University of Alberta

The Framework of TRIZ-enhanced-Value Engineering Analysis and Its Knowledge Management

by

Xiaoming Mao ©

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This thesis is dedicated to my mother,

who passed away around 6:30am on May 3, 2007.

Abstract

VE has become an integral aspect of the development of many major construction projects over the years. However, there are some shortcomings in the conventional VE process: (1) The use of a function analysis system technique (FAST) diagram as the basis for the VE exercise may restrain the VE team's creativity, as the FAST diagram usually provides too many details upfront regarding the lower-level project functions. (2) The creativity phase, which is the critical stage of the VE process, relies mainly on freethinking-based creativity tools, such that the chance of generating an innovative solution is limited by individual VE team members' experience, knowledge, and creativity. (3) There is a lack of direction in problem solving and a lack of effort in developing and evaluating alternative plans, both of which serve to reduce the efficiency and effectiveness of the VE exercise. (4) Finally, VE analysis usually starts from scratch without adequately utilizing the knowledge generated from previous VE exercises, which leads to an increased likelihood of "reinventing the wheel" and consequently the waste of resources. To overcome these shortcomings, this thesis first presents development of an enhanced VE framework (referred to as the TRIZ-enhanced-VE framework), which incorporates inventive problem-solving techniques (Russian abbreviation: TRIZ) in order to enhance the creative capability of the VE team and guide the VE process to effectively and efficiently generate "focused" ideas toward innovative solutions to the essential problems. Moreover, this study proposes a value engineering knowledge management system (VE-KMS) to facilitate the creativity phase of VE through live capturing, extracting, and reusing the best engineering and construction knowledge obtained from this stage. The architecture of the proposed database for VE knowledge management copes with the workflow of the creativity phase of the TRIZ-enhanced-VE study. While reviewing TRIZ theories, this research also identifies the difficulty involved in finding solutions for Substance-Field (Su-Field) analysis and therefore has condensed 76 standard solutions into seven general principles. As a result, the logic of TRIZ in general is improved and the application of Su-Field analysis becomes more efficient.

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September 2008

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Chapter 1: Introduction

1.1 Value Engineering in Construction Industry

At present, the construction industry has become a trillion-dollar business worldwide. As such, the effect of a relatively small share of cost savings encountered during the course of project development across industry will be very significant. Also, it is well known that decisions made at the early stage of a project's life cycle will have more considerable influence on the project's total cost.

Among the methodologies being utilized during the early stages of project planning and design to improve project value and cut costs, Value Engineering (VE) is the most reputable one. VE is an approach which searches for the least costly alternative while maintaining the functions and quality of a product or system. The recommendations created by multi-disciplinary VE teams improve the value of a project without compromising the designed project functions. The reader will note that the term Value Engineering is interchangeable with Value Analysis and Value Management, and has been widely applied in many areas, such as strategic planning, quality improvement, management studies, and manufacturing.

Through the promotion of the U.S. Department of Defense, VE was introduced into construction field in 1963. It has now become mandatory in many federal department-owned projects in the U.S. with values exceeding ten million dollars. As Zimmerman and Hart (1982) estimated in their book, a 3 to 5% construction cost saving is expected as a result of conducting VE studies.

While VE is penetrating more ground and increasingly turning into a routing step in the engineering planning and design process, mixed feedback has been obtained from users. According to the ENR website poll, about half of respondents agree that VE is a valuable constructability tool, whereas around 43% of the respondents consider it to be nothing more than a marketing ploy. These contradictory opinions may have been partly a result of whether these respondents had obtained innovative ideas that improved their projects' value during their previous VE exercises.

Some users have complained that function analysis is difficult to perform and might potentially restrain the VE team's creativity since the FAST diagram provides too many details upfront about the lower-level project functions. Since the creativity phase of VE relies primarily on brainstorming and some other freethinking-based creativity tools, the chance of generating an innovative solution in a VE exercise is limited by the participants' experience, knowledge, and creativity. Furthermore, in a VE exercise, little effort is made to understand and formulate the essential problem, a strategy which can guide the inspiration in such a manner that the search for effective and robust solutions becomes more efficient. Instead, one assumption in the VE exercise is that quantity brings quality. As a result, VE exercises involve a significant amount of time spent at coming up with a broad field of project alternatives, and consequently VE does not allow for sufficient time to develop and evaluate each alternative.

On the other hand, little research has been conducted to investigate how to reutilize the ideas and solutions obtained from previous VE studies for future projects or how to share this knowledge throughout the entire company or the whole industry. In fact, the construction industry is still practicing VE in the same fashion as it was fifty years ago.

Each VE study begins from scratch and its success solely relies on the VE team members' experience and competence.

Therefore, there exists a great need to improve the efficiency and effectiveness of conventional VE. The author has thus conducted this research and consequently developed an enhanced VE framework which incorporates TRIZ into its creativity phase. Furthermore, a VE knowledge management system has been created for VE knowledge acquisition, representation, and retrieval. While conducting these studies, the author also identified an opportunity to ease the process of identifying the appropriate solutions for Su-Field analysis. Consequently, 76 standard solutions, the solution pool for Su-Field analysis, were condensed into seven generalized principles.

1.2 Background

1.2.1 Engineering Design

Engineering design is the initial phase of a project life cycle during which the sponsoring department analyzes project objectives, develops understanding of issues and constraints, envisions alternative solutions, quantifies project scope, cost and schedule, and details the best option to a degree which is sufficient to facilitate material procurement, manufacturing, and construction.

Wiese and John (2003) have considered engineering design to be engineers' fundamental contribution to society. They have simplified this concept in the format shown in Figure 1.1, which clearly presents the iterative nature of engineering design in addition to the four most important functions: (1) to establish the primary objective of the project; (2) to analyze the problem and create a number of alternative options; (3) to evaluate all project alternatives and identify the one which best addresses the primary need and; (4) to choose and implement the best option.

