loss in time, the problem can be formulated as a contradiction between the two characteristics: characteristic Number 28 (Accuracy of measurement) and Number 25 (Waste of time). Using these two generic characteristics, the matrix directs the solution search process toward the resolution principles that were most frequently used in similar cases. In this example, as shown in Fig. 1, the contradiction points to principle Number 24 (Intermediary), 34 (Rejecting and regenerating parts), 28 (Mechanics substitution), and 32 (Changing the color). A further explanation of these principles can be found in TRIZ literature. Complete lists of the system characteristics and resolution principles given in the standard contradiction matrix of TRIZ are given in the Appendix.

Construction Knowledge Consolidation Framework

Knowledge-Representation Schema

Based on the concepts described in the previous sections, a knowledge-representation schema is formulated for storing the knowledge associated with innovative solutions of construction

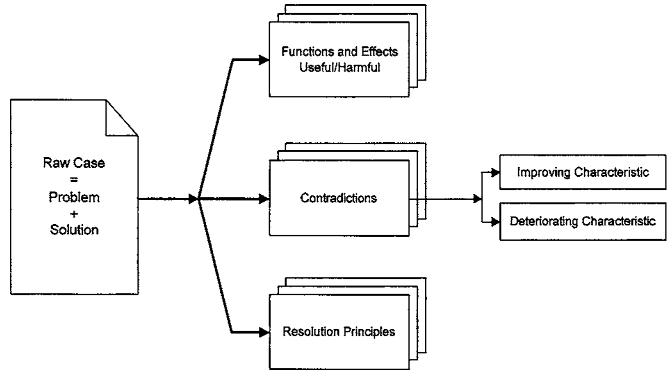

Fig. 2. Knowledge representation of problem solutions

problems. The main components of an inventive problem based on TRIZ's contradiction matrix concepts are contradictions. Contradictions are pairs of two conflicting system requirements. These requirements can be represented from a finite list of generic system characteristics. Therefore a single contradiction can be further decomposed into two characteristics that negatively affect each other. According to TRIZ concepts, the solution direction of an inventive problem can be provided by one or more resolution principles. These principles are finite and generic in nature.

Using this breakdown, a knowledge representation schema can be formulated as demonstrated in Fig. 2. A case is represented by a solution of a technical construction problem. It can be represented in terms of the contradictions that cause the problem and the resolution principles followed in solving the problem. As these two elements are generic, a third one is introduced to add problem related definitions. This component is the set of functions delivered in the case. Therefore in order to break down a case according to this schema, the case is decomposed into three main elements: a set of functions, a set of contradictions, and a set of resolution principles. The functions describe the objectives of the system using domain-dependent terminology. These objectives can be useful effects to achieve, or harmful effects to eliminate, or a combination of both.

The "contradictions set" contains pairs of characteristics that conflict with each other. Each of these characteristics is generic in the sense that it does not depend on problem-related terminology and can be used for describing other cases. A case may contain more than one contradiction.

Finally, the resolution principles represent the domain-independent heuristics that are used in the solution. A principle represents an abstraction of how the main contradictions in the case were removed or substantially reduced. A case may also contain more than one principle.

Proposed Framework

Using the knowledge representation schema discussed in the previous section, a framework is proposed for consolidation and retrieval of knowledge used in solving construction problems as shown in Fig. 3.

The framework depends on accumulating the expertise of a construction company in an abstract format using generic heuristics or principles. These principles are extracted from problem solutions that the company successfully implements. The extraction process can be performed by a knowledge management team with proper training in TRIZ concepts. During the analysis phase of the study described in this paper, the team consisted of two part

