UNIVERSITY OF ALBERTA

A FRAMEWORK FOR SYSTEMATIC IMPROVEMENT OF CONSTRUCTION SYSTEMS

BY

YASSER MOHAMED ©

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This thesis is dedicated with love and admiration to my mother and my father,
to my beloved brothers, and my wife;
the people who taught me what life is all about.

ABSTRACT

The construction industry has a number of peculiar characteristics that distinguish it from other industries. These peculiarities require a unique suite of modeling and analysis tools for managing construction production. The research presented in this thesis describes new methodologies in the areas of knowledge management, and construction simulation modeling.

The research explored the Theory of Inventive Problem Solving (TRIZ) as a unique theory for managing innovation. The theory was applied in its native form to a number of case studies in the area of utility tunnel construction, which showed a number of advantages in the theory in addition to a number of limitations. The research also extended the use of TRIZ by utilizing a similar approach to consolidate and preserve the knowledge used in solving construction field problems.

A simulation framework was then conceptualized and prototyped based on some of TRIZ fundamentals. The framework builds on the principles of function analysis and combines them with state-based simulation and software agent concepts to formulate a hybrid simulation approach that provides new possibilities in construction simulation. Among these possibilities are dynamic topological modification of simulation models and development of intelligent simulation agents. The framework was prototyped as a template under Simphony's development environment and used for building a sample special purpose simulation template for tunneling operations.

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Chapter 1 - Introduction

1.1 Management of construction production

While some industries such as the manufacturing industry have experienced remarkable improvements in performance over the past two decades, the construction industry has not demonstrated comparable improvement over the same period of time. The lack of an explicit theory for construction and lack of process innovation are two of the main causes for hindering construction performance. (IGLC, Alarcon 1997)

The special features and characteristics of the construction industry require the formulation of a unique production theory and related tools that efficiently describes and controls the mechanics of the production systems on construction sites (Koskela 2000). Koskela (2000) also concluded that such theory and tools need to integrate the transformation, flow, and value concepts found in the manufacturing industry's views of production instead of adopting one of them. One of the requirements of such a theory is to stimulate radical innovation in production systems as well (Koskela and Ruben 2000).

This research aims to explore and define new modeling and analysis techniques as a foundation towards a generic and integrated framework for managing construction production.

1.2 Background

1.2.1 Limitations of previous approaches

1.2.1.1 Construction processes modeling tools

Modeling production systems and being able to experiment with the models represent a cheap and reliable means for quantifying and evaluating the performance of the system under different conditions. However, the peculiarities of the construction industry and its production systems raise the need for a special class of modeling tools that can accommodate these peculiarities.

Methods like CPM and PERT were criticized by a number of researchers for being not a true model of the construction process. These methods lack the adequacy to model complex logic and resource constraints in a construction process (Koskela 2000, and Howell and Ballard 1997).

Simulation is considered one of the powerful tools for modeling construction operations. However, despite the numerous simulation tools that have been developed for the construction industry, the use of simulation by industry personnel was limited (Hajjar 1999). Hajjar and AbouRizk (2002) developed a Special Purpose Simulation (SPS) modeling approach, which overcomes many of the obstacles that used to limit the use of simulation modeling in the construction industry. A number of simulation modeling tools were successfully developed and used based on that approach. The SPS approach allows an engineer to examine different solutions and scenarios for a construction operation and choose the optimum one. The engineer generates alternative solutions by changing the structure of the model (i.e. flow of processes) and/or parameters of its elements in order to improve the performance of the model. Mathematical optimization algorithms can be used for searching for optimality by changing the parameters of elements in a model (e.g. Hajjar and AbouRizk 1998). However, the search for optimality among structurally different models is mainly guided by the knowledge and experience of the engineer.

1.2.1.2 Knowledge management and problem solving in construction

Knowledge is viewed as a valuable asset of any organization. Corporations are finding that they must incorporate both continuous improvement and organizational learning in order to improve business results and compete in a global economy (Fisher 1997). Different approaches have been used in the construction literature for preserving knowledge and reusing it for solving new problems. The basic approach is based on documenting problem solutions as a common way for preserving the knowledge used in these solutions. Reuse of such knowledge depends on the end-user's ability to first locate the appropriate documents and then study and extract the relevant knowledge from them. An intermediate approach uses automated tools to assist the user search and locate relevant documents and multimedia material that relates to a particular subject. Many construction companies use similar approach to share project lessons learned among their employees. This approach helps the user locate relevant documents and materials but does not help extracting reusable knowledge from them.

The third approach extracts knowledge from different sources for a specific domain and tries to automate its reuse using AI techniques like expert systems and case-based reasoning. This approach focuses on providing detailed solutions for problems within the same domain but is strictly limited in extrapolating solutions outside its domain.

1.2.2 Theory of Inventive Problem Solving (TRIZ)

The theory of inventive problem solving (TRIZ) provides a systematic methodology for solving difficult problems. TRIZ ideology is based on two major ideas: "Contradiction" and "Ideality". One of the main strengths of the theory is focusing on solving contradictions in a system without introducing compromises. Originally developed by the Russian engineer Genrich Altshuller in the mid 50s, the theory is based on studying and analyzing patents in different technological fields. Altshuller himself studied more than 400,000 patents worldwide. To date, TRIZ specialists have analyzed approximately 2 million patents. The analysis of these patents in the different areas of engineering resulted in several important discoveries, which form the TRIZ philosophy. The followings are summaries of the main TRIZ concepts: (Savransky 2000)

- Every design product evolves according to regularities, which are general for every engineering domain. These regularities can be studied and used for inventive problem solving, as well as for forecasting the further evolution of any design product.
- An inventive problem can be represented as a contradiction between new requirements to a design product, which is no longer capable of meeting the requirements. Finding an inventive solution to the problem means elimination of the contradiction under the condition that no compromise is allowed.
- Design products, like social systems, evolve through the elimination of various types of contradictions. The principles for eliminating the contradictions are common for all areas of technology.

- There is a universal criterion of the best possible solution: ideality. The degree of ideality means the ratio between useful effects produced by a design product and material, energy and information expenses necessary to produce the useful effects.
- Frequently, when searching for inventive solution to a problem formulated as a contradiction, there is the need to use physical knowledge unknown to the domain engineer. To organize and guide the search for appropriate physical knowledge, pointers to physical effects should be used. In the pointers, the physical phenomena are identified with the lists of technical functions, which can be achieved on the basis of the phenomena.

Based on these concepts, a number of tools were developed for systematic analysis and solution of inventive problems. Examples of these tools are the contradiction matrix, physical contradiction resolution principles, and evolution paths (Savransky 2000).
The theory is intended to be generic to all technical engineering fields and, nevertheless, there are attempts to generalize its principles to other soft-fields like social and economic ones. A search for previous applications of the theory in the construction domain did not reveal any. The theory of TRIZ has a number of unique and strong concepts that are believed to be useful to problem solving in the construction industry by use in direct native format and/or by building on the same first-principles.

1.2.3 Research motivation and scope

From the previous discussion it can be seen that there is a need for radically different modeling and analysis tools that suits the peculiarities of the construction industry. Simulation-based tools have the potential to capture some of these peculiarities and researches in construction simulation show improvement in the adoption of simulation-based techniques by the industry. Although simulation tools provide the means to model an existing system and experiment with it, improving the performance of the system depends on the knowledge and experience of the user. The theory of inventive problem solving TRIZ provides a unique approach for extraction, consolidation, and reuse of knowledge that is believed to be useful for solving construction problems and improving construction methods. It is envisioned that an integrated methodology for managing and improving production on construction projects can be formulated using the principles of TRIZ and the modeling capabilities of simulation. However, some basic research needs to be conducted before such a methodology can be formulated. The scope of this thesis is limited to defining some of the foundations for such a methodology.

1.3 Thesis objectives and anticipated contributions

The objectives of the research presented in this thesis are:

1. To explore and evaluate the tools and concepts of TRIZ as a methodology for systematic and structured innovation.
2. To demonstrate and make use of the concepts of TRIZ for improving construction knowledge extraction and representation.
3. To integrate TRIZ's problem solving concepts with simulation modeling techniques in order to provide a framework for systematic improvement of construction processes.

This research has the following anticipated contributions:

1. This study represents the first research effort in using TRIZ in the construction domain. The introduction of this theory is expected to trigger a number of succeeding researches and practical applications.
2. The study introduces a new approach for consolidating construction knowledge that has a generic format and assists rather than replaces the human problem-solving process.
3. The research in the simulation domain in this study explores new approaches in construction simulation, which are expected to push the boundaries and modeling capabilities of the current construction simulation techniques.
4. This research also provides a foundation for future integration between simulation modeling and knowledge-based improvement of construction production systems.

1.4 Research methodology

In order to accomplish the proposed research objectives, the following approach will be followed:

1. Survey and study the literature on TRIZ and the state of the art in its applications.
2. Apply TRIZ in its native format to a number of cases in the construction domain to assess its adaptability to the nature of construction problems.
3. Define the requirements for facilitating the use of TRIZ in day-to-day analysis and decision making in construction.
4. Conceptualize a simulation-modeling framework for construction projects that builds on TRIZ tools and concepts or derivatives of them, which may represent a foundation for future integration with these tools.
5. Develop a prototype of the proposed framework using the Simphony development environment to demonstrate the methodology and its feasibility.

1.5 Thesis organization

Chapter 2 of the thesis introduces the basic concepts of TRIZ through the utilization of them in a number of case-studies to evaluate their usability in the construction field. Chapter 3 introduces a study that makes use of TRIZ concepts to develop a new approach for extracting and consolidating technical construction knowledge. Chapter 4 discusses a framework for building simulation models that utilizes function analysis concepts of TRIZ and represents a new approach in construction simulation. Final discussion and recommendations for future research are provided in Chapter 5.

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Chapter 2 - Application of The Theory of Inventive Problem Solving (TRIZ) In Tunnel Construction

2.1 Introduction

Innovative solutions offer the potential for significant company, industry and social benefits. Construction companies are looking for design and process innovations to improve their product and services and decrease their costs to meet the increasing demand for complex facilities and shrinking sources of materials and labor. Despite the importance of innovation, there is a lack of systematic and structured theory for managing innovative improvement in the construction industry. The problem is of two folds: 1) creating the business environment that motivates and adopts innovative solutions, and 2) managing the technical knowledge and innovative information required for generating effective innovative solutions in a structured and systematic way without "re-inventing the wheel". The first part of the problem was addressed by a number of researchers as discussed in the next section. For the second part, there is no structured format for achieving it, especially when it comes to solutions that cross the boundaries between different industries. Most of the common problem solving approaches depend mainly on trial and error and the level of expertise and creativity of the problem solver.

This chapter presents an application of the Theory of Inventive Problem Solving (TRIZ) (Savransky 2000) in the tunnel construction domain. The theory provides a structured approach for solving technical problems and makes use of cross-disciplinary knowledge for generating innovative solutions. The case studies presented in this chapter make use of a number of TRIZ instruments to generate conceptual solutions for improving or solving problems of the TBM tunneling operations. The use of these instruments reveals some of the strengths of the theory and highlights some of the potential areas for further research to make the theory easily usable in the day-to-day technical decision making process in construction.

In each of the case studies presented in this chapter, the original case is explained followed by an application of a number of TRIZ tools to the case. The outcomes of the tools' application and generated solutions are then compared to actual solutions or existing technologies that deal with the case study at hand. A discussion of each case study is then presented highlighting the advantages and/or disadvantages realized. An overall discussion and conclusion of the chapter is given at the end.

2.2 Background

2.2.1 Innovation in the Construction Environment

2.2.1.1 Importance of Innovation in Construction

Innovation has many benefits that include increase in economic growth and increase in productivity. It can result in market growth due to the introduction of new or improved products. Construction innovation in particular may also provide social benefits by reducing the costs of constructed facilities and making them affordable for a greater proportion of the population. Innovations also increase the technical feasibility of construction projects that would, otherwise, appear beyond the technological barrier. They may also provide non-monetary benefits in the form of better company competitive position and improved reputation. (Slaughter 1998)

During the different phases of a construction project life cycle, innovation plays an important role for improving constructability of the project. However, during field operations phase, its role is magnified according to the Construction Industry Institute (CII), which states: "Constructability is enhanced when innovative construction methods are utilized" as a principle for improving constructability during field operations (CII 1986). Although the impact of innovative modifications during field operations is less than the impact during conceptual planning or design, it is still considered significant (O'Conner 1988). A study by Jergeas (2001) shows that the "use of innovative construction methods" is among the areas that have the largest gaps between the potential benefits of application and the benefits actually realized in practice. Among the application barriers identified in that study are the lack of knowledge of the latest construction methods and techniques, and the organizational resistance for changes (Jergeas 2001).

2.2.1.2 *What is innovation?*

There is some disagreement as to what is considered an innovation. Innovation can be subjectively defined as methods that are not generally considered common practice across the industry and are generally creative solutions responsive to field challenges or adoption of non-construction technologies (O'Conner 1988). An innovation does not necessarily mean an invention. In contrast, it does not require a detailed design or physical manifestation and it does not have to be novel with respect to the existing arts, but only to the creating institution (Freeman 1989, Slaughter 1998). The definition given by O'Conner is the one adopted in this study with the addition that the innovative method or solution need only be novel to the creating institution and not necessarily to the whole industry. Hence, an innovative solution is a method that is not considered common practice across the creating institution.

2.2.1.3 *Research in construction innovation*

Research in construction innovation deals with it from different perspectives. One approach investigates the requirements for creating an innovation-friendly business environment that encourages and adopts innovative solutions. Samples of such approach are found in: Tatum 1984, Tatum 1986, Tatum 1987, Nam 1992, Slaughter 1998, and Koskela 2000.

Another approach focuses more on the knowledge acquisition aspects of innovation. One study that follows that approach was conducted by Toole (2001) and shows that successful innovative building products follow four technological trajectories and that the success of future innovative products can be predicted by evaluating their progress along those four trajectories (Toole 2001). Another study by Kangari (1997) shows that effective information gathering is one of the key elements that contribute to the development of innovative construction technology in Japan. That study also concluded that a crucial link between innovation and business strategy in a large construction firm in Japan was found to be the long-range technology forecasting that integrates action of today with the vision of tomorrow (Kangari 1997). A third study shows that U.S. project managers rely heavily on trade magazines and conversations with internal colleagues for information about innovations and that firms' efforts to facilitate information seeking by their project managers focus primarily on information from internal sources, through reports of "lessons learned" and other means (Veshosky 1998).

2.2.2 Theory of Inventive Problem Solving (TRIZ)

Although the scope of the study by Toole (2001) is limited to one type of design products and only in the construction domain, the argument that successful innovations follow predictable paths is consistent with the discoveries of Altshuller, who realized that technical systems, in general, evolve according to regularities, which are generic for all engineering domains. These regularities can be studied and used for innovative and inventive problem solving, as well as for forecasting the further evolution of any design product in design terms (Savransky 2000).

The Theory of Inventive Problem Solving referred to as TRIZ, was originally developed by Altshuller in the mid 50's. TRIZ is based on studying and analyzing patents in different technological fields. Altshuller studied more than 400,000 patents in deriving this theory. To date, TRIZ specialists have analyzed approximately 2 million patents. The analysis of these patents in the different areas of engineering resulted in several important discoveries, which form the theoretical basis of TRIZ and can be summarized as follows:

> "Technological systems evolve not "accidentally" but in accordance with certain patterns. These patterns can be revealed from the world's accumulation of patent information, and intentionally applied for the purpose of advancing a system through its evolutionary stages" (Altshuller et. al. 1999)

These patterns can be used to solve difficult problems, forecast the evolution of technological systems, and create and enhance the tools used for inventive problem solving.

Based on this concept, some tools were developed for systematic analysis and solution of inventive problems. Examples of these tools are "Evolution Patterns", "Contradiction Matrix", "Physical Contradiction Resolution Principles", "Substance Field (Su-Field) Analysis", and "Ideal Final Result (IFR)" (Savransky 2000). The following sections briefly describe some of these tools.

2.2.2.1 *Evolution Patterns*

The following list shows eight basic evolution patterns defined in TRIZ. More detailed patterns can be derived from these basic ones for specific engineering fields (Altshuller et. al. 1999). These patterns and their derivatives can be used to evaluate a technical system and suggest improvements for that system and/or forecast the expected evolutions in that system. The eight patterns are:

1. Stages of evolution of a technological system
2. Evolution toward increased ideality
3. Non-uniform development of system elements
4. Evolution toward increased dynamism and controllability
5. Increased complexity followed by simplification
6. Evolution with matching and mismatching elements
7. Evolution toward micro-levels and increased use of fields
8. Evolution toward decreased human involvement

2.2.2.2 *Contradiction Matrix*

A technical system has several characteristics (e.g. weight, size, speed, reliability etc.) that describe its physical state. When trying to improve one of these characterisitics (parameters), other characteristics may deteriorate as a result. In such situation a technical problem (technical contradiction) arises and calls for a solution. Conventional solutions usually propose a compromise between the "improving" and "deteriorating" parameters. An innovative solution is achieved by resolving the technical contradiction without introducing a compromise (Altshuller 1998).

Altshuller identified 39 system parameters as being most often associated with technical contradictions. He also identified principles that were similarly used in patents from different fields to resolve the contradictions that occur between any pair of these parameters.

The result is a contradiction matrix, which is a 39x39 table formed by placing these engineering parameters in rows and columns. Each cell in the matrix represents a particular technical contradiction, and contains a set of numbers that corresponds to a set of inventive principles that has been successfully applied to resolve the contradiction (Altshuller et. al. 1999, Savransky 2000). Figure 2.1 illustrates a part of the matrix. The cell highlighted in the figure represents the contradiction between "Waste of Time" and "Accuracy of Manufacturing". That is, for example, an activity needs to be eliminated to improve the waste of time but the elimination of this activity causes accuracy of manufacturing to deteriorate. The numbers shown in the list are references to the principles most commonly used for resolving this type of contradiction ordered by their frequency of use. In this case, the principles are : "24. Intermediary", "26. Copying", "28. Mechanics Substitution", and "18. Mechanical Vibration". The full matrix is provided in Appendix 1.

			Parameter that is getting worse				
	Engineering Parameters		27	28	29	30	31
			Reliability	Accuracy of Measurement	Accuracy of Manufacturing	Harmful factors acting on object from outside	Harmful factors developed by an object
Parameter to be improved	23	Loss of Substance			35, 10, 24, 31		
	24	Loss of Information			-		
	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 Measurement		Physical Contradiction	-		

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

Figure 2.1Contradiction Matrix

2.2.2.3 *Physical Contradiction Principles*

Physical contradiction represents the situation when the same characteristic of an element is required to take two conflicting values. For example, an element should have high temperature to work correctly and should have low temperature not to destroy another element (Savransky 2000). Altshuller proposed 11 methods to resolve physical contradictions (Altshuller et. al. 1999). These methods are:

1. Separation of opposite requirements in space.
2. Separation of opposite requirements in time.
3. Combining homogeneous or heterogeneous systems into a super-system.
4. Transition from a system to anti-system or to a combination of system and anti-system.
5. The whole system has property C while its parts have property anti-C.
6. Transition to a system that works on the micro-level.
7. Changing the phase state of part of a system or of its environment.
8. Dynamic phase state of a system part (changing the phase state depending on the working conditions).
9. Utilization of phenomena associated with phase transitions.
10. Replace a mono-phase substance with a dual-phase-state substance
11. Physical-Chemical transition: substance creation/elimination as a result of composition/decomposition, ionization/recombination, etc.

2.2.2.4 *Substance Field (Su-Field) Analysis*

Su-Field analysis is an analytical tool for building functional models. Every system is created to perform a certain function. The function represents an action toward a certain object. This action is performed by another object. As illustrated in Figure 2.2, this situation can be modeled by a triangle whose corners represent two objects (substances, S1 and S2) and an action (field, F1). Three general situations for the action in a Su-Field model may exist. The action is satisfactory, insufficient, or harmful. A substance may be an article or tool and a field may be some form of energy. A complex system can be modeled by multiple su-field triangles. (Altshuller et. al. 1999)

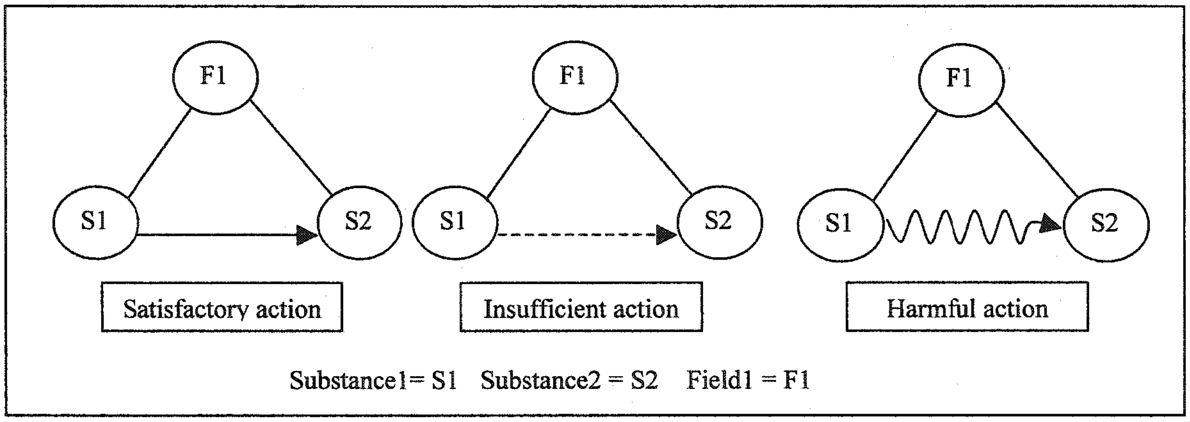

Figure 2.2 Su-Field Models

A set of 76 standard solutions is provided with this tool to help modify the su-field model. These rules provide "tips" for how the system should be modified. Selection of one or more standard solution depends on the type of modification required in the system and the constraints that apply to it (Savransky 2000). For example, if it is necessary to eliminate the harmful action of a field on a substance, the problem can be solved by introducing a second substance that "draws off" the harmful action as shown in Figure 2.3. An application of this solution is illustrated in Russian Patent Number 152492 where several narrow trenches are suggested to be dug alongside underground cables to protect them from cracking during very cold winters (Altshuller et. al. 1999).

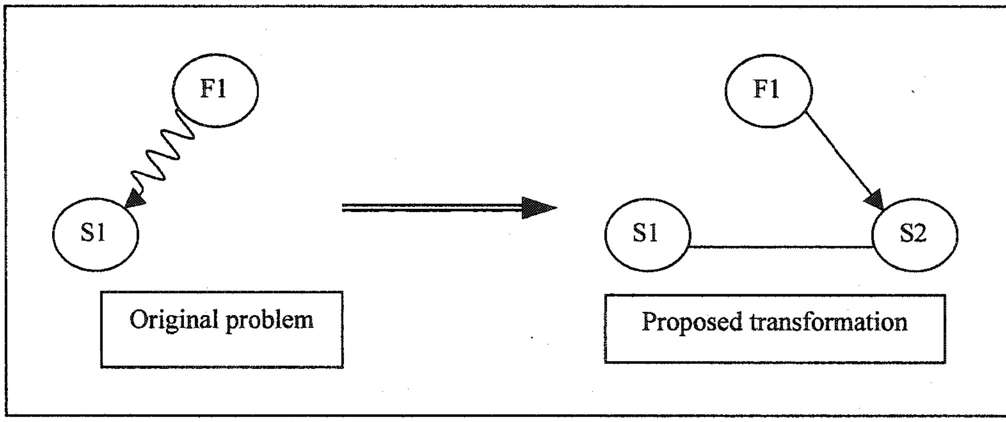

Figure 2.3 Drawing off a Harmful Action

2.2.2.5 *Ideal Final Result*

The "Ideal Final Result" (IFR) is the absolutely best output of a situation regardless of the solution that leads to that output. Although formulating an IFR does not provide a solution by itself, it is a very useful support tool that helps during the analysis of a problem. Formulating the IFR of a problem helps accentuate the contradiction in the problem, which is a critical step towards solving it. It also provides the opportunity to apply "backward" search for a solution (i.e. starting from the goal instead of starting from the current inefficient solution) (Savransky 2000).

2.3 TRIZ Application In Tunnel Construction

2.3.1 Brief description of the Tunneling Process

Tunneling projects involve three main processes: excavation, dirt removal, and tunnel support. The process of tunnel construction commences with the excavation and liner support of a vertical shaft to a depth corresponding to the invert level of the tunnel excavation. The other typical tunnel activities are excavation and support of the undercut area (an enlargement at the bottom of the shaft used for staging material handling and dirt removal operations), excavation of the tunnel and tail tunnel, disposal of dirt from the tunnel face, hoisting the dirt to the ground level, lining the tunnel, extending the services and rail tracks, and the excavation and support of the removal shaft (if a TBM is used).

When using a TBM for tunnel excavation, surveying is regularly undertaken to ensure that theTBM follows the required alignment. The common practice is to use a laser guidance system to achieve that goal. A laser beam is used to mark the targeted direction for the TBM. The beam hits a target on the machine and the machine operator tries to maintain the beam on the target during excavation. The laser beam is produced by a gun located far behind the machine and set by a surveying crew according to the design axis of the tunnel.

During TBM excavation, a system for dirt removal works in parallel to remove the dirt out to ground level. One or more trains of muck cars are usually used for that purpose. The cars get loaded with dirt at the tunnel face, travel to the undercut area, and get dumped to the ground level using a crane. If more than one train is used, the undercut area should be arranged to allow switching between empty and loaded trains and muck cars.

The remainder of this chapter demonstrates the use of TRIZ for producing solutions for problems associated with TBM tunneling of utility tunnels.

2.3.2 Case Study 1: Enhancing tunnel productivity through innovations in TBM guidance system

2.3.2.1 Problem Description

The overall production rate of the tunneling process depends on synchronizing all tunneling activities to maximize the utilization of resources and minimize the waiting times. When activities fall off the synchronized pattern, the production rate gradually drops. A study undertaken by Mohamed and AbouRizk (2001), revealed that the reduction of the surveying cycle could contribute to about 0.9m/shift increase in production for a typical 3m diameter tunnel with an average advance rate of 8m/shift . A simulation model for an actual tunneling project used in that study showed that survey time had the most significant effect on the overall production among other factors that affected the project. Therefore, improvement of the TBM guidance system to reduce surveying times was considered feasible for further investigation.

The TBM alignment problem emerges from trying to maintain a correct path for the TBM at all time. As shown in Figure 2.4, when the TBM hits a curve in the tunnel path, the laser beam deviates from the target and a surveying crew has to reset the gun to ensure correct alignment of the TBM. The resetting process requires suspension of the excavation operation because the TBM cannot be operated without proper alignment with the tunnel design path, and the survey crew occupies the tracks that lead to the tunnel face.

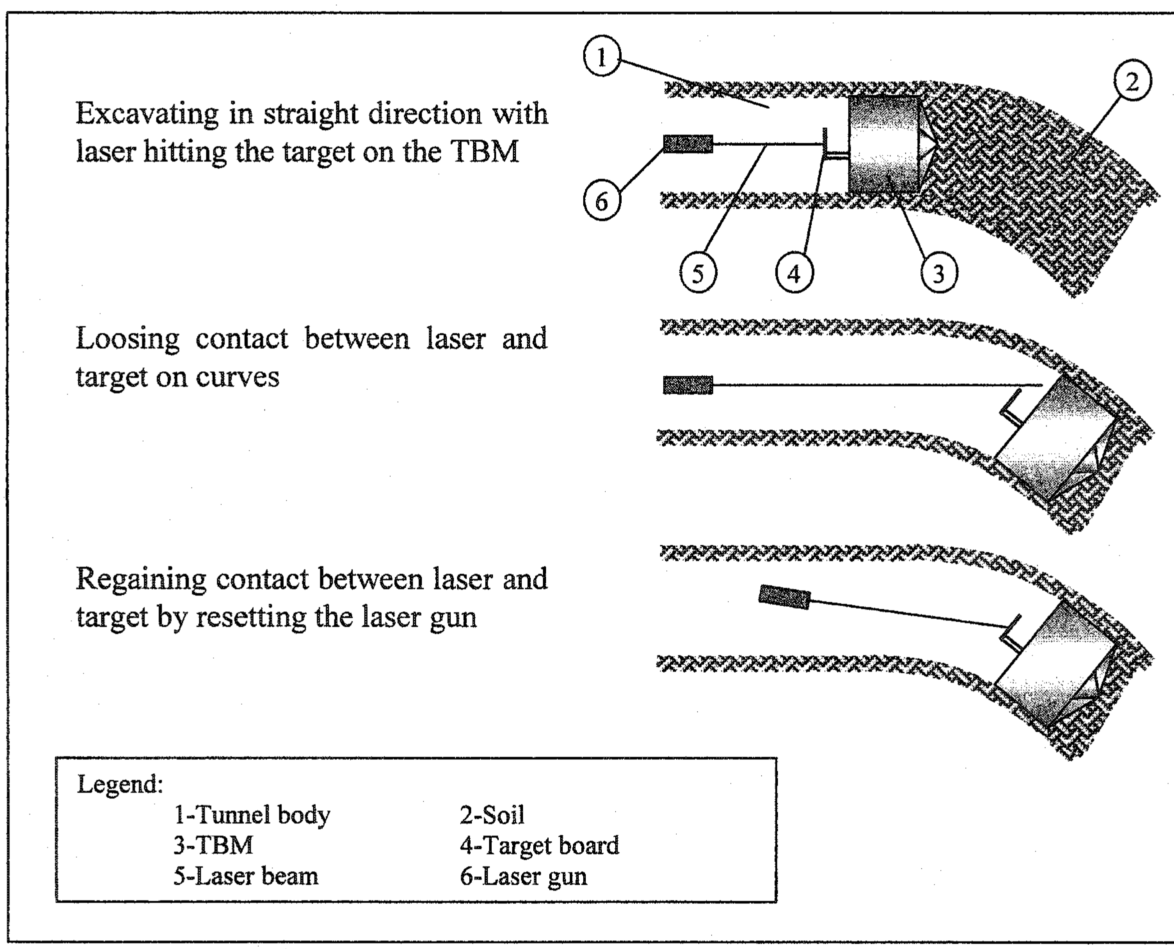

Figure 2.4 Illustration of TBM alignment problem

2.3.2.2 Application of TRIZ Tools

Three tools of TRIZ are applied to this problem to produce a conceptual solution for it, namely: 1) Contradiction Matrix, 2) Substance-Field Analysis and 3) Patterns of Evolution. As illustrated in Figure 2.5, TRIZ tools provide a solution through reformulating the problem into a generic form, which should not use any domain-specific terminology. One of the advantages of this approach is to free the problem solver from "physiological inertia", which is the unconscious tendency of the solver to limit her thinking boundaries by the meanings of the words used for describing the problem (Savransky 2000). Once a generic problem is formulated, a number of principles or standard solutions are suggested for solving it. These solutions act like pointers to conceptual solutions for the original problem.

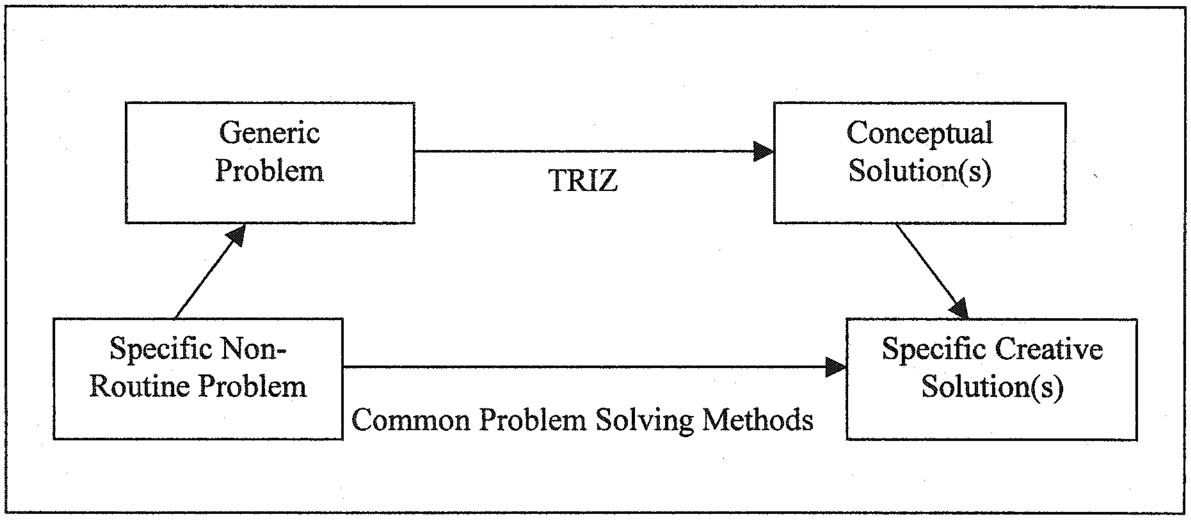

Figure 2.5 TRIZ vs. Common Problem Solving Approaches (Savransky 2000)

Contradiction Matrix Analysis

Formulating the generic problem

While using the contradiction matrix, the generic problem should be formulated in the form of one or more contradictions that take place between different parameters of the system. In this case, the goal of the TBM alignment system is to make sure that the TBM is excavating in the right direction all the time.

However, to achieve the above goal, the system has to be adjusted from time to time to correct the path of the TBM when it goes on a curve or gets misaligned for any other reason. The adjustment process forces a complete shutdown of the excavation process. The contradiction in this situation is between accuracy of TBM excavation and the wasted time due to resetting of the laser alignment system.

The generic engineering parameters that are defined in the matrix and correspond to this situation are parameter number 25 (Waste of Time) and parameter number 29 (Accuracy of Manufacturing).

The problem can then be described in generic terms as follows:

> In order to improve the waste of time of the system, the accuracy of manufacturing gets worse.

Resolution Principles from the Matrix

A contradiction is represented by the "improving engineering parameter" defined in the horizontal direction and the one that gets worse, which is defined in the vertical direction. The intersection of these two parameters defines a cell in the matrix that contains a number of principles that are mostly used to resolve that contradiction. Explanation and examples of conceptual solutions based on these principles are provided as well. For resolving the contradiction between (Waste of Time) and (Accuracy of Manufacturing), the principles shown in Table 2.1 are suggested by the matrix:

Table 2.1 Resolution Principles for the TBM guidance problem (Altshuller 1998)

Resolution Principle	Explanation
24. Intermediary	▪ Use an intermediary carrier article or intermediary process ▪ Merge one object temporarily with another (which can be easily removed)
26. Copying	▪ Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies ▪ Replace an object or process with optical copies ▪ If visible optical copies are already used, move to infrared or ultraviolet copies.
28. Mechanics substitution	▪ Replace a mechanical means with a sensory (optical, acoustic, taste, or olfactory) means. ▪ Use electric, magnetic, and electromagnetic fields to interact with the object. ▪ Change from static to movable fields, from unstructured fields to those having structure ▪ Use fields in conjunction with field-activated particles (e.g., ferromagnetic)
18. Mechanical vibration	▪ Oscillate or vibrate an object ▪ If oscillation exists, increase its frequency ▪ Use an object's resonant frequency ▪ Use piezoelectric vibrators instead of mechanical ones. ▪ Use combined ultrasonic and electromagnetic field oscillations.

Generating Domain Specific Conceptual Solutions

Based on the general principles suggested for resolving the generic contradiction, a number of concepts can be derived to resolve the TBM guidance problem. These concepts are listed in the following section categorized by the principles that led to them:

Intermediary

- Use carriers in between the laser gun and the target that can be easily adjusted to trace curves.

Copying

- Instead of interacting with the TBM itself, interact with a copy of its coordinates.
- Use a copy of the surveying crew to do the resetting (automate the resetting process).

Mechanics Substitution

- Use a different kind of fields other than laser to detect the actual and design coordinates of the TBM. That field should be more controllable.