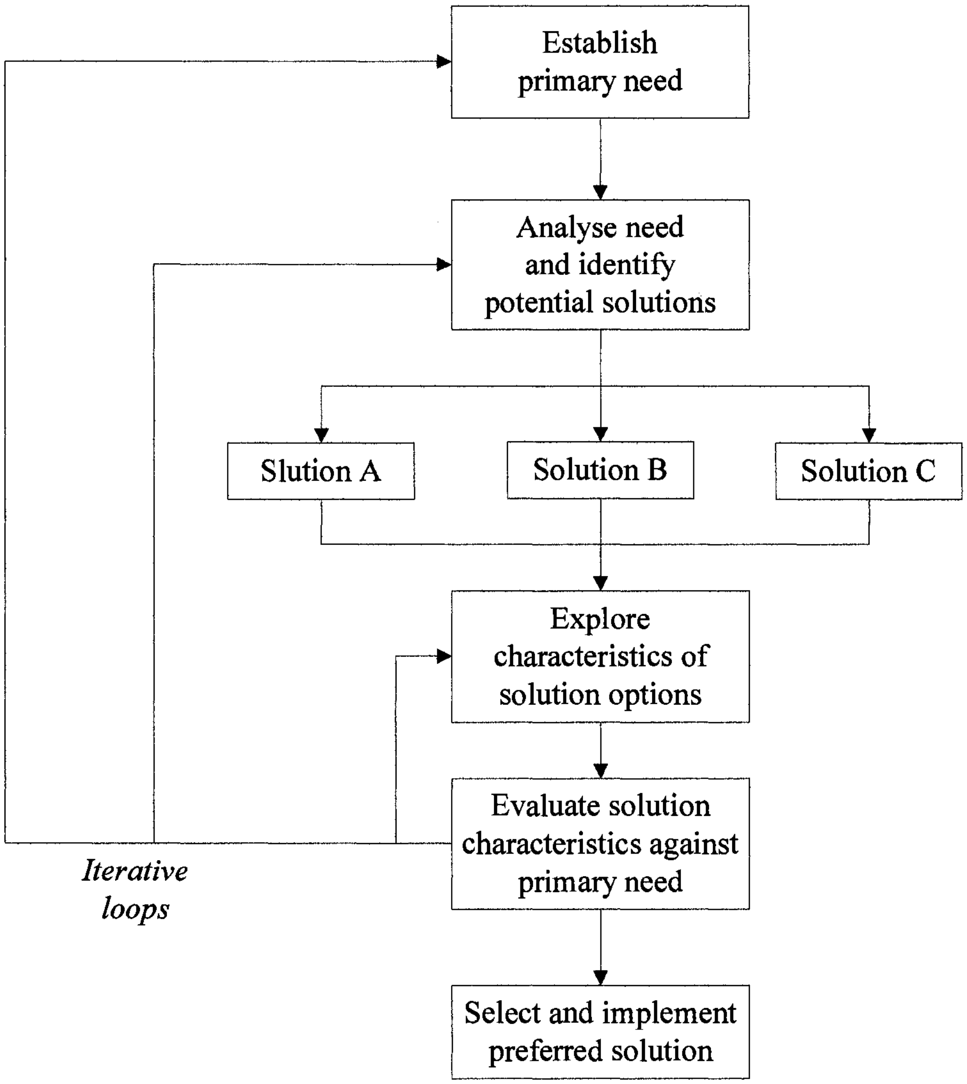

Figure 1.1: A Fundamental Engineering Design Process (Wiese and John, 2003)

1.2.2 Value Engineering

While following the above flowchart for decades, engineers have consistently endeavored to find a more efficient methodology to develop a project in a more cost-effective manner. In recent years, one of the most practiced project planning approaches has been VE, a process first developed by Mr. Lawrence D. Miles in the 1940s while he had been working for General Electric. He first came up with VE while attempting to assist GE in providing the necessary functions to meet the required performance at the least cost.

VE is a systematic project analysis, planning, and design approach which relies on the involvement of a multi-disciplinary team. The objective of VE is to provide necessary functions at the lowest project initial cost or life cycle cost while realizing the requirements for safety, quality, durability, aesthetics, operability, and maintainability. VE has been applied in the various stages of project development, including preliminary design, detailed engineering, and construction planning.

VE follows the essence of the engineering design process as illustrated in Figure 1.1, but it is delivered in a more systematic format. A complete VE practice contains three phases: a pre-workshop phase, a workshop phase, and a post-workshop phase.

1.2.3 Theory of Inventive Problem Solving (TRIZ)

"TRIZ" is the Russian acronym for "Theory of Inventive Problem Solving" which was created by Genrich Altshuller some 50 years ago in the former Union of Soviet Socialist Republics. TRIZ was initiated and developed based on one assumption: creative innovations that advance technology obey certain universal principles of invention. If these rules can be identified and codified, they can be taught to people in order to make the process of invention more straightforward and predictable. As a result of exhaustively analyzing over 2.5-million innovative patents around the world, Genrish

Altshuller and his successors verified this hypothesis and identified a number of rules as listed below:

- All innovations follow a small number of inventive principles and strategies, which are repeated across industries and scientific fields.
- Technology evolution trends are highly predictable across industries and sciences.
- The best solutions transform the unwanted or harmful elements of a system into useful resources.
- The best solutions also actively seek out and destroy the conflicts and trade-offs in most designs.

The above principles distinguish TRIZ from the freethinking-based creativity techniques normally used in conventional VE exercises. Based on these principles, over the course of 50 years, numerous concepts and tools for innovative problem solving have been developed, including Su-Field analysis, Technical Contradiction, Contradiction Matrix, 40 Inventive Principles, ARIZ, and others. These technologies enable users to control the process of innovation.

1.2.4 Knowledge Management in Construction Industry

Knowledge management is a process to create, secure, capture, coordinate, combine, retrieve, and distribute knowledge (Lin et al. 2005). The effective application of existing knowledge can create innovation, and can improve business performance and client satisfaction, whereas the failure to capture and reuse the knowledge kept in previously accomplished projects will increase the likelihood of "reinventing the wheel" and consequently encountering a waste of resources and a loss of profits (Kamara et al. 2002a; 2002b).

Knowledge management is particularly important within the construction industry. First, the construction industry is extremely competitive due to tight construction schedules, low profit margins, as well as the complexity, diversity, and non-standardized production process involved. In this regard, effective knowledge management will facilitate the generation of new technologies and processes, which will improve the industry's productivity, profitability, and competitiveness (Clough et al. 2000; Pathirage et al. 2006). Second, the construction industry is a project-based industry, and as such is much more fragmented than many other industries. The formation of a project team (including engineering, procurement, and construction professionals) is temporary and project-specific. Without a knowledge management system, it is difficult to reuse a professional's knowledge if he or she leaves the company or if he or she is no longer a team member.