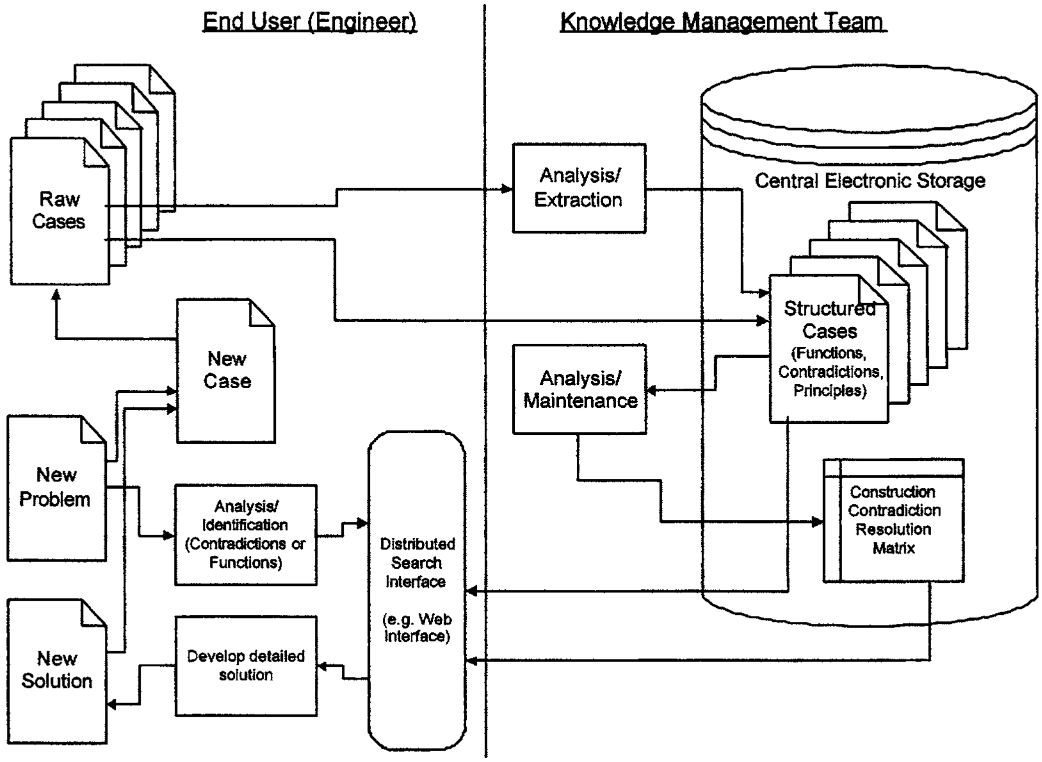

Fig. 3. Knowledge consolidation framework

time engineers (a student and a research engineer) with TRIZ background occasionally liaising with technical personnel who possesses more detailed knowledge about the analyzed cases. Such a team would also be responsible for maintaining a central problem-solving knowledge base for the company, which holds the analyzed cases in addition to a TRIZ-like contradiction matrix that relates the principles to the different contradictions. Maintaining the knowledge base involves updating the contents of the matrix depending on the observed frequency of use of the existing and new resolution principles, and the technical characteristics involved in the contradictions.

A user should be able to search the knowledge base using an identified contradiction in the problem or by functions or effects required to be achieved (or eliminated if they are harmful).

Uniqueness of Approach Proposed in Framework

The proposed knowledge extraction and consolidation approach represents a new methodology for analyzing, preserving, and accumulating technical construction knowledge. Instead of accumulating cases of problem solutions in raw format and using them "as is" for conducting search using key words or work-type classifications, the proposed approach aims at generating more value from these pieces of information by extracting the "essence" of each of them. It aims at processing the cases to separate the generic principles that contributed to the development of their solutions.

Using a traditional search approach, a case that deals with a particular problem may have no value in solving a completely different problem that belongs to another work category. However, by extracting some high-level generic principles from that case, it could give useful directions to solve the new problem.

Consider for example the case described by Elazouni (1997). The case in its raw format describes a detailed solution for improving constructability of steel silos during field operations. The method depends on inverting the sequence of field operations such that the uppermost part of the silo is completed at grade and then lifted up gradually to allow the building of the successive parts. The purpose is to always work at grade, thus eliminating the need for scaffolding, and to attain other benefits (Elazouni 1997).

Although the detailed solution is important for steel silos construction, it is of less value to other construction domains. However, the principles applied while developing that solution can be reusable and are, therefore, of high value. In fact, similarity can be observed between the steel silos solution, the concept of the lift slab, and a solution for improving construction of submerged pile caps described by Elazouni and Abd El-Razek (2000). Although the three cases deal with completely different construction components, the underlying principles that govern the construction methods are very similar. Such principles are not explicitly described in the detailed solutions although unconsciously used by the engineers who develop them.