Mechanical Vibrations

- Use sound or ultra-sound waves to detect the location of the TBM

Exhibit 1

Based on the above analysis, in order to create a more ideal TBM guidance system, one or more of the following guidelines should be used in driving its detailed design:

- It can be a segmented system with intermediary carrying points that can be easily adjusted.
- It can be one that adjusts and resets itself automatically.
- It may also depend on something other than laser to locate the TBM and deliver the coordinates to it. Sound waves or ultra-sound waves may also be investigated as a way for detecting and correcting the location of the TBM.

Section 2.3.2.3 translates these guidelines into practical solutions and compares them to the evolution of TBM guidance systems in the industry.

Substance-Field Analysis

Formulating the generic problem

The substance field analysis (Su-Field) is based on translating the problem into a generic model in the form of a number of substances (objects) interacting together through one or more fields. At least 2 substances and one field should exist to form a complete su-field model. A set of standards solutions is provided in TRIZ for solving the different problems that might occur within a su-field model. Selection of a solution is based on the type of improvement required in the model, and the constraints that apply to the problem. For the TBM guidance system a su-field model can be formulated as shown in Figure 2.6

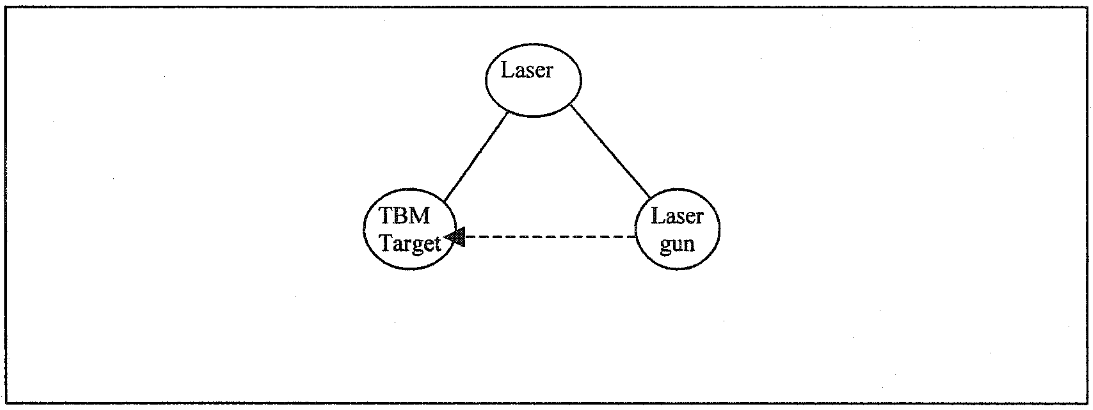

Figure 2.6 TBM laser guidance Su-field model

The following standards are suggested in this case (Altshuller 1999):

1. Transformation of Su-Field components into independently controlled Su-Fields and construction of chain Su-Field.

2. Replace uncontrollable (or weakly controllable) working field with controllable (well controllable one)

Generating Domain Specific Conceptual Solutions

The above generic solutions may be translated into the following domain-specific ones:

1. Use carrying articles between the laser gun and the target that can be easily controlled

2. Change the type of field that transfers the coordinates to the machine from an optical (laser) field to another form.

Exhibit 2

The su-field analysis suggests that compared to the current TBM guidance system, the design of a new system should provide multiple laser carrying objects that are easily controlled. It may also depend on a different type of field instead of laser.

Evolution Patterns

TRIZ identifies eight main patterns and several sub-patterns along which a system will evolve. Examining the status of an existing system in light of these patterns, helps forecast the characteristics of a more evolved system. Examination of the current TBM guidance system according to some of these patterns is illustrated in the following table:

Table 2.2 Evaluating TBM guidance system according to evolution patterns

Evolution Pattern	Possible implication on new TBM guidance design
Technique physical status Pattern Solid > liquid > gas > plasma > field > vacuum	The current system uses a laser optical field for completing its function. According to this evolution pattern a more evolved guiding system would use vacuum (no field).
Interactions in technique Continuous > vibrating > resonant	The current system works continuously. A more evolved system is expected to work in a vibrating or rhythmic manner
Degree of dimensionality 0D > 1D > 2D > 3D	The current system works in one dimension (i.e. the laser beam is shot between two points). A more evolved system is expected to use more dimensions.
Adaptability Rigid > dynamic > multi-hinge > elastic > soft > field flexibility	The current system is barely dynamic. A more evolved system would have multi-hinge and eventually it will need no hinges and depend on the absolute flexibility of a field.
Degree of human involvement In general a system evolves towards higher level of automation and less involvement of human in its function	This suggests that the degree of automation would increase in a more evolved TBM guidance system

Exhibit 3

According to the above examination, the design of a more evolved guidance system should involve one or more of the following features:

1. A system that does not use laser.
2. A system that works in a rhythmic manner (e.g. it resets at TBM stoppage times or only provide guidance when TBM needs it).
3. A system that uses two or three-dimensional space.
4. A system that is more flexible and depends on multiple-hinges-like components.
5. A system that has lower degree of human involvement.

2.3.2.3 Case discussion and comments

The above analysis using different TRIZ tools shows a significant similarity in the results emerging from them. Using exhibits 1, 2 and 3, the following set of characteristics of a more evolved TBM guidance system can be derived:

1. A system with increased automation and less human involvement. The resetting process in the current system is the component that has the highest human involvement and therefore has the highest potential for automation.
2. A system that consists of a larger number of intermediate, independent, more controllable sub-components. The current system has a laser gun that is fixed in its location until adjusted during the resetting process. A more evolved system may have a more controllable laser gun and may also have some adjustable prisms that carry the laser between the laser gun and the TBM.
3. A system that uses multi-dimensional space. The current system uses one laser beam to locate the TBM in one plane. A more evolved system may use more than one laser to locate the TBM in 3-D space.

4. A system that depends on a different type of field that is more controllable and flexible to follow TBM movement. The use of sound or ultra sound waves is suggested for investigation.
5. A system that works in a more resonant and rhythmic manner. Laser resetting may be done only when TBM guidance is not needed (i.e. while installing and expanding liners or during breaks)

The above characteristics represent directions for generating new design improvements for the TBM guidance system. Guided by such directions, an expert or group of experts in the field of surveying and TBM guidance instruments should be able to produce detailed implementations in a structured format, instead of following random paths.

In this case study, a comparison between the current state-of-the-art technologies in TBM guidance systems and the suggested conceptual solutions is performed to examine the validity of the suggested concepts. The following sections discuss the results of this comparison.

A market search for available TBM guidance systems was conducted to evaluate the features available in these systems compared to the characteristics identified above. Two distinctively different categories of systems could be commercially found. Each of these categories features one or more of the identified characteristics.

The first category of guidance systems depend on laser for detecting the location of the TBM and for measuring and correcting the deviation of the TBM from the required alignment. The second category depends on inertial navigation principles that are used in military and aircraft navigation.

The first laser-based category includes a number of commercially available systems with varying features. It was found that these features comply with the characteristics identified using TRIZ in the following aspects:

1. Higher degree of automation: All of the surveyed systems depend on a laser theodolite instead of a laser gun. The theodolite can be manually or remotely adjusted. Almost all of the systems have a higher degree of automation than the one analyzed in this case study. They feature central processing computer system that

manages the resetting and repositioning of the laser theodolite in addition to the deviation of the TBM from the designed alignment. Some of these systems even provide the capability of interfacing with the TBM controls for automatic correction of TBM movement.

2. Intermediate, independent, and more controllable sub-components: some of the systems include a remote prism that acts as a base-point for the laser theodolite. The laser theodolite is located at intermediate stations between the TBM and the remote prism. The theodolite follows the movement of the TBM but uses the remote prism as a permanent guide to determine its exact position.

3. Multi-dimensional space: One of the systems found in the survey showed the use of two laser beams instead of one. The two beams are used to accurately locate the TBM by interfacing with two target prisms mounted at two different locations on the TBM.

The second inertia-based category uses gyroscopes and accelerometers to measure the movement of the TBM relative to its original position. There was only one company that manufactures these systems for tunnel construction and their system is not yet used by any tunnel builder. However, this category represents a manifestation of the following two characteristics identified using TRIZ:

1. Use of different fields: These systems use the earth's magnetic field to detect the movement of the TBM.

2. Rhythmic or resonant functions: The detection of the location of the TBM is resonant to its movement compared to the continuous monitoring using laser.

The above comparison shows a significant matching between actual advance in TBM guidance systems (that are not used by the City of Edmonton) and the generic solutions suggested by TRIZ tools. The suggested conceptual solutions covered almost all the features that are scattered in different guidance system implementations. This fact raises one of the strengths of TRIZ, which is the potential ability to systematically guide the innovative improvement process instead of leaving it to trial and error.

Through the use of the selected TRIZ tools, some of the suggested principles seemed not to make much sense (i.e. changing the mechanics of the system, and working in rhythmic form). However, upon investigating the high-end technologies in TBM guidance, some of these principles were clarified by new systems (i.e. inertia based systems). The inertia-based systems originate from military applications and are just starting to penetrate into the tunneling industry. This raises another strength of TRIZ, which is the use of multi-disciplinary knowledge in suggesting solution principles and the ability to foresee improvements beyond the boundaries of the industry domain knowledge.

2.3.3 Case Study 2: Installing large diameter pipes into finished tunnel

2.3.3.1 <u>*Problem Description*</u>

In the Rossdale Water Intake tunnel constructed by the City of Edmonton, prefabricated pipes had to be installed inside a utility tunnel after it had been completely excavated and lined. Figure 2.7 shows a schematic for the problem. Each pipe section had a length of 7.5m, 1.35m inner diameter and 10cm wall thickness. The tunnel is supported using steel ribs with an outer diameter of 2.08m. This configuration resulted in an average clearance of 14cm between the outer diameter of the pipes and the inner diameter of the ribs. Moving the pipes to the tunnel entrance area was not a problem as it was an open excavation pit with an area of 10.7m length and 7.3m width. The problem was how to carry and install such large pipe sections with the available tight clearance.

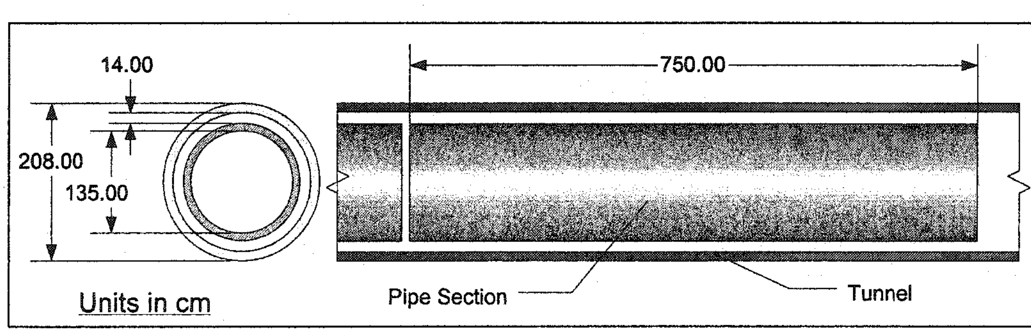

Figure 2.7 Pipe installation problem

2.3.3.2 *Application of TRIZ Tools*

The main conflict in this problem is due to the very limited workspace. In other words, the use of traditional pipe handling equipment becomes inconvenient because of the limited workspace. Using TRIZ's contradiction matrix, the problem can be generically formulated as contradiction between "7. Volume of Mobile Object" and "33. Convenience of Use" or "5. Area of Mobile Object" and "33. Convenience of Use". The area is assumed as a parameter is this case because of the tight clearance between the cross-sectional area of the tunnel and that of the pipe. Using the contradiction matrix, the principles shown in Table 2.3 are suggested:

Table 2.3 Resolution Principles for the pipe carrier problem (Altshuller et. al. 1998)

Resolution Principle	Explanation
15. Dynamicity	A. Allow or design the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition. B. Divide an object into parts capable of movement relative to each other. C. If an object (or process) is rigid or inflexible, make it movable or adaptive.
13. Do it in reverse	A. Invert the actions used to solve a problem B. Instead of an action dictated by the requirements, one implements the opposite action. C. Make movable parts or the external environment fixed, and fixed parts movable. D. Turn the object or process "upside down".
17. Transition into new dimension	A. Difficulties involved in moving or relocation an object along a line are removed if the object acquires the ability to move in two dimensions (along a plane). Accordingly, problems connected with movement or relocation of an object on one plane are removed by switching to a three-dimensional space. B. Use a multi-story arrangement of objects instead of a single-story arrangement. Use a multilayered assembly of objects instead of a single layer. C. Incline the object or turn it on its side D. Use another side of a given area. E. Use optical lines falling onto neighboring areas or onto the reverse side of the area available.
30. Flexible films or thin membrane	A. Use flexible shells and thin films instead of three-dimensional structures. B. Isolate the object from the external environment using flexible shells and thin films.
12. Equipotentiality	A. In a potential field, limit position changes (e.g., change operating conditions to eliminate the need to raise or lower objects in a gravity field).

The actual solution designed and used by the City of Edmonton for this problem is illustrated in Figure 2.8. The solution includes a specially designed pipe carrier that holds the pipe section from the inside and lift it slightly enough to clear the rail tracks. Once the new section is moved close enough to the last installed section, the carrier moves down till is rests on a set of intermediate support wheels. The front boogie assembly is collapsed and moved into the installed section. With the front of the carrier supported inside the last installed section, the carrier moves the new section into position.

The above solution shows typical implementation of principles 15, 17, and 12 listed in the above table. The carrier works from the inside area of the pipe instead of the common outside (17. New Dimension). The carrier depends on a number of hydraulic jacks that change positions relative to each other to adapt to the position of the pipe (15. Dynamicity). The carrier also uses some sort of equipotentiality by using minimal raising and lowering of the pipe (12. Equipotentiality).

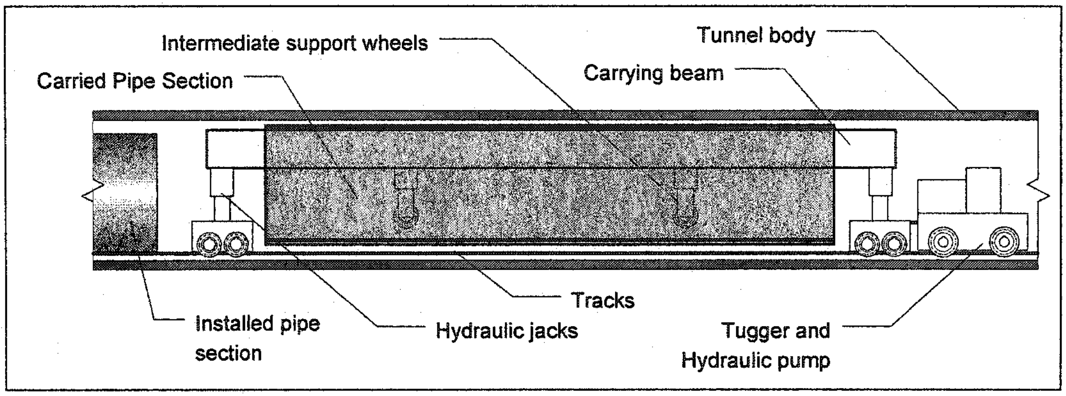

Figure 2.8 Pipe carrier solution

2.3.3.3 Case discussion and comments

This case represents an implementation of the contradiction matrix tool of TRIZ. Although the case is relatively simple, the identification of the contradiction in the case was found not to be straightforward. Characteristics like "Weight of Mobile Object", "Length Of Mobile Object", "Manufacturability", and "Complexity of Control" were all thought of as candidates for formulating a contradiction. However, examination of the core source of the problem shows that the volume or, even more precisely, the cross section area of the pipe is contradicting with convenience of use of traditional material handling equipment. This demonstrates a level of difficulty in using the matrix without enough training and familiarity with its terms and what they mean.

On the other hand, most of the principles suggested from the matrix match the concepts used in the actual solution of the problem, which indicates that using these principles might enable an engineer without extensive experience in material handling equipment to probably reach a similarly effective solution.

2.3.4 Case Study 3: Increasing Dirt Removal Productivity through Innovative Material handling

2.3.4.1 Problem Description

During tunnel construction, the dirt removal system is designed to remove the soil excavated by the TBM from the tunnel face to the ground level. One of the common practices is to use one or more trains of muck-cars that hauls dirt from the TBM at tunnel face to the undercut area where a crane hoists dirt out to ground level. The main focus in this case study is on the operations taking place at the undercut area.

The goal of the dirt removal system at the undercut is to move the dirt hauled from tunnel face by muck cars to the ground level allowing empty muck-cars to return to the TBM as fast as possible to prevent delays to the TBM. The duration a train of muck-cars takes to dump its load depends on the number of cars in the train, the depth of the shaft, the capacity of each muck-car, and the dumping mechanism.

One of the main harmful effects that needs to be removed from the dirt removal system is the delay it may cause to the excavation system. That delay results from TBM waiting for muck-cars to dump and travel back to tunnel face.

2.3.4.2 *Application of TRIZ Tools*

The following section uses three tools of TRIZ to analyze the dirt removal system using muck-cars. These tools are: the Ideal Final Result (IFR), Physical Contradiction Principles, and Substance field analysis.

Ideal Final Result and Physical Contradiction Analysis

One of the useful tools used in TRIZ for identifying the contradictions in a system is to formulate the ideal result of the system. The IFR of the dirt removal system is:

"To empty muck cars and make them ready to travel to tunnel face in 0 time"

The above statement leads to the following contradictions:

"A muck car should spend time to dump dirt. However, a muck car should spend no time to return to tunnel face"

"A muck car has to be loaded with dirt when it arrives to undercut, however, in the same time, it has to be empty to return to tunnel face"

The above examples of contradictions are identified in TRIZ literature as physical contradiction. This means an attribute of an object has to take a certain value at a certain time, while it has to take a different/opposite value at the same time (e.g. muck-car is loaded and empty at the same time). TRIZ provides a set of physical contradiction principles for resolving such contradictions.

From Altshuller's list of heuristics the following may apply to this case:

Principles 1 and 2: "Separation of contradicting properties in space" or " Separation of contradicting properties in time"

Both heuristics imply using more than one set of muck cars. Each would have the property "empty" at certain space/time and the property "not empty" at another space/time. The standard practices use these principles by providing more than one train for dirt removal. When the loaded train arrives to the undercut area, the empty one leaves to tunnel face right away.

Principle 6 "A transition to a system operating on the micro-level"

This heuristic implies transition from moving the whole muck car to moving only the dirt particles. This principle is used in common practice in the form of conveyer belts that moves dirt from tunnel face to ground level. Another concept that can be investigated base on this principle is the use of vacuum or air suction to move the dirt.

Principle 7 "An alternation of the phase state of a part of the system or the environment"

This implies changing the state of the soil particles to a different state. This suggests solidifying the soil and moving it as one concrete block or, liquefying it and use suction or pumping to move it.

Substance-Field Analysis

The formulation of the problem using the Su-Field terminology is as follows:

Substance 2 (S2) = Crane

Substance 1 (S1) = Muck car

Field (F1) = Mechanical

Useful and harmful effects exist in the current situation (crane moves dirt but delays muck cars). Or, in other words, the efficiency of the action between the crane and the muck-car needs to be improved. One of the standard solutions that Altshuller described for solving such Su-Field problems suggests introducing a new, free, or sufficiently inexpensive substance S3 between the substances S1 and S2, which preferably represent a modification of S1 or S2. Figure 2.9 shows a schematic for this standard transformation.

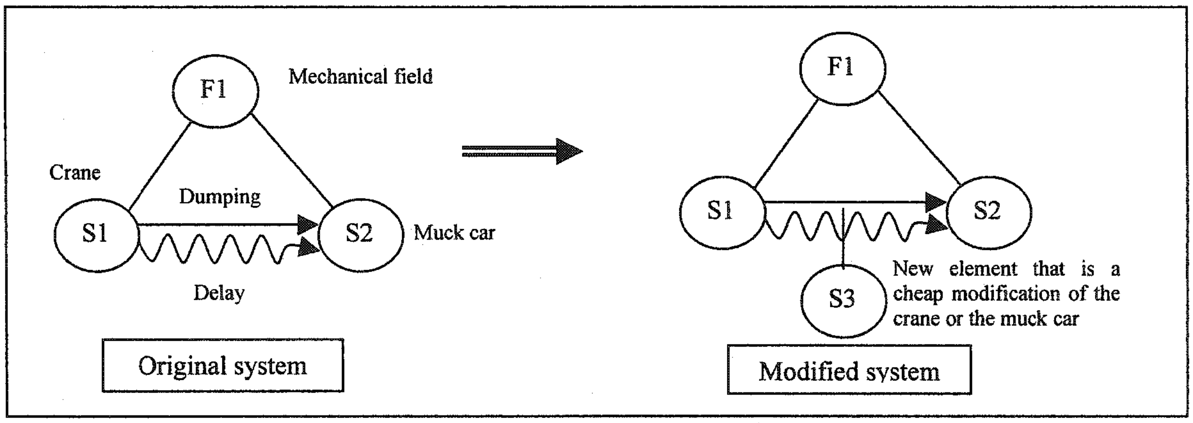

Figure 2.9 Standard Solution for harmful Su-Field action (Altshuller et. al. 1999)

By applying this heuristic to the dirt removal system, the following conceptual solutions can be used:

One solution is actually a common practice that is used in many tunneling projects. As shown in Figure 2.10, the solution depends on the crane lifting a hopper or sump where the muck-cars dump their load inside the undercut instead of moving the muck-car as a whole. The hopper or sump in this case represents S3, which is kind of a modification of S2 (the muck-car).

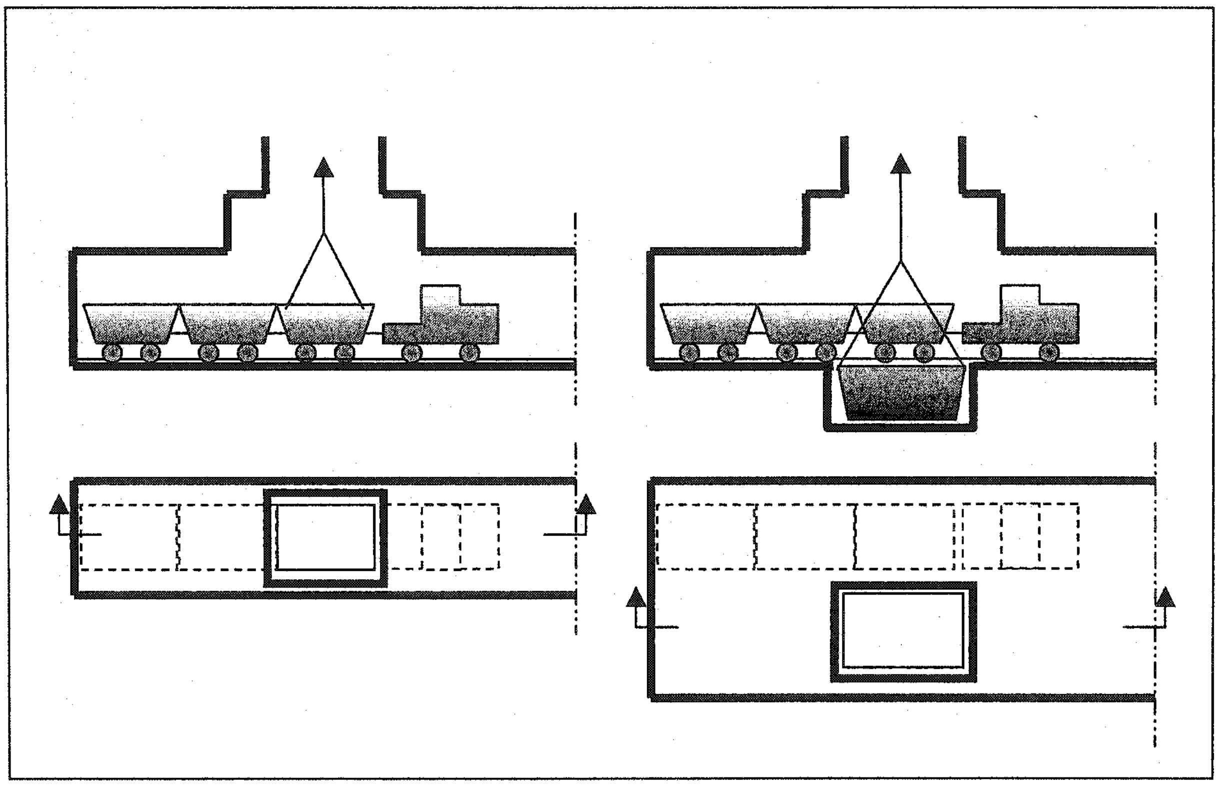

Figure 2.10 Hoisting of muck-cars vs. hoisting of a sump.

Although the solution shown in Figure 2.10 may increase the hoisting efficiency, it might produce some harmful effects in terms of space requirements. Another solution is developed by introducing S3 in the form of muck-cars liners made from strong fabrics that allows moving only the liners by the crane without having to move the whole car. Such solution would minimize the space requirement compared to the first one. Figure 2.11 illustrates this solution. Although this solution was generated only by using the Su-Field heuristics, a patent search revealed a quite similar patent for mucking dirt using container bags. The abstract and illustration of that patent are shown in Appendix 2 (esp@cenet, Patent Number: JP2000240394).

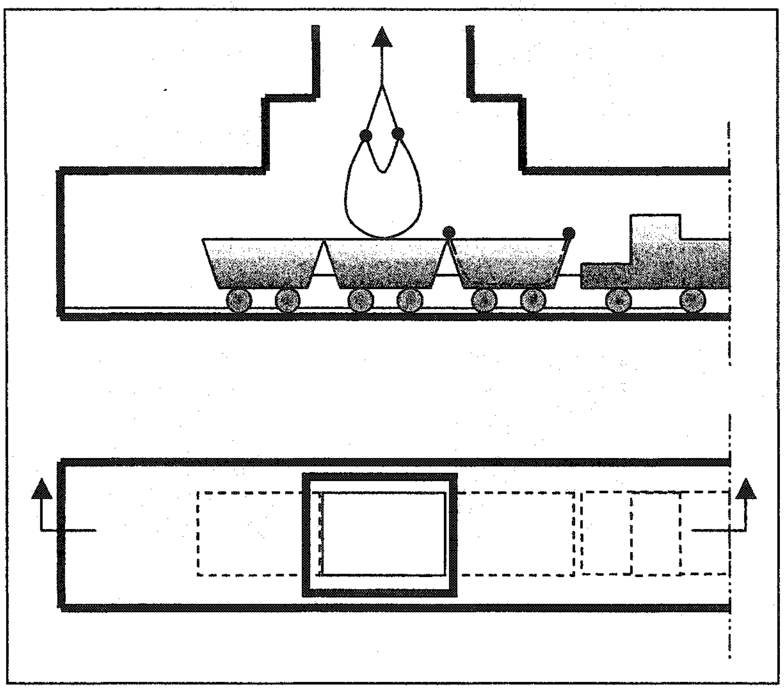

Figure 2.11 Muck-car liners

2.3.4.3 Case discussion and comments

This case represents the use of Physical Contradiction Principles and Ideal Final Result (IFR) tools of TRIZ. Although IFR does not suggest a principle or solution by itself, it is quite useful in formulating the problem and accentuating the contradiction in the problem.

The case shows that the heuristics suggested by different tools give directions to most of the different solutions that are used by tunnel builders for improving the dirt removal process. In addition, they also point to new concepts that are not commonly used for such a problem (e.g. air vacuum and muck-car liner bags). A patent search showed that one of these concepts (i.e. dirt removal bags) is already patented by a Japanese company. This demonstrates the strength of TRIZ in directing the problem solver to the most effective solutions without the need for vast experience or lengthy trial and error.

2.3.5 *Case Study 4: Dirt Removal in an Undercut Area of Limited Space*

2.3.5.1 *Problem Description*

During the underground construction of the LRT system in downtown Edmonton, one of the main problems was the dirt removal. The undercut area of the tunnel had a limited space that did not allow using common undercut layouts. Figure 2.12 shows a typical undercut layout and the layout in the LRT tunnel case. In the typical case, a tail tunnel is excavated at the back of the undercut area. The train of loaded muck-cars moves into the undercut allowing one muck-car to be positioned under the shaft opening. Once the muck-car is dumped, the train moves to allow the next loaded car to dump. The tail tunnel in this case allows the empty cars to move back, freeing space for the loaded ones. The tracks are usually positioned directly under the shaft opening so that a crane can easily move the muck-cars.

In the LRT case, a parking lot located at the back of the undercut area prevented the excavation of a tail tunnel. In addition, the only shaft opening that could be used for moving dirt was not directly positioned over the tracks.

The muck-cars available for use are equipped with a dumping mechanism that allows them to flip their bucket and dump their load into a sump without being removed from the tracks. A crane hoists the sump to the ground level. The capacity of the sump is equivalent to the capacity of one muck-car.

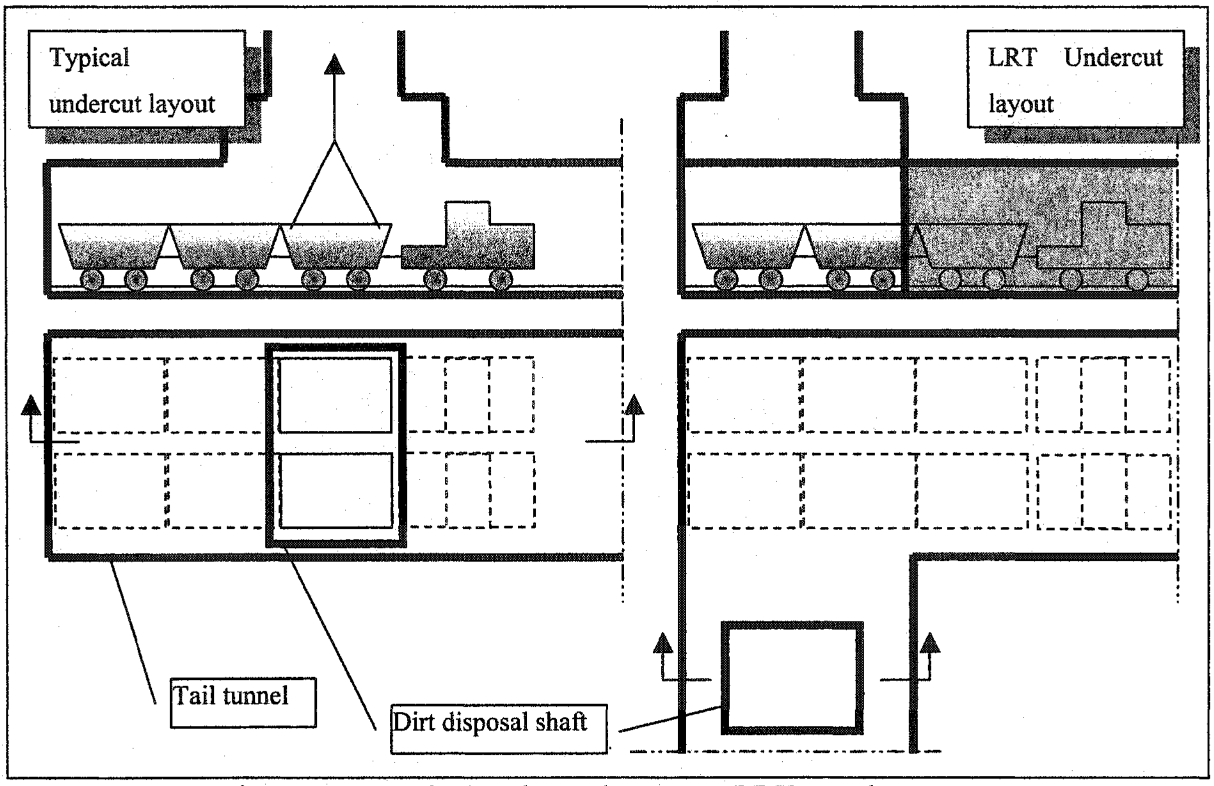

Figure 2.12 Typical undercut layout vs. LRT case layout

2.3.5.2 <u>Application of TRIZ Tools</u>

Resolution principles

The contradiction matrix is used for analyzing this problem. The system that is analyzed in this case is the dirt removal system with a main goal of dumping the loaded muck cars and making them ready to move to the tunnel face as fast as possible. By examining the changes from the normal undercut layout and the one that exists in this case, it is obvious that the length of the tracks became shorter, the area of the system as a whole became smaller and the shape became different. Each of these parameters affected negatively the productivity of the system. This leads to three pairs of TRIZ contradictions. Table 2.4 shows a list of these contradictions together with the principles proposed from the matrix to resolve them. Table 2.5 shows a list of the principle ranked by their frequency of suggestion and the standard explanation of each.

Table 2.4 Contradictions in the LRT Undercut Problem (Altshuller et. al. 1998)

Improving Parameter	Deteriorating Parameter	Principles
4. Length of Stationary Object	39. Capacity/Productivity	30. Flexible films or thin membranes 14. Spheroidality 7. Nesting (Matrioshka) 26. Copying
6. Area of Stationary Object	39. Capacity/Productivity	10. Prior Action 15. Dynamicity 17. Transition into new dimension 7. Nesting (Matrioshka)
12. Shape	39. Capacity/Productivity	17. Transition into new dimension 26. Copying 34. Rejecting and Regenerating Parts 10. Prior Action

Table 2.5 Resolution Principles for the undercut problem (Altshuller et. al. 1998)

Resolution Principle	Explanation
7. Nesting (Matrioshka)[1]	A. Place one object into another; place each object, in turn, inside the other. B. Make one part pass through a cavity of the other.
10. Prior Action	A. Perform, before necessary, a required change of an object, (either fully or partially). Carry out all or part of the required action in advance. B. Pre-arrange objects so that they can act from the most convenient place and without losing time for their delivery.
17. Transition into new dimension	A. Difficulties involved in moving or relocation an object along a line are removed if the object acquires the ability to move in two dimensions (along a plane). Accordingly, problems connected with movement or relocation of an object on one plane are removed by switching to a three-dimensional space. B. Use a multi-story arrangement of objects instead of a single-story arrangement. Use a multilayered assembly of objects instead of a single layer. C. Incline the object or turn it on its side D. Use another side of a given area. E. Use optical lines falling onto neighboring areas or onto the reverse side of the area available.
26. Copying	Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies Replace an object or process with optical copies If visible optical copies are already used, move to infrared or ultraviolet copies.
14. Spheroidality	A. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical, from parts shaped as a cube (parallelepiped) to ball-shaped structures.

[1] Name of Russian nesting doll, which is often used for the principle.

	B. Use rollers, balls, spirals, and domes. C. Go from linear to rotary motion, use centrifugal forces
15. Dynamicity	A. Allow or design the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition. B. Divide an object into parts capable of movement relative to each other. C. If an object (or process) is rigid or inflexible, make it movable or adaptive.
30. Flexible films or thin membranes	A. Use flexible shells and thin films instead of three-dimensional structures. B. Isolate the object from the external environment using flexible shells and thin films.
34. Rejecting and Regenerating Parts	A. Discard (by dissolving, evaporating, etc.) portions of an object that have fulfilled their functions or modify these directly during operation. B. Conversely, restore consumable parts of an object directly in operation.

Applying the resolution principles to the case

The principles suggested by the matrix in the previous section were used to conceptualize solutions without knowing the actual solution that was used on site. All possible solution concepts were generated first before examining them against the detailed dimensions and geometrical constraints of the site. These concepts are generated by trying to apply the principles either to each individual component (i.e. tracks, muck-cars, sump) of the system, to the system as a whole, or to a group of components. The following sections describe some of these concepts. The first two concepts were geometrically possible to fit into the actual dimensions of the undercut. The remaining concepts were not possible.

<u>Concept 1</u>

Using the principles of “Spheroidality”, “Dyanamicity”, and “New Dimension”, a rotating disk is to be added at the last section of tracks. The muck-car is to be dumped to an opening on one side of the disk. The dirt would then be transferred down a slope under its own weight to the sump. The disk would rotate the empty muck-car 180° degrees off the incoming track and replace it back on the outgoing track. The sump in this case needs to be located at an elevation lower than the lowest point of the slope. A modification of this concept includes using a section of the tracks at 90° angle from the incoming tracks. In this case the disk rotates only 90°. The muck-car moves to the cross track section and dumps directly to the sump. Then it moves back to the disk, which rotates the remaining 90° to the outgoing tracks. Figure 2.13 illustrates this concept.