1.3 Problem Statement

From the literature review, it has become clear that VE is an explicit procedure to achieve cost-effectiveness for a product, a project, or a system. However, there are some weaknesses in the current VE analysis which hamper its efficiency and effectiveness, the most significant of which are outlined below:

a. Importance of Function Analysis has been over-emphasized: It is questionable whether or not function analysis is in fact the core of VE. Some researchers (Palmer et al. 1996) considered VE workshop rather than Function Analysis to be the critical factor involved in ensuring the success of VE. Previous VE applications also indicated that VE could be successfully practiced either with or without function analysis. Moreover, some users have complained that function analysis is difficult to perform and might potentially restrain the VE team's creativity since the FAST diagram provides too many details upfront about the lower-level project functions.

b. Limitations of VE participants' experience, knowledge, and creativity: The VE team members' expertise and imagination are the only resources used to create alternative solutions. As one of VE's fundamental rules, group thinking is helpful to stimulate and rebound individual member's ideas, and results in a solution pool with large quantity and variety. However, it is often not sufficient to obtain break-through ideas from VE participants' contributions alone.

c. Lack of effort in understanding and formulating essential problems: VE has no preferable direction by which to search for solutions, a condition which is largely to the result of a lack of understanding of the system's essential problems. Both intuitive and analytical tools applied during VE's creativity phase are intended to defeat psychological inertia and generate intuitive solutions in a random manner.

d. Lack of effort in developing and evaluating alternative plans: VE analysis does not provide enough time to analyze project alternatives. Instead, most ideas originate from the creativity phase can be eliminated during the evaluation phase using the Gut Feeling Index within a couple of hours. It seems more appropriate for the VE team to develop and analyze a number of conceptual plans thoroughly than to generate dozens of ideas without any detailed evaluation.

On the contrary, TRIZ, a knowledge-based creativity technique, is equipped with a group of technical tools as a comprehensive approach to create innovative solutions for problems. In fact, the majority of VE's weak points are TRIZ's strengths. Rather than searching out an optimal solution from a big collection of ideas, TRIZ first simplifies problems to their basic formats, forcing a complete understanding of the essential problems. Next, TRIZ will offer the standard solutions - the methodologies that have been successfully used to solve similar problems in the past. TRIZ's intellectual power does not depend on the participants' presence or their collective imagination. Instead, it is embedded in TRIZ's methods and tools, which are derived from the analyses of 2.5 million patents across industries and domains.

A few researchers have explored the possibility of combining VE and TRIZ together. Dull (1999) has pointed out the strengths and weaknesses of both VE and TRIZ, and has discussed how to merge VE with TRIZ in three permutations. Chuksin and his colleagues (2003) integrated VE analysis and the TRIZ method to improve a stripping grain-harvesting machine, and found that the hybrid method is highly efficient in improving technical design. Although the TRIZ and Brainstorming are opposite in terms of the thinking approach (systematic vs. random), Nakamura (2001) reasoned that these are in fact complementary and their integration could lead to more efficient thinking.

These studies indicate the possibility of integrating VE with TRIZ. However, the proposals described in these papers are premature and not practical enough to be implemented in VE practice. This is partially because utilizing TRIZ knowledge is not an easy task. Normally, new users must invest significant effort to familiarize themselves with TRIZ as its body of knowledge is considerable. In addition, some TRIZ tools, such as effect database, may not be applicable to the construction industry. Some other tools, such as the 76 standard solutions for Su-Field analysis, may be too complicated for regular application. Therefore, TRIZ tools need to be selected and even simplified before being incorporated into VE process.

1.4 Thesis Objectives and Anticipated Contributions

The focus of this research is on improving the performance of current VE practice. As such, the recognized study objectives include:

- Fully reviewing all up-to-date TRIZ concepts and tools in order to understand which ones can fit best into the creativity phase of VE analysis. The secondary objective of this review is to simplify and condense the standard solutions for Su-Field analysis in order to make its application more efficient.
- Developing a systematic procedure to improve the performance of conventional VE practice through integration with TRIZ. This new framework is primarily intended to improve the efficiency and inventiveness of the workshop of conventional VE.
- Developing a knowledge management system for VE analysis. This experiment is intended to enhance the creativity power of VE through live collection and retrieval of the knowledge generated during VE session.

The anticipated contributions of this research are listed as follows:

- The ultimate purpose of conducting this study is to improve the current VE approach. It is expected that this work will increase projects' value if the enhanced VE approach is accepted as a part of a routing engineering exercise.

- This research is also expected to introduce a knowledge management system to the VE process. Because this is a pilot study in the area of managing VE knowledge, follow-up studies and applications will be inspired in order to better define and validate this concept.
- This research will eventually facilitate the innovation of construction technology, since TRIZ has the potential to generate more inventive ideas than those creativity methods being used by conventional VE study.

1.5 Research Methodology

The following steps will be implemented in order to complete this study:

- Review available literature regarding VE, TRIZ, and knowledge management in construction in order to identify opportunities for improvement of current VE process.
- Analyze TRIZ tools in order to better understand which ones can fit into the creativity phase of VE and how well these methods can solve problems related to construction.
- Simplify and tailor those TRIZ tools which will be applied during the creativity phase of the VE process.
- Develop the framework for TRIZ-enhanced-VE analysis by modifying the existing VE procedure as well as by combining TRIZ concepts and tools.

- Test the practicality of the TRIZ-enhanced-VE framework through a case study and student term projects and survey.
- Propose a knowledge management system for TRIZ-enhanced-VE analysis.
- Test the proposed VE knowledge manage framework by developing a sample knowledge management database system.

1.6 Thesis Organization

This dissertation is organized in the following sequence:

- Chapter 2 gives the full literature review about Value Engineering analysis, TRIZ, and knowledge management in construction.
- Chapter 3 discusses the applications of a number of selected TRIZ tools within the construction domain, all of which will be integrated into the creativity phase of TRIZ-enhanced-VE analysis.
- Chapter 4 summarizes and condenses 76 standard solutions into seven general principles.
- Chapter 5 introduces the framework of TRIZ-enhanced-VE, in which the various TRIZ theories and creative tools are incorporated in the VE process to reinforce VE's creative capability.
- Chapter 6 summarizes the results of the students' application and survey with respect to the TRIZ-enhanced-VE analysis.
- Chapter 7 presents a knowledge management system for VE knowledge acquisition, representation, and retrieval, which aligns with the proposed TRIZ-enhanced-VE process.