Using the proposed knowledge consolidation approach to extract metaknowledge from the steel silos case, the problem in the original situation can be reduced to a contradiction between "Manufacturability" on one side and "Convenience of use" on the other side. This contradiction was resolved in this case by reversing the traditional sequence of construction and making elements of the construction system more dynamic. So the solution of the case is reduced to the implementation of two principles: "Do it in reverse" and "Dynamicity." The terms "Manufacturability," "Convenience of use," "Do it in reverse," and "Dynamicity" are generic enough to describe cases of completely different nature from the steel silos case. In fact, these terms now provide a link between the three construction solutions (i.e., steel silos, lift slab, submerged pile caps), which would otherwise seem totally unre-

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lated. By appending the details of the solutions to these generic descriptors, they can provide good guidance to an engineer who searches for a solution to a new problem not necessarily related to any of the original problems.

The critical part of the proposed framework is building the knowledge base component by extracting and consolidating knowledge from a large number of case studies. Even though the findings of Altshuller indicate that a finite set of contradictions and resolution principles can be representative of a large number of inventive solutions in different engineering fields, these findings appear to apply mainly to complex problems. The type of knowledge we need to represent in construction represents a lower degree of difficulty and creativity in most cases and as such may be more challenging. In order to test the feasibility of our approach, we developed a prototype and tested its effectiveness using information from a major construction contractor. An electronic implementation of the knowledge-base component was developed to facilitate the evaluation of the approach and assess the required modifications for it. The next sections describe that component and the results of using it for analyzing a number of cases.

Development of Knowledge-Base Component

Contradiction Resolution Database

To evaluate the feasibility of the proposed knowledge-base component, first a database system was designed and implemented to provide a tool for storage, retrieval, and analysis of the extracted knowledge from a large number of cases. Second, a repository of "lessons learned" technical summaries provided by a major construction company was studied. The knowledge from these summaries was extracted using the format described in the previous sections and accumulated in the database system.

The database is designed to allow for breaking down a case using the standard engineering characteristics and resolution principles of TRIZ. In addition, it allows adding new characteristics and principles that do not exist in the standard TRIZ contradiction matrix so that a customized matrix can be built and updated with more cases analyzed and entered in the database. The database also allows for associating each case with a set of useful/harmful effects or functions that represent the objective(s)of the case. The retrieval of information from the database can be done by querying it for principles and sample cases used for resolving a complete contradiction (i.e., two conflicting characteristics), by querying it for a single characteristic to be improved or removed, or by the functions required to be achieved.

Knowledge Extraction and Population of Database

A repository of "lessons learned" summaries was the main source for knowledge extraction. These lessons learned were collected by a general contractor in the form of one page descriptions of the problem and its solution. The summaries included both technical and administrative lessons. Approximately 90 technical cases were used. A technical case is analyzed and fed into the database if it meets the following criteria: (1) it has enough of a description in the summary to obtain good understanding of the problem and its solution, and (2) it represents an innovative nontrivial solution. Fifty five cases passed these criteria and were further analyzed.

Each case was analyzed to extract the following:

1. The main functions/effects produced by the system described in the case and the classification of these functions/effects as useful or harmful;
2. The contradictions in the case as a pair of two conflicting parameters and a description of each contradiction; if a standard TRIZ parameter cannot be found a new one is proposed; and
3. The resolution principle that best represents the solution described in the case; if a standard TRIZ principle cannot be found a new one is proposed.

The following section describes an example from these cases.

Sample Case 1: Lifting Heavy Elevator Machinery

Analyzing Case

One of the cases entered into the database deals with moving heavy machinery. The case description as reported in the "lessons learned" summary is as follows (some personal, and project related data were masked for confidentiality):

> "How do you move an 8,000 lb piece of machinery without the use of overhead tower cranes or hoist beams? —, project coordinator on the — project in — informs us that when faced with such a dilemma, they simply floated it on a film of air!
>
> When an elevator armature required replacement on the 40th floor of the now occupied — office tower, its replacement (weighing 8,000 lbs) was maneuvered across the office floor covering a distance of 200 ft using four air float bearing skids. Each of the skids consisted of a flexible urethane diaphragm sealed around the circumference and attached to the center of the skid. Weighing only 5 lbs, the 12 in. square skids were placed under the corners of the machine. A flow of air supplied to each skid inflated the diaphragm and the floor. Supported on this film of air, the 8,000 lb load was easily moved requiring as little as 8 lbs of lateral force to guide the machine to the desired location.
>
> A timber mat with a plywood sheathing surface was constructed to distribute the applied loads over a sufficient area so as not to exceed the structural capacity of the floor slab. It was discovered however, that the bearing skids lost their film of air over the joints of the plywood surface causing the machine to come to rest. To alleviate this problem polyethylene plastic was applied with a second layer of plywood sheathing added. All corresponding joints of the plywood layers were staggered to minimize air pressure loss. With these modifications, the air float system worked effectively during the entire operation." (Courtesy of PCL Constructors Inc.)