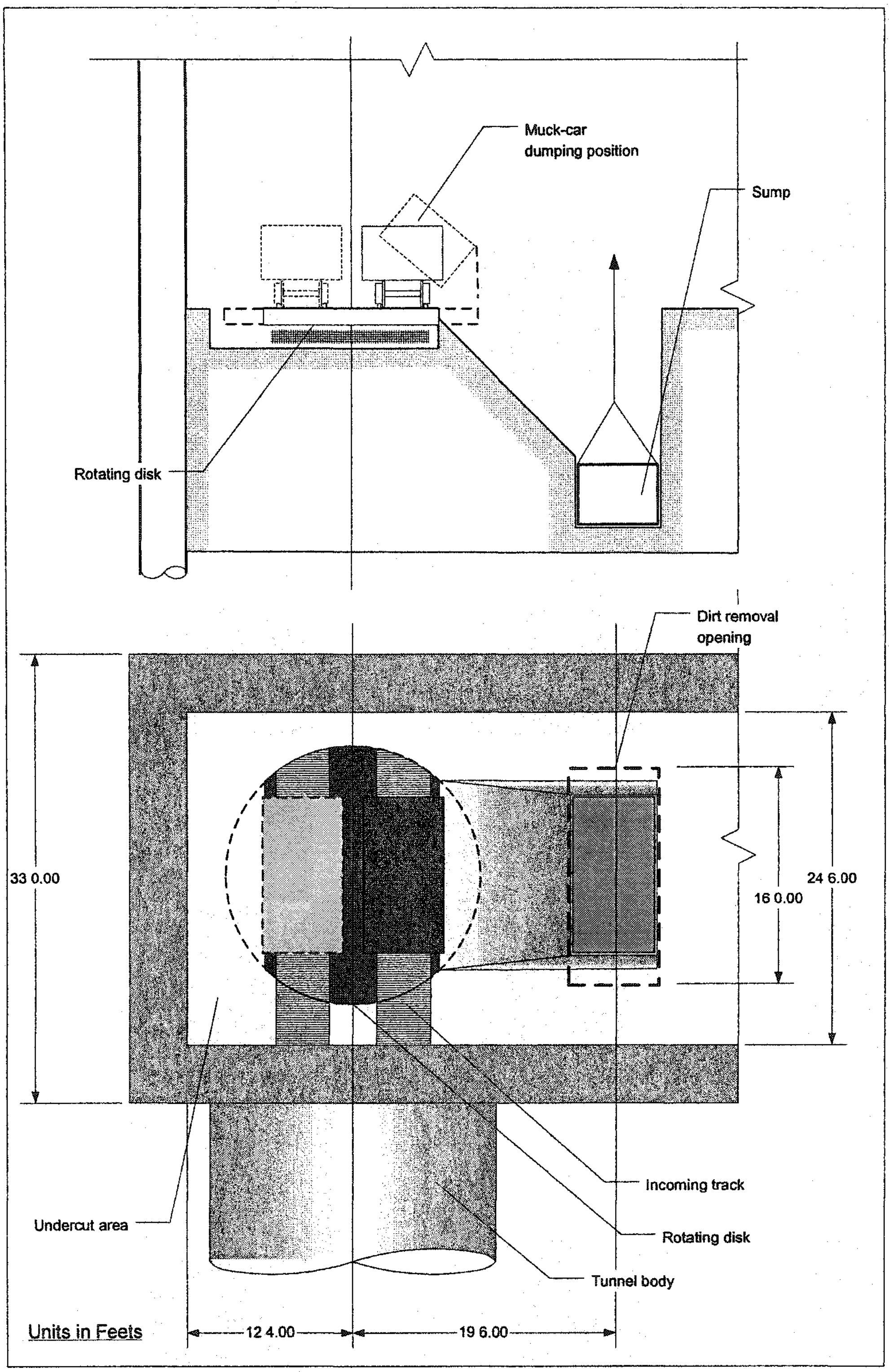

Figure 2.13 One rotating disk

Concept 2

Using the same principles as in "Concept 1", the one rotating disk may be replaced by two smaller ones. Disk 1 rotates the loaded car off the incoming track and set it on the cross tracks. The muck-car dumps to the sump and moves back to disk 2, which rotates to align the car with the outgoing tracks. Figure 2.14 illustrates this concept.

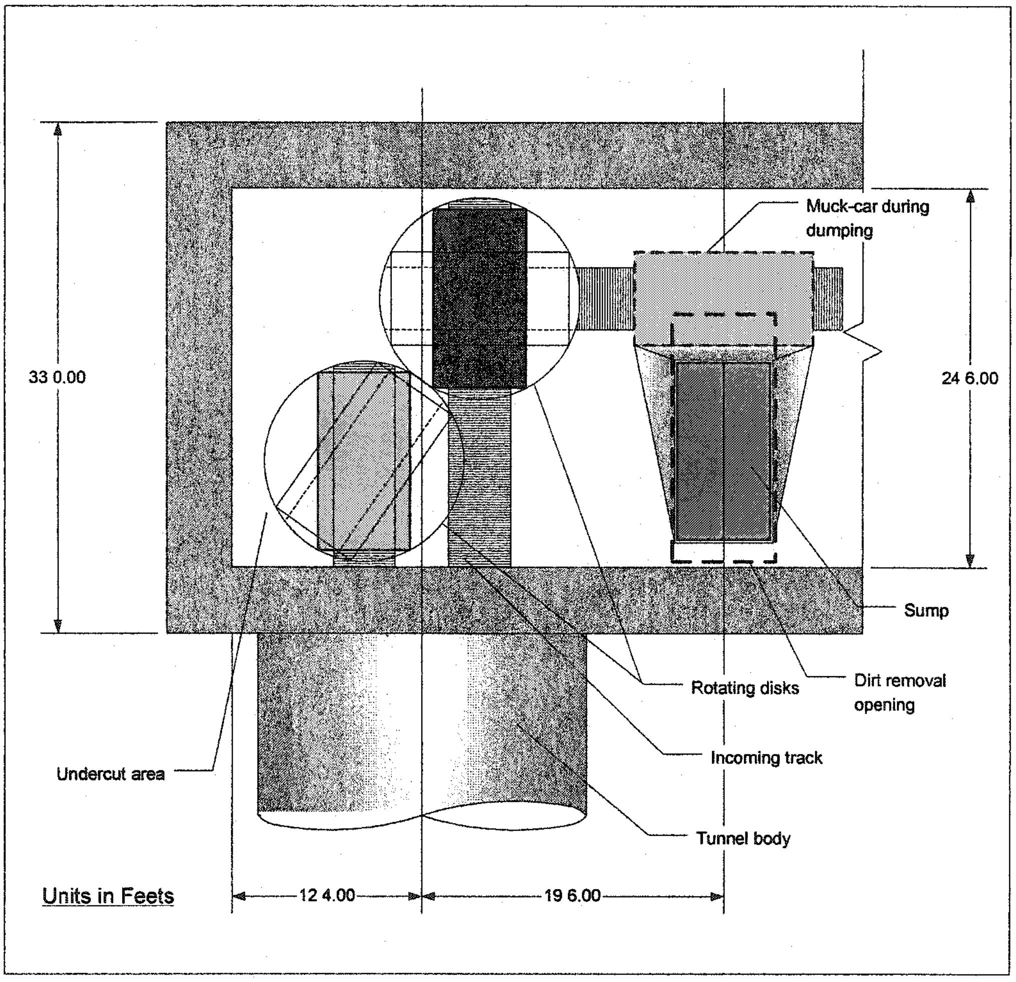

Figure 2.14 Two rotating disks

Concept 3

"Nesting" was repeated twice in the proposed principles from the matrix. Based on this principle, the limited length of the tail tracks can be overcome by "Nesting" the muck cars once they are empty. This would call for a change in the design and shape of the muck car. Figure 2.15 shows a proposed design that allows nesting empty cars. This will significantly reduce the required length at the back of the undercut. In the LRT case, the allowed space at the back of the undercut was so limited that it couldn't even accommodate nested cars. In addition, the problem of transferring dirt to the sump would still remain unsolved. However, the concept remains quite possible to apply in the normal situations, in which case, a considerable reduction in the tunnel tail length can be achieved.

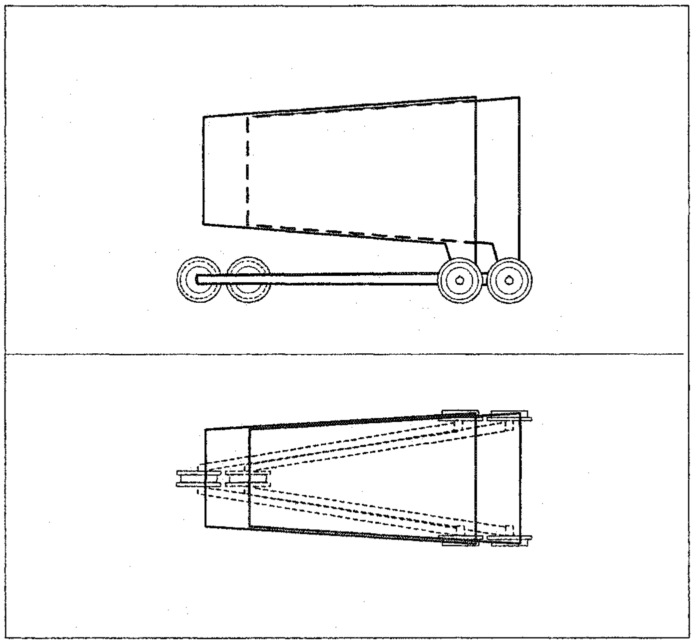

Figure 2.15 Nested muck-cars

Concept 4

This concept depends on the principle of "Transition into new dimension". It suggests having an over-head crane that moves the muck-cars laterally between the incoming track, the sump, and the outgoing track. This concept was rejected because there was a constraint that calls for freeing all the space above the muck-cars for material handling operations.

Actual solution used for the case

The actual solution used by the City of Edmonton is shown in Figure 2.16. In this solution the last section of the track, which carries the loaded muck car, is allowed to move sideways. The whole section of the track with the muck-car on is carried by a movable carrier. The carrier moves sideways on a second set of tracks located at a lower level underneath the undercut area. First, the track section is moved with the loaded muck-car to the sump where the muck-car dumps directly to the sump. The carrier then moves back to line up with the outgoing tracks and the empty muck-car is released there. The solution obviously makes use of the principles of "Dynamicity" by allowing the tracks to move sideways instead of being fixed, and "Transition Into New Dimension" by utilizing another plane at a lower level for the movement of the muck-cars.

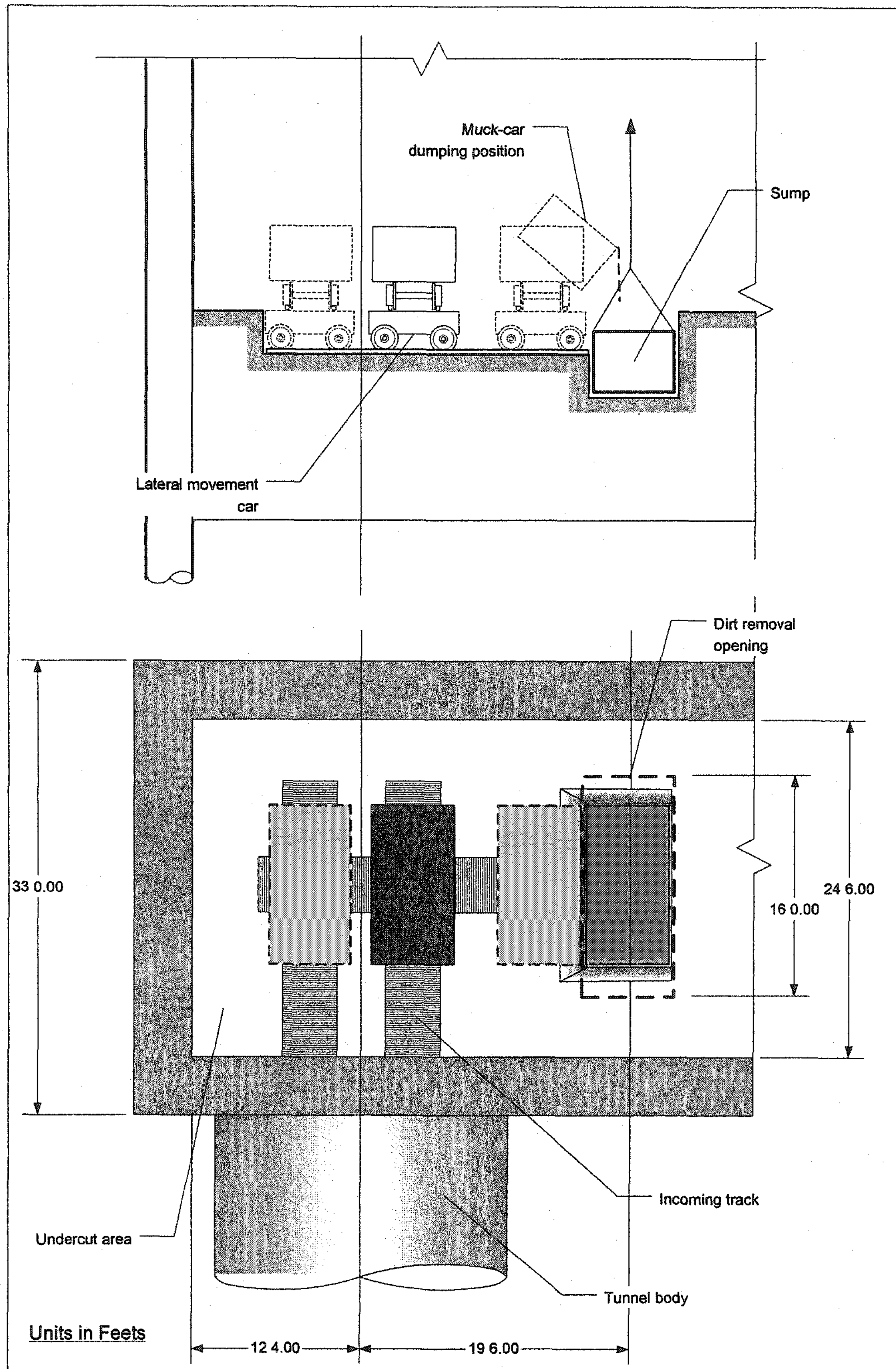

Figure 2.16 Actual solution of the LRT undercut problem

2.3.5.3 *Case discussion and comments*

This case demonstrates the usefulness of the principles suggested by TRIZ. Although the author is not an expert in tunnel construction, a number of possible solutions were generated guided by the suggested principles. Furthermore, the actual solution that was developed by an expert utilizes two of the suggested principles. It is therefore assumed that by using the TRIZ analysis approach for solving innovative problems, an expert or group of experts would be able to generate more effective solutions in a systematic manner. The side-effects of the TRIZ approach can also be useful. Some of the conceptual new solutions that may not fit a particular case may be very effective in others (e.g. nested muck-cars).

The case, however, also points to the level of difficulty associated with formulating the contradictions in the problem. In this case, all possible contradictions were formulated and all the suggested principles were examined in order of their frequency of suggestion by the matrix, which can be a useful approach to overcome this difficulty.

2.4 Overall Discussion

2.4.1 Realized strengths of TRIZ

The use of the TRIZ tools for analyzing a number of tunneling problems showed that the tools gave useful principles that lead to possible solutions. The principles are generic in nature and require the use of creative analogy to transfer them into problem-specific solutions. When comparing actual solutions with principles suggested from TRIZ tools, significant similarities are found between the two. This shows an advantage of this approach, which is the ability of guiding the problem solver towards the most effective solutions for a problem. This guidance should minimize the randomness in the search and systematize and focus the efforts of the experts on the most promising and effective solution paths.

In some cases, TRIZ principles actually pointed to solutions that are not yet used in the industry. One of these new solutions was found as an emerging technology (i.e. inertial navigation) while another as a patented case (i.e. dirt removal bags). This shows another advantage of TRIZ, which is the use of multi-disciplinary knowledge in suggesting solution principles and the ability to foresee improvements beyond the boundaries of the industry domain knowledge. Although some principles and suggestions may seem to be "out-of-context", further pursuing of search along their path may reveal highly effective solutions. Such solutions may not be obvious at the beginning only because they lie outside the domain of knowledge of the problem solver (e.g. replacing the laser field in TBM guidance).

The last realized strength of TRIZ is its seamless generic approach for consolidating knowledge that can be reused for solving a wide spectrum of technical problems. The fact that TRIZ tools depend on a finite number of solution principles and heuristics suggests an opportunity of following a similar approach for guiding the solution of non-technical problems as well.

2.4.2 Research areas and requirements for facilitating TRIZ use in day-to-day technical decision making

Despite the realized strengths of TRIZ, a number of areas need to be researched in order to make use of it in the day-to-day decision-making process in construction. One of these areas is the problem formulation. An ill-defined problem means a misleading set of principles. Therefore, some tools are needed to highlight the main contradictions in a situation and facilitate an accurate formulation of the problem.

The transformation of the generic principles into problem-specific solutions depends mainly on the ability of the problem solver to analogically generate solutions from his/her domain of knowledge that comply with these principles. A knowledge base of domain-specific sample solutions that illustrates the different principles would provide a useful source of examples that help trigger more analogical solutions.

When new solutions are conceptualized, the feasibility and risks associated with these solutions have to be assessed specially when such solutions represent parts of a superior system. The TBM guidance and the LRT undercut cases represent examples of these solutions. In such cases, tools are needed to test the impact of the new solutions, which may not yet exist in reality, on the overall existing system. In the TBM guidance and

LRT undercut cased, this assessment would answer questions like: how much time can be saved by using the new system? or what would be the overall tunnel production rate if the new system is used?

2.5 Conclusions

This chapter introduced an application of the Theory of Inventive Problem Solving (TRIZ) in the field of utility tunnels construction. The theory is applied in its native form to a number of problems. A number of TRIZ tools were used to generate conceptual solutions for each problem. A comparison between the suggested solutions and the actual or existing solutions showed that they closely match each other. The TRIZ tools were able to point to most of the features that existed in the actual solutions. The tools were also able to point to solutions that are not yet widely used in the tunneling industry although successfully used in other disciplines like military and oil industry. Despite the realized power of the theory, further research and tools are required to facilitate its day-to-day use in the construction industry. These tools include problem formulation tools, solution testing and analysis tools, and knowledge consolidation tools.

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Chapter 3 - Technical Knowledge Consolidation using TRIZ

3.1 Background

Construction projects are unique and therefore field problems associated with them may have little similarities. Construction projects involve many disciplines and require integration of knowledge from civil, mechanical, electrical, and other engineering domains.

Several approaches are described in the literature for knowledge acquisition, consolidation and representation in the construction domain. The most basic approach is by 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), Abdel-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, artificial neural networks, or case-based reasoning. Examples of these applications are found in the work of Mohan (1990), Chao and Skibniewski (1995), and Adriti and Tokdemir (1999). The knowledge stored in these applications is usually structured to allow re-usability in an electronic form. It is also a strictly domain-specific knowledge that aims at providing detailed solutions for a particular domain of problems and cannot be used outside that domain. Extrapolating for solving problems from the same domain but outside the knowledge-base (i.e. rule-base of an ES, case-base of CBR system, or training set of ANN) is usually very limited.

The common feature between the above approaches is that they strive to capture and preserve knowledge and construction know-how as a very valuable asset to any construction company.

The previous chapter introduced TRIZ as a tool for inventive problem solving. The theory and concepts of TRIZ utilize 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 research described in this Chapter attempts to develop an approach for representing and navigating knowledge by emulating the process used by Altshuller in the development of TRIZ.

3.2 Objectives and Scope

TRIZ is based on extracting meta-knowledge from cases (patents) in different technical fields. Because the extracted knowledge is not domain specific, it can be reapplied to new problems. The objective of this study is to develop a framework for preserving and accumulating contractors' experience in dealing with technical construction problems using a similar approach to the one used in TRIZ.

The previous chapter discussed the use of TRIZ tools in their native forms and showed their advantages in generating solutions for technical problems. The generic nature of these 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.

The scope of this study focuses mainly on the Contradiction Matrix tool of TRIZ with the following main objectives:

- Test the practicability of the matrix in representing technical construction problems.
- Develop a prototype framework for consolidating the technical knowledge used for solving construction problems by using the same concept used in building the matrix, which provides a new approach for preserving construction companies' know-how knowledge in an abstract format.
- Propose a structure for making the above knowledge accessible for construction personnel for solving new problems.

3.3 Construction Knowledge Consolidation Framework

3.3.1 TRIZ's Innovation Heuristics

Altshuller classified inventive problems into five levels according to the creativity level used in solving them; with level 1 pertaining to the lowest 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 3.1. After analyzing a large number of patents, he found that level 1, 2, and 3 represent the largest portion of patents while high level inventions of level 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[1] and patents demonstrates the existence of several common principles forming the basis for the majority of contemporary inventive ideas" (Altshuller 2000)

[1] Similar to a patent, but where the patent-holding party is the Russian government.

Table 3.1 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%

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 happened 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 Altshuller's observations, it is assumed in this study that it is possible to extract a finite number of generic heuristic rules that can be used for solving construction problems of varying applications.

3.3.2 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 the same or other characteristics or 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 contradiction is not overcome or substantially reduced. Altshuller and his coworkers distinguished three types of contradictions.

- 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.
- Second type is "Technical contradiction" where an action has simultaneously useful and harmful effects on sub-components of the system or on the system as a whole.
- The third type is "Physical contradictions" where a given component should have property "A" to deliver some function and property "non-A" or "anti-A" (e.g. an empty/loaded muck-car) to satisfy the conditions of a problem or to prevent some harmful effects (Savransky 2000).

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.

Based on the above concepts, a knowledge-representation schema is formulated for storing the knowledge associated with innovative solutions of construction problems. Figure 3.1 shows the outlines of that schema.

An innovative case is decomposed according to the proposed schema 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 recognized in the case in domain-dependant 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.

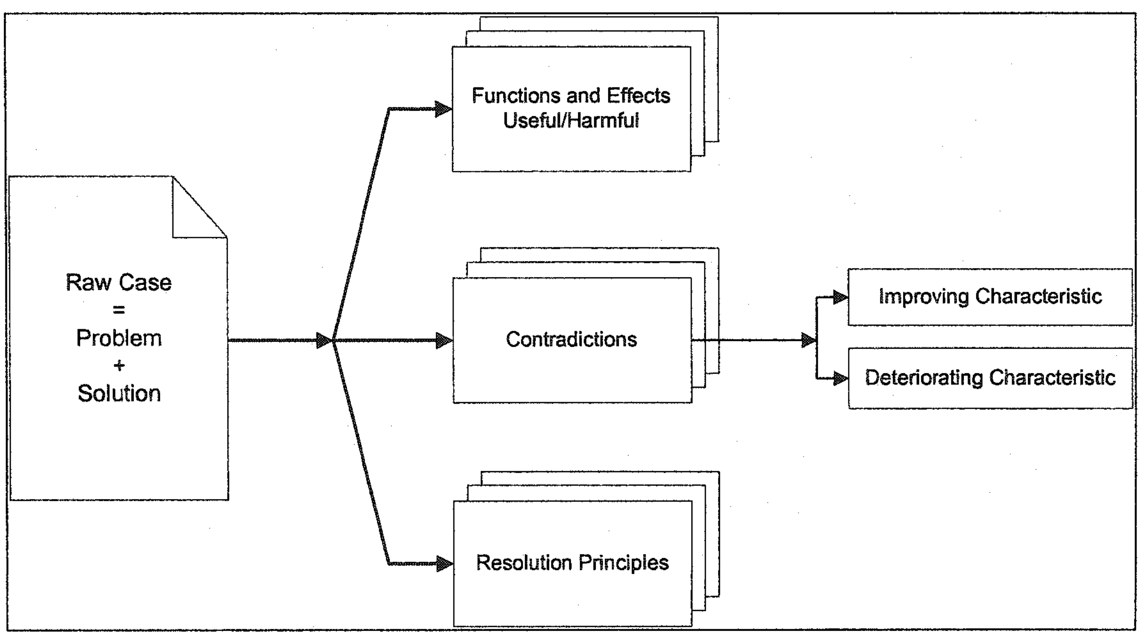

Figure 3.1 Knowledge Representation of Problem Solutions

3.3.3 Proposed Framework

Based on the knowledge representation schema discussed in the previous section, a framework is proposed for consolidation and retrieval of knowledge used in solving construction problems. Figure 3.2 shows a schematic of the proposed framework.

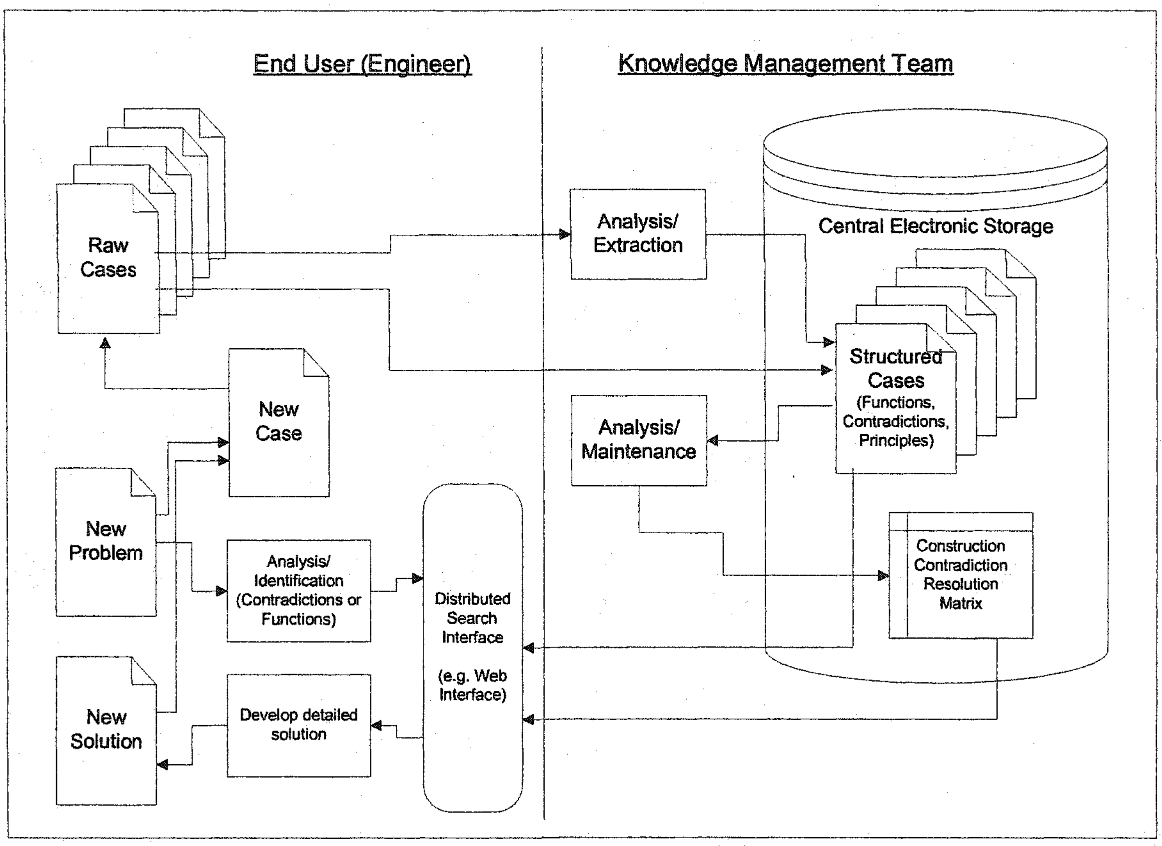

Figure 3.2 Knowledge Management Architecture

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. Such a team would also be responsible for maintaining a central problem-solving knowledge base for the company, which holds all 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 a realized contradiction in the problem or by functions or effects required to be achieved in the problem (or eliminated from the problem if they are harmful). To overcome the ambiguity in the meaning of the principles for new users, each principle should be supplemented by examples of its application in different cases. The user should then develop the detailed solution for the new problem guided by the set of principles suggested from the knowledge-base search and a number of sample cases that support each of these principles.

3.3.4 Uniqueness of The Approach Proposed in The 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. Figure 3.3 illustrates the proposed approach for extracting and consolidating knowledge.

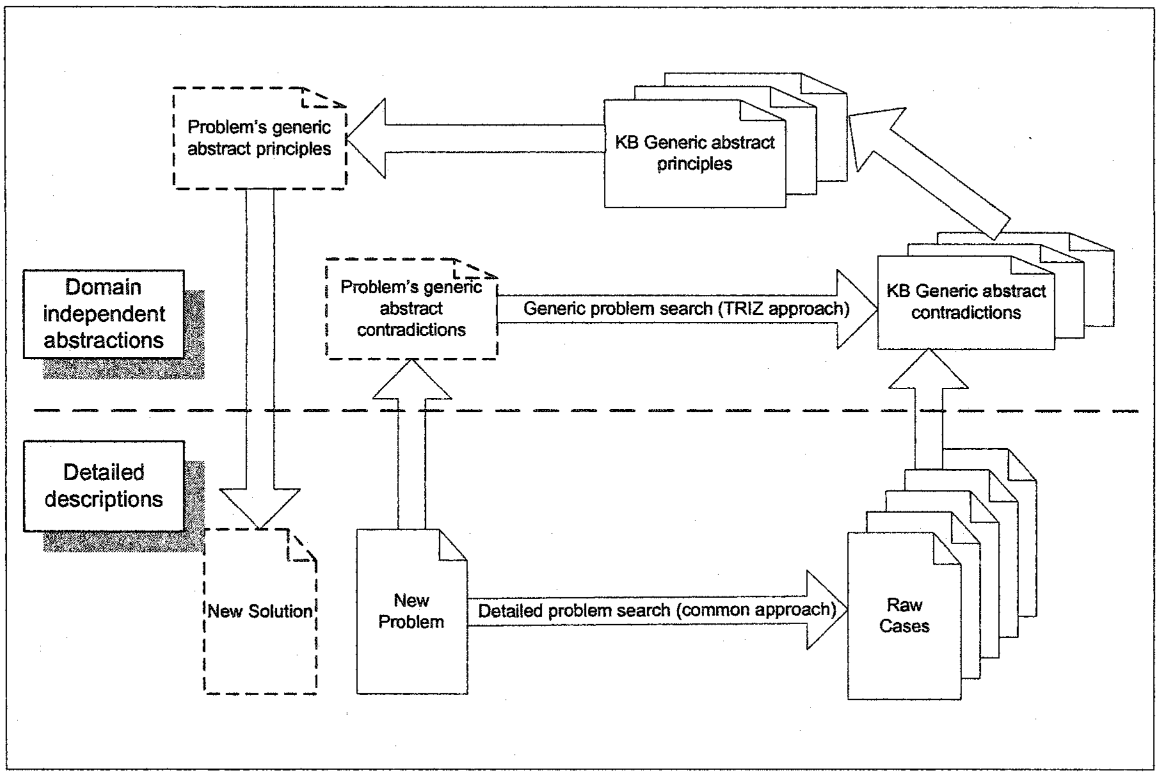

Figure 3.3 Proposed knowledge consolidation approach

Consider for example the tunnel undercut case (Case study 4) described in the first Chapter. The case in its raw format describes a detailed solution for moving muck-cars around a limited undercut area of a tunneling project. A muck-car is moved between the incoming track, a sump, and the outgoing track by mounting it with part of the track on another carrier that moves in a lateral direction. It is highly unlikely that the same problem would repeat with similar configurations considering the unique feature of construction projects. Therefore, the detailed solution of the problem would have less value to the organization as a whole although the principles applied while developing that solution can be reusable and are, therefore, of high value. Unfortunately, such principles are not explicitly described in the detailed solution although unconsciously used by the engineer who develops the solution.

On the other hand, by extracting meta-knowledge from the case, the cause of the problem can be reduced to a contradiction between "Work Area" and "Shape of Work Area " on one side and "Productivity of the System" on the other side. This contradiction was resolved in this case by making elements of the system more dynamic and moving in another dimension of the space, which is manifested in the form of moving a part of tracks that are usually fixed and utilizing a carrying car moving laterally in a second plan (see Figure 2.16). So the solution of the case all reduces to the "Dynamicity" and "New Dimension" principles. Apparently, the terms "Work Area", "Shape of Work Area ", "Productivity of the System", "Dynamicity", and "New Dimension" are generic enough to describe cases of completely different nature from the tunnel-undercut case. By appending the detailed case 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 tunneling at all.

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. In addition, despite that the findings of Altshuller suggests the validity of the assumption that a finite set of contradictions and resolution principles can be representative of a large number of inventive solutions in different engineering fields, it is not necessarily true that the same sets are representative of construction problems with lower degree of difficulty and creativity. Therefore, it is necessary to prototype the knowledge-base component and apply it to real cases to test the feasibility of the proposed approach. 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 the development of that component and the results of using it for analyzing a number of cases.

3.4 Development of the Knowledge-Base Component

3.4.1 Contradiction Resolution Database Structure

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 following sections discuss the structure of the database system and the knowledge extraction process.

Figure 3.4 shows a simplified Entity-Relationship diagram for the database. The main entity in the database is the "system" entity, which represents a case of innovative solution for a construction problem. A system has a hyperlink to an HTML document that provides a detailed description of it. It can be a part of another system and it can have many sub-systems as well. A system also performs a number of functions and these functions can be useful or harmful to other systems. They can also be primary, supportive or auxiliary functions. Each system provides a solution that relates to one or more inventive principles, which may or may not be part of the standard TRIZ matrix. The original problem, which a system is created to solve is represented by one or more contradictions between engineering parameters. The parameters may or may not be part of the standard TRIZ matrix. Figure 3.5 shows the details of tables and relationships in the database.