- Chapter 8 provides final discussions and recommendations for future research.

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Chapter 2 - Literature Review - TRIZ, Value Engineering, and Value Engineering Knowledge Management

2.1 Introduction

This chapter provides background knowledge about the current VE practice, the Theory of Inventive Problem Solving, and knowledge management related to the VE in order to inform the following chapters of this thesis. There are five sections included in this chapter.

The first section introduces the conception of VE analysis and its accompanying creativity tools. In detail, the contents covered in this portion review the definition and history of VE, discuss its standard procedure and its contributions in application at various stages of project development, and analyze those intuitive and analytical creativity tools which may be applied in VE.

The second section discloses the weaknesses of current VE due to its nature of practice. These factors explain why the overall opinion on VE is still controversial, even though it has become a routing exercise in the development of many projects. As a result, the discussions present the areas in which existing VE needs to be improved.

The third section briefly reviews the TRIZ theory and its major tools, including the contradiction matrix and 40 inventive principles, separation principles, patterns of evolution, Su-Field analysis and 76 standard solutions, scientific and technical effects, and ARIZ. Furthermore, this section discusses previous application of TRIZ in construction as a tool to foster innovation.

The fourth section summarizes previous studies which have attempted to integrate TRIZ with VE. It is clear from this summary that TRIZ has been identified as an analytical and knowledge-based creativity tool with great potential to enhance the effectiveness of VE at the creativity phase.

The last section introduces the concepts of knowledge and knowledge management and then discusses the importance of knowledge management in VE, pointing out that more studies need to be done in order to capture knowledge obtained through VE analysis and share it within companies and across industry. Since the research specifically related to VE knowledge management is inactive, the research regarding knowledge management in construction in general has been reviewed in order to gain a better understanding on how to consolidate, store, and retrieve construction-related knowledge.

2.2 Value Engineering

VE is an organized effort to analyze the functions of systems, equipment, facilities, services, and supplies for the purpose of achieving the essential functions at the lowest life cycle cost consistent with the required performance, reliability, quality, and safety (Younker 2003). Dell'Isola (1988) has defined VE as the process of relating the functions, quality, and costs of the project in the determination of optimum solutions for a project. A VE program provides organizations with a definitive tool to improve the value of any product, project, or process. This technique has been widely used by government agencies, financial institutes, manufacturers, design/construction contractors, and other stakeholders.

As has been mentioned, Lawrence D. Miles originated the value methodology while working for General Electric in the 1940s. Due to the shortage of critical materials, he was led to develop an approach which consumed less materials and money to realize the same function of products. Soon after, the Bureau of Ships of America chose to use the value analysis process during design to reduce cost, and they went on to coin the term Value Engineering to refer to the process. This was the first government organization to recognize the value of VE and officially advocate its application. Today, the departments of transportation in most of the United States have a policy of applying VE to projects that exceed 10 million dollars. A typical cost savings ranging from 3-5% has been estimated for these projects as a result of using VE.

VE is a process through which a multi-disciplinary team reviews project plans and identifies strategies by which to improve high cost functions. In fact, it does not aim to find the errors and omissions of a design at all. Normally, VE should be applied at the early stages of project design. Younker (2003) has suggested that a VE team should review projects at 30% and 65% completion of the design. Redesign costs could exceed potential savings if a value improvement solution is offered when major design has been completed. However, VE should not be ruled out at the construction stage, because contractors' practical experience, construction plans, and purchase options could lead to substantial cost reductions.

2.2.1 The Procedure of Value Engineering

A complete VE practice contains three phases: a pre-workshop phase, a workshop phase and a post-workshop phase. Efforts at the pre-workshop phase are made to ensure that appropriate information will be delivered to VE team members. All required information for the VE process will ideally be sent to those members prior to the VE workshop, so that the VE team members can find enough time to understand project background and collect up-to-date project information. The workshop is the most critical component of the VE analysis. During this phase, the project value will be increased by either increasing functions, decreasing cost, or both. Ultimately, the project's value will not be changed until value improvement solutions are implemented in the post-workshop phase.

As a formalized procedure to achieve cost-effectiveness for products, projects, or systems, the VE workshop consists of six steps as listed below (Younker 2003):