When analyzing this case, the first step was to identify the useful functions/effects to achieve and/or the harmful ones to avoid in the case. The main useful function to be achieved in the case is to "move heavy elevator machinery." However this function cannot be achieved using regular material handling equipment because of a harmful effect from the surrounding environment, which is the "limited workspace." So, "move heavy elevator machinery" and "limited workspace" were used for functions/effects input.

The second step is to identify the standard and/or proposed contradictions in the case. A sample of the standard parameters and principles is shown in Fig. 1, while a more complete list of

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system standards is available in the Appendix. Apparently the weight of the machine is one source of the problem. If the machine were of lighter weight, it could be moved using small lifting equipment or even human power. Therefore the first contradicting parameter can be identified as “1. Weight of mobile object.” On the other side of the contradiction, the closest standard parameter that can describe the deterioration happening because of the increase in weight is “37. Complexity of control.” Although this contradiction seems to describe the problem, the approach followed in analyzing these cases was to try to identify all possible contradictions in the case. A second contradiction can be identified as well between “7. Volume of mobile object”and “37. Complexity of control.” The volume of the machine is also considered a factor in this problem because if the machine were of small volume, traditional methods could be used and maneuvering the machine around the space would be easier. Based on this analysis, two standard contradictions were entered into the system. One between standard parameter “1” and “37,” and the second between parameter “7” and “37.”

The third step in the analysis is to identify the proposed contradictions if any. In this case, two parameters were proposed for better description of the problem. The first is “Handling/relocation” and the second is “Workspace.” Using these proposed parameters, two contradictions can be identified. One is between “Workspace” and “Handling/relocation” and the second between “Weight of mobile object” and “Handling/relocation.”

The last step in the analysis is to identify the principles used in solving the problem and how they were used. In this case “Pneumatic or hydraulic construction” is obviously one of them as the traditional mechanical lift using cranes is replaced by pneumatic lift provided by floating the machine over a thin film of pressured air. Another principle used in the case is “Flexible films or thin membranes,” which is manifested in the use of polyurethane covering for the mats to prevent air pressure loss. This principle is not directly related to the original contradiction in the case and is only used to solve a new problem with the pneumatic lift technique. However, it is also extracted and entered into the system as an example for the use of the principle.

This case is one of the cases that has good match between the actual solution and the principles proposed by the standard TRIZ matrix. Using the two standard contradictions identified in the case, the matrix proposes using the following principles:

- 29 Pneumatic or hydraulic construction (proposed twice from the two contradictions),
- 26 Copying (proposed twice from the two contradictions),
- 28 Replacement of mechanical system, and
- 4 Asymmetry.

Adding Case to Database

Once the above analysis is completed, the case is entered into the database. The details of the case are broken down and abstracted to a corresponding set of contradictions, functions, and resolutions principles.

Fig. 4 shows the decomposition of the case into different entries in the database. These entries can be classified, in general, into two categories; entries based on the standard matrix and entries proposed for an extended matrix.

One of the main objectives of using an electronic system to store the cases is to be able to customize a contradiction matrix that represents solution directions for construction problems. The entry of proposed contradictions and proposed principles serve this objective. In this case there were no proposed principles to replace the standard ones. However, one nonstandard parameter