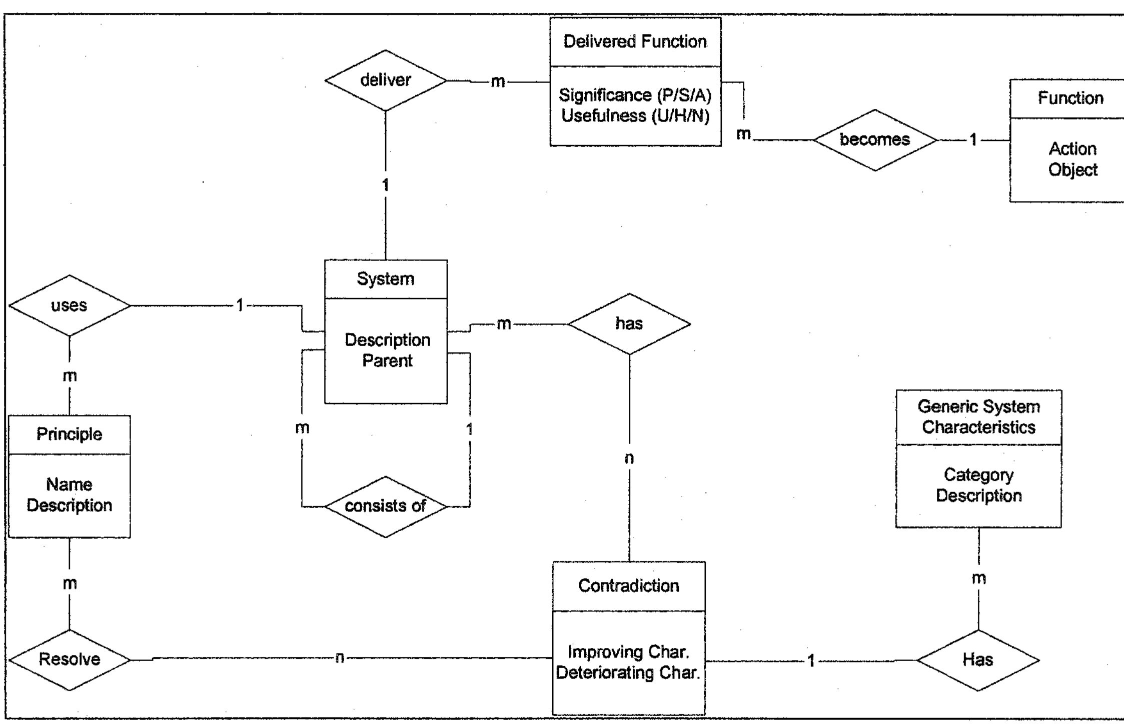

Figure 3.4 Entity-Relationship diagram

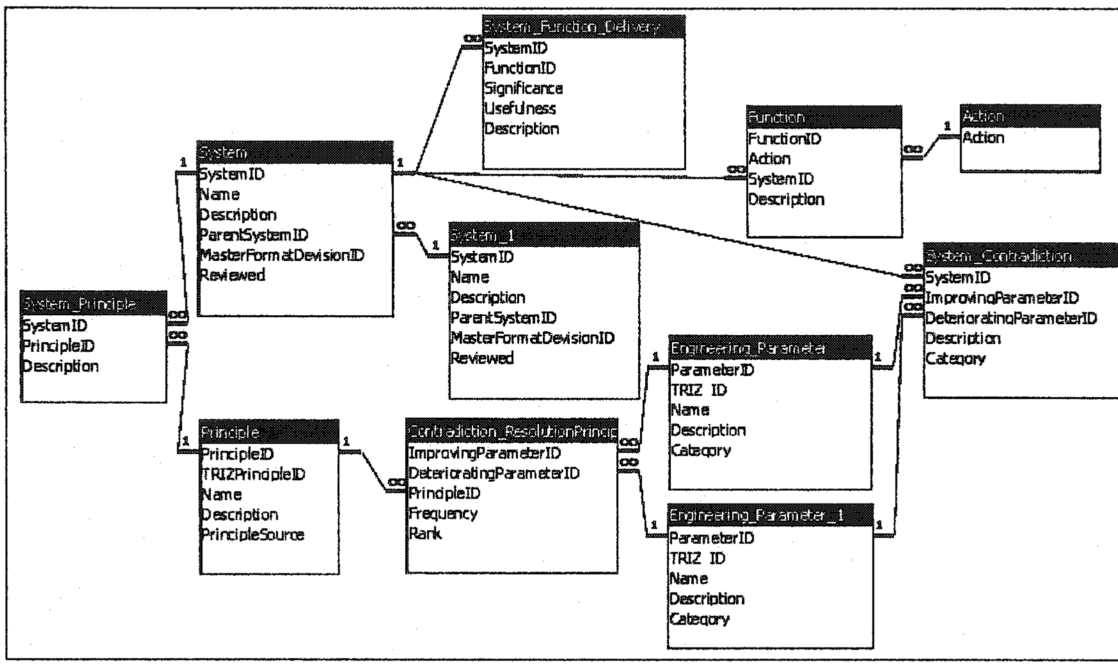

Figure 3.5 Main database tables and relationships

3.4.2 *Database Usage*

The main objectives of the database system are: 1) storage and analysis of innovative cases, and 2) search and retrieval of cases as examples of inventive principles uses. The first objective is intended for users with good knowledge of TRIZ and preferably good construction experience. The form shown in Figure 3.6 represents the input screen for entering a new case. The user has to analyze the case and extract from it the information required for input in the screen. This information includes: functions or effects of the system, contradictions in the system, and solution principles used.

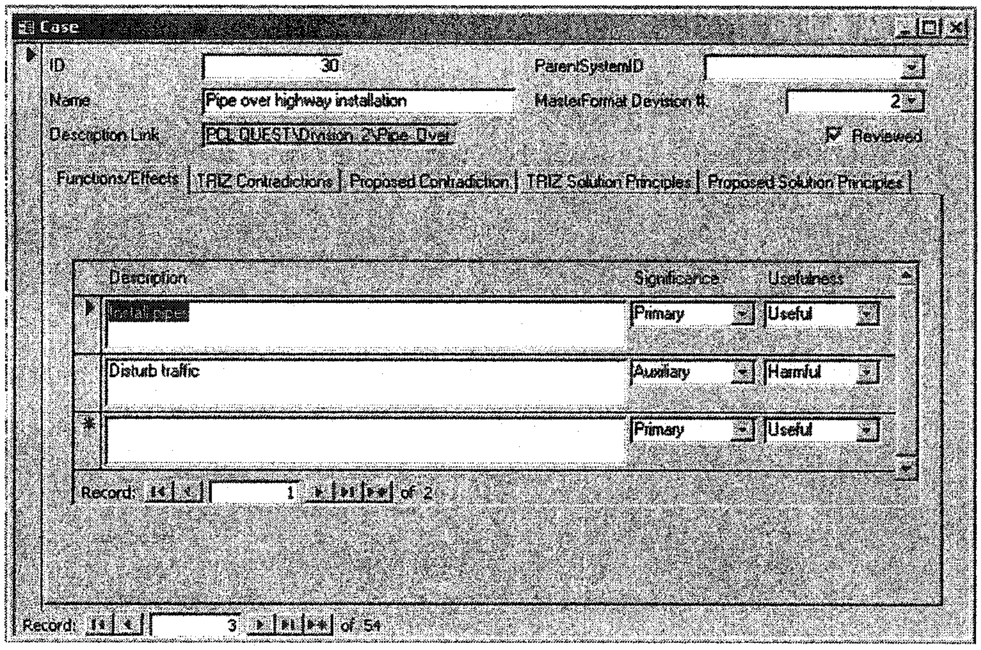

Figure 3.6 System functions/effects input form

A contradiction in a system can be defined in standard TRIZ parameters or, if not representative enough, in user-defined parameters. Figure 3.7 shows the two screens for both cases.

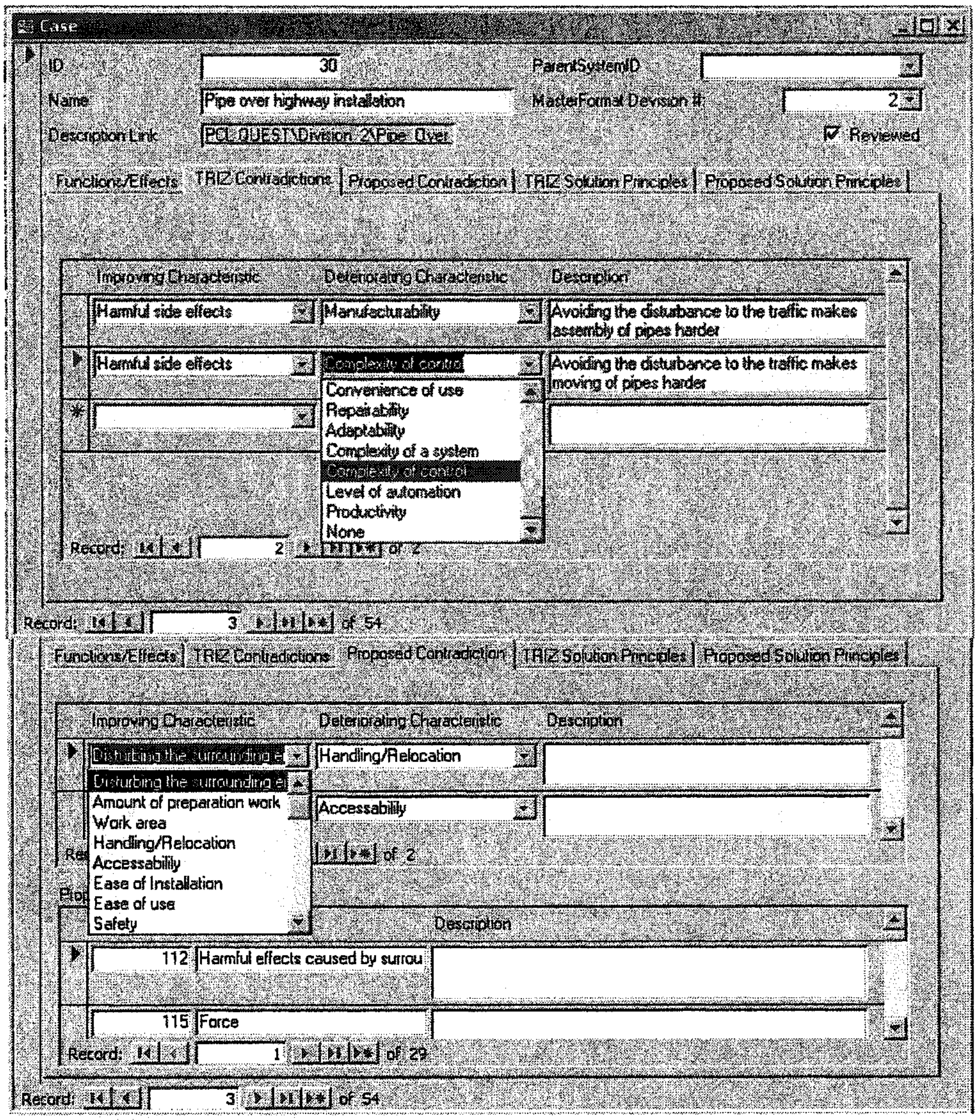

Figure 3.7 System contradiction forms

The last part of information required is the principles that are used in the case to solve the problem. The principles may belong to the standard TRIZ principles or they may be user defined. Figure 3.8 shows the input screen for the standard principles.

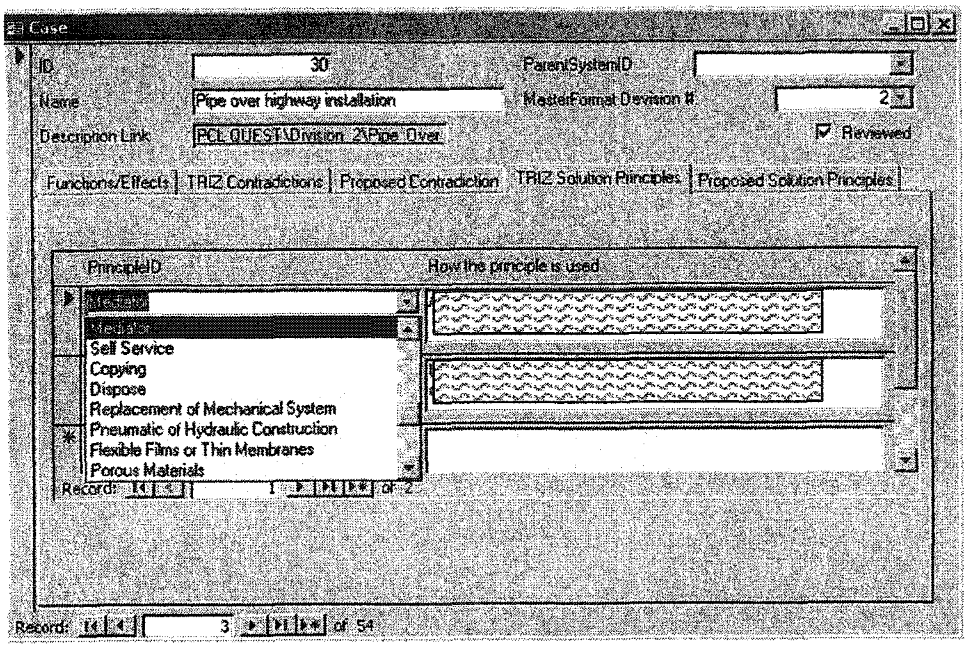

Figure 3.8 Standard TRIZ principles input form

The second use of the database system is intended to serve the process of searching for a solution for a new problem. The user has to first identify the contradiction in the new problem. The contradiction should be formulated as a pair of a system characteristic to improve and a system characteristic that deteriorates consequently. It was found while analyzing some cases that the problem may not represent a complete contradiction and therefore only one improving or deteriorating characteristic can be identified. The incomplete contradiction was also included as a way for search. Search can also be done using functions or effects. The user can search for a particular function or effect that needs to be achieved or eliminated (i.e. useful or harmful). Figure 3.9 shows screen shots of the search forms.

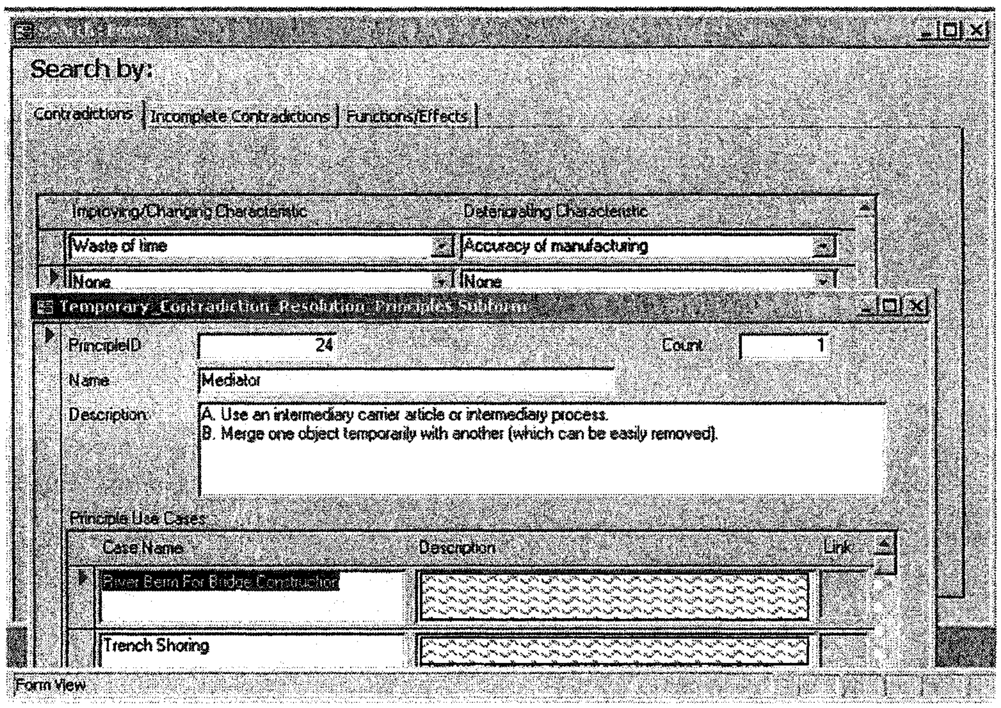

Figure 3.9 Results of contradiction search

The contradiction search results represent a set of principles from the contradiction matrix in addition to a set of use-cases for each principle. The use-cases represent examples of different uses of the principle from real construction problems. The function/effects search results represent a set of functions/effects delivery cases (i.e. cases of solutions capable of achieving the required functions/effects).

3.4.3 Knowledge Extraction and Population of The Database

55 cases were analyzed from a repository of "lessons learned" summaries. A case is analyzed and fed into the database if it meets the following criteria: 1) it deals with a technical problem, 2) it has enough description in the summary to obtain good understanding of the problem and its solution, and 3) it represents an innovative non-trivial solution.

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.
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 examples from these cases.

3.4.4 Sample Case 1: Lifting Heavy Elevator Machinery

3.4.4.1 *Analyzing the 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 (personal, and company related data were replaced by the symbol [XX] for confidentiality):

> "How do you move an 8000 lb. piece of machinery without the use of overhead tower cranes or hoist beams? [XX], project coordinator on the [XX] project in [Canadian city] 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 [XX] Phase I office tower, its replacement (weighing 8000 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 five lbs., the 12" 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 8000 lb. load was easily moved requiring as little as eight 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)

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. 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 floor 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 propose 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.
32 Changing the Color.
4 Asymmetry

3.4.4.2 *Adding the case to the 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. Figure 3.10 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.

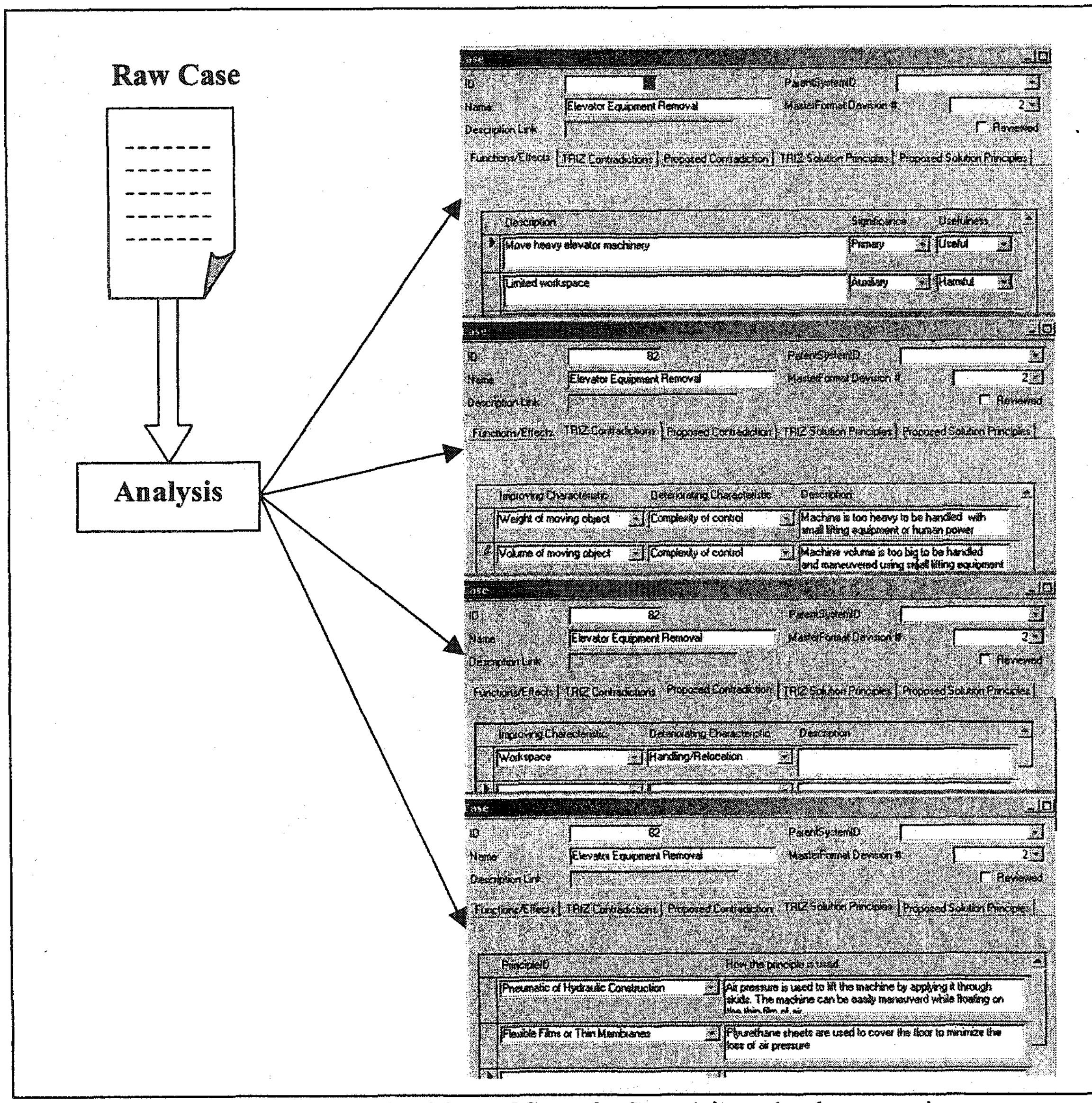

Figure 3.10 Decomposition of Sample Case 1 into database entries.

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

3.4.5 Sample Case 2: Improving Construction of Steel Silos

This case describes an innovative solution for improving constructability of steel silos during field operations. The case is described by Elazouni (1997) and is not one of the "lessons learned" summaries used in this study. However, the case is used here to illustrate the proposed knowledge extraction and representation approach. It was selected because the level of innovation in its solution is similar to that shown in the "lessons learned" summaries and the case description is publicly accessible.

3.4.5.1 *Analyzing the case*

The description of the case given by Elazouni (1997) involves many details about the construction method and sequence. The following excerpt shows the general outlines of the problem and solution.

> "Bolted silos with corrugated steel sheets are used extensively since they resist deformations. This type of silo is usually fabricated of corrugated steel sheets of 2.8-mm thickness, which is gradually reduced to 0.4-mm sheets at the top of the silo. Sheets of 2.0 X 1.0-m dimensions are delivered by the manufacturer to the site. The sheets are rolled at the shop to form the curvature that creates the required radius of the silo when constructed. The silo is erected on a reinforced concrete base, and the discharging equipment and interior ventilation ducts are embedded in the concrete base. The traditional method of construction involves using an interior scaffolding inside the silo to erect and bolt sheets in place. Extra lifts of the scaffold are added as work proceeds. In addition, external scaffolding is erected outside the silo to provide a platform for another worker to help in fastening bolts and handling sheets. After the walls are erected and the top covered, the interior scaffolding is taken apart and is moved outside through an exit door at the bottom of the silo.
> This paper introduces a new method for the construction of bolted silos with corrugated steel sheets. This method offers a substantial opportunity for enhancing constructability during field operations. The novelty in this method is represented by 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 work always at grade, thus eliminating the need for scaffolding, and to attain the other benefits of working at grade. This method has already been used to build many silos of capacities up to 1,500 X 103 kg (12-m diameter X 23-m height) in Egypt. The main objective of this paper is to document this experience so as to maintain awareness and share experience among constructors." (Elazouni 1997)

The first step in analyzing the case is to identify the useful functions/effects to achieve and/or the harmful ones to avoid. The main useful function to be achieved in this case is to "Assemble a steel silo". There is no harmful function shown in the case that really prevents the achievement of the useful function. However, it is required to increase the efficiency of delivering the useful function. So, this step results in "assemble a steel silo" as a useful function entry to the database.

The second step is to identify the standard and/or proposed contradictions in the case. Based on the useful function identified in the case, one side of a contradiction can be "32. Manufacturability", which is the closest standard TRIZ parameter that can describe the assembly process of the silo. As discussed earlier in this chapter, "Administrative Contradictions" are of little value in pointing to a technical solution. Therefore, "increasing efficiency" of the traditional silo assembly method is not considered a useful part of a contradiction. In search for what characteristic really deteriorates when assembling the silo using the traditional method, it can be concluded that the amount of preparation work and construction steps are considered too many. That is, the "Convenience of use" (standard parameter 33) of the original technique can represent the other part of the contradiction. One can also formulate a contradiction between "4. Length of stationary object" and "32. Manufacturability" as the assembly of a silo becomes harder when its length increases. Based on this analysis two standard contradictions can be entered into the database. One between standard parameter "32" and "33" and the second between "4" and "32".

The third step in the analysis is to identify the proposed contradictions. In this case, to better describe the situation in the case, one would use "Ease of Assembly of an object" and "Amount of preparation work" instead of "Manufacturability" and "Convenience of use" respectively. The first two parameters are, therefore, entered as proposed parameters because they do not exist in the standard TRIZ matrix.

The last step is to identify the principles used in solving the problem and how they are applied in the solution. In this case the most obvious principle used is "13. Do it in reverse". Compared to the original construction method which builds the silo from the bottom up, the new method suggests building the silo from the top first so that the successive lower parts are build on grade. Another principle that is not as contributing to the solution as the first one is "15. Dynamicity". The silo structure, which is stationary in the original method, becomes more mobile (moves up gradually) in the new method. So, the case results in two entries under the standard principles screen in the database.

In this case, the standard matrix suggested seven principles for resolving the identified contradictions. Out of the seven listed below, two match the actual solution of the case (i.e. principle number 13, and 15).

2. Extraction.
5. Consolidation.
13. Do it in Reverse.
15. Dynamicity.
16. Partial or Excessive Action.
17. Transition Into a New Dimension.
27 Dispose.

3.4.5.2 Adding the case to the database

After completing the analysis of the case, the outcomes are entered into the database. The details of the case are broken down and reduced to a corresponding set of contradictions, functions and resolutions principles representing the merits of the case. Figure 3.11 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.

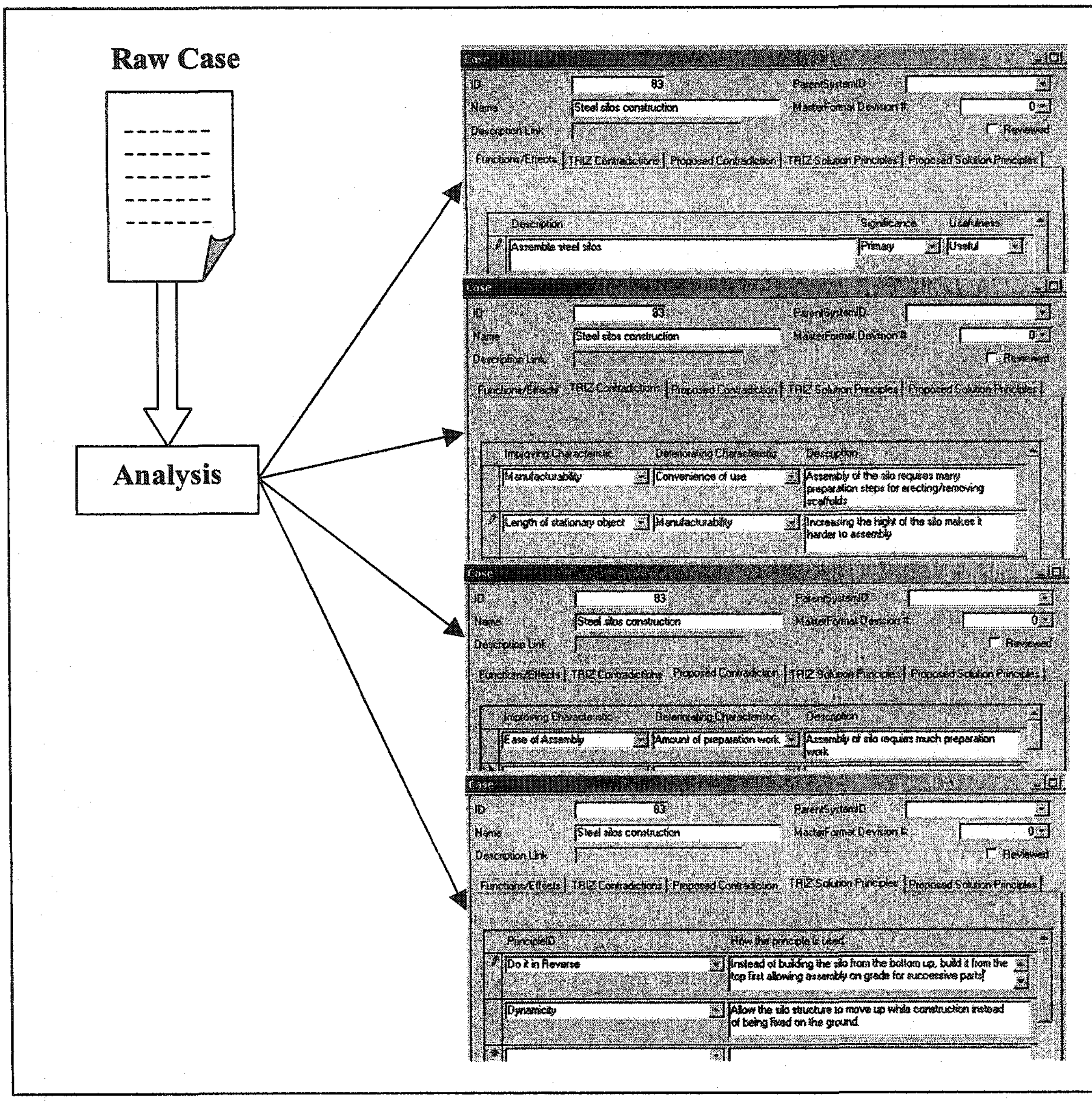

Figure 3.11 Decomposition of Sample Case 2 into database entries.

In this case there were no proposed principles to replace the standard ones. However, two non-standard parameter were used the proposed contradiction (i.e. "Ease of assembly" and "Amount of preparation work"). Both parameters existed in the system as a result of the analysis of previous cases. Such entries help in extending the matrix and customizing it to construction problems.

About 50 more cases similar to the ones described above were analyzed and added to the database. These cases resulted in 24 new or rephrased parameters that were added to the database system to expand the matrix. The following sections include a list of these proposed parameters among other findings observed after adding these cases.

3.5 Discussion and Findings

3.5.1 Principles Use Frequencies

In the number of cases analyzed, the standard TRIZ principles showed a good representation of the solutions. There was no need to propose new principles. Furthermore, the solutions were represented by only a subset of the total standard principles (30 out of 40 principles). The frequencies of use of some principles are higher than others. Figure 3.12 shows the frequencies of principles use in the analyzed cases.

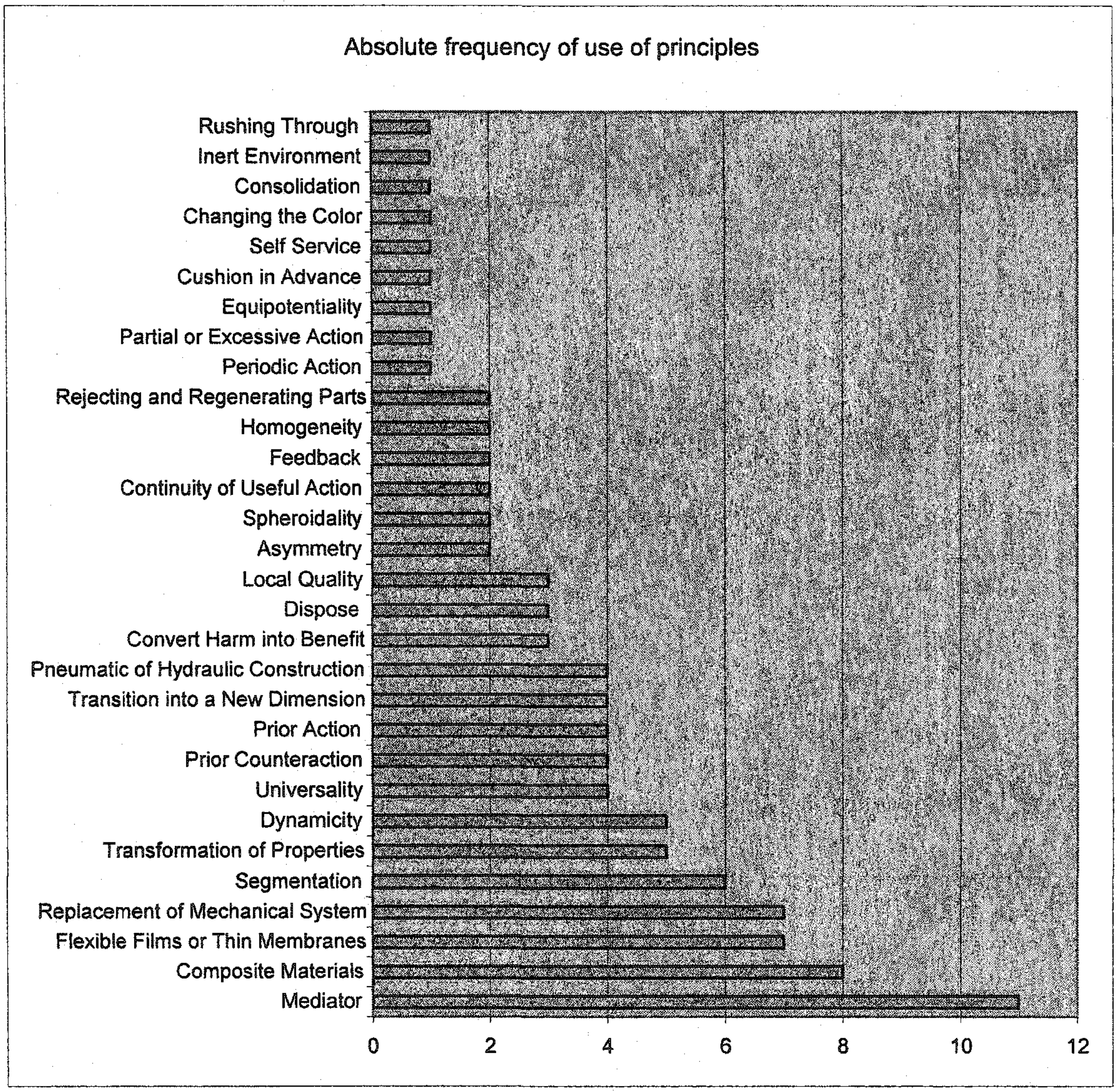

Figure 3.12 Frequencies of use of different principles

The fact that the "Mediator" principle has the highest frequency gives an indication that some of the cases could actually be better analyzed using the Su-Field tool, which deals more with the structure of the system and the introduction of new elements or fields. Such problems are generally categorized by lower difficulty level in TRIZ.

3.5.2 Parameters Use Frequencies

Figure 3.13 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 vs. improving one. Higher use of one parameter as deteriorating does not necessarily mean it is widely used as improving.

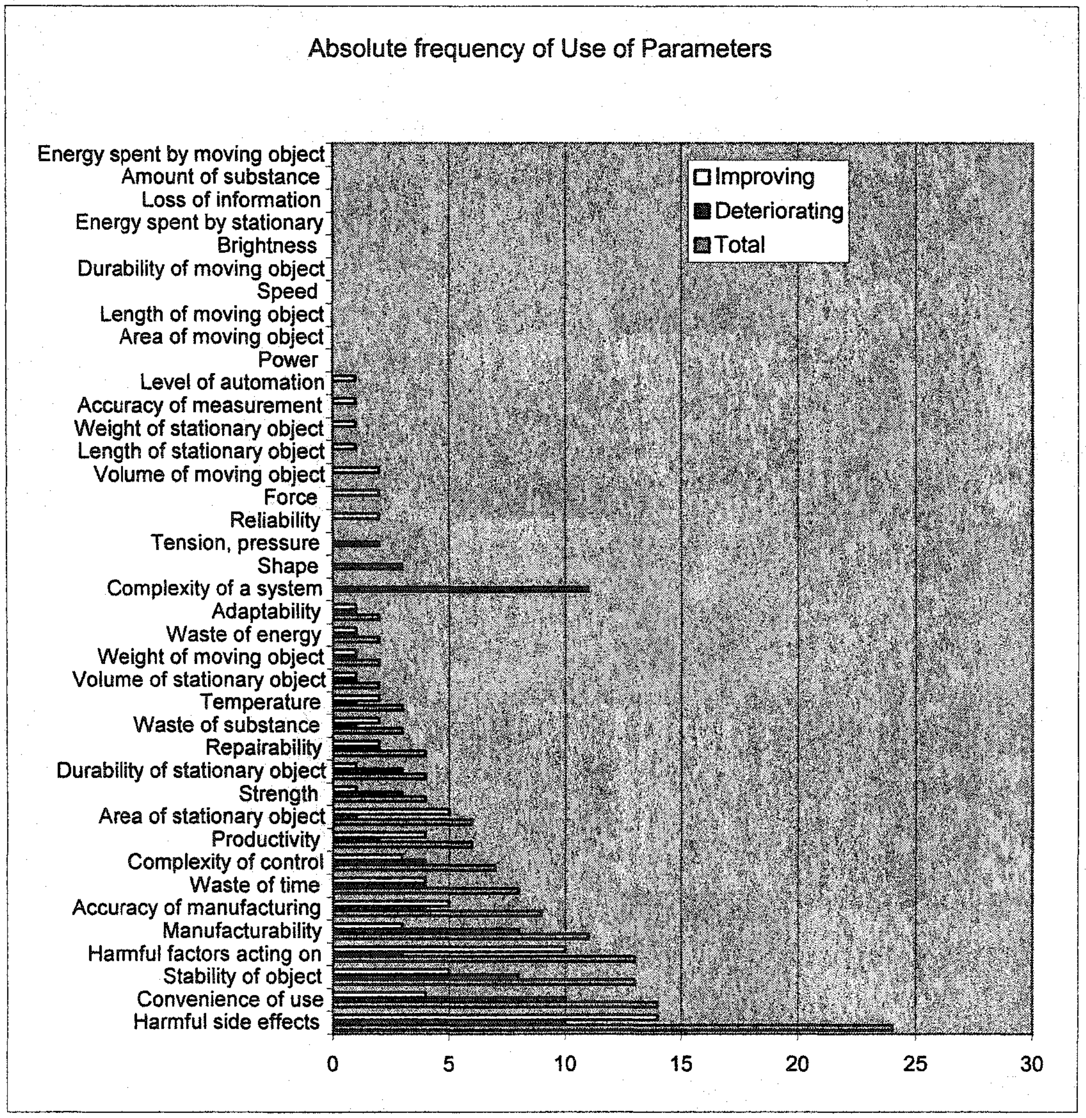

Figure 3.13 Frequencies of use of different parameters

A total of 24 parameters needed to be added to provide better description of the problems. Table 3.2 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.