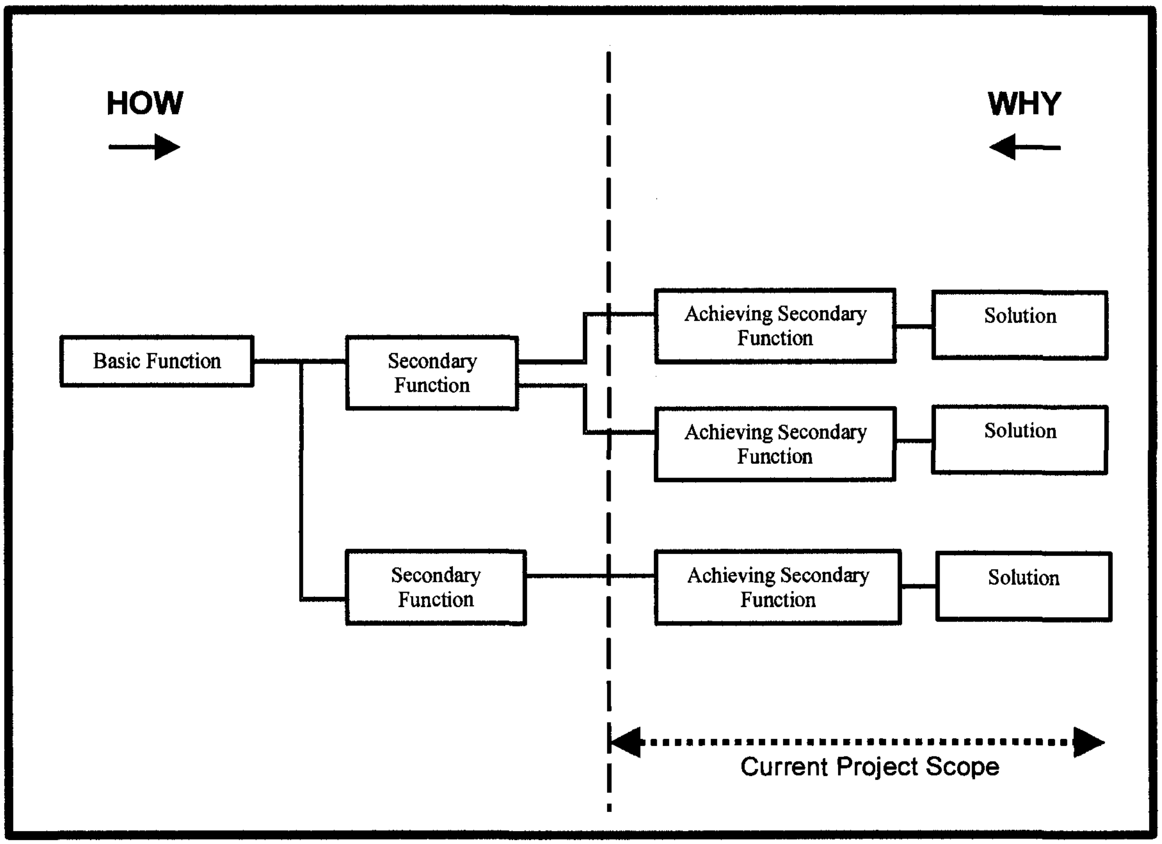

Figure 2.1: Functional Analysis Systems Technique

Step 1: Information and Function Analysis

Recognized as the backbone of the VE process, function analysis assists VE team members in reviewing the proposed project in order to fully define the scope of the project and clearly identify the basic functions where effectiveness could be improved or potential significant cost savings may be encountered. These basic functions are organized into a Function Analysis Systems Technique (FAST) diagram as illustrated in Figure 2.1, which serves as a tool to help the VE Team visualize the functions that different portions of a project must perform. As a method of stimulating organized thinking about any given subject, a FAST diagram allows managers to set priorities for analysis and to assess the compatibility of project alternatives.

Step 2: Creativity

The VE team selects specific functions for further analysis on the basis of cost and potential for improvement. Formal brainstorming sessions and sometimes other creativity techniques such as checklist and morphological analysis are used to generate a number of alternative methods by which to achieve the anticipated functions. Due to its simplicity, brainstorming has been widely accepted, and has become the most frequently used creativity tool. As team interactions increase its efficiency, six to eight persons are normally selected to form a group. In addition, the brainstorming group will be expected to conform to four regulations: (1) criticism is forbidden during an idea producing session, (2) wider ideas are encouraged, (3) the quality of ideas comes from a quantity of ideas, and (4) new thoughts can be formulated by combing through and improving other members' ideas.

Step 3: Evaluation

Analyses are performed by first passing or failing each of the brainstormed ideas, then combining or grouping similar ideas. The VE team as a whole discusses and records the advantages and disadvantages of each idea, and any ideas which have survived these discussions are selected as candidates for further development.

Step 4: Development

Detailed technical examinations follow, including investigations with regard to specific quantities, costs, and calculations for ideas which carry the potential for significant savings. Economic analyses of technically feasible alternatives are made. Ideas that pass the technical and economical analyses and which, in the opinion of the VE team, should be incorporated into the project are outlined in formal proposals.

Step 5: Presentation and Report

All ideas, calculations, and cost analyses recorded during the VE process are compiled in order to present the results of the study to the key decision-makers. A report is prepared to document the analysis methodology, the results of the VE analysis, and the proposal's disposition.

Step 6: Implementation

Accepted proposals are incorporated into the project and actual savings are recorded, where a number of different versions of a VE process can be found in current practice. The number of steps can vary from five to six or even more, but the number of steps is less important than the essential approach involved.

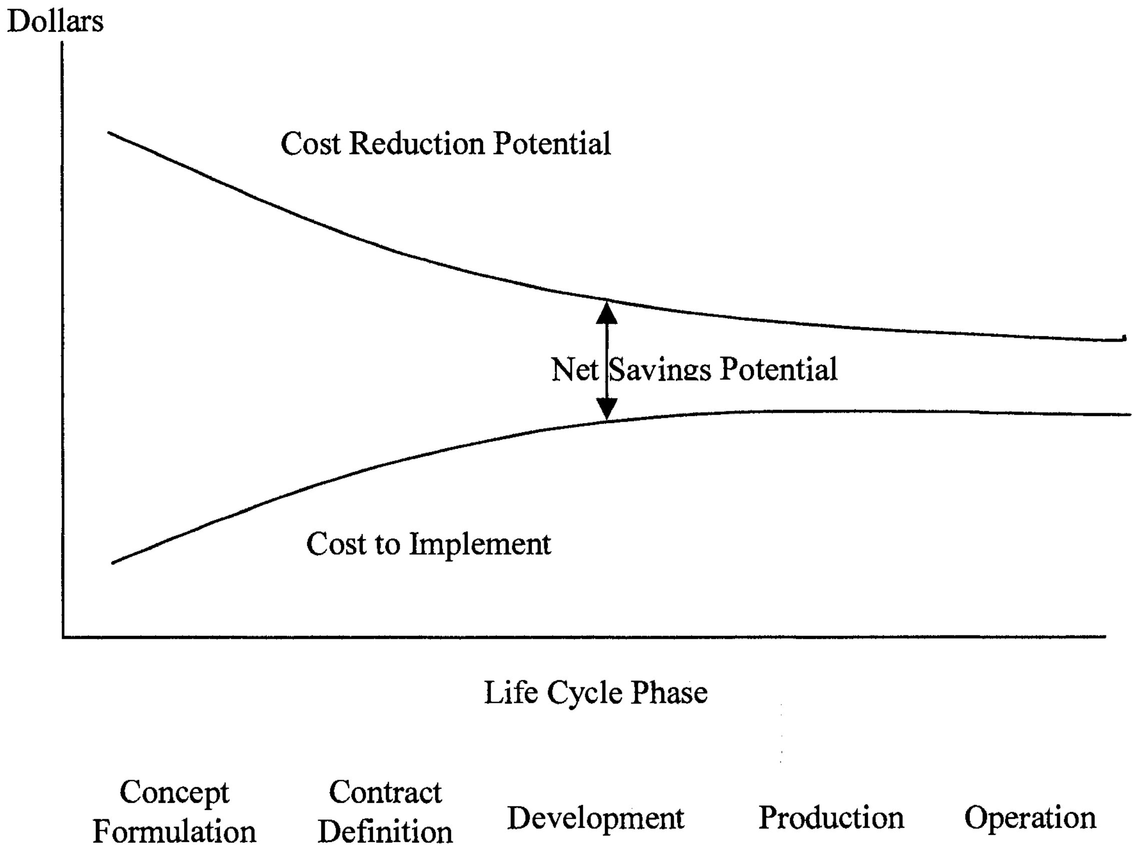

Figure 2.2: VE Savings Potential during Life of a Typical System

2.2.2 Value Engineering Saving Potential

As Parker (1977) has asserted, VE practice can be applied at any stage of project development. However, according to Figure 2.2, the contribution of net potential savings resulting from VE decreases as a project progresses through its life cycle. In order to maximize the investment return, then, VE should be performed as early as possible.