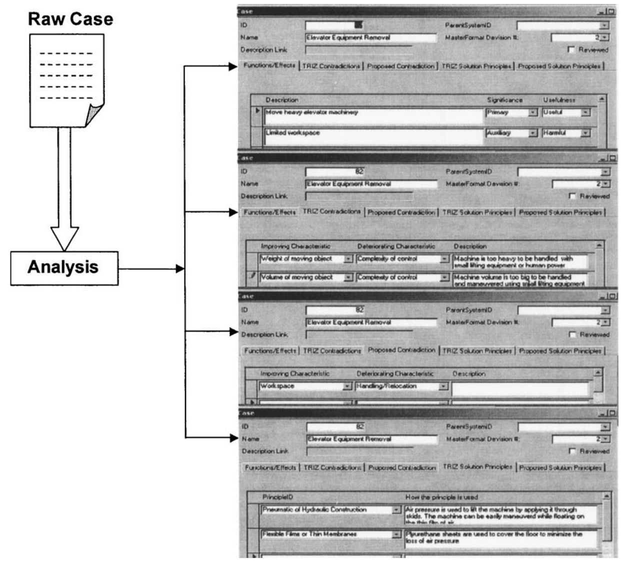

Fig. 4. Decomposition of sample case 1 into database entries

was added to the system under the proposed contradiction (i.e., “Workspace”) while another nonstandard parameter was selected from the list previously proposed by other cases (i.e., “Handling/relocation”). The accumulation of such entries over time helps in reforming the matrix and enhancing it to be more usable in solving construction problems.

Discussion and Findings

Frequency of Principle Use

Fig. 5 shows the frequency of principles use in the analyzed cases. For example, the “Mediator” principle was used 11 times to describe solutions in the analyzed cases. This means that these solutions, regardless of their details, depend mainly on introduc-

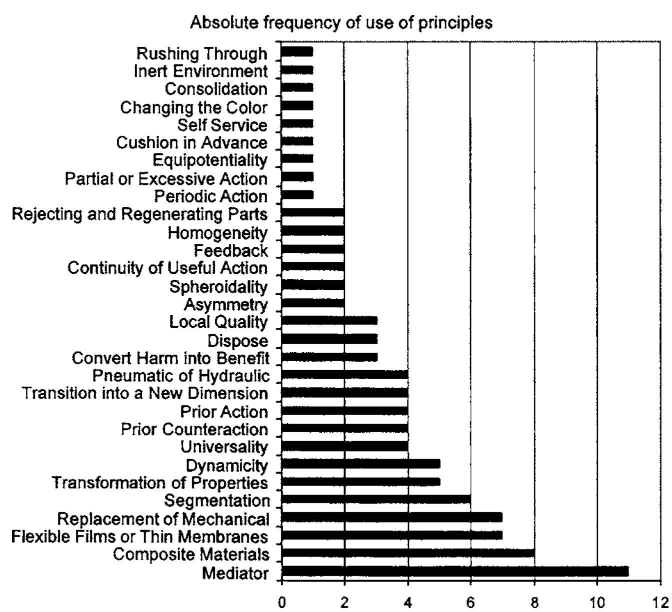

Fig. 5. Frequencies of use of different principles

Table 2. Proposed Parameters

Proposed parameter	Frequency of use as deteriorating	Frequency of use as improving
Aesthetics	5	1
Handling/relocation	5	6
Complexity of process	4	0
Disturbing the surrounding environment	4	6
Work area	3	2
Accessibility	3	1
Ease of use	3	1
Fragility	2	0
Loss of heat	2	0
Shrinkage	1	2
Ease of installation	1	1
Harmful effects caused by surrounding environment	1	2
Amount of preparation work	1	0
Cycle time	1	2
Ability to properly and completely form	0	2
Safety	0	2
Insulation	0	1
Ease of disassembly	0	1
Water tightness	0	1
Ease of detection	0	1
Flexibility	0	1
Reuse ability	0	1
Ease of assembly	0	1
Workspace	0	1

ing a "Mediator" element. A generic description of this principle is given in TRIZ literature as "a. use of an intermediary object to transfer or carry out an action, or b. temporary connection of an object to another one that is easy to remove" (Altshuller 1998).

As one of the objectives of the study is to investigate the suitability of the standard TRIZ matrix for describing innovative construction solutions, new principles would be added only if the standard principles of TRIZ failed to give an acceptable description of the solution.

In the number of cases analyzed, the standard TRIZ principles showed a good representation of the solutions. This conclusion is based on the fact that there was no need to propose any new principles to better describe the analyzed cases. Furthermore, the solutions were represented by only a subset of the total standard principles (30 out of 40 principles).

Frequency of Parameter Use

Unlike the standard TRIZ principles discussed in the previous section, a total of 24 parameters needed to be added to provide a better description of the problems. Table 2 shows a list of the proposed parameters. Some of these proposed parameters represent only rephrasing of standard parameters. However, this indicates some limitation in the ability of the standard parameters to describe a wide range of problems.