Table 3.2 Proposed Parameters

	Proposed Parameter	Frequency of use as Deteriorating	Frequency of use as Improving
1	Aesthetics	5	1
2	Handling/Relocation	5	6
3	Complexity of process	4	0
4	Disturbing the surrounding environment	4	6
5	Work area	3	2
6	Accessibility	3	1
7	Ease of use	3	1
8	Fragility	2	0
9	Loss of Heat	2	0
10	Shrinkage	1	2
11	Ease of Installation	1	1
12	Harmful effects caused by surrounding environment	1	2
13	Amount of preparation work	1	0
14	Cycle Time	1	2
15	Ability to properly and completely form	0	2
16	Safety	0	2
17	Insulation	0	1
18	Ease of Disassembly	0	1
19	Water tightness	0	1
20	Ease of Detection	0	1
21	Flexibility	0	1
22	Reuse ability	0	1
23	Ease of Assembly	0	1
24	Workspace	0	1

3.5.3 Defining Contradictions

One of the realized problems 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. One of the reasons of this difficulty could be the nature of the problem itself. Some problems represent an incomplete Su-Field, in which case, the matrix is not the best tool to use.

3.5.4 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 towards 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 effective search. Defining such standards is out of the scope of this study. However, the recent OCCS (The Overall Construction Classification System 2001) standards include a promising approach towards a standard function definition format.

3.5.5 Matching Actual vs. Standard Matrix Recommendation

From 101 actual principles used in the analyzed cases, 40 principles match the standard recommendation of the matrix. Figure 3.14 shows the matching principles and number of matches for each. A 40% match indicates that if the standard matrix were used to solve these problems, it would have guided the user to a different direction in 60% of the cases. The cause of this mismatch can be attributed to a number of reasons:

1. The actual solution does not represent the only solution of the problem. Other solutions may be generated from other principles in the matrix.
2. The analyzed cases were not screened for difficulty level. TRIZ in general is intended for use with problems of high level of difficulty (i.e. inventive problems). If a problem is trivial, TRIZ tools may not be the suitable tools to use.
3. The matrix is not the only tool of TRIZ. The theory includes other tools each of which suites different types of problems.
4. The matrix was build by analyzing patents. Knowledge and technology used in patents build up with time, so should the matrix. This observation is also reported in some TRIZ literature (Savaransky 2000).

Therefore, it is recommended to build on the contradiction matrix rather than use it as-is. The system proposed in this chapter could help this to take place. The system should expand to use other TRIZ tools, as the matrix may be unsuitable for solving some problems.

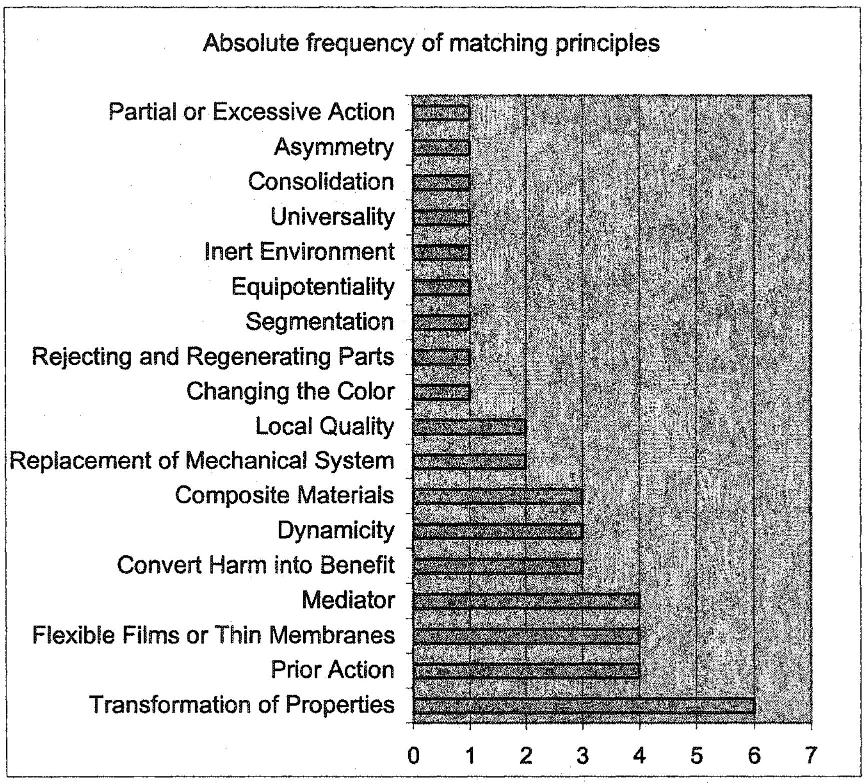

Figure 3.14 Matching principles

3.5.6 Limitations of the 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.

3.6 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 database system was developed to analyze the information collected from the different cases and to help 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 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.

When comparing the principles recommended from the standard matrix to the principles used in the actual solutions, there was a 40% match between the two. The relatively low match indicates the need for extending the matrix and customizing it to the nature of construction problems.

The proposed database structure provides a useful framework for managing the building process of the matrix and the search and retrieval of information as well. However, a multimedia web-based implementation is recommended to provide better representation, distribution, and accessibility of the information stored in the database.

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Chapter 4 - Building Intelligent Simulation Models

4.1 Introduction

The process of improving any production system involves a number of steps. Figure 4.1 shows some of the generic steps that can be followed for improving any construction system. The process starts by studying the existing system followed by building a model of the system. Once a valid model is available, experiments and modifications to the model are conducted to improve system performance, which is evaluated using the model. Once the performance measured from the model is satisfactory, the necessary modifications are implemented in the real system and the whole process can be repeated again.

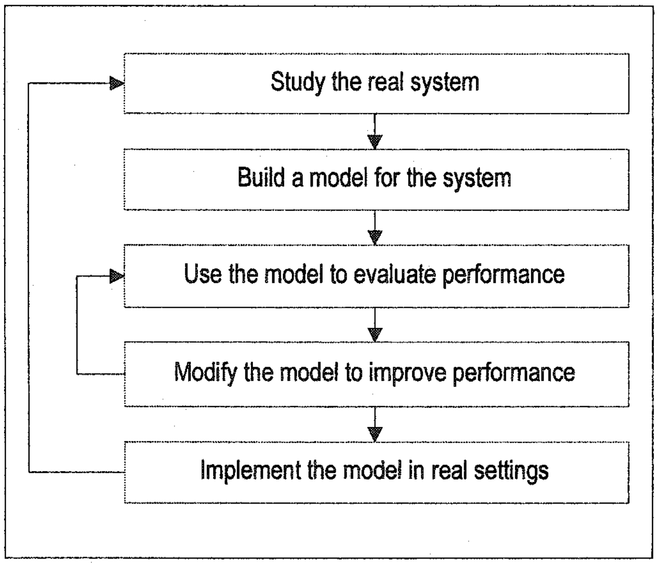


Figure 4.1 Generic steps for improving a construction system

Modeling methodologies may vary depending on the nature of the construction system to be modeled. In the construction domain, simulation techniques are among the powerful approaches that can model a wide spectrum of systems and account for the randomness and uncertainty, which are common features of construction operations.

The approach used for modifying a model also varies according to the modeling methodology used and the nature of the modeled system. The TRIZ theory described in the previous chapters represent an approach for producing effective model modifications. The theory directs the user to produce innovative solutions to improve a component of the system. However, it does not provide the tools for identifying which components are more significant to improve. In addition, the solutions produced using TRIZ may not necessarily be the most economically feasible ones and have to be evaluated in view of the whole system. Therefore, the use of TRIZ or any similar approach for improving a construction system has to be considered as part of a complete framework that allows evaluating any new solutions through suitable modeling techniques.

This chapter describes the development a simulation methodology that accommodates the type of modifications produced using TRIZ. By combining the modeling methodology described in this chapter and the problem solving approach of TRIZ described in the previous chapters, a complete framework can be formulated for systematic improvement of construction systems. Scope is limited to the development of concepts required to enable integration of simulation techniques and TRIZ. Full integration and implementation of these concepts represent recommendation for future work.

4.2 Background

4.2.1 Simulation in Construction

Early simulation users were required to build a model by writing programming code using languages like FORTRAN, and experimenting by directly manipulating the computer program. This was followed by the introduction of simulation specific programming environments where users write simulation specific code or access a provided function library. In the next phase of development, a host of systems were introduced that allowed for alternative model development. This meant that modelers no longer had to write code directly. Graphical modeling made it possible to define the simulation model by creating, manipulating and linking a number of available basic building blocks. This meant that users no longer had to be proficient in programming. (Hajjar 1999)

Several simulation languages were developed and can be used for modeling construction operations. General-purpose simulation languages include Visual SLAM (Pritsker and O'Reilly 1997), GPSS/H (Crain and Smith 1994), SIMAN/Cinema (Profozich and Sturrock 1994), and SIMSCRIPT (Russell 1993). These systems are capable of supporting simulation modeling in any domain, including manufacturing, industrial engineering, and construction.

Other languages have been developed specifically for construction, such as CYCLONE (Halpin 1976). Many CYCLONE-based systems have been developed to extend the functionality of CYCLONE, such as RESQUE (Chang 1987), STROBOSCOPE (Martinez and Ioannou 1994), and RISim (Chua 2002). CYCLONE-based languages are not domain specific and can be used for modeling different construction domains.

Special purpose simulation (SPS) tools were also introduced by focusing on one particular domain of construction operations and facilitate modeling projects within that domain with remarkable ease. Examples of these are: Ap2Earth (Hajjar and AbouRizk 1996), CRUISER (Hajjar and AbouRizk 1998) and CSD (Hajjar, AbouRizk and Xu 1998). As a result of the research effort in developing SPS tools, a unified modeling methodology was then introduced and implemented as a development environment called "Simphony" which significantly reduces the time required for developing SPS tools (Hajjar 1999).

4.2.2 SPS Requirements

Hajjar (1999) defined SPS as a means for facilitating the use of simulation techniques in the construction industry. He identified a number of requirements for achieving SPS' convenience of use by construction personnel. These requirements can be summarized in providing the user with a set of modeling elements that map to real physical or logical components of the target process being analyzed. Each of these elements should encapsulate all parameters and statistics necessary for describing its behaviors and analyzing its performance.

4.2.3 Knowledge and Experimentation with Simulation Models

An engineer experiments with simulation models of construction processes in order to optimize the performance of these processes. During such experimentation, the engineer may change the numeric parameters of the model or the sequence or logic of the operation (i.e. structural change of the model). Mathematical optimization algorithms can be used for searching for optimality by changing the parameters of elements in a model (e.g. Hajjar and AbouRizk 1998). However, the search for optimality among structurally different models is mainly guided by the knowledge and experience of the engineer. In order to make a simulation model assist the engineer do such an optimality search the elements in the simulation model have to possess some sort of intelligence and awareness of their goals and the interdependence between their functions and other elements' functions.

TRIZ-like heuristics and consolidated knowledge may be used for assisting or driving such a topological search. However, without a suitable simulation framework, the use of such an approach would be a complex process that requires a user who is highly knowledgeable in both TRIZ-like abstract heuristics and in simulation techniques. This knowledge should be thorough enough to enable easy and effective mapping of changes recommended by generic heuristics into structural and behavioral changes in the simulation model and its sub-models. Such level of knowledge is rarely available outside the academic research environment.

The current simulation methodologies available for modeling construction operations lack behavior causality knowledge in their structure. Instead, they depend on mapping the operation into a flow of consecutive tasks with duration associated with each and are, therefore, not suitable for automated modification of model structure. It is therefore necessary to conceptualize a simulation framework that can effectively accommodate structural manipulation of simulation models by possessing some intelligence and causality knowledge.

4.2.4 Agents and Simulation

The term agent is derived from the concept of agency, referring to employing someone to act on behalf of a client to perform a certain task. Intelligent agents are used under different names such as: "software agents", "wizards", "knowbots", and "softbots" (Turban and Aronson 2001). There are, as well, several definitions of what an intelligent agent is. Examples of these definitions are:

"Intelligent agents are software entities that carry out some set of operations on behalf of a user or another program, with some degree of independence or autonomy and in so doing, employ knowledge or representation of the user's goals or desires." (Turban and Aronson 2001 based on IBM white paper definition)

"Autonomous agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and doing so realize a set of goals or tasks for which they are designed." (Maes 1995)

"Agents are software modules with cognitive abilities that can work as assistants to the users. They can observe and sense their environments as well as affect it." (Oren et. al. 2000)

Although there are some differences between the various definitions of intelligent agents, there are some common abilities that are thought of when discussing intelligent agents. Among these abilities are: autonomy, perception, reasoning, understanding, learning, goal processing and goal-directed knowledge processing. (Oren et. al. 2000; and Turban and Aronson 2001)

Oren (2000) defined three types of synergy that agents and simulation have. First is agent simulation, which is the simulation of intelligent entities that can be represented by agents such as humans, intelligent platforms, equipments, and destructive devices. Second is agent-based simulation where agents are used to generate model behavior in simulation to offer additional possibilities to numerical simulation. Third is agent-supported simulation where agents are used in simulation support operations such as user interface operations.

4.2.5 Declarative and State-Based Simulation

The declarative modeling approach suggests that the modeler looks at the world through a sequence of changes in state. Declarative models contain two primary components: states and events. They can be embedded within an object and are suitable for representing the dynamics within the object that constitutes a part of a larger model. The basic types of state-based declarative models are: deterministic, nondeterministic, and production rule/logic. Figure 4.2 shows a general algorithm for state-based modeling approach where the transition from one state to another depicts the model type. (Fishwick 1995)

> *Start simulation*
>   *Set current time to zero*
>   *Set start state to any state in the automaton*
>   *While not (end of simulation) do*
>   *Output current state information*
>   *Update current time by* ΔT
>   *Transition to next state using:*
>   *{current input (deterministic),*
>   *sampling from probability distribution (Markov),*
>   *or production rules (logic calculations)}*
>   *End while*
> *End simulation*

Figure 4.2 State-based Simulation Algorithm (Fishwich 1995)

Traditional deterministic declarative models and nondeterministic models using Markov tables for transition require the enumeration of all state-to-state transitions. The declarative approach is based on state structure. That is, if a state matches a certain structure, a mechanism in the model defines the transition to the next state. Therefore, the use of production systems and formal logic methods provides more general power. Using production systems and formal logic terms, a state is equivalent to the current set of facts (truths) in the system while time is assigned to each production or inference so that the process of forward chaining produces a temporal flow. (Fishwick 1995)

4.2.6 Simulation and Innovation

One of the lessons learned in developing and managing innovative construction technologies in Japan is the use of simulation. Simulation modeling of an innovative technology allows testing it in increasingly realistic and complex settings (Kangari and

Miyatake 1997). Once a problem is identified in a construction system, and a solution is formulated, the real implementation of such solution becomes risky unless sufficiently tested and evaluated. Testing and evaluation have to take into considerations the effects of the solution on all the other components of the system. When the interaction between the different components involves randomness and uncertainty, evaluating a new solution becomes a nontrivial task and simulation can be a useful tool to assist such evaluation.

As a methodology for innovative problem solving, one of the difficulties in TRIZ is identifying the problem. When dealing with a complex system with many components interacting and affecting each other, the identification of the sources of problems in the system becomes a difficult task without using the proper tools. Simulation is considered to be a useful tool in such cases as well (Miller and Domb 2002).

TRIZ analysis concepts focus on the elements involved in a system and the goal or "primary function(s)" of each of them. While a system is designed to perform one or more primary functions, which are useful functions by default, it usually produces one or more harmful functions as well. This type of contradiction between useful and harmful functions is what causes the ideality of the system to decrease and calls for innovative solutions to resolve it. Innovative resolution of contradictions assumes minimal or no compromise between conflicting requirements. Therefore, it deals with all the components of a system (including natural components) as resources that can be used in one way or another for providing more useful functions without added costs (Savransky 2000). When comparing this type of analysis to traditional simulation analysis used in construction, a significant difference in the concepts is realized. Most of the simulation modeling approaches tend to isolate a set of system components and abstract them to represent resources that support predetermined set of functions.

4.3 Research Objectives

The objectives of this part of the research are to develop a simulation framework that allows automated improvement of the modeled operation based on model topology modifications. Based on the background discussion, this objective can be further decomposed into a number of requirements and criteria that need to be available in the framework. These requirements and criteria are as follows:

- Allow simulation behaviors to be focused on the functions of elements and maximize the separation between element functions and other simulation constructs. The framework should focus on the functions of each element of the system as a way for identifying the reason behind creating the element and should allow flexible manipulation of these functions. It should also allow flexible integration between elements based on their functions.
- Maintain SPS concepts of providing the user with modeling elements that resembles actual components of the construction system.
- Maintain f lexibility o f c ustomizing S PS e lements u sing v isual g eneral-purpose-simulation (GPS) constructs.
- Maintain encapsulation of elements' behaviors to allow an element to merge easily in models that contains elements from different SPS domains
- Maintain the integrity of elements communication when integrating them with elements from different SPS domains.
- Allow autonomy of elements so that an element can react according to the conditions of the surrounding environment without central controller and without limited sequence of actions, which is a requirement that facilitates modeling complex systems
- Allow flexibility in changing the structure of the model by adding or deleting elements during the simulation and engaging them in the simulation model at any point of time.

4.4 Simulation Framework Architecture

The proposed framework builds on the unified modeling methodology as described by Hajjar (1999), which is implemented in the Simphony simulation environment. Figure 4.3 shows a schematic of the main components of the proposed framework. The framework depends on two levels of details. The first level holds SPS elements that resemble real-world elements (e.g. trucks, loaders, roads) and is intended for use by the construction engineer with minimal knowledge in simulation. This level works as an interface between the general purpose simulation abstractions and the user by exposing only the input and output parameters that relate to real-world decisions.

The second level holds visual general-purpose constructs that link to the SPS elements and provide their simulation behaviors. It is intended for use by SPS tool developers with good knowledge in simulation techniques. This level contains three main components; functions, function transition processor, and the elements' communication pool.

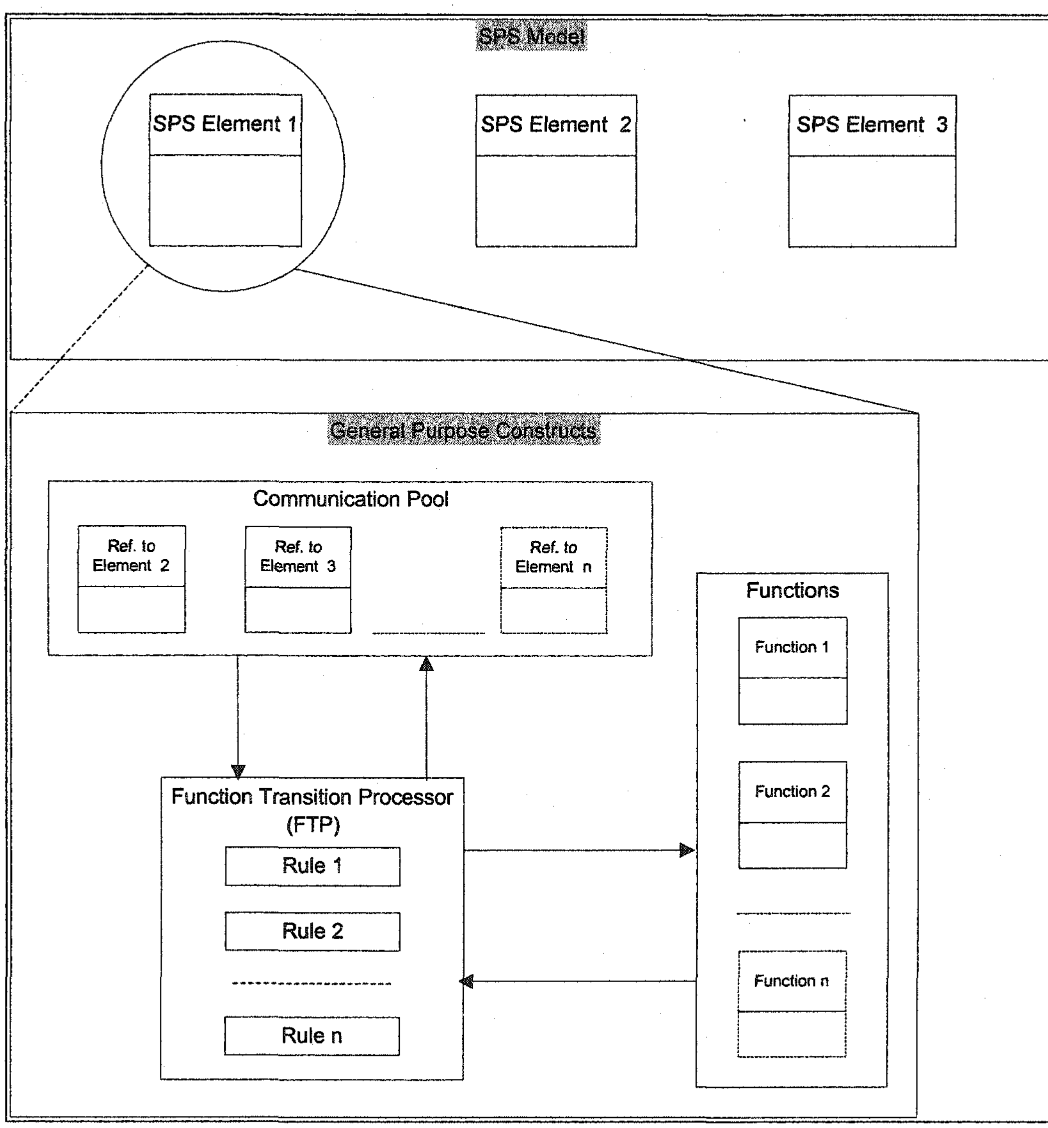


Figure 4.3 Main Components of Function-Based Simulation Framework

Functions enable the developer to describe the behavior of the element in a manner beyond what current simulation techniques allow. In particular, they provide the means for representing "why" an element exists in a system.

The function transition processor (FTP) describes "how" an element delivers these functions.

Within the current simulation modeling techniques, the main focus of the model is on the time it takes an element to complete tasks, which are arranged in a predetermined and static sequence represented by a flow diagram (e.g. CYCLONE and SLAM networks). The use of an explicit FTP with flexible transition mechanism allows development of autonomous elements that adapt to the conditions of its surrounding environment.

The third component is the "Communication" Pool of an element, which provides the necessary interface for communicating with other elements in the model during simulation. The following sections provide more detailed description of the different components of the framework.

4.4.1 SPS Modeling Element

A SPS modeling element is a virtual representation of a real element of a construction operation. As described by Hajjar (1999) a customizable generic modeling element can be used for that purpose. Such an element allows customization of its attributes, statistics, graphical representation and other behaviors in order to mimic the behavior of a real-world element. For example, a truck in an earthmoving operation can be represented by an SPS element that has a truck image as a graphical representation and attributes such as "Speed" and "Capacity", and statistics such as "Waiting Time" and "Cycle Time".

The customizable modeling element is already available in the Simphony simulation environment and can be modified to accommodate the additional requirements of the proposed framework.

4.4.2 Functions

The concept of using functions to describe the behaviors of different elements in a simulation model is derived from TRIZ's concepts of technical systems analysis (Savransky 2000) and coincides as well with function analysis concepts of Value Engineering (V/E) (Dell'Isola 1997). The main benefit of function analysis is focusing on achieving the required function in a system without being influenced by a particular physical element that is commonly used for delivering such a function.

Any element of a real system exists to achieve specific function(s). These functions are actions that the element takes and influences other elements or element attributes in the system. For example, a truck in an earthmoving operation has a set of functions such as "Haul dirt", "Dump dirt", and "Travel to loading area". Not all functions of an element represent the reason of existence of the element. Usually one or more are the primary functions (or "Basic functions" in V/E terms) while the rest are secondary or auxiliary. For example, "haul dirt" is the primary function of the truck in an earthmoving system while "moving back to the loading area" is only required to achieve the primary function. If a truck is to be replaced by another element, that element should maintain the same primary function (i.e. "haul dirt").

The relationship between elements in a construction system can also be described in terms of functions dependencies. The followings are examples of how this can be done:

- An element may not be capable of delivering its primary function without a simultaneous support by a function from another element. For example, one of the truck's functions is to load dirt, it cannot perform this function without a support from a loader to load the dirt from ground and move it to the truck. If a truck could do these supportive functions (i.e. load dirt and move it into its bucket), there would be no need for the loader, which is a case realized in using scrapers for earthmoving.
- An element may exist to deliver a function, which is merely required to counteract a harmful function of another element. For example, road maintenance equipments are usually used in earthmoving operations to counteract the harmful road deterioration effects produced by the trucks. By eliminating these harmful functions, the need for the road maintenance function vanishes and so do the need for the equipment that delivers it.
- An element may deliver a function as a support for another function performed by the same element or another element. For example, a truck moves back to the

loading area as a supportive function to the next hauling trip. On the other hand, a conveyer belt removes this supportive function and provides continuous hauling.

Most of the general-purpose construction simulation languages handle the relationships between elements in a simulation model by abstracting one or more of the elements involved in the process in the form of resources represented by numbers in the model (e.g. CYCLONE, and SLAM). This abstraction masks all the functions that these elements produce in the system and therefore presumes that their existence is equivalent to the delivery of their primary functions.

The proposed framework attempts to make a clear distinction between an element and its functions. For example, when a truck is ready for loading, it does not require a loader equipment but, more specifically, requires a "load and move dirt" supportive function. This means that if the function could be delivered by any element in the system, the production process should continue.

For an element to deliver a function, it has to be in a certain state. For example, for a truck to "dump dirt" (a function), it has to be "at dumping site" and "loaded" (a state). Therefore, delivery of different functions is closely tied to the transition of an element from one state to another and the conditions that govern such transition. A state transition mechanism associated with each modeling element is supposed to provide control over the function delivery sequence of the element.

4.4.3 Function Transition Processor (FTP)

A state transition can be accomplished using different mechanisms. The proposed framework depends on defining a function transition processor (FTP) for each modeling element. This processor controls the delivery of the element's functions according to the changes in the state of the element. This processor can be implemented in different formats and it is envisioned that elements in the same simulation model may have different mechanisms for running their FTP's.

One of these mechanisms is the use of production rules, which is the one chosen for implementation in this study. Each modeling element may have its own set of rules that control the transition of the element from one state to another and, consequently, its function delivery sequence. The rules in the FTP should have access to the attributes of their owner (parent) element and of other elements that the parent element can communicate with. The reason for that are: 1) to enable an element to sense the environment by reading the values of these attributes while deciding the next transition, and 2) to enable the element to change these value while executing function effects.

The following section describes a simplified example of how this component may control a truck and loader elements in an earthmoving operation.

Consider a simple earthmoving operation, which starts with a truck getting loaded by a loader and then travels to the dump site, dumps its load, and travels back to the loading site. The loader's function is to "Load dirt". The truck's functions are to "Load dirt", "Haul dirt", "Dump dirt", and "Travel back". The rules that govern the delivery of these functions are listed in Figure 4.4.

LOADER

Functions:
- Load dirt

Attributes:
- Availability (available/not available)
- Current function (loading/Idle)

TRUCK

Functions:	delivery time
Load dirt	2min.
Haul dirt	10min.
Dump dirt	1min.
Travel back	7min.

Attributes:
- Location (loading site, road, dumping site)
- Load (empty/loaded)

LOADER FTP

If *loading* then *not available*
If *Idle* then *available*

TRUCK FTP

IF *at loading site* AND *empty* AND *loader available*
THEN load dirt AND *loaded* after loading time

IF *at loading site* AND *loaded*
THEN haul dirt AND *at dumping site* after hauling time

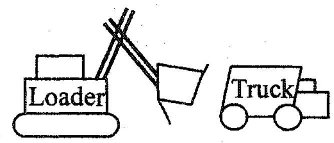
IF *at dumping site* AND *loaded*
THEN dump dirt AND *empty* after dumping time

IF *at dumping site* AND empty
THEN travel back AND *at loading site* after travel time

Figure 4.4 Functions and FTP of a Simple Earthmoving Operation

Assuming that the initial state of the truck is "empty and at the loading site" and of the loader is "available", a call to the FTP would result in a transition to "loaded and at loading site" state after a time equal to the loading time. This transition involves the delivery of "load dirt" function by both the loader and the truck. Another call to the FTP at this point of time will result in the truck delivering "Haul dirt" during a period of time after which the truck state becomes "loaded and at dumping site" and the simulation would continue in the same way. A list of the sequence of simulation execution is shown in Table 4.1.

Table 4.1 Simulation execution sequence based on the proposed approach.

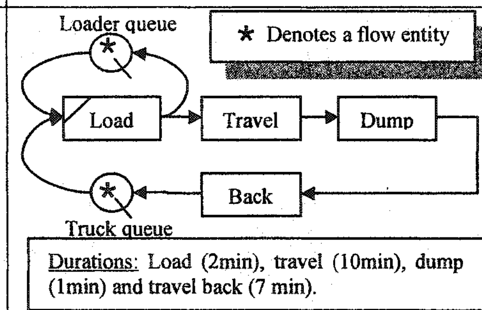
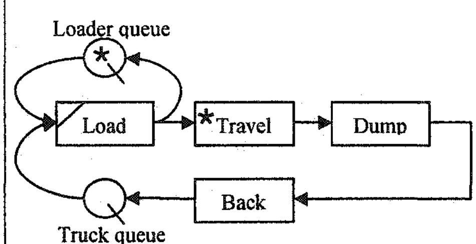
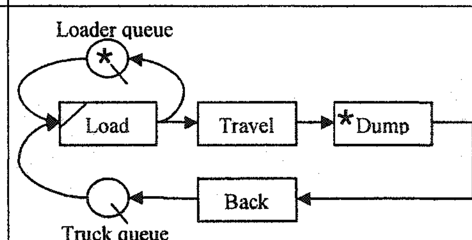
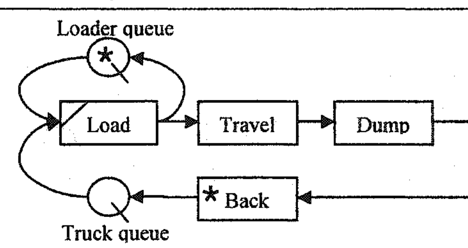
Sim. Time	Simulation execution actions	Illustration of state changes
0	▪ Start simulation and initialize variables ▪ Call FTP for each element and get the next function transition based on their current state. ➢ Loader can start "Load dirt". ➢ Truck can start "Load dirt" as its supportive function from the loader is available. ▪ Truck schedules an end for "Load dirt" delivery at time (0+2min) and calls a synchronized delivery of its supportive function from the loader. ▪ Immediate effects of starting "Load dirt" are executed causing the loader state to change to be "unavailable" ▪ Time advances to the nearest scheduled end-of-function-delivery event (2min)	 Loader: -Loading -Unavailable Truck: -Empty -At loading site
2	▪ Each element calls its FTP for executing the effects of ending "load dirt" ➢ Loader state changes to "available" ➢ Truck state changes to "loaded". ▪ Each element calls its FTP to get the next function transition based on the new states. ➢ Truck can start "Haul dirt" ▪ Truck schedules an end for "Haul dirt" delivery at time (2+10min). ▪ Immediate effects of starting "Haul dirt" are executed causing the truck state to change to be "on road". ▪ Time advances to the nearest scheduled end-of-function-delivery event (12min)	-Idle -Available -Loaded -On road
12	▪ Truck element calls its FTP for executing the effects of ending "Haul dirt" ➢ Truck state changes to "at dump site". ▪ Each element calls its FTP to get the next function transition based on the new states. ➢ Truck can start "Dump dirt" ▪ Truck schedules an end for "Dump dirt" delivery at time (12+1min). ▪ Time advances to the nearest scheduled end-of-function-delivery event (13min)	-Idle -Available -Loaded -At dump site
13	▪ Truck element calls its FTP for executing the effects of ending "Dump dirt" ➢ Truck state changes to "empty". ▪ Each element calls its FTP to get the next function transition based on the new states. ➢ Truck can start "Travel back"	-Idle -Available -Empty -On road

	▪ Truck schedules an end for "Travel back" delivery at time (13+7min). ▪ Immediate effects of starting "Travel back" are executed causing the truck state to change to be "on road". ▪ Time advances to the nearest scheduled end-of-function-delivery event (20min)	

Traditional simulation techniques can simulate the same example. Table 4.2 shows the sequence of simulation execution using the CYCLONE methodology. Other methodologies that depend on flow units or entities would follow similar sequence.

One of the main differences between the proposed technique and the traditional techniques is enabling autonomy of modeling elements. The behavior of the truck element is controlled by the element itself and not by the structure of the model network as shown in the CYCLONE example. This means that more functions can be added to the element with their corresponding FTP entries to simulate more complex decisions of real-world elements. To do such a change using the current techniques, it would require a complete change in the model network structure that can only be done manually. A more complex example is demonstrated at the end of this chapter where traditional simulation techniques can hardly replace the proposed one.

Table 4.2 Simulation execution sequence using CYCLONE methodology

Sim. Time	Simulation execution actions	Illustration of flow changes
0	▪ Start simulation and initialize variables ▪ Find work tasks that can commence at time 0 ➢ "Load" task can commence. ▪ Flow entities from "loader" queue and "truck" queue are transferred to the "load" task ▪ No other tasks can commence and simulation clock is advanced to the end time of the "load" task (0 + 2min)	
2	▪ Flow entities from the "load" task are transferred out to the "loader" queue and the "travel" task ▪ Find work tasks that can commence at time 2 ➢ "Travel" task can commence ▪ No other tasks can commence and simulation clock is advanced to the end time of the "travel" task (2 + 10min)	
12	▪ Flow entity from the "travel" task is transferred out to the "dump" task ▪ Find work tasks that can commence at time 12 ➢ "Dump" task can commence ▪ No other tasks can commence and simulation clock is advanced to the end time of the "dump" task (12 + 1min)	
13	▪ Flow entity from the "dump" task is transferred out to the "travel back" task ▪ Find work tasks that can commence at time 13 ➢ "Travel back" task can commence ▪ No other tasks can commence and simulation clock is advanced to the end time of the "travel back" task (13 + 7min)	

4.4.4 Communication Pool

One of the expected difficulties when running simulation models that contain different modeling elements is the communications between elements. The "communication pool" component of the proposed framework is introduced to act as a declaration section for the modeling element where the developer can define the types of elements that an element can communicate with. For example, a truck in an earthmoving operation may communicate with a loader element, a road element or other truck elements. Once the types are defined, the function dependencies between the element and others in its communication pool can be defined. However, binding a declared type to a particular instance may only be done after starting a simulation run. It is expected that a hierarchy of types (i.e. class inheritance) can be defined for different modeling elements so that elements from the same parent class should be able to deliver the same functions.

4.4.5 Fulfilling The Objective of The Framework

The proposed components of the framework are expected to meet the requirements defined under Section 2 in a number of ways as shown in Figure 4.5. The function-based approach and explicit function transition processor should allow modeling elements to gain autonomy in controlling their behaviors and consequently allow them to engage in the simulation at any point of time by adapting to the overall state of the simulation model at that point. This feature is also essential for dynamically changing the structure of the model. The function-based approach provides the means for optimality search among models with different topology by allowing elements to replace each others as long as they deliver the same function. The use of SPS at the user layer to mask GPS details provides the necessary requirements for maintaining SPS user friendliness and flexibility of development.