Parker has also explained that VE may be utilized in different stages of a project for various purposes:

Concept Formulation Stage

This phase aims at translating project requirements and specifications into feasible facility concepts which can achieve certain functionalities. The engineering competence of VE members is crucial during this stage, as the VE efforts made during this step will fundamentally decide whether or not a project is on the right track to achieve the functions needed.

Design Development Stage

At this stage, the project concepts are defined, and preliminary drawings and outline specifications are drafted. As a result, there will be sufficient information to conduct project quantity take-off and cost estimation. Meanwhile, this is the best time to question project performance as well. A VE study may identify alternatives which offer improved value by analyzing the essential requirements, technical characteristics, and design tasks.

Final Design Stage

Design details are formulated and schedules are created during this phase. Continuous VE effort is still essential to eliminate unnecessarily restrictive requirement details or unnecessary functions. However, redesign from VE efforts normally cannot be accomplished economically at this point unless the life cycle savings of the project is large enough to justify the expense.

Construction Stage

VE could be performed internally or by the contractor during the construction phase. Internal VE may be accomplished by reviewing specific contract requirements and initiating change orders to save money. Furthermore, change order is reviewed in an attempt to prevent adding unnecessary functions as well as to create alternatives that could reduce costs or remove the necessity for the change in the first place.

Operation Stage

Since the total cost of a project is affected by operation, maintenance, and other supporting costs, reducing operation costs can lead to the reduction of project life cycle cost. During the operation phase, VE study provides a last opportunity to address life cycle cost if this process had been omitted earlier due to a lack of time or some other factor.

2.2.3 Creativity Tools for Value Engineering

Brainstorming and a number of other types of creativity techniques have been applied in the creativity phase of VE. Creativity techniques can facilitate individuals or groups to become more creative so that they can solve their problems in a more innovative and efficient manner. The objective of the creative thinking process is to promote thinking outside the recognized boundaries; to encourage curiosity; to think beyond conventional ideas; to depend on the imagination; and to randomly envision numerous alternatives (Candy 1997; Schlange and Juttner 1997).

Creativity methods can be classified into two main categories: intuitive techniques and analytical techniques. Intuitive techniques, such as Brainstorming, Brainwriting, and Six Hats, tend to overcome psychological inertia by inspiring random thinking from an individual or a group. Although these freewheeling techniques may often generate half-completed or apparently insignificant ideas, in many cases they increase the opportunity for solving problems. Analytical techniques, on the other hand, have clear rules to follow. For instance, the Morphological Matrix requests users to: (a) list the attributes of the situation, (b) place as many alternatives as one can think of below each attribute, (c) mix different alternatives to create a new situation, and (d) evaluate and improve the mixture for final selection. As the known information is reorganized through certain procedures, this process helps to solve problems using novel strategies. Analytical techniques include Morphologic Analysis, Concept Mapping, Lotus Blossom, Mind Mapping, etc.

Among the creativity tools being currently used by VE, brainstorming is the one most often employed to develop good alternatives for a project. Brainstorming is utilized to generate new ideas by freeing the mind to accept any idea suggested, thus allowing freedom for creativity. During the brainstorming, all ideas are equal, and it is expected that some of the greatest ideas initialized from random, nonsense thoughts will be translated, adapted, refined, twisted or inverted by other team members into unforeseen solutions. This approach is designed for a group of 5 to 10 participants, each of whom will have a relevant and diverse background related to the task at hand. As Bottger and Yetton (1987) discovered, the experience level, expertise, and competence of group members; group development level; and the level of diversity within the brainstorming group are important factors in generating creative results in a productive manner.

Other than intuitive and analytical techniques, a knowledge-based creativity methodology, TRIZ, has been recently developed in this regard. It enables participants to control the course of innovation and push it to a previously unreachable level (Clarke 1999). The theory of TRIZ and its potential to empower the effectiveness of VE will be discussed in sections 2.4 and 2.5.

2.3 Weaknesses of Current Value Engineering Process

VE has been widely practiced in the construction industry and has become an integral part of many construction projects over the years. The outcomes generated by the multi-disciplinary team in the VE process often improve the value of the project without sacrificing the designed project functions. However, the overall expert opinion regarding VE is still mixed. Through thorough investigation, it seems that the following reasons could account for the uncertainty of the outcomes of VE study which has resulted in mixed user feedbacks.

Importance of Function Analysis was Over Emphasized

Although some VE researchers (Dell'Isola 1988; Zimmerman and Hart 1982) have recognized the contributions of function analysis to the success of VE study and have concluded that VE is merely a cost cutting tool if utilized without function analysis, other scholars have presented evidence which still questions the necessity of function analysis. Palmer and his colleagues (1996) have stated that the outputs of VE have little or no relationship with function analysis. In fact, they have further argued, alternatively, that VE workshop itself is a critical factor, and one which has been heavily influenced by the team leader's personality, the time of the study, the interaction between members of the VE team, the input of the design team, and the role of the client. Shen and Liu (2003) identified and ranked the critical success factors of VE study according to the statistical analyses which had been based upon the feedbacks of VE experts. The results suggested that the VE team, the client, the facilitator, and other related players all have important roles in contributing to the success of VE process. Still, factors related to the VE team itself were found to account for the most significant impact. Accordingly, Shen and Liu recommended carefully forming a VE study team according to such criteria as professional experience level, VE study experience, member's personalities, and assurance of a multi-disciplined group.

In addition, the different practices in different countries have also led some observers to question the value of function analysis. Shen (1997) compared VE approaches implemented in USA and Australia. This research found that standard American VE process needs 40 hours to be combined with function analysis, whereas Australia's requires only about 8 to 24 hours not counting the execution of FAST-diagram-based function analysis. Palmer and his colleagues (1996) also found that, in fact, more than 50% of VE consultants develop a FAST diagram in less than half of their VE applications. These controversial practices raise a question: how important is it to have function analysis if both American and Australian practices are effective?