Fig. 6 shows the frequencies of use of the parameters as deteriorating or improving and the total of both. Some of the standard parameters given in the matrix were not used at all. There is some inconsistency between the use of a certain parameter as deteriorating versus an improving one. Higher use of one parameter as deteriorating did not necessarily mean it was widely used as improving.

Defining Contradictions

One of the problems realized when analyzing some cases is the difficulty of recognizing a clear contradiction in the problem. In many cases only one parameter could be identified as deteriorating or improving. One of the reasons for this difficulty could be the nature of the problem itself. According to TRIZ, some problems may represent an incomplete substance-field (a tool for modeling the structure of a technical system), in which case, the contradiction matrix is not the best tool to use.

Defining Functions and Effects

Defining the goal of the system in terms of functions or effects that need to be achieved (or removed) was found to be a useful step toward identifying contradictions in the system. A contradiction is a result of trying to achieve a useful function while preventing a harmful one at the same time. The introduction of function definitions with each case can also be useful for search and case retrieval purposes. One format for defining functions is the use of an action verb plus a noun that describes an object or an attribute of an object. However, the same action can be described by many verbs, and many nouns can describe the same object. Having standards for function definition is necessary for allowing an effective search. Defining such standards is out of the scope of this study. However, the recent Overall Construction Classification System (OCCS 2001) standards include a promising approach towards a standard function definition format.

Limitations of Proposed Framework

The proposed knowledge consolidation framework is limited to providing ideas that can guide an engineer in solving a technical problem instead of providing him/her with a complete workable solution. The principles proposed from the framework represent search directions where the engineer can locate the most effective solutions but do not guarantee that a workable solution will be found. By supplementing these principles with examples of previous solutions that utilized them successfully, the engineer is expected to analogically generate solutions for the problem at hand. The human element is therefore essential while using the proposed framework for solving new problems.

The human element is also required for building up and maintaining the knowledge base in the framework. This process requires continuous human involvement for analyzing new cases and updating the matrix based on the analysis of these cases.

Conclusions and Recommendations

A study of a number of "lessons learned" cases has been carried out. The study used an approach similar to the one used for building TRIZ's contradiction matrix to consolidate the technical knowledge used for solving construction field problems. A framework was developed to analyze the information collected from the different cases and to help in the search and retrieval of information for solving new problems.

The analysis of the cases shows that the standard principles of TRIZ are highly representative of the solutions of the problems

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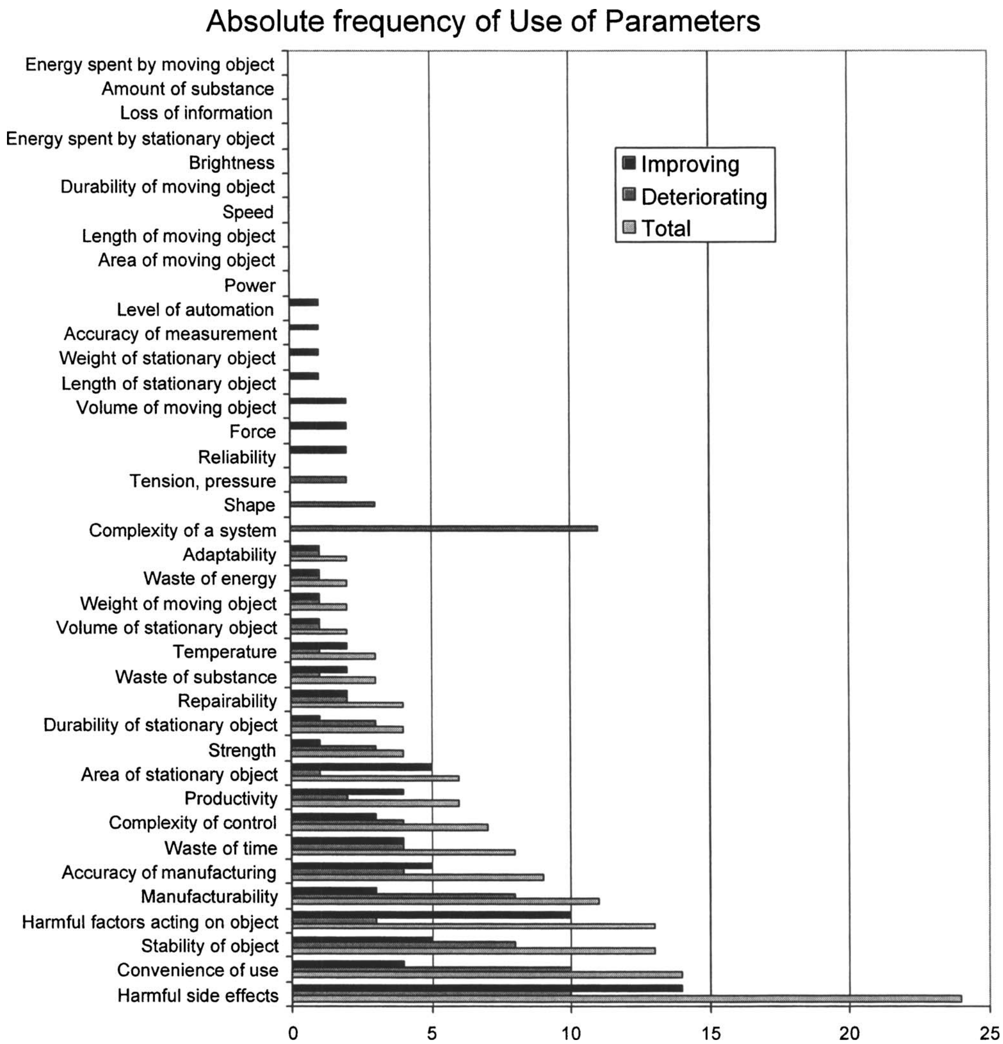