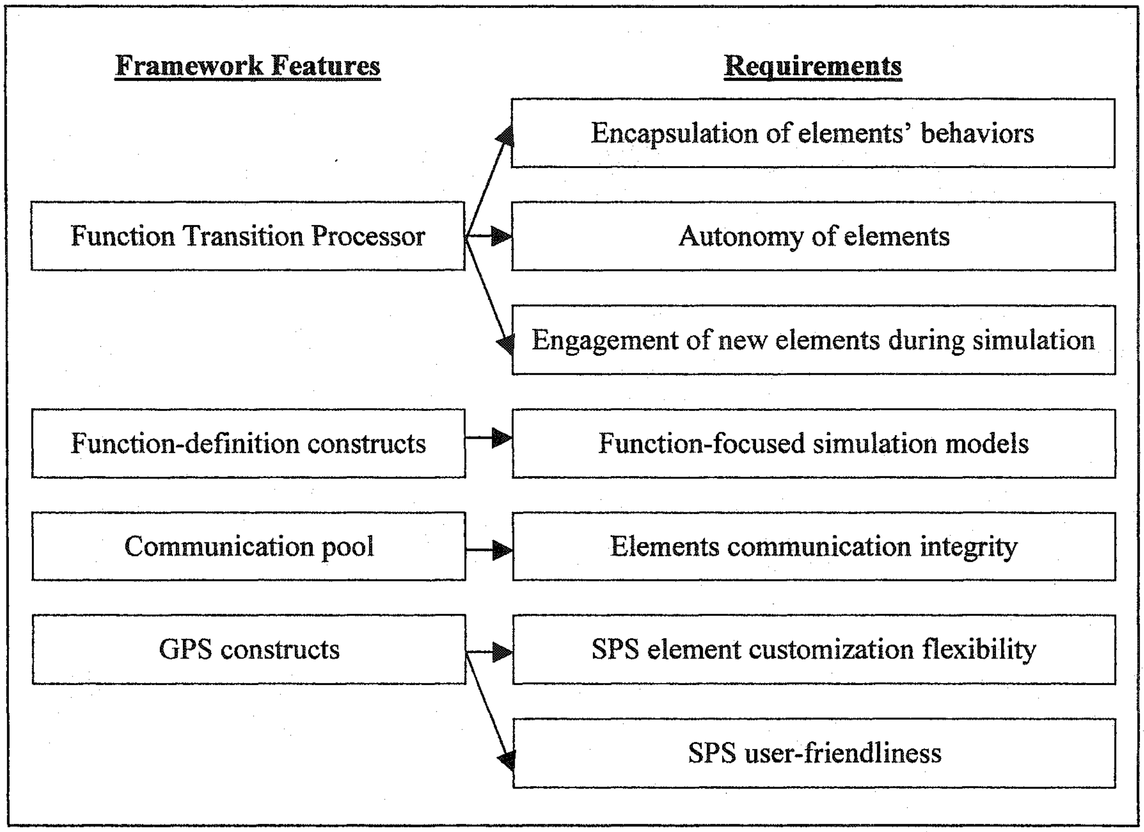


Figure 4.5 Function-Based Simulation Framework Features vs. Design Requirements

The following sections describe a prototype implementation of this framework using the Simphony development environment. A "Function Modeling" template is developed as a GPS template to provide visual constructs, which can then be used for customizing the behaviors of SPS elements. The function-modeling template is used for building an SPS template for tunneling operations. The elements' behaviors in the tunneling template are customized using constructs from the "Function Modeling" template. A special element (train management agent) is created as part of the tunneling template to illustrate the concept of automating structural improvements in the simulation model.

4.5 Framework Implementation

The framework is prototyped in the form of a general-purpose template in Simphony (Function Modeling Template). The elements of this template are shown in Figure 4.6. The highest level in the hierarchy includes three main element types, each of which may have other elements at lower hierarchical levels.

First is the function transition processor (FTP Element), which controls the transition of the SPS element from one function to another. The FTP may contain a number of rules at a lower hierarchical level and each rule may contain a number of conditions and effects at a lower level as well. The conditions and effects are represented by different modeling elements to model the different situations.

Second is the main function(s) of the SPS element (Function Elements). Each function element may contain a number of supportive functions at the lower hierarchical level to define its dependency on others.

Third is the communication pool (Communication Pool Element), which contains references to other modeling elements that can communicate with the parent SPS element. These references are represented by a set of "Communication Elements".

The following sections include a description of the behaviors of each modeling element in the template.

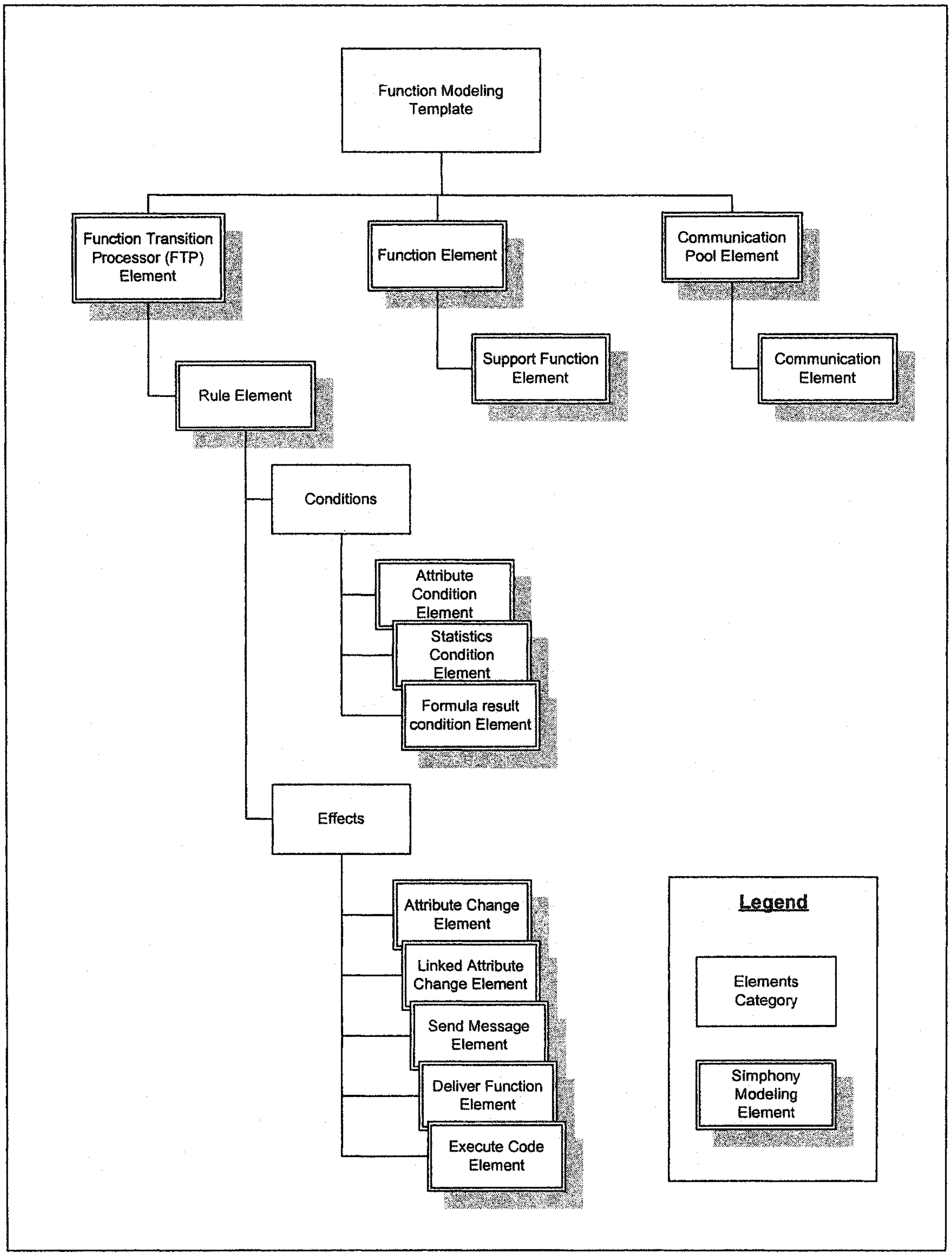


Figure 4.6 Hierarchy of elements of the function-modeling template

4.5.1 *Function Element*

This element defines a function that the parent SPS element can deliver. The function is defined in terms of an action verb and an object and can be described as useful, harmful, or neutral. In addition, it can be described as primary, supportive, or auxiliary function. The function is associated with a delivery rate and a delivery quantity, which determine the duration the parent element takes to complete the delivery of the function. Both the rate and the quantity can be linked to an attribute of the parent element, to the rate/quantity of a supportive function, or to a script of code that calculates their values.

If the function delivery depends on availability of supportive functions from other elements, these supportive functions should be defined as child elements of the main function. When the function is executed, it simultaneously executes all supportive functions. Figure 4.7 shows the execution algorithm of a function when the function is invoked by the FTP element.

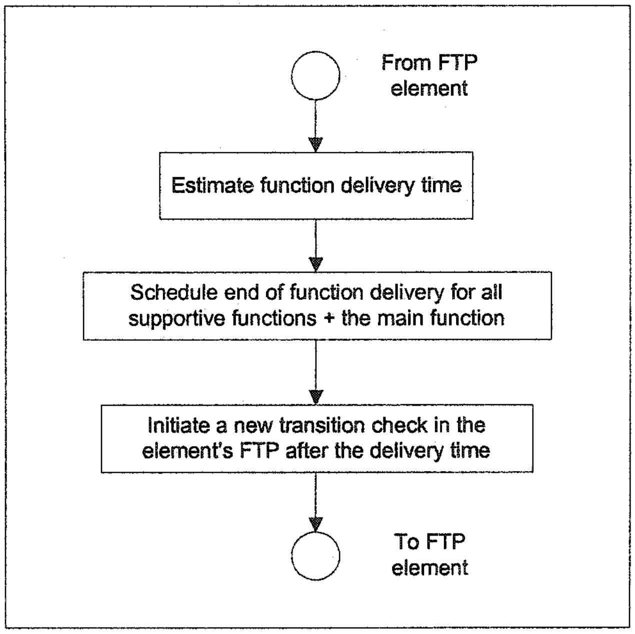


Figure 4.7 Execution Algorithm of a Function

4.5.2 Supportive Function Element

The supportive function element holds a reference to a function in a different element that is required to execute the main function. For example, the loading of a truck requires a supportive loading function from a loader.

4.5.3 Communication Pool Element

This element works as a container for references to all the other elements that can communicate with its parent. A SPS element may contain only one communication pool. For example, an element that models an earthmoving truck may contain references to loader, road, and other truck elements in its communication pool.

4.5.4 Communication Element.

This element represents a reference to an element or a group of elements of the same type. A number of communication elements constitute the communication pool of their parent.

4.5.5 Function Transition Processor (FTP) Element

This element defines the mechanism by which the parent element moves from delivering one function to another. In the developed template, the element holds a collection of rules that provide the control of delivering different functions by its parent element. Each of these rules has a number of conditions to transfer the element to a new state and/or effects that result from being in that state. The rules, conditions and effects are described in the following sections. The FTP also contains the main simulation execution algorithm. Figure 4.8 shows a flow chart for that algorithm.

The execution begins by consulting the rules for producing the effects of the last function delivery and then for transition to the next possible function delivery. The rule consultation follows an emulation of forward chaining inference that allows rechecking of rules if a new rule is fired within the same consultation session. The result of such consultation is the transition of the parent element from one state to another and consequently delivery of a new function during a period of time. Once function delivery is completed after certain amount of time, the FTP is automatically invoked again. The FTP begins by examining the rules that produce the effects of ending the function and then examines the rules that control the transition to the next one.

Once a rule is fired, the effects associated with the rule are executed. All effects are executed instantaneously except for "Action effects", which correspond to delivery of functions during a period of time. Such effects result in sending a message to the corresponding function, which consequently schedules an end of delivery event after certain amount of time.

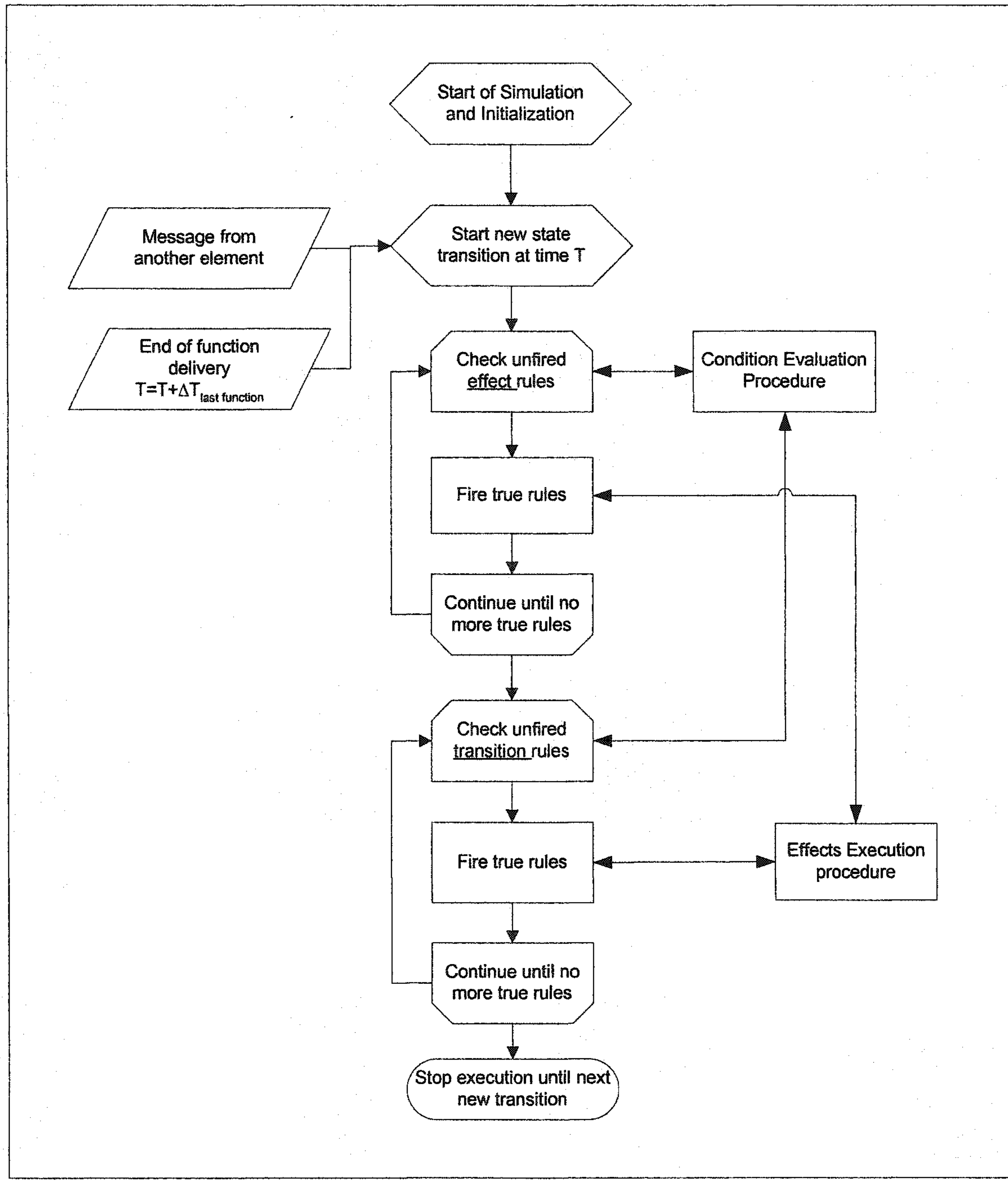


Figure 4.8 The Main Simulation Algorithm for The Function-Modeling Template

4.5.6 Rule Element

A rule element is a manifestation of a production rule as used in expert systems and logic programming. It takes the form of:

IF (conditions) THEN (effects)

The rule element is a construct that holds a collection of conditions and effects. A rule becomes true if all the conditions are true and all effects are thus executed.

4.5.7 Conditions Elements

A number of elements are available for describing the different conditions that may exist in a model. Conditions may be related to attributes of an element, statistics collected by an element, or a calculated value based on a script of code. These three types are represented by the "Attribute Condition", "Statistics Conditions", and "Formula value Condition" elements respectively. For each of these types, the value given by the attribute, statistics, or formula is compared to a value given by the developer.

A special case of a condition element exists if one of the effects in the rule is an action effect (i.e. a function delivery). In such case this effect implicitly represents a condition as well. The main function linked to the effect is checked while checking the conditions in the rule. If all the supportive functions of this main function are available, the condition is considered true. Otherwise, the condition is false, the rule fails, and the main function registers a waiting request with the supportive function that is not available.

4.5.8 Effect Elements

A number of elements are available for describing the different effects that may emerge after or during a certain state of an element. The effects available are shown in Table 4.3 together with a description for each. As mentioned in the description of conditions, the action effect represents a special case as it also implies a condition of availability of all functions that support its main function.

Table 4.3 Effect Elements

Effect element	Description
Attribute effect	Change the value of an element attribute
Linked attribute effect	Transfer the value of an element attribute to another
Function attribute	Change an attribute of a function of the parent
Message effect	Send message to an element to trigger a call to its FTP
Action effect	Deliver a function
Code execution effect	Execute a script of code

4.6 Building SPS Tools Using The Proposed Framework

In order to develop a SPS tool using the function-modeling template, a developer makes use of visual general-purpose simulation constructs to generate the desired behaviors of the SPS modeling elements. The SPS modeling elements are mainly used as carriers of attributes. These attributes are defined for each element according to the physical attribute of the real-world object in addition to the requirements for experimenting with the simulation model. The SPS elements work mainly as an interface between the user and the details of the general-purpose models that produce the simulation behaviors. This feature is important to maintain the concept of SPS, in which case, the user is assumed to be knowledgeable in the construction domain but not necessarily in simulation techniques.

After analyzing the construction system for which the SPS tool is built, the developer should map the system into a set of SPS modeling elements that resemble the real-world elements as close as possible. For each of these elements the developer needs to identify what other elements it needs to communicate with. The developer can then define the main functions that an element is capable of delivering and the supporting functions required for each of them. The rules that govern the delivery of each of these functions can then be defined in the element's FTP. Each function may have rules to control "when" it can be delivered and the instant effects that result from starting that delivery. In addition, the function may have rules for defining the "effects" that result from finishing the delivery of the function such as: changing element attributes, or starting another function. Once an element is customized, it can be stored in the user elements library for future use. Different renderings of the same SPS element can be stored to model different scenarios.

4.7 Development of SPS Tunneling Template – A Demonstration of How The Proposed Framework Can Be Used.

4.7.1 The TBM tunneling process

Tunnel construction using tunnel-boring machines (TBM) involves three main processes: excavation, dirt removal, and tunnel support. The construction process commences with the excavation and liner support of a vertical shaft to a depth corresponding to the invert level of the tunnel excavation. The other typical tunnel activities are excavation and support of the undercut area (an enlargement at the bottom of the shaft used for staging material handling and dirt removal operations), excavation of the tunnel and tail tunnel, disposal of dirt from the tunnel face, hoisting the dirt to the ground level, lining the tunnel, extending the services and rail tracks, and the excavation and support of the removal shaft.

The dirt handling process involves the transportation and disposal of spoil from the tunnel face to the shaft, where it is lifted to the surface. Spoil can be hauled horizontally using trains or belt conveyors. The selection criterion depends on the tunnel site conditions. Belt conveyers have the advantage of providing a continuous spoil removal system. However, they typically require excessive maintenance. Train haulage is energy efficient, and compatible with most excavating and loading methods, and is adaptable to almost all sizes of tunnels. Trains can also be fitted with special cars capable of transporting laborers and support liners. Depending on the tunnel diameter, a single- or double-track system can be used. In most cases, a track switching system is utilized at the undercut to allow multiple trains to share a single track. The working shaft is utilized to remove the spoil and to transport the construction materials and personnel.

4.7.2 Elements of the Template

The objective of developing this SPS tunneling template was to test the applicability of the function-based simulation approach and whether it is capable of producing the required simulation behaviors for different modeling elements. Table 4.4 shows a list of the elements available in the template and a description of each. The following sections describe the functions and governing rules of each of these elements.

Table 4.4 Elements of function-based tunneling template

Modeling Element	**Icon**	**Description**
TBM		Models the work of the tunnel boring machine
Tunnel body		Models the completed structure of the tunnel
Soil profile		Models the soil structure along the tunnel path. It holds child element to represent the changes in soil type along the different segments of the tunnel.
Soil segment		Models one type of soil along the design path of the tunnel
Train		Models a train for moving dirt from tunnel face to undercut
Laser guidance		Models the laser guiding system for maintaining alignment of TBM
Train management agent		Monitors the need for trains and introduces more trains when needed

4.7.2.1 <u>TBM</u>

The main functions of the TBM are to excavate soil, install liners, and expand liners. In order to excavate soil, a number of supportive functions must be available. These supportive functions are: load dirt, which is delivered by the trains, guide TBM, which is delivered by the laser guidance system, and resist excavation, which is delivered by the soil profile element. Excavation is also dependant on having the last section of the tunnel lined and liners expanded. The delivery duration of the excavation function depends on the stroke length of the TBM and the penetration rate of the soil where the TBM is working. The effects of finishing excavation are advancing the TBM location by one meter, and adding another excavated section to the tunnel body.

Installation of liners depends on having the last section of the tunnel excavated. When the liners are installed, the TBM can start expanding them. The durations of installing and expanding liners are directly linked to attributes of the TBM that the user can enter. The following Figure shows the graphical representation and properties of the TBM element.

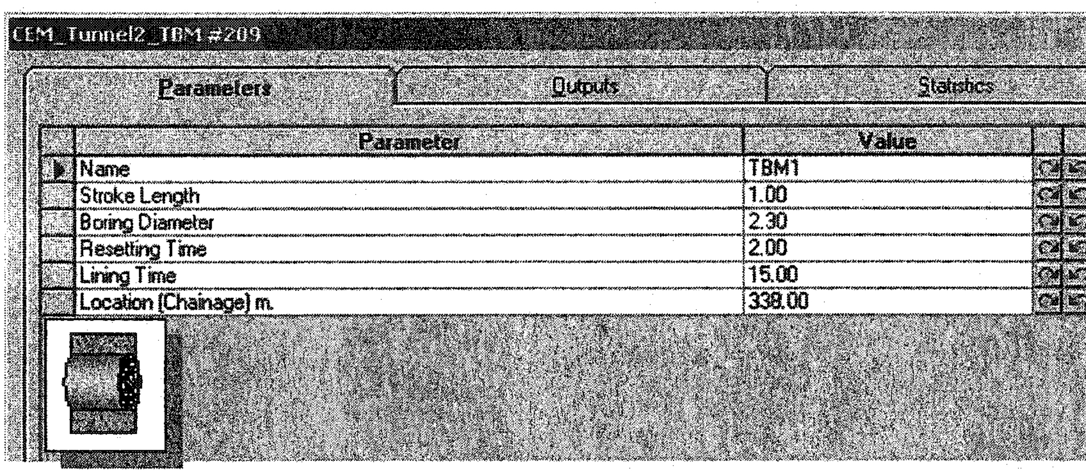


Figure 4.9 Properties and graphical representation of the TBM element

4.7.2.2 Tunnel body

The only function modeled for tunnel body is to support trains. This function is a supportive function for trains. The tunnel body provides access to tunnel face so that trains can haul dirt from tunnel face to the undercut area and return back. The element is customized so that it can hold only one train at a time. This means that once a train is inside the tunnel, all other trains have to wait in the undercut area. The following Figure shows the graphical representation and properties of the "Tunnel body" element.

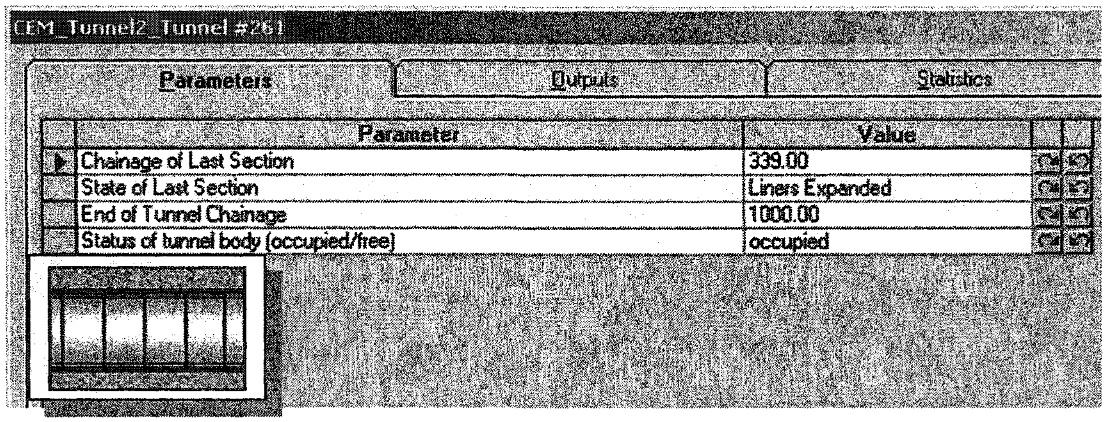


Figure 4.10 Properties and graphical representation of the "Tunnel body" element

4.7.2.3 Soil profile

The modeled function of soil profile is to resist excavation. This function is a harmful one as it slows down the excavation process. The rate of this function is represented by the penetration rate of the soil segment at which the TBM is located. The following Figure shows the graphical representation and properties of the "Soil profile" element.

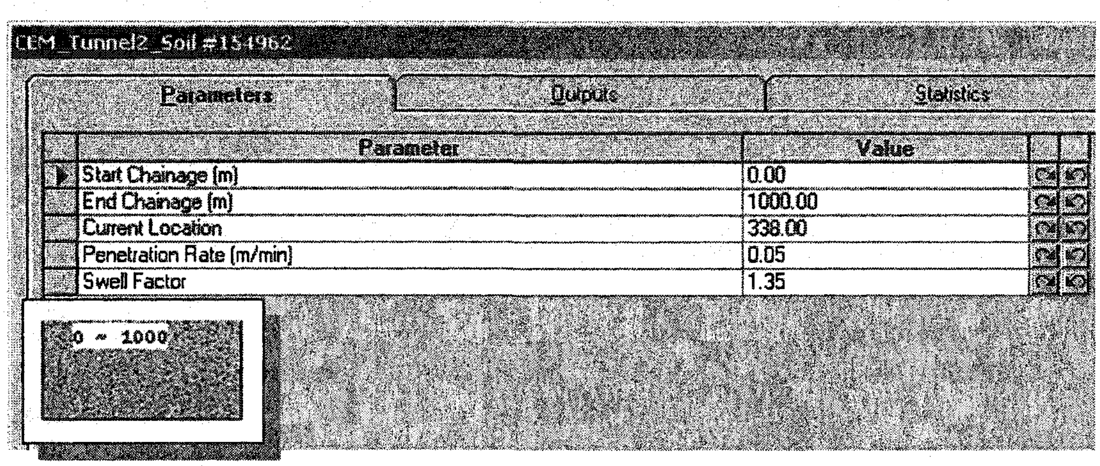


Figure 4.11 Properties and graphical representation of the "Soil profile" element

4.7.2.4 Soil segment

This element does not deliver any functions. However, a number of instances of the element model the variation in soil types along the path of the tunnel. This element can only be created as a child of the soil profile element. The following Figure shows the graphical representation and properties of the "Soil segment" element.

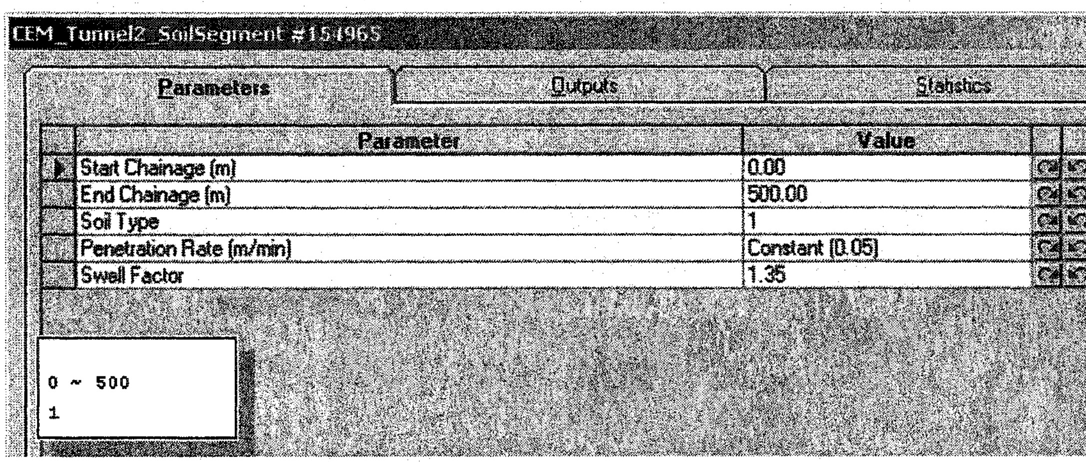


Figure 4.12 Properties and graphical representation of the "Soil segment" element

4.7.2.5 *Train*

A train delivers the following functions. It loads dirt, hauls dirt, dumps dirt, and moves back to the tunnel face. To load dirt, the train has to be located at the tunnel face. To haul dirt, the train has to be loaded and at the tunnel face. To dump dirt, the train has to be at the undercut area and loaded. To move back to tunnel face, the tunnel body has to be free (i.e. nothing else is occupying it), the train is at the undercut area, and the train is empty. The following Figure shows the graphical representation and properties of the Train element.

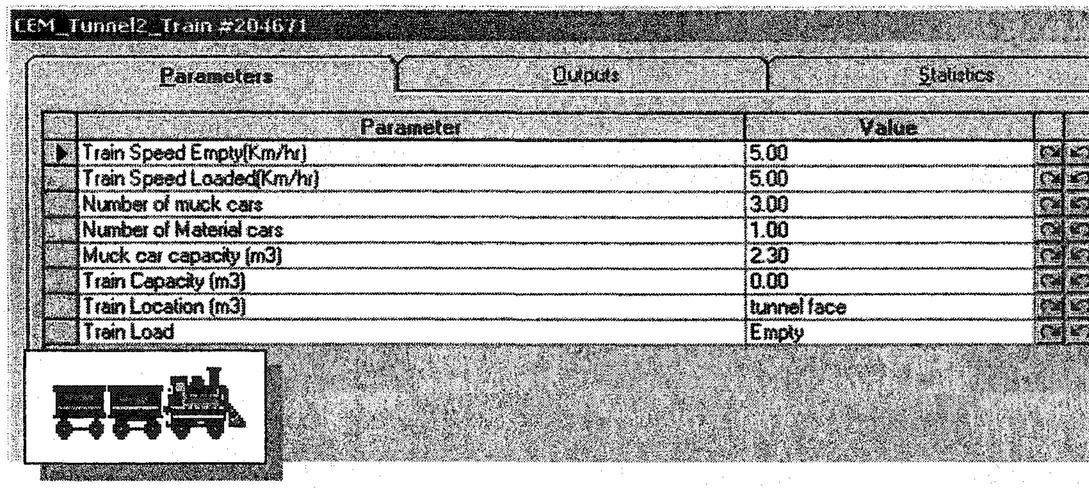


Figure 4.13 Properties and graphical representation of the Train element

4.7.2.6 *Laser guidance*

The laser guidance element delivers guidance to the TBM and also resetting of the laser gun at certain intervals. TBM guidance is a supportive function for TBM excavation while laser resetting is a harmful function for the excavation process. The following Figure shows the graphical representation and properties of the "Laser guidance" element.

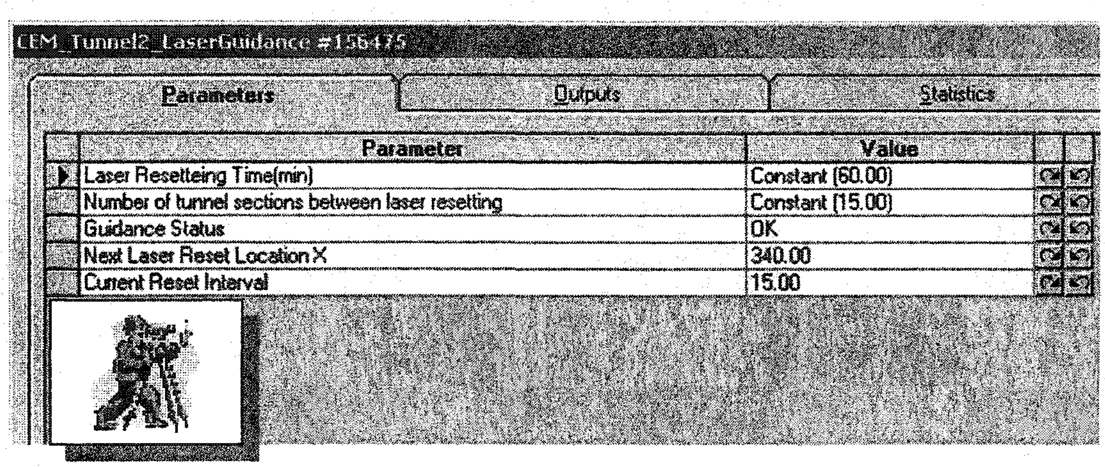


Figure 4.14 Properties and graphical representation of the "Laser guidance" element

4.7.2.7 *Train management agent*

This element is not a part of the tunnel construction process. However it works as an agent for the user to monitor the need of the TBM for trains and introduces a new train when needed. The main function of the element is to monitor TBM waiting time for trains. This function is done at constant periods of time that the user can set (e.g. at end of every simulated day). One observation is collected at the end of each period. The observation corresponds to the average waiting time of TBM for the "load dirt" supportive function during that period. A new train is introduced if the observations show an increase in the average waiting time and the average waiting time is greater than a certain threshold value (e.g. 5 min). The new train is represented by a new modeling element that is added during the simulation and engaged in the process as an empty train at the undercut area. The following Figure shows the graphical representation and properties of the "Train management agent" element.

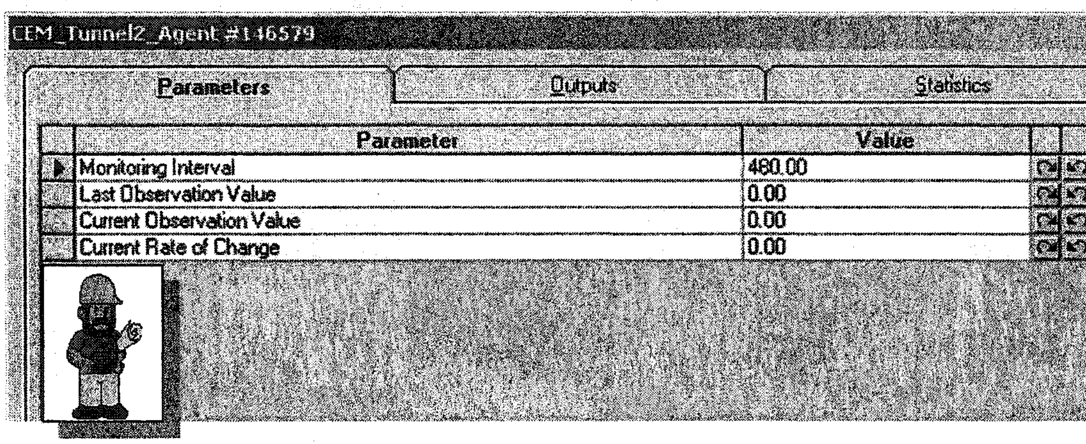


Figure 4.15 Properties and graphical representation of the "Train management agent"

4.7.3 A Sample Model using the Tunneling template

This section describes a tunneling model that is built using the template. The objective of the case is to test and evaluate some of the benefits and limitations of the function-based approach used in building the template. The case represents a one-way TBM tunneling process for a 1000m tunnel. The soil profile contains 2 different segments with different penetration rates for each.

4.7.3.1 <u>Model building</u>

The model is built by dragging the different tunneling components from the user elements library and dropping them on the project layout window. The model includes instances of the main elements that constitute the tunnel construction system. It has a TBM, a tunnel body, a soil profile, a train, a guidance system, and a train agent. Figure 4.16 shows the elements of the model.

Once the elements are created, the attributes of each are set to the values that represent the initial state of the element. For example, the finished length of the tunnel, the location and load (full or empty) of the trains, the settings of the TBM (stroke length, liners installation and expansion time), laser resetting frequencies, and penetration rates of the different soil segments.

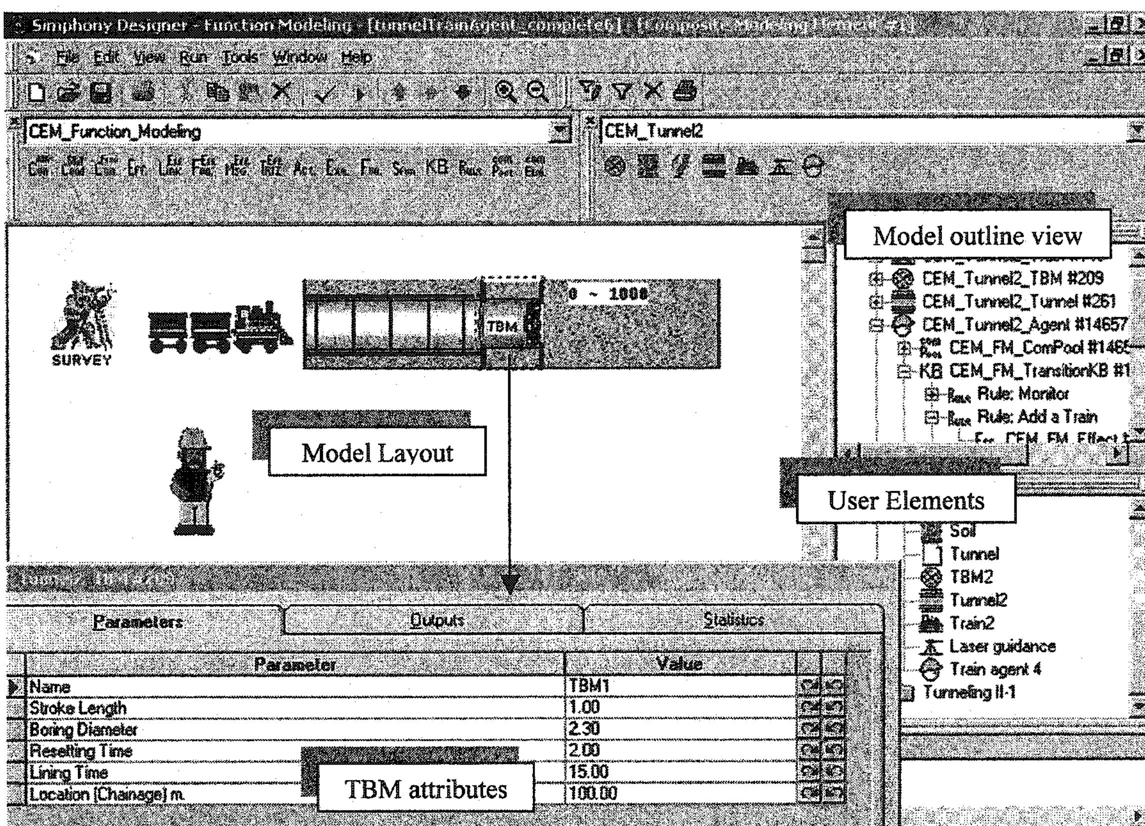


Figure 4.16 Screen shot of model layout of the sample model

The next step is to identify the relationships between the different elements. The relationships between elements created using the proposed function-based template are mainly indications that an element can communicate with another. These relations are all defined by binding the communication elements to instances of other elements or groups of them. Figure 4.17 shows an example of this process.

Although this way is not user-friendly for the intended user of an SPS template, it is intended by design. It is envisioned that advancement in the design of SPS template using this approach will include the ability to design a communication pool population schema for each template. The purpose of that schema is to allow the user to populate the communication pools of each modeling element in a user-friendly manner that depends only on resemblance to reality. Examples of such a schema are the mapping of spatial relations between elements in a 3D model or the X-Y location of an element in a 2D model. Intelligent agents can be part of these schemas to assist the user build models easier.

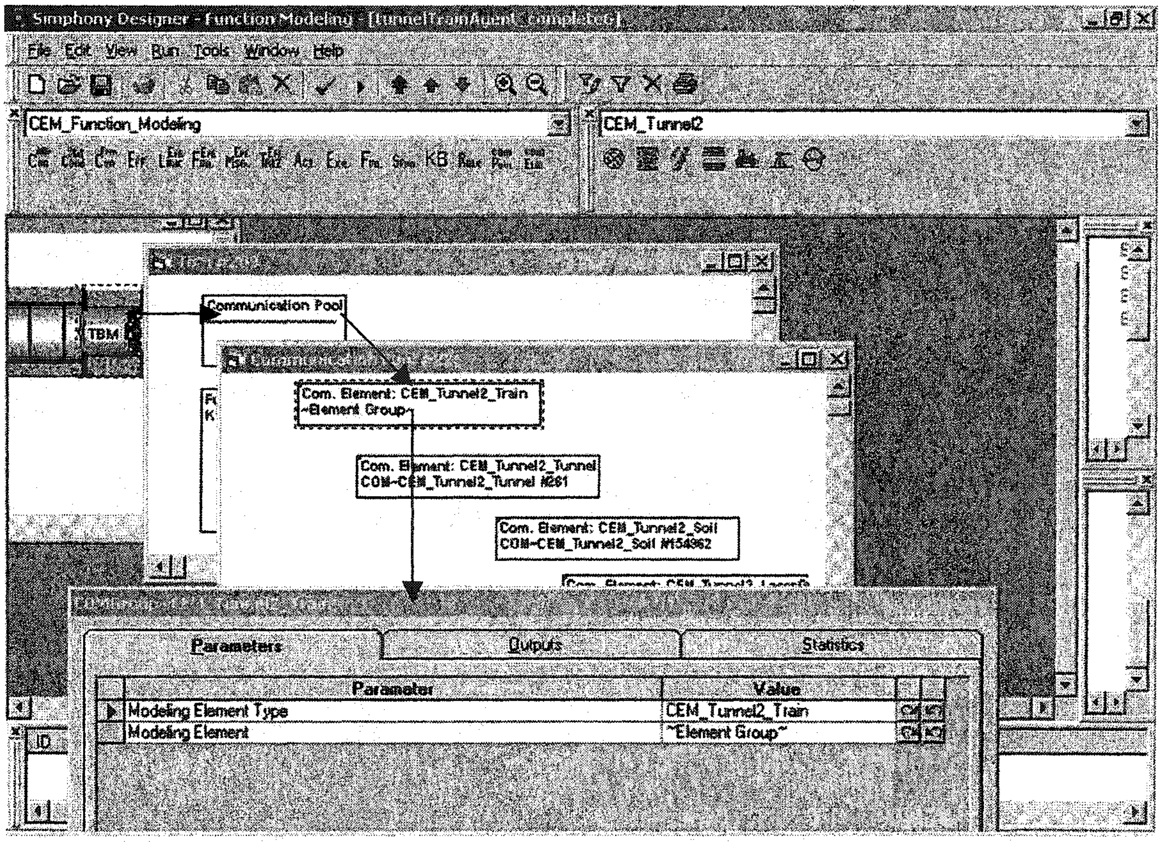
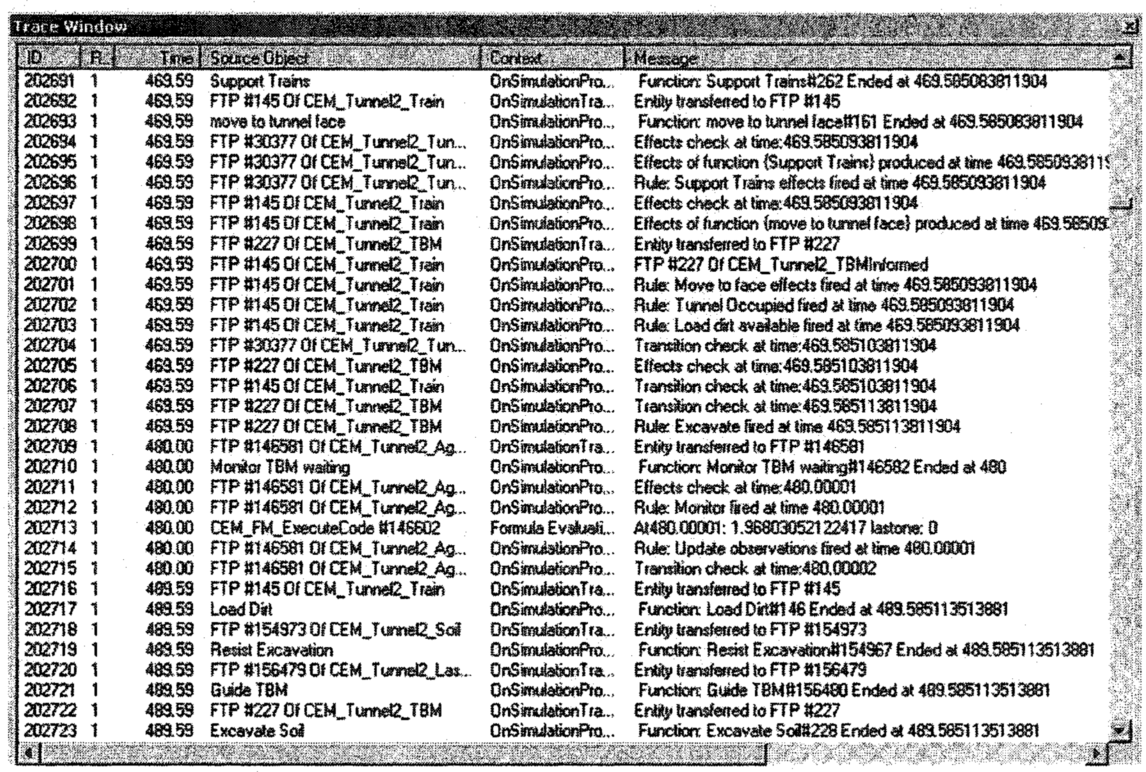


Figure 4.17 Binding communication elements to instances in the model.

4.7.3.2 *Model simulation*

The model is run for 2400 min, which corresponds to five 8 hrs-days. The tunneling is started at a completed length of 280 m, which represents the expected length at which the TBM may start waiting for trains based on deterministic calculations. Trace messages are produced from the different elements in the model to verify the flow of the simulation events in the model. Figure 4.18 shows a part of that trace. The flow of events corresponds to the expected flow based on the constant values used in the element attributes.



Trace Window

ID	R	Time	Source Object	Context	Message
202691	1	469.59	Support Trains	OnSimulationPro...	Function: Support Trains#262 Ended at 469.585083811904
202692	1	469.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationTra...	Entity transferred to FTP #145
202693	1	469.59	move to tunnel face	OnSimulationPro...	Function: move to tunnel face#161 Ended at 469.585083811904
202694	1	469.59	FTP #30377 Of CEM_Tunnel2_Tun...	OnSimulationPro...	Effects check at time:469.585093811904
202695	1	469.59	FTP #30377 Of CEM_Tunnel2_Tun...	OnSimulationPro...	Effects of function {Support Trains} produced at time 469.58509381
202696	1	469.59	FTP #30377 Of CEM_Tunnel2_Tun...	OnSimulationPro...	Rule: Support Trains effects fired at time 469.585093811904
202697	1	469.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationPro...	Effects check at time:469.585093811904
202698	1	469.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationPro...	Effects of function {move to tunnel face} produced at time 469.58509
202699	1	469.59	FTP #227 Of CEM_Tunnel2_TBM	OnSimulationTra...	Entity transferred to FTP #227
202700	1	469.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationPro...	FTP #227 Of CEM_Tunnel2_TBMInformed
202701	1	469.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationPro...	Rule: Move to face effects fired at time 469.585093811904
202702	1	469.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationPro...	Rule: Tunnel Occupied fired at time 469.585093811904
202703	1	469.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationPro...	Rule: Load dirt available fired at time 469.585093811904
202704	1	469.59	FTP #30377 Of CEM_Tunnel2_Tun...	OnSimulationPro...	Transition check at time:469.585103811904
202705	1	469.59	FTP #227 Of CEM_Tunnel2_TBM	OnSimulationPro...	Effects check at time:469.585103811904
202706	1	469.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationPro...	Transition check at time:469.585103811904
202707	1	469.59	FTP #227 Of CEM_Tunnel2_TBM	OnSimulationPro...	Transition check at time:469.585113811904
202708	1	469.59	FTP #227 Of CEM_Tunnel2_TBM	OnSimulationPro...	Rule: Excavate fired at time 469.585113811904
202709	1	480.00	FTP #146581 Of CEM_Tunnel2_Ag...	OnSimulationTra...	Entity transferred to FTP #146581
202710	1	480.00	Monitor TBM waiting	OnSimulationPro...	Function: Monitor TBM waiting#146582 Ended at 480
202711	1	480.00	FTP #146581 Of CEM_Tunnel2_Ag...	OnSimulationPro...	Effects check at time:480.00001
202712	1	480.00	FTP #146581 Of CEM_Tunnel2_Ag...	OnSimulationPro...	Rule: Monitor fired at time 480.00001
202713	1	480.00	CEM_FM_ExecuteCode #146602	Formula Evaluati...	At480.00001: 1.96803052122417 lastone: 0
202714	1	480.00	FTP #146581 Of CEM_Tunnel2_Ag...	OnSimulationPro...	Rule: Update observations fired at time 480.00001
202715	1	480.00	FTP #146581 Of CEM_Tunnel2_Ag...	OnSimulationPro...	Transition check at time:480.00002
202716	1	489.59	FTP #145 Of CEM_Tunnel2_Train	OnSimulationTra...	Entity transferred to FTP #145
202717	1	489.59	Load Dirt	OnSimulationPro...	Function: Load Dirt#146 Ended at 489.585113513881
202718	1	489.59	FTP #154973 Of CEM_Tunnel2_Soil	OnSimulationTra...	Entity transferred to FTP #154973
202719	1	489.59	Resist Excavation	OnSimulationPro...	Function: Resist Excavation#154967 Ended at 489.585113513881
202720	1	489.59	FTP #156479 Of CEM_Tunnel2_Las...	OnSimulationTra...	Entity transferred to FTP #156479
202721	1	489.59	Guide TBM	OnSimulationPro...	Function: Guide TBM#156480 Ended at 489.585113513881
202722	1	489.59	FTP #227 Of CEM_Tunnel2_TBM	OnSimulationTra...	Entity transferred to FTP #227
202723	1	489.59	Excavate Soil	OnSimulationPro...	Function: Excavate Soil#228 Ended at 489.585113513881

Figure 4.18 A Segment of the trace messages produced from the simulation

Each main function in an element has a statistic output that shows its overall waiting for supportive functions. Each supportive function has another statistic that shows how much it contributes to the waiting of its main function. The train management agent uses that statistic of the "load dirt" supportive function of the TBM to monitor the need for trains to speed up the dirt removal process. Figure 4.19 shows the full tracking of the TBM waiting for loading dirt by trains. Figure 4.20 shows the observations collected by the train agent at the end of each working day. Both figures show the drop in waiting time after introducing a second train after 1440 minutes of simulation time.

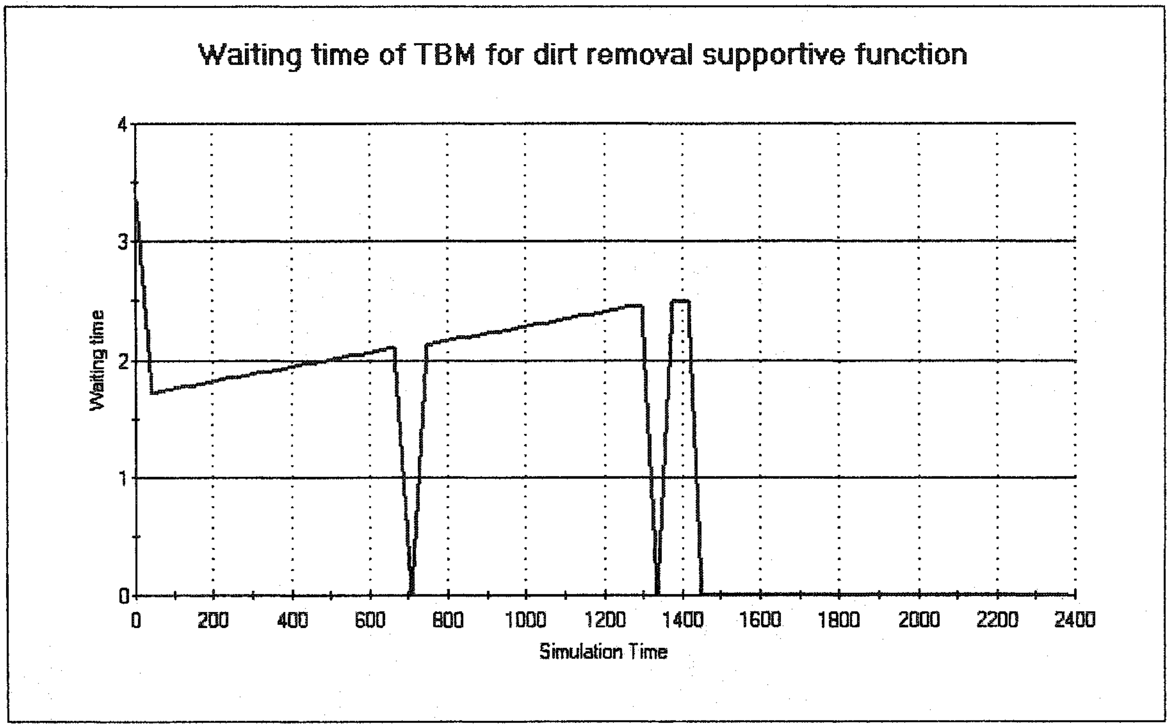


Figure 4.19 Waiting time of TBM for dirt removal by trains

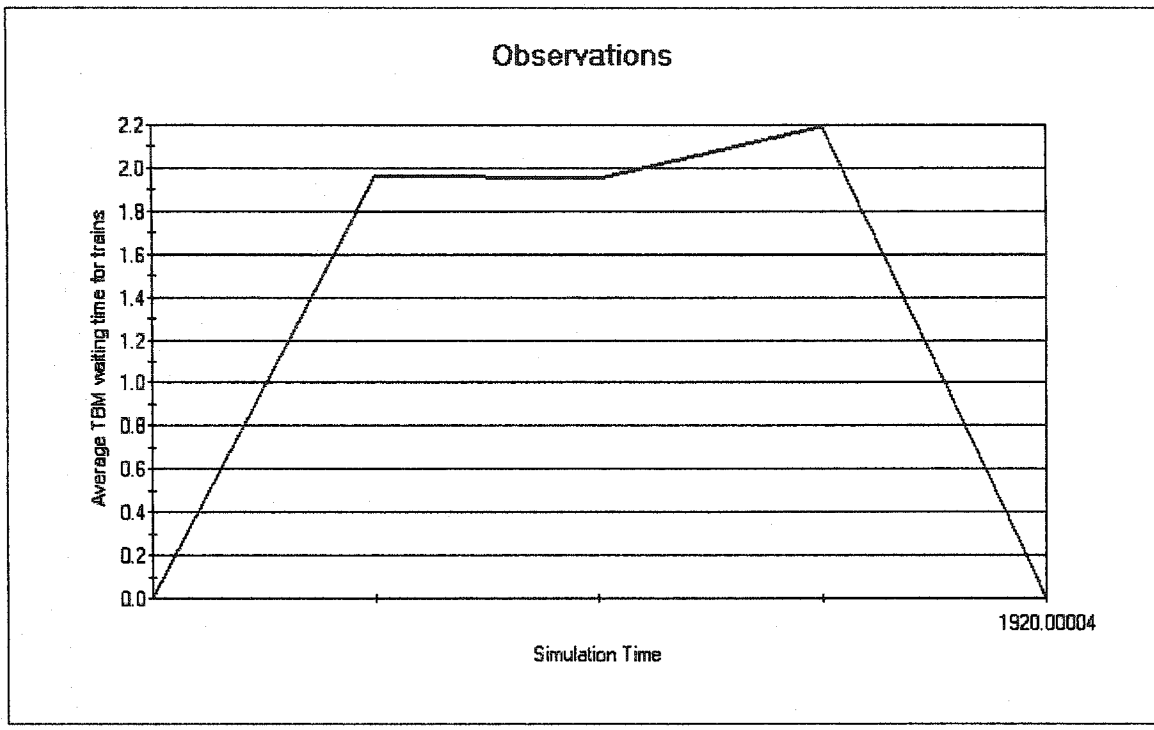


Figure 4.20 Average waiting at the end of each working day as collected by the train agent

4.7.3.3 Divergence from current state-of-the-art

The tunnel model simulated using the proposed function-based framework introduces modeling and simulation potentials that cannot be easily achieved using the currently available approaches for construction simulation.

The ability to modify the structure of the tunneling model by introducing a new train element during run time is currently not possible using any of these approaches. Using CYCLONE-like tools or SLAM-like tools, the trains would have to be abstracted to a numeric parameter in a queue element (CYCLONE case) or a resource element (SLAM case). A parallel network can then control the parameter. If the element to be introduced would change the logic or the flow of events in the simulation, it would not be possible without manual modification of the model network. For example, introducing an intermediate shaft in the tunnel to reduce the train travel time or switching to hand tunneling techniques at certain positions in the tunnel causes the tunneling process to flow in a different way. Flow modification is also necessary if the introduced element has many functions with some being useful and others harmful. For example replacing muck-cars with a conveyer belt provides continuous dirt removal but introduces higher chances for breakdown.

These types of model modifications are usually done manually while experimenting with the simulation model. Using current simulation tools, an engineer needs to run the simulation model, evaluate some performance measures, make adjustments and modifications to the model and re-run the simulation again. However, many of the model modifications may be considered common solutions if we know when they are necessary. For example, introducing another train is a common decision if the TBM starts to wait for trains and the user need not wait until the end of the simulation experiment to do this modification then starts the simulation again.

Figure 4.21 shows a model for the same tunneling case. The model is build using Simphony's common template, which has similar elements to Visual SLAM. Part (a) of the figure shows the original model or the base case scenario, which has the exact same conditions of the model layout shown in Figure 4.16. After running the model for 2400 min, the user may get the waiting time of the TBM as shown in the chart on part (b) of the figure. Based on this chart, the user would decide to introduce a second train at time 1440min. In such case, the user has to modify the original model to add another resource at 1440min as shown in part (c). The effect of that modification is shown in part (d) of the figure. This process would repeat until the user is satisfied with the performance of the model. The process tends to be very time consuming and unpractical when realizing that a typical tunneling project may take hundreds of days to complete and requires many routine decisions similar to introducing a dirt removal train.

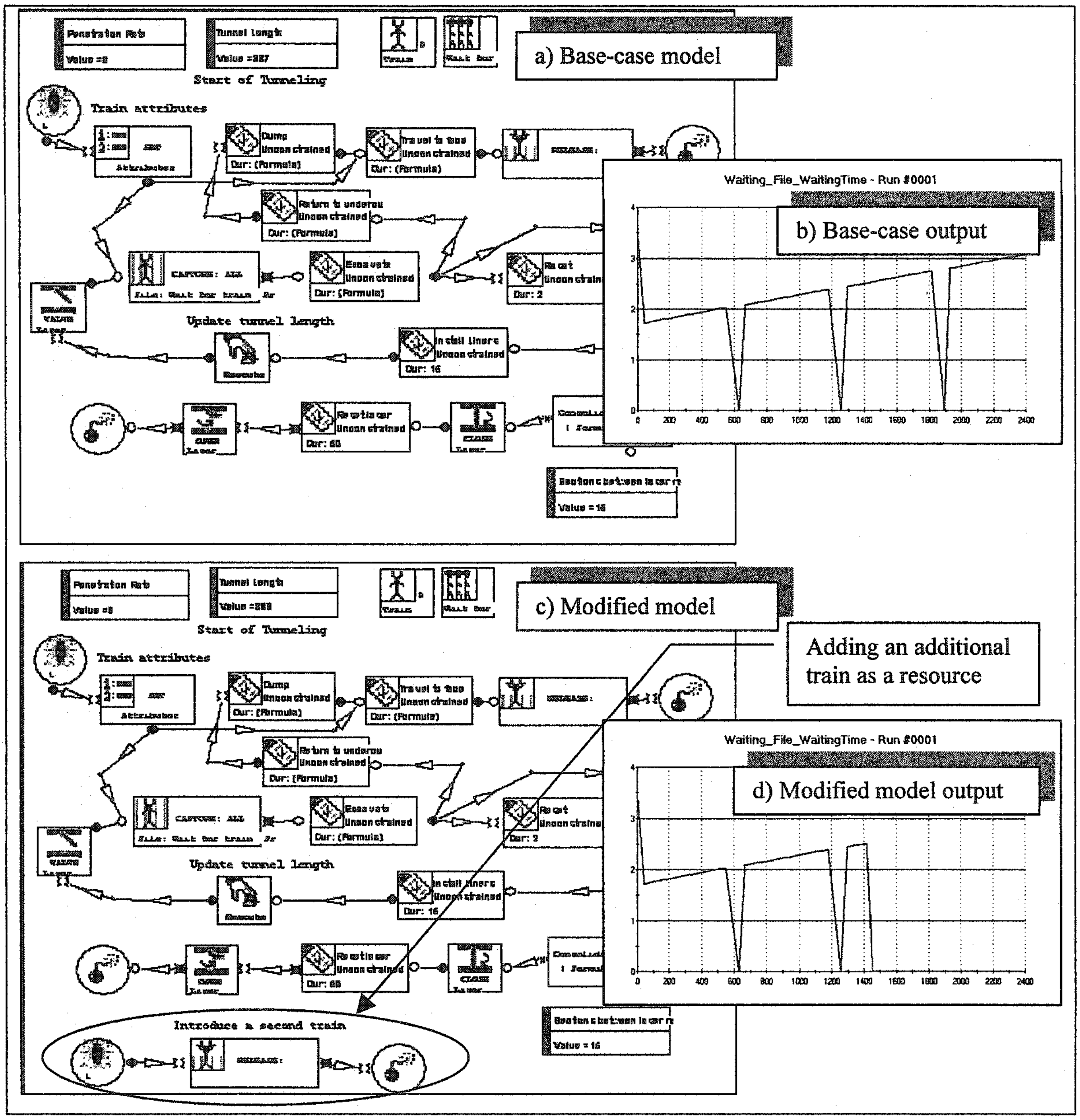


Figure 4.21 Modifying a GPS model to minimize TBM waiting

In fact, most construction operations are carried out in a complex environment that may include many of these routine decisions. To simulate such a complex environment it would be very useful to have a simulation agent(s) capable of dynamically performing or suggesting some of these decisions on behalf of the user. The introduced methodology provides a more suitable foundation for achieving that.

4.8 Discussion

4.8.1 Benefits and Possibilities Under The Proposed Framework

The proposed framework represents a new approach for creating SPS tools and building simulation models in construction. The modeling and simulation possibilities under this framework include:

1. Dynamic topological changes to the simulation model.

This ability is achieved because each element is described in terms of its functions and because each function can be delivered in a multitude of ways that can be harnessed from a knowledge base. This enables dynamically changing the structure of the model during the simulation to maintain certain performance measures. For example, a more evolved version of the tunneling template described in this chapter may suggest for the user if an intermediate shaft is needed in the tunnel or not and where it should be located and what is the effect of that on the production. It may also test different alternatives for dirt removal (e.g. trains vs. conveyer belt) and suggest which one should be used. The possibilities in other construction domains are limitless as the creation of new elements during a construction project usually results in changes in the construction methods and operations that cannot be captured dynamically using the current simulation techniques.

2. Intelligent simulation.

The proposed framework allows building autonomous modeling elements that are capable of controlling their behaviors based on the conditions of their surrounding environment. The elements may also learn from the environment by storing information and processing it and they can influence other elements accordingly. The tunneling example described in this chapter demonstrated an agent that is capable of observing waiting times during a simulation run and making a decision based on these observations. Such an agent can be embellished to include a more advanced decision-making technique and an observing and learning process that spans over multiple simulation runs, multiple model layouts, and user responses. This enables making simulation experimentation more effective and user-friendly by automating many of the routine decisions that would, otherwise, be done manually between simulation runs.

3. Tapping into innovative problem solving.

Given the abilities described in (1) and (2) and given the foundation of knowledge representation and management described in Chapter 3, we can use knowledge stored in the knowledge-base to find ways to direct the simulation towards optimality. Although not implemented in this chapter, this can be achieved since the knowledge base and the simulation models are structured around functions. This requires developing standards for function definition that can be followed in building the knowledge base and the simulation modeling elements. Once such standards are available, they would act as the link between a knowledge base of innovative solutions (as described in Chapter 3) and the simulation models. In such case, the user (or an intelligent electronic agent) can experiment with alternative elements that deliver the same function, compare their effects on the overall performance of the model and choose the most optimum alternative.

4. Better foundation for model update and visualization.

The state-based approach used in the framework provides a good foundation for updating the model as part of the control process during construction. The actual states of elements in a construction project can be synchronized, either manually or automatically, with their virtual counterparts in the simulation model to continually reflect the actual progress status of the project. This enables the use of the model to test and evaluate alternative corrective measures to achieve the required levels of performance. It also provides a good foundation for visualization and animation of the model as elements states can be easily mapped to animation key-frames.

4.8.2 Limitations and proposed changes

One of the limitations of the proposed framework is the slow processing performance. It is proposed to create back-end support libraries to provide the necessary services for FTP rules management and inference. Parallel processing is also an option that can be investigated for improving performance. The impeded autonomy in the behaviors of elements can be useful in facilitating parallel processing.

Improvements in the area of user model building interface are required. The current approach only allows population of an element's communication pool through a manual process of selecting instances of elements that exist in the model. This process should be automated so that it closely resembles the actual project building sequence. Integrating this process with 2-D and 3-D modeling is an area that could be researched.

A number of services were required in Simphony as a development environment in order to produce the required behaviors of the function-modeling template. These include the following:

- Prioritization of events scheduled at the same time
- Ability to create a hierarchy of element types with inheritance of attributes, functions, and statistics.
- Ability to dynamically initialize an element during simulation by loading new elements code on-request and adding new events to the event calendar and statistics to the statistics database.

In order for users to be able to alternatively use different modeling elements based on their function delivery capabilities, standardized definitions of functions need to be developed. This will enable categorizing and searching elements based on their functions. This process can be manual or automated using an intelligent agent.

The current function and state-transition mechanism is based on rule-based systems concepts. It is believed that this transition mechanism can be replaced by other pattern-matching techniques such as neural networks or belief networks. Different elements may have different mechanisms for transition from one state to another according to the nature of each of them.

One of the difficulties associated with autonomous agents, which is reported as well in the literature, is the debugging and verification process during development. Special tools have to be developed to facilitate this process.

4.9 Conclusions

This study represented a new function-based framework for building SPS tools and models. The framework makes use of intelligent agent concepts, declarative state-based concepts and TRIZ function analysis concepts to customize the behaviors of SPS modeling elements. The framework was prototyped as a template using the Simphony development environment. A tunneling template was built based on the framework to evaluate it and demonstrate its use. The framework enables creating modeling elements that features intelligent agents abilities. The elements can autonomously control their behaviors according to the conditions of their surrounding environment. The framework's function and state-based modeling approach provides useful features that are necessary for modeling and controlling complex systems that involve different disciplines. In addition it provides a good foundation for dynamic topological optimization of simulation models as opposed to numerical optimization performed using mathematical techniques. Limitations of the approach are identified and recommendations are proposed to overcome these limitations.

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Chapter 5 - General Discussion and Conclusions

5.1 Research Summary

The research presented in this thesis was motivated by the lack of effective modeling and analysis tools that suits the peculiarities of the construction industry. The research focused on two main areas: 1) simulation-based modeling, which has the potential to capture the uncertainty and randomness in construction systems, and 2) theory of inventive problem solving (TRIZ), which represents a radically different approach for extraction, consolidation, and reuse of technical knowledge.

The research began by studying TRIZ and applying it in its native form to some construction problems. Four case-studies were analyzed using a number of TRIZ tools. The outcomes of these cases are presented in Chapter 2 of the thesis. The cases represented technical problems that were encountered in the field of utility tunnel construction. In search for solutions to these problems, TRIZ tools showed advantages by guiding the search to the most effective solutions. One of the realized strengths of the theory was its seamless generic approach for consolidating multi-disciplinary knowledge that can be reused for solving a wide spectrum of technical problems. Due to this feature, the used tools were capable of pointing to solutions that are not yet widely used in the industry although successfully used in other industries. Despite the realized strengths of TRIZ when using its classic form, it was also realized that it needs a considerable amount of training and practice to master its use.

Another study presented in Chapter 3 of the thesis used the generic knowledge consolidation and abstraction approach of TRIZ to analyze and preserve technical construction knowledge collected from "lessons learned" summaries. A framework was proposed in that study to facilitate the knowledge extraction, and retrieval process and make it more usable in day-to-day technical decision-making by extending and enhancing the standard contradiction matrix tool of TRIZ. The study also showed that the inventive principles provided in the standard matrix are highly representative of the actual solutions of the analyzed cases while the technical parameters are less representative. The methodology followed in that study represents a useful approach for customizing TRIZ tools to the nature of construction problems.

Based on the unique modeling requirements for construction systems, TRIZ's function analysis concepts, state-based simulation concepts, and intelligent agents concepts, a hybrid function-based simulation framework was conceptualized and prototyped. The details of that framework are presented in Chapter 4. The framework represents a new approach for creating special purpose simulation (SPS) tools and building simulation models in construction. The proposed function-based framework provides possibilities that cannot be easily achieved using current state-of-the-art techniques in construction simulation. Such possibilities include 1) dynamic topological changes to the simulation models, 2) intelligent simulation agents, and 3) ability of future integration with TRIZ-like knowledge bases.

5.2 Research Contributions

The research effort described in this thesis has a number of contributions to the construction research arena. These contributions can be summarized in the following main themes:

1. Pioneer use of TRIZ in the construction field

   The research presented in the thesis is the first attempt to make use of TRIZ in the field of construction engineering. It is expected that the introduction of the theory to the construction community will greatly affect the way the community handles and develops innovations. It will also trigger a number of successive research tracks that benefit from the theory in ways beyond what is described in this thesis.

2. New approach for knowledge consolidation and abstraction

   The approach described in the thesis for extracting and preserving technical construction knowledge represents a unique approach that could add a considerable value to contracting companies' know-how asset. It also helps building up the overall organizational knowledge of a company in a seamless way.

3. Intelligent simulation modeling

   The framework proposed in the thesis contributes in a number of ways to the construction simulation research. It provides a new possibility for improving performance through simulation experimentation by topological optimization of the simulation models using TRIZ-like heuristics as opposed to numerical optimization using mathematical techniques and provides the suitable foundation for testing and evaluating innovative solutions. It also introduces the concept of intelligent agents to construction simulation. It is expected that such agents will assist in making simulation techniques more usable and beneficial to the industry.

5.3 Recommendations for Future Research

The presented research exposes other research areas that need further investigation, study, and development. The following are some of these areas:

- Exploration of other TRIZ instruments and concepts, and customizing special construction-oriented tools from them. In particular, the "Standard Su-field solutions", "Patterns of evolutions", and "Effects' knowledge-base" are among the candidate areas for investigation.
- Creating the link between TRIZ' innovative heuristics and the simulation models is another area for investigation. It is expected that a robust set of function definitions standards plus a well-structured knowledge base of solutions could provide that missing link.
- Expanding the knowledge representation and consolidation research started in this thesis horizontally by completing the proposed knowledge management framework and analyzing and adding more innovative solutions to it. Mastering and systematizing innovation is an amazing goal that seems achievable by pursuing research in this direction.
- Implementing the proposed function-based simulation framework as a back-end service in Simphony to improve the processing performance and investigating the use of parallel processing architectures with the proposed framework.
- Investigating the use of different pattern-matching techniques for controlling elements' state and function transitions in the proposed framework. Neural networks and belief network techniques are expected to provide alternatives to the current production rules one.

- Investigating the possibilities of visualizing simulation models by binding key modeling elements states in the proposed framework to animation key-frames.
- Investigating the possibilities of using simulation models as part of the control process by creating a framework for updating the states of the modeling elements based on actual status of their real-world counterparts.

Appendix 1 - TRIZ' Standard Contradiction Matrix[1]

Characteristics

TRIZ ID	Name	Description
1	Weight of moving object	The mass of the subsystem, element, or technique in a gravitational field. The force that the body exerts on its support or suspension, or on the surface on which it rests.
2	Weight of stationary object	The mass of the subsystem, element, or technique in a gravitational field. The force that the body exerts on its support or suspension, or on the surface on which it rests.
3	Length of moving object	A geometric characteristic described by the part of a line (straight or curved and not necessarily the longest) that can by measured by any unit of linear dimension, such as meter, inch etc.
4	Length of stationary object	A geometric characteristic described by the part of a line (straight or curved and not necessarily the longest) that can by measured by any unit of linear dimension, such as meter, inch etc.
5	Area of moving object	A geometric characteristic described by the part of a plane enclosed by a finite continuous line that can be measured in a square unit of dimension. The part of a surface occupied by the subsystem.
6	Area of stationary object	A geometric characteristic described by the part of a plane enclosed by a finite continuous line that can be measured in a square unit of dimension. The part of a surface occupied by the subsystem.
7	Volume of moving object	A geometric characteristic described by the part of a space that can by measured in a cubic unit of dimension. The part of a space, either internal or external, occupied by the subsystem.
8	Volume of stationary object	A geometric characteristic described by the part of a space that can by measured in a cubic unit of dimension. The part of a space, either internal or external, occupied by the subsystem.
9	Speed	The velocity of the subsystem. The rate of a process or action in time that can be measured by any linear unit of length divided by a time unit.
10	Force	Any interaction that can change the subsystem's condition due to the interaction between subsystems.
11	Tension, pressure	Tension on or inside the subsystem.
12	Shape	The external contours, boundaries, that separate the subsystem

1 Sources:

Altshuller, Genrich. 1998. "40 Principles: TRIZ Keys to Technical Innovation", (Lev Shulyak and Steven Rodman, Trans.), Technical Innovation Center, MA.

Savransky, Semyon D. 2000. "Engineering of Creativity: Introduction to TRIZ Methodology of Inventive Problem Solving". CRC press, New York.

TRIZ ID	Name	Description
		from the environment or other subsystems. The appearance of the subsystem in the space.
13	Stability of object	The ability of the subsystem to keep its integrity (wholeness). Steadiness of the subsystem's elements in time. Wear, chemical decomposition, disassembly, and growth of entropy are all decreases in stability.
14	Strength	The ability of the subsystem to resist a change in response to force. Resistance to breaking.
15	Durability of moving object	The time during which the subsystem can perform useful and /or neutral functions (durability). It can be estimated as the average period between failures, the service life.
16	Durability of stationary object	The time during which the subsystem can perform useful and /or neutral functions (durability). It can be estimated as the average period between failures, the service life.
17	Temperature	The thermal condition of the subsystem. Liberally includes other thermal parameters, such as heat capacity, that affect the rate of temperature change.
18	Brightness	Light flux per unit area. Also any other illumination characteristics of the subsystem, such as light intensity, degree of illumination.
19	Energy spent by moving object	The subsystem's requirements.
20	Energy spent by stationary object	The subsystem's requirements.
21	Power	The time rate of energy usage due to which the subsystem's functions are performed.
22	Waste of energy	Use of energy (such as heat) that does not contribute to the job being done (compare with 19 and 20). Reducing energy loss sometimes requires heuristics that are different from the heuristics for improving energy usage. Consequently, energy waste is a separate parameter.
23	Waste of substance	Partial or complete, permanent or temporary loss of some of the subsystem's materials or elements.
24	Loss of information	Partial or complete, permanent or temporary loss of data or access to data in or by the subsystem. Frequently includes sensory data such as aroma, texture, etc.
25	Waste of time	Time is the duration of an activity. Improving the loss of time means reducing the time taken out of the activity. "Cycle time reduction" is a common term.
26	Amount of substance	The number of subsystem's materials or elements that might be changed fully or partially, permanently or temporarily.
27	Reliability	The subsystem's ability to perform its intended function in predictable ways and conditions.
28	Accuracy of measurement	The closeness of the measured value to the actual value of the subsystem parameter.
29	Accuracy of manufacturing	The closeness of the actual characteristics of the subsystem to the specified or required characteristics that can be achieved during the subsystem production. (Note that manufacturing precision is often connected with the quality of the subsystem.)
30	Harmful factors	Susceptibility of the subsystem to externally generated harmful

TRIZ ID	Name	Description
	acting on object	effects.
31	Harmful side effects	A harmful effect that is generated by the subsystem as part of its operation within the technique, and that reduces the efficiency or quality of the functioning of the subsystem or whole technique.
32	Manufacturability	The degree of facility, comfort, ease, or effortlessness in manufacturing or fabricating of the subsystem.
33	Convenience of use	Simplicity and ease of operation. The technique is not convenient if it requires many steps to operate or needs special tools, many highly skilled workers, etc. Often a convenient process has high yield due to the possibility to do it right.
34	Reparability	Quality characteristics such as convenience, comfort, simplicity, and time to repair faults, failures, or defects in the subsystem.
35	Adaptability	The ability of the subsystem to respond positively to external changes, and the versatility of the subsystem that can be used in multiple ways under a variety of circumstances.
36	Complexity of a system	The number and diversity of elements and element interrelationships within the subsystem. The user may be an element of the subsystems that increases the complexity. The difficulty of mastering the subsystem is a measure of it complexity.
37	Complexity of control	Measuring or monitoring the subsystems that are difficult, costly, and require much time and labor to set up and use, that have fuzzy relationships between components, or that have components that interfere with each other, demonstrating " difficult to detect and measure".
38	Level of automation	The ability of the subsystem to perform its functions without human interface. The lowest level of automation is the use of a manually operated tool. For intermediate levels, humans program the tool, observe its operation, and interrupt or reprogram as needed. For the highest level, the machine senses the operation needed, programs itself, and monitors its own operations.
39	Productivity	The number of functions or operations performed by the subsystem or whole technique per unit of time, the time for a unit function or operation. The output per unit of time or the cost per unit of output. (see also parameters 19-21).

Inventive Principles

Principle ID	Name	Description
1	Segmentation	A. Divide an object into independent parts. B. Make an object modular. C. Increase the degree of fragmentation or segmentation.
2	Extraction	A. Separate (extract) an interfering part or property from an object, or single out the only necessary part (or property) of an object.
3	Local Quality	A. Change an object's structure from uniform (homogenous) to non-uniform, change an external environment (or external influence) from uniform to nonuniform. B. Make each part of an object function in conditions most suitable for its operation. C. Make each part of an object fulfill a different and useful function
4	Asymmetry	A. Change the shape of an object from symmetrical to asymmetrical. B. If an object is asymmetrical, increase its degree of asymmetry.
5	Consolidation	A. Merge identical or similar objects, assemble identical of similar parts to perform parallel operations. B. Make operations contiguous or parallel; bring then together in time
6	Universality	A. Make a part or object perform multiple functions; eliminate the need for other parts.
7	Nesting (Matrioshka)	A. Place one object into another; place each object, in turn, inside the other. B. Make one part pass through a cavity of the other.
8	Counterweight	A. To counter the weight of an abject, merge it with other objects that provide lift. B. To compensate for the weight of an object, make it interact with the environment (e.g., use aerodynamic, hydrodynamic, buoyancy, and other forces)
9	Prior Counteraction	A. If it is necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects. B. Create actions in an abject that will later oppose known undesirable working actions.
10	Prior Action	A. Perform, before necessary, a required change of an object, (either fully or partially). Carry out all or part of the required action in advance. B. Pre-arrange objects so that they can act from the most convenient place and without losing time for their delivery.
11	Cushion in Advance	A. Prepare emergency means beforehand to compensate the relatively low reliability of an object.
12	Equipotentiality	A. In a potential field, limit position changes (e.g., change operating conditions to eliminate the need to raise or lower objects in a gravity field).
13	Do it in Reverse	A. Invert the actions used to solve a problem (e.g., instead of cooling and objects, heat it)

Principle ID	Name	Description
		B. Instead of an action dictated by the requirements, one implements the opposite action. C. Make movable parts or the external environment fixed, and fixed parts movable. D. Turn the object or process "upside down".
14	Spheroidality	A. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical, from parts shaped as a cube (parallelepiped) to ball-shaped structures. B. Use rollers, balls, spirals, and domes. C. Go from linear to rotary motion, use centrifugal forces
15	Dynamicity	A. Allow or design the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition. B. Divide an object into parts capable of movement relative to each other. C. If an object (or process) is rigid or inflexible, make it movable or adaptive.
16	Partial or Excessive Action	A. If 100 percent of an object is hard to achieve using a given solution method, the problem may be considerably easier to solve by using " slightly less" or "slightly more" of the same method.
17	Transition into a New Dimension	A. Difficulties involved in moving or relocation an object along a line are removed if the object acquires the ability to move in two dimensions (along a plane). Accordingly, problems connected with movement or relocation of and object on one plane are removed by switching to a tree-dimensional space. B. Use a multi-story arrangement of objects instead of a single-story arrangement. Use a multilayered assembly of objects instead of a single layer. C. Incline the object or turn it on its side D. Use another side of a given area. E. Use optical lines falling onto neighboring areas or onto the reverse side of the area available.
18	Mechanical Vibration	A. Oscillate or vibrate an object. B. If oscillation exists, increase its frequency. C. Use an object's resonant frequency. D. Use piezoelectric vibrators instead of mechanical ones. E. Use combined ultrasonic and electromagnetic field oscillations.
19	Periodic Action	A. Instead of continuous action, use periodic or pulsating actions. B. If and action is already periodic, change the periodic magnitude or frequency.
20	Continuity of Useful Action	A. Continue on actions; make all parts of an object perform UF and /or NF at full load, all the time. B. Eliminate all idle or intermittent actions.
21	Rushing Through	A. Conduct a process or certain stages (e.g., destructible, harmful, or hazardous operations) at high speed.
22	Convert Harm into Benefit	A. Use harmful factors (particularly harmful effects of the environment or surroundings) to achieve a positive effect.

Principle ID	Name	Description
		B. Eliminate the primary harmful action by adding it to another harmful action to resolve the problem. C. Amplify a harmful factor to such a degree that it is no longer harmful.
23	Feedback	A. Introduce feedback (referring back, cross-checking) to improve a process or action. B. If feedback is already used, change its magnitude or influence.
24	Mediator	A. Use an intermediary carrier article or intermediary process. B. Merge one object temporarily with another (which can be easily removed).
25	Self Service	A. Make an object serve itself by performing auxiliary helpful functions. B. The object should service/organize itself and carry out supplementary and repair operations. C. Use waste resources, energy, or substances.
26	Copying	A. instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies. B. Replace an object or process with optical copies. C. If visible optical copies are already used, move to infrared and ultraviolet copies.
27	Dispose	A. Replace an expensive object with multiple inexpensive objects, compromising certain qualities (such as service life, for instance).
28	Replacement of Mechanical System	A. Replace a mechanical means with a sensory (optical. Acoustic, taste, or olfactory) means. B. Use electric magnetic, and electromagnetic fields to interact with the object. C. Change form static to movable fields, from unstructured fields to those having structure. D. Use files n conjunction with field-activated particles (e.g., ferromagnetic)
29	Pneumatic of Hydraulic Construction	A. Use gas and liquid parts of an object instead of solid parts (e.g., inflatable, filled with liquids, air cushion, hydrostatic, hydroreactive). B. Use the Archimedes forces to reduce the weight of an object. C. Use negative or atmosphere pressure. D. A spume or foam can be used as a combination of liquid and gas properties with lightweight.
30	Flexible Films or Thin Membranes	A. Use flexible shells and thin films instead of three-dimensional structures. B. Isolate the object from the external environment using flexible shells and thin films.
31	Porous Materials	A. Make an object porous or add porous elements (inserts, coatings, etc.). B. If and object is already porous, use the pores to introduce a useful substance or function.
32	Changing the Color	A. change the color of an object or its external environment. B. Change the transparency of an object or its external environment.

Principle ID	Name	Description
		C. In order to observe objects or processes that are difficult to see, use colored additives. If suck additives are already used, employ luminescence traces.
33	Homogeneity	A. Make objects interacting with a given object of the same material (or material with identical properties).
34	Rejecting and Regenerating Parts	A. Discard (by dissolving, evaporating, etc.) portions of an object that have fulfilled their functions or modify these directly during operation. B. Conversely, restore consumable parts of an object directly in operation.
35	Transformation of Properties	A. Change and object's physical aggregate state (e.g., to a gas, liquid or solid). B. Change the concentration or consistency (see also principle F below). C. Change the degree of flexibility (see also Principle 15). D. Change the temperature. E. Change other characteristics of a technique.
36	Phase Transition	A. Use phenomena that occur during phase transitions (e.g., volume changes, loss or absorption of heat, etc.).
37	Thermal Expansion	A. Use thermal expansion (or contraction) of materials. B. If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.
38	Accelerated Oxidation	A. Replace common air with oxygen-enriched air B. Replace enriched air with pure air C. Expose air or oxygen to ionizing radiation. D. Use ionized oxygen. E. Replace ozonized (or ionized) oxygen with ozone.
39	Inert Environment	A. Replace a normal environment with an inert one. B. Add neutral parts or inner additives to and object.
40	Composite Materials	A. Change from uniform to composite (multiple) materials.

TRIZ's Contradiction Matrix

Deteriorating Characteristic

Improving Characteristic

	1	2	3	4	5	6	7	8	9	10	11
1			8,34,29,15		38,34,29,17		40,29,28,2		8,38,2,15	8,37,18,10	40,37,36,10
2				35,29,10,1		7,35,30,13		5,35,2,14		8,35,19,10	29,18,13,10
3	8,34,29,15				4,17,15		7,4,35,17		8,4,13	4,17,10	8,35,1
4		40,35,29,28				7,40,17,10		8,35,2,14		28,10	35,14,1
5	4,29,2,17		4,18,15,14				7,4,17,14		4,34,30,29	35,30,2,19	36,28,15,10
6		40,30,29		9,7,39,26						36,35,18,1	37,36,15,10
7	40,29,26,2		7,4,35,1		7,4,35,1				4,38,34,29	37,36,35,15	6,37,36,35
8		35,19,14,10	19,14	8,35,2,14						37,2,18	35,24
9	38,28,2,13		8,14,13		34,30,29		7,34,29			28,19,15,13	6,40,38,18
10	8,37,18,1	28,18,13,1	9,36,19,17	28,10	19,15,10	37,36,18,1	37,19,15,12	37,36,2,18	28,15,13,12		21,18,11
11	40,37,36,10	29,18,13,10	36,35,10	35,16,14,1	36,28,15,10	37,36,15,10	6,35,10	35,24	6,36,35	36,35,21	
12	8,40,29,10	3,26,15,10	5,4,34,29	7,14,13,10	5,4,34,10		4,22,15,14	7,35,2	35,34,18,15	40,37,35,10	34,15,14,10
13	39,35,21,2	40,39,26,1	28,15,13,1	37	2,13,11	39	39,28,19,10	40,35,34,28	33,28,18,15	35,21,16,10	40,35,2
14	8,40,15,1	40,27,26,1	8,35,15,1	36,28,15,14	40,34,3,29	9,40,28	7,15,14,10	9,17,15,14	8,26,14,13	3,18,14,10	40,3,18,10
15	5,34,31,19		9,2,19		3,19,17		30,2,19,10		5,35,3	2,19,16	3,27,19
16		6,27,19,16		40,35,1				38,35,34			
17	6,38,36,22	35,32,22	9,19,15	9,19,15	39,35,3,18	38,35	40,39,34,18	6,4,35	36,30,28,2	35,3,21,10	39,35,2,19
18	32,19,1	5,32,2	32,19,16		32,26,19		2,13,10		19,13,10	6,26,19	
19	31,28,18,12		28,12		25,19,15		35,18,13		8,35	26,21,2,16	25,23,14
20		9,6,27,19								37,36	
21	8,38,36,31	27,26,19,17	37,35,10,1		38,19	38,32,17,13	6,38,35	6,30,25	35,2,15	36,35,26,2	35,22,10
22	6,28,19,15	9,6,19,18	7,6,2,13	7,6,38	30,26,17,15	7,30,18,17	7,23,18	7	38,35,16	38,36	
23	6,40,35,23	6,35,32,22	39,29,14,10	28,24,10	35,31,2,10	39,31,18,10	36,30,29,1	39,31,3,18	38,28,13,10	40,18,15,14	37,36,3,10
24	35,24,10	5,35,10	26,1	26	30,26	30,16		22,2	32,26		
25	37,35,20,10	26,20,10	5,29,2,15	6,30,24,14	5,4,26,16	4,35,17,10	5,34,2,10	35,32,18,16		5,37,36,10	4,37,36
26	6,35,31,18	35,27,26,18	35,29,18,14		29,15,14	40,4,2,18	29,20,15		35,34,29,28	35,3,14	36,3,14,10
27	8,40,3,10	8,3,28,10	9,4,15,14	29,28,15,11	17,16,14,10	40,4,35,32	3,24,14,10	35,34,2	35,28,21,11	8,3,28,10	35,34,19,10
28	35,32,28,26	35,28,26,25	5,28,26,16	32,3,28,16	32,3,28,26	32,3,28,26	6,32,13		32,28,24,13	32,2	6,32,28
29	32,28,18,13	9,35,28,27	37,29,28,10	32,2,10	33,32,29,28	36,29,2,18	32,28,2	35,25,10	32,28,10	36,34,28,19	35,3
30	39,27,22,21	24,22,2,13	4,39,17,1	18,1	33,28,22,1	39,35,27,2	37,35,23,22	39,34,27,19	35,28,22,21	39,35,18,13	37,22,2
31	39,22,19,15	39,35,22,1	22,17,16,15		39,2,18,17	40,22,1	40,2,17	4,35,30,18	35,3,28,23	40,35,28,1	33,27,2,18
32	29,28,16,15	36,27,13,1	29,17,13,1	27,17,15	26,13,12,1	40,16	40,29,13,1	35	8,35,13,1	35,12	37,35,19,1
33	25,2,15,13	6,25,13,1	17,13,12,1		17,16,13,1	39,18,16,15	35,16,15,1	4,39,31,18	34,18,13	35,28,13	32,2,12
34	35,27,2,11	35,27,2,11	28,25,10,1	31,3,18	32,15,13	25,16	35,25,2,11	1	9,34	11,10,1	13
35	8,6,15,1	29,19,16,15	35,29,2,1	35,16,1	7,35,30,29	16,15	35,29,15		35,14,10	20,17,15	35,16
36	36,34,30,26	39,35,26,2	26,24,19,1	26	16,14,13,1	6,36	6,34,26	16,1	34,28,10	26,16	35,19,1
37	28,27,26,13	6,28,13,1	26,24,17,16	26	2,18,17,13	39,30,2,16	4,29,16,1	31,26,2,18	4,35,3,16	40,36,28,19	37,36,35,32
38	35,28,26,18	35,28,26,10	28,17,14,13	23	17,14,13		35,16,13		28,10	35,2	35,13
39	37,35,26,24	3,28,27,15	4,38,28,18	7,30,26,14	34,31,26,10	7,35,17,10	6,34,2,10	37,35,2,10		36,28,15,10	37,14,10

Deteriorating Characteristic

Improving Characteristic	12	13	14	15	16	17	18	19	20	21	22
1	40,35,14,10	39,35,14,1	40,28,27,18	5,35,34,31			32,19,1	35,34,31,12		36,31,18,12	6,34,2,19
2	19,14,13,10	40,39,26,1	28,27,2,10		6,27,2,19	32,28,22,19	35,32,19		28,19,18,1	22,19,18,15	28,19,18,15
3	8,29,10,1	8,34,15,1	8,35,34,29	19		19,15,10	32	8,35,24		35,1	7,39,35,2
4	7,15,14,13	39,37,35	28,26,15,14		40,35,1	38,35,3,18	3,25			8,12	6,28
5	5,4,34,29	29,2,13,11	40,3,15,14	6,3		2,16,15	32,19,15,13	32,19		32,19,18,10	30,26,17,15
6		38,2	40		30,2,19,10	39,38,35				32,17	7,30,17
7	4,29,15,1	39,28,10,1	9,7,15,14	6,4,35		39,34,18,10	2,13,10	35		6,35,18,13	7,16,15,13
8	7,35,2	40,35,34,28	9,17,15,14		38,35,34	6,4,35				6,30	
9	35,34,18,15	33,28,18,1	8,3,26,14	5,35,3,19		36,30,28,2	19,13,10	8,38,35,15		38,35,2,19	35,20,19,14
10	40,35,34,10	35,21,10	35,27,14,10	2,19		35,21,10		19,17,10	37,36,16,1	37,35,19,18	15,14
11	4,35,15,10	40,35,33,2	9,40,3,18	3,27,19		35,29,2,19		37,24,14,10		35,14,10	36,25,2
12		4,33,18,1	40,30,14,10	9,26,25,14		32,22,19,14	32,15,13	6,34,2,14		6,4,2	14
13	4,22,18,1		9,17,15	35,27,13,10	39,35,3,23	35,32,1	32,3,27,15	19,13	4,29,27,18	35,32,31,27	6,39,2,14
14	40,35,30,10	35,17,13		3,27,26		40,30,10	35,19	35,19,10	35	35,28,26,10	35
15	28,26,25,14	35,3,13	3,27,10			39,35,19	4,35,2,19	6,35,28,18		38,35,19,10	
16		39,35,3,23				40,36,19,18				16	
17	32,22,19,14	35,32,1	40,30,22,10	39,19,13	40,36,19,18		32,30,21,16	3,19,17,15		25,2,17,14	38,35,21,17
18	32,30	32,3,27	35,19	6,2,19		35,32,19		32,19,1	35,32,15,1	32	6,16,13,1
19	29,2,12	24,19,17,13	9,5,35,19	6,35,28,18		3,24,19,14	2,19,15			6,37,19,18	24,22,15,12
20		4,29,27,18	35				35,32,2,19				
21	40,29,2,14	35,32,31,15	28,26,10	38,35,19,10	16	25,2,17,14	6,19,16	6,37,19,16			38,35,10
22		6,39,2,14	26			7,38,19	32,15,13,1			38,3	
23	5,35,3,29	40,30,2,14	40,35,31,28	3,28,27,18	38,27,18,16	39,36,31,21	6,13,1	5,35,24,18	31,28,27,12	38,28,27,18	35,31,27,2
24				10	10		19			19,10	19,10
25	4,34,17,10	5,35,3,22	3,29,28,18	28,20,18,10	28,20,16,10	35,29,21,18	26,19,17,1	38,35,19,18	1	6,35,20,10	5,32,18,10
26	35,14	40,2,17,15	35,34,14,10	40,35,3,10	35,31,3			34,29,18,16	35,31,3	35	7,25,18
27	35,16,11,1		28,11	35,3,25,2	6,40,34,27	35,3,10	32,13,11	27,22,19,11	36,23	31,26,21,11	35,11,10
28	6,32,28	35,32,13	6,32,28	6,32,28	26,24,10	6,28,24,19	6,32,1	6,32,3		6,32,3	32,27,26
29	40,32,30	30,18	3,27	40,3,27		26,19	32,3	32,2		32,2	32,2,13
30	35,3,22,1	35,30,24,18	37,35,18,1	33,28,22,15	40,33,17,1	35,33,22,2	32,19,13,1	6,27,24,1	37,22,20,2	31,22,2,19	35,22,21,2
31	35,1	40,39,35,27	35,22,2,15	33,31,22,15	39,22,21,16	35,24,22,2	39,32,24,19	6,35,2	22,19,18	35,2,18	35,22,21,2
32	28,27,13,1	13,11,1	3,10,1	4,27,1	35,16	27,26,18	28,27,24,1	28,27,26,1	4,1	27,24,12,1	35,19
33	34,29,28,15	35,32,30	40,32,3,28	8,3,29,25	25,16,1	27,26,13	24,17,13,1	24,13,1		35,34,2,10	2,19,13
34	4,2,13,1	35,2	9,2,11,1	29,28,27,11	1	4,11	15,13,1	28,16,15,1		32,2,15,10	32,19,15,1
35	8,37,15,1	35,30,14	6,35,32,3	35,13,1	2,16	35,3,27,2	6,26,22,1	35,29,19,13		29,19,1	18,15,1
36	29,28,15,13	22,2,19,17	28,2,13	4,28,15,10		2,17,13	24,17,13	29,28,27,2		34,30,20,19	35,2,13,10
37	39,27,13,1	39,30,22,11	3,28,27,15	39,29,25,19	6,35,34,25	35,3,27,16	26,24,2	38,35	35,19,16	19,16,10,1	35,3,19,15
38	32,15,13,1	18,1	25,13	9,6		26,2,19	8,32,19	32,2,13		28,27,2	28,23
39	40,34,14,10	39,35,3,22	29,28,18,10	35,2,18,10	38,20,16,10	35,28,21,10	26,19,17,1	38,35,19,10	1	35,20,10	35,29,28,10

Deteriorating Characteristic

Improving Characteristic	23	24	25	26	27	28	29	30	31	32	33
1	5,35,31,3	35,24,10	35,28,20,10	31,3,26,18	3,27,11,1	35,28,27,26	35,28,26,18	27,22,21,18	39,35,31,22	36,28,27,1	35,3,24,2
2	8,5,30,13	35,15,10	35,26,20,10	6,26,19,18	8,3,28,10	28,26,18	35,17,10,1	37,22,2,19	39,35,22,1	9,28,1	6,32,13,1
3	4,29,23,10	24,1	29,2,15	35,29	40,29,14,10	4,32,28	37,29,28,10	24,17,15,1	17,15	29,17,1	7,4,35,29,15
4	35,28,24,10	26,24	30,29,14		29,28,15	32,3,28	32,2,10	18,1		27,17,15	25,2
5	39,35,2,10	30,26	4,26	6,30,29,13	9,29	32,3,28,26	32,2	33,28,22,1	39,2,18,17	26,24,13,1	17,16,15,13
6	39,18,14,10	30,16	4,35,18,10	40,4,2,18	40,4,35,32	32,3,28,26	36,29,2,18	39,35,27,2	40,22,1	40,16	4,16
7	39,36,34,10	22,2	6,34,2,10	7,30,29	40,14,11,1	28,26	28,25,2,16	35,27,22,21	40,2,17,1	40,29,1	30,15,13,12
8	39,35,34,10		35,32,18,16	35,3	35,2,16		35,25,10	39,34,27,19	4,35,30,18	35	
9	38,28,13,10	26,13		38,29,19,18	35,28,27,11	32,28,24,1	32,28,25,10	35,28,23,1	35,24,21,2	8,35,13,1	32,28,13,12
10	8,5,40,35		37,36,10	36,29,18,14	35,3,21,12	35,24,23,10	37,36,29,28	40,35,18,1	36,34,3,13	37,18,15,1	3,28,25,1
11	37,36,3,10		4,37,36	36,14,10	35,19,13,10	6,28,25	35,3	37,22,2	33,27,2,18	35,16,1	11
12	5,35,3,29		34,17,14,10	36,22	40,16,10	32,28,1	40,32,30	35,22,2,1	35,1	32,28,17,1	32,26,15
13	40,30,2,14		35,27	35,32,15		13	18	35,30,24,18	40,39,35,27	35,19	35,32,30
14	40,35,31,28		3,29,28,10	29,27,10	3,11	3,27,16	3,27	37,35,18,1	35,22,2,15	32,3,11,10	40,32,28,2
15	3,28,27,18	10	28,20,18,10	40,35,3,10	2,13,11	3	40,3,27,16	33,28,22,15	29,22,21,16	4,27,1	27,12
16	38,27,18,16	10	28,20,16,10	35,31,3	6,40,34,27	26,24,10		40,33,17,1	22	35,10	1
17	36,31,29,21		35,28,21,18	39,30,3,17	35,3,19,10	32,24,19	24	35,33,22,2	35,24,22,2	27,26	27,26
18	13,1	6,1	26,19,17,1	19,1		32,15,11	32,3	19,15	39,35,32,19	35,28,26,19	28,26,19
19	5,35,24,18		38,35,19,18	34,23,18,16	27,21,19,11	32,3,1		6,35,27,1	6,35,2	30,28,26	35,19
20	31,28,27,18			35,3,1	36,23,10			37,22,20,10	22,19,18	4,1	
21	38,28,27,18	19,10	6,35,20,10	4,34,19	31,26,24,19	32,2,15	32,2	31,22,2,19	35,2,18	34,26,10	35,26,10
22	37,35,27,2	19,10	7,32,18,10	7,25,18	35,11,10	32		35,22,21,2	35,22,21,2		35,32,1
23			35,18,15,10	6,3,24,10	39,35,29,10	34,31,28,16	35,31,24,10	40,33,30,22	34,29,10,1	34,33,15	32,28,24,2
24			32,28,26,24	35,28,24	28,23,10			22,10,1	22,21,10	32	27,22
25	39,35,18,10	32,28,26,24		38,35,18,16	4,30,10	34,32,28,24	28,26,24,18	35,34,18	39,35,22,18	4,35,34,28	4,34,28,10
26	6,3,24,10	35,28,24	38,35,18,16		40,3,28,18	28,2,13	33,30	35,33,31,29	40,39,35,3	35,29,27,1	35,29,25,10
27	39,35,29,10	28,10	4,30,10	40,3,28,21		32,3,23,11	32,11,1	40,35,27,2	40,35,26,2		40,27,17
28	31,28,16,10		34,32,28,24	6,32,2	5,23,11,1			28,26,24,22	39,33,3,10	6,35,28,18	34,17,13,1
29	35,31,24,10		32,28,26,18	32,30	32,11,1			36,28,26,1	4,34,26,17		35,32,23,1
30	40,33,22,19	22,2,10	35,34,18	35,33,31,29	40,27,24,2	33,28,26,23	28,26,18,10			35,24,2	39,28,25,2
31	34,10,1	29,21,10	22,1	39,3,24,1	40,39,24,2	33,3,26	4,34,26,17				
32	34,33,15	32,24,18,16	4,35,34,28	35,24,23,1		35,18,12,1		24,2			5,2,16,13
33	32,28,24,2	4,27,22,10	4,34,28,10	35,12	8,40,27,17	34,25,2,13	35,32,23,1	39,28,25,2		5,2,12	
34	35,34,27,2		32,25,10,1	28,25,2,10	16,11,10,1	2,13,10	25,10	35,2,16,10		35,11,10,1	26,15,12,1
35	2,15,13,10		35,28	35,3,15	8,35,24,13	5,35,10,1		35,32,31,11		31,13,1	7,16,15,14,1
36	35,29,28,10		6,29	3,27,13,10	35,13,1	34,26,2,10	32,26,24	40,29,22,19	19,1	27,26,13,1	9,27,26,24
37	24,18,10,1	35,33,27,22	9,32,28,18	3,29,27,18	8,40,28,27	32,28,26,24		29,28,22,19	21,2	5,29,28,11	5,2
38	5,35,18,10	35,33	35,30,28,24	35,13	32,27,11	34,28,26,10	28,26,23,18	33,2	2	26,13,1	34,3,12,1
39	35,28,23,10	23,15,13		38,35	38,35,10,1	34,28,10,1	32,18,10,1	35,24,23,13	39,35,22,18	35,28,24,2	7,28,19,1

Deteriorating Characteristic

Improving Characteristic

	34	35	36	37	38	39
1	28,27,2,11	8,5,29,15	36,34,30,26	32,29,28,26	35,26,19,18	37,35,3,24
2	28,27,2,11	29,19,15	39,26,10,1	28,25,17,15	35,26,2	35,28,15,1
3	28,10,1	16,15,14,1	26,24,19,1	35,26,24,1	26,24,17,16	4,29,28,14
4	3	35,1	26,1	26		7,31,26,14
5	15,13,10,1	30,15	14,13,1	36,26,2,18	30,28,23,14	34,26,2,10
6	16	16,15	36,18,1	35,30,2,18	23	7,17,15,10
7	10	29,15	26,1	4,29,26	35,34,24,16	6,34,2,10
8	1		31,1	26,2,17		37,35,2,10
9	34,28,27,2	26,15,10	4,34,28,10	34,3,27,16	18,10	
10	15,11,1	20,18,17,15	35,26,18,10	37,36,19,10	35,2	37,35,3,28
11	2	35	35,19,1	37,36,2	35,27	37,35,14,10
12	2,13,1	29,15,1	29,28,16,1	39,15,13	32,15,1	34,26,17,10
13	35,2,16,10	35,34,30,2	35,26,22,2	35,29,23,22	8,35,1	40,35,3,23
14	3,27,11	32,3,15	28,25,2,13	40,3,27,15	15	35,29,14,10
15	29,27,10	35,13,1	4,29,15,10	39,35,29,19	6,10	35,19,17,14
16	1	2		6,35,34,25	1	38,20,16,10
17	4,16,10	27,2,18	2,17,16	35,31,3,27	26,2,19,16	35,28,15
18	17,16,15,13	19,15,1	6,32,13	32,15	26,2,10	25,2,16
19	28,17,15,1	17,16,15,13	29,28,27,2	38,35	32,2	35,28,12
20				35,25,19,16		6,1
21	35,34,2,10	34,19,17	34,30,20,19	35,19,16	28,2,17	35,34,28
22	2,19		7,23	35,3,23,15	2	35,29,23,10
23	35,34,27,2	2,15,10	35,28,24,10	35,18,13,10	35,18,10	35,28,23,10
24				35,33	35	23,15,13
25	32,10,1	35,28	6,29	32,28,18,10	35,30,28,24	
26	32,25,2,10	3,29,15	3,27,13,10	3,29,27,18	8,35	3,29,27,13
27	11,1	8,35,24,13	35,13,1	40,28,27	27,13,11	38,35,29,1
28	32,13,11,1	35,2,13	35,34,27,10	32,28,26,24	34,28,2,10	32,28,24,10
29	25,10		26,2,18		28,26,23,18	39,32,18,10
30	35,2,10	35,31,22,11	40,29,22,19	40,29,22,19	34,33,3	35,24,22,13
31			31,19,1	27,21,2,1	2	39,35,22,18
32	9,35,25,11,1	2,15,13	27,26,1	6,28,11,1	8,28,1	35,28,10,1
33	32,26,12,1	34,16,15,1	32,26,17,12		34,3,12,1	28,15,1
34		7,4,16,1	35,25,13,11,1		7,35,34,13	32,10,1
35	7,4,16,1		37,29,28,15	1	35,34,27	6,37,35,28
36	13,1	37,29,28,15		37,28,15,10	24,15,1	28,17,12
37	16,12	15,1	37,28,15,10		34,21	35,18
38	35,13,1	4,35,27,1	24,15,10	34,27,25		5,35,26,12
39	32,25,10,1	37,35,28,1	28,24,17,12	35,27,2,18	5,35,26,12	

Appendix 2 - Patented Mucking Method Using Container Bags[1]

Patent Data

MUCKING METHOD FOR TUNNEL AND MUCK CAR

Patent Number:	JP2000240394
Publication date:	2000-09-05
Inventor(s):	OBARA YOSHIYUKI;; URATA OSAMU;; SUGAWARA HISAYA
Applicant(s):	SHIMIZU CORP
Requested Patent:	JP2000240394
Application Number:	JP19990046089 19990224
Priority Number(s):	
IPC Classification:	E21D9/12
EC Classification:	
EC Classification:	
Equivalents:	

Abstract

PROBLEM TO BE SOLVED: To muck debris from tunnel of a small section efficiently. SOLUTION: A plurality of muck cars 20 running forward and backward in prescribed allotted sections are allocated on tracks between the vicinity of a face 2 of a tunnel extended with the advance of the face and a pithead 8 of the tunnel. The muck produced at the face 2 is put in a container bag 10 which is brought into the vicinity of the face 2 and set temporarily in a folded state. The container bag 10 fully loaded with the muck is carried toward the pithead 8 by the muck car 20 waiting at a starting point A. The container bag 10 is transferred from the muck car 20 arriving at a load transfer point B, the terminal of the prescribed allotted section, to the subsequent muck car 20 waiting to run for carriage through the next section. Furthermore, cyclic running wherein the muck car 20 emptied after the operation for transfer returns to the starting point is executed for each of the allocated muck cars 20, and thereby the muck produced at the face 2 of the tunnel is brought to the pithead 8 thereof.

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[1] Source: (http://ep.espacenet.com/espacenet/)

Patent Illustration