While it is questionable whether or not function analysis is in fact the core of VE study, Fong (1998) discovered based on his questionnaire survey that 42 out of 112 VE consultants agree or strongly agree that it is difficult to perform function analysis. Palmer and his colleagues (1996) also concluded in their holistic appraisal of VE for construction in the U.S. that "despite its outward simplicity, function analysis is extremely difficult and takes a great deal of time and experience." According to Shen's (1997) comments, many hours in VE sessions have to be spent to educate participants since most of them are not familiar with VE processes and principles.

In fact, from the author's VE experience, most team members other than facilitator are unfamiliar with VE application. Therefore, it is a major challenge for VE participants to learn how to develop a FAST diagram and grasp the concept in the course of only a few hours just prior to the execution of function analysis. It seems that function analysis, regarded as a key component of VE, may not be able to play the role it was meant to play.

Limitations of VE Participants' Experience, Knowledge and Creativity

Because VE is heavily reliant upon brainstorming and other freethinking and large-quantity-based creativity techniques which in turn are still directly or indirectly dependent upon the creativity of the brainstorming technique, the outcomes stemming from this idea generation step are limited by the VE participants' experience, knowledge, and creativity (Dull 1999). In other words, the VE team members' expertise and imagination are the only resources available in this step by which to create alternative solutions. It is for this reason that numerous studies (e.g., Palmer 1996; Shen and Liu 2003) have underscored that the personalities of VE participants constitute one of the most critical factors at play, a factor which may dictate the success of VE process.

As one of VE's fundamental rules, group thinking is helpful to stimulate and rebound individual member's ideas, and can result in a solution pool with ideas of a large quantity and variety. However, it has been commonplace to have no fresh and creative ideas coming out of VE sessions (Sawaguchi 2000), mainly because people working in and related to certain industry-fields have been trained for so many years to understand problems from certain angles and to resolve them using certain approaches. As such, VE participants' contributions are often far less than sufficient to generate break-through ideas.

Other than the issues addressed in the above discussion, all of which were identified through the literature review, the author has also identified the following shortcomings associated with current VE analysis.

Lack of Efforts in Understanding and Formulating Essential Problems

VE fails to seek high quality ideas from the outset of the exercise, a reality which is largely due to a lack of understanding of the system's essential problems. Instead, one assumption being made is a quality idea results from a quantity of ideas being generated. As a result, the VE team spends considerable time generating ideas in an attempt to find desired solutions. Depending on the complexity of a problem, the request for the number of collected ideas will differ significantly. If anticipated solutions are within the VE members' experience and knowledge, fewer ideas will be needed, whereas the demand for ideas will be substantially increased if expected solutions are beyond the team members' expertise. However, there is no guarantee in this regard that ideas which transcend physiological inertia will be born.

Lack of Efforts in Developing and Evaluating Alternative Plans

To be distinguished from technical invention, where a novel idea may bring light to and essentially resolve an entire problem, the development of a project plan is in fact much more complicated. Judgment about a concept cannot be made until all its impacts—related to project cost, schedule, safety, constructability, durability and so on—have been analyzed. Furthermore, a project requires a group of concepts rather than a single idea in order to form a comprehensive proposal in accomplishing its objectives. As such, much effort will be required to fine-tune every individual thought so that they can work together seamlessly as a whole. Unfortunately, VE practice does not allow enough time to do so. Instead, most ideas originating from the creativity phase are eliminated during the evaluation phase within a few hours using the Gut Feeling Index—a rough and subjective assessment criteria. It is thus questionable whether or not each alternative idea can be fairly evaluated. It seems more appropriate for the VE team to develop and analyze a number of conceptual plans thoroughly than to generate dozens of ideas without a detailed evaluation.

Existing Resources Not be Fully Used

The VE process does not set out to fully utilize the existing resources in a project system. Normally, ideas intended to help realize required functions are expected to bring new components into an existing system. Similar to an ecological system—where the introduction of a new species could potentially destroy its natural balance—with VE additional components could likely have a negative impact on the existing system. In fact, less or no requests of new system components would be needed if consideration had first been given to how to rely on and fully utilize existing resources. Consequently, negative impacts would be minimized or eliminated and the system would become more ideal. In this regard, Altshuller (1996) has shown that systematic progress which approaches ideality is tightly associated with the utilization of available resources.

2.4 Theory of Inventive Problem Solving (TRIZ)

As mentioned, TRIZ is a Russian acronym for the "Theory of Inventive Problem Solving". As a knowledge-based problem-solving methodology, TRIZ includes a series of approaches by which to analyze problems from different angles and seek inventive solutions (Savransky 2000). Altshuller initially developed TRIZ in 1946. After studying more than 200,000 patents, he found that the same fundamental principles appeared repeatedly in inventions from different industries and in different years, and that the most creative patents have been embedded with solutions which satisfy contradictory requirements. He then extracted and compiled the fundamental innovative principles behind those inventions into an organized body of knowledge, and named it TRIZ.

As TRIZ researchers have determined, this generalized body of knowledge presupposes that (1) the advancement of inventions obeys certain universal principles of creation, (2) that all innovations across industries and sciences follow a small number of inventive principles, (3) that technology evolves according to certain trends, (4) that the idealization of a solution is a process to either destroy conflicts and trade-offs or to transform harmful elements of a system into useful resources (Creax 2007). As a result, TRIZ researchers have developed a group of interrelated concepts and knowledge management tools in an attempt to assist inventors seeking ideal solutions in a relatively simple and predictable manner.

As schematically illustrated in Figure 2.3, TRIZ contains a number of concepts and tools that guide systematic approaches and generic principles to formulating and analyzing problems, generating creative ideas, and forecasting the evolutionary trend of a system or project. One advantage of TRIZ is that it can overcome psychological inertia, which represents the key barrier to personal creativity and problem-solving ability. TRIZ allows problem solvers to generate creative ideas and solutions that transcend their own knowledge, experience, and expertise (Dull 1999).

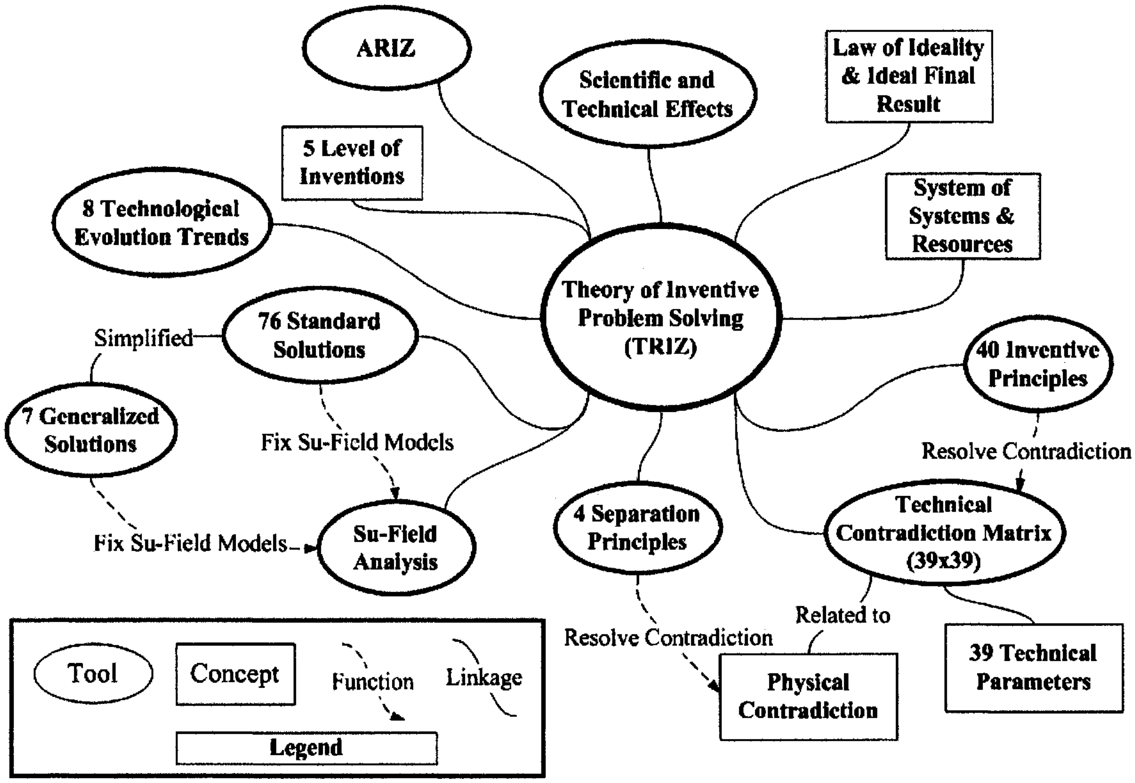

Figure 2.3: TRIZ Concepts and Tools

2.4.1 Law of Ideality

One of the fundamental findings of TRIZ is that any system obeys the Law of Ideality and will be consistently evolved to become simpler, more reliable, effective, and ultimately perfect during its lifetime. TRIZ defines Ideality as follows:

$$\text{Ideality} = \text{Useful functions} / (\text{harmful functions} + \text{costs}) \qquad (1)$$

Theoretically, an ideal system is the one that performs the function at zero cost and with no harm. While a system is approaching ideality, it costs less and becomes simpler and more efficient. Ideality always reflects the maximum utilization of existing resources within the system or organization, including some free resources—such as gravity, air, heat, magnetic field, and light, or some idle resources—such as existing features, company experience, and the skills of employees, which can be added to the system at either minimal or no cost (Apte 2005; Zanni and Rousselot 2006).

The Law of ideality changed the conventional rule, which stated that extra components must be added in order to realize new functions. Moreover, keeping the ideal objective in mind during the problem solving process helps control the introduction of new substances into the system, which usually increases cost and potentially causes a contradiction with existing substances or components of the system.

2.4.2 Systems and Resources

TRIZ considers a technical system to be a "system of systems". In other words, a system is a three-level hierarchical system, including a base system, a sub-system, and a super-system. A base system consists of sub-systems which provide various specific functions. On the other hand, a base system is more closely associated with a super-system. The sub-system may contain many parts and components. For instance, a monitor is a sub-system of a computer as well as the super-system of the screen if it is considered as a base system.

The TRIZ concept presupposes that resources exist within the three levels in any kind of format, such as space, time, function, substance, property, energy, field, etc. The objective of a system's evolution is mainly to improve those less developed components which conflict with other, better-developed parts. Furthermore, the system development pursues ideality by utilizing available resources. In other words, the progress towards ideality greatly depends upon how available resources are utilized in a technical system.

2.4.3 Level of Innovation

Recognizing that not every invention carries the same inventive value, TRIZ categorizes innovations into five levels as summarized in Table 2.1 (Mazur 1995; Apte 2005).

- Level 1: Apparent solutions (32% of all patents). Routine design problems are solved by methods well known within the specialty. No invention is needed here.
- Level 2: Minor improvements, removing some contradictions (45% of all patents). Methods are known within the industry. 40 Inventive Principles are applied in order to separate and solve technical contradictions. Also, this level requires knowledge from different areas within the same field.
- Level 3: Major improvements requiring Su-Field analysis (18% of all patents). Fundamental improvements are made to an existing system using methods known outside the industry. 76 Standard Solutions and Scientific and Technical Effects are applied.
- Level 4: Radical change / new concept (4% of all patents). A new generation is developed to perform the primary functions of the system using new principles. The solution here is typically more scientific than technological in nature. ARIZ is utilized to describe the real problem and deliver possible new solutions.
- Level 5: Discovery previously unknown (1% of all patents). A rare scientific discovery or pioneering invention is uncovered.

It is clear that about 95% of problems engineers face have been solved within their industry, whereas only in 1% of cases have experts failed to find a solution to the problems. It is also noted that the number of trials needed to produce solutions using traditional creativity methods will be radically increased as the level of inventiveness increases.

Table 2.1: Levels of Inventiveness

Level	**Degree of Inventiveness**	**% of Solutions**	**Source of Knowledge**	**Approximate # of Solutions to Consider**
1	Apparent solution	32%	Personal knowledge	10
2	Minor improvement	45%	Knowledge within company	100
3	Major improvement	18%	Knowledge within the industry	1,000
4	New concept	4%	Knowledge outside the industry	100,000
5	Discovery	1%	All that is knowable	1,000,000

2.4.4 TRIZ Tools