Fig. 6. Frequencies of parameters use

while the standard parameters are less representative and need to be extended. The fact that the principles set is of relatively small size (40 principles) makes the option of using the principles without guidance from the matrix a feasible alternative. This means the problem solver may scan the principles and their interpretations and examples, and use the relevant ones without the need to formulate a contradiction. This approach is also described in TRIZ literature.

There were some difficulties in formulating a complete contradiction for some cases. This difficulty can be attributed to the nature of the problem or the suitability of the contradiction matrix tool. It is recommended to include other tools in the analysis of the cases so that the best tool for a particular case could be selected.

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Appendix. Standard System Characteristics of Theory of Inventive Problem Solving and Inventive Principles

System Characteristics

ID	Name
1	Weight of moving object
2	Weight of stationary object
3	Length of moving object
4	Length of stationary object
5	Area of moving object
6	Area of stationary object
7	Volume of moving object
8	Volume of stationary object
9	Speed
10	Force
11	Tension, pressure

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ID	Name
12	Shape
13	Stability of object
14	Strength
15	Durability of moving object
16	Durability of stationary object
17	Temperature
18	Brightness
19	Energy spent by moving object
20	Energy spent by stationary object
21	Power
22	Waste of energy
23	Waste of substance
24	Loss of information
25	Waste of time
26	Amount of substance
27	Reliability
28	Accuracy of measurement
29	Accuracy of manufacturing
30	Harmful factors acting on object
31	Harmful side effects
32	Manufacturability
33	Convenience of use
34	Repairability
35	Adaptability
36	Complexity of a system
37	Complexity of control
38	Level of automation
39	Productivity

Inventive Principles

ID	Name
1	Segmentation
2	Extraction
3	Local quality
4	Asymmetry
5	Consolidation
6	Universality
7	Nesting (Matrioshka)
8	Counterweight
9	Prior counteraction
10	Prior action
11	Cushion in advance
12	Equipotentiality
13	Do it in reverse
14	Spheroidality
15	Dynamicity
16	Partial or excessive action
17	Transition into a new dimension
18	Mechanical vibration
19	Periodic action
20	Continuity of useful action
21	Rushing through
22	Convert harm into benefit
23	Feedback
24	Mediator
25	Self service
26	Copying
27	Dispose
28	Replacement of mechanical system
29	Pneumatic of hydraulic construction
30	Flexible films or thin membranes
31	Porous materials
32	Changing the color
33	Homogeneity
34	Rejecting and regenerating parts
35	Transformation of properties
36	Phase transition
37	Thermal expansion
38	Accelerated oxidation
39	Inert environment
40	Composite materials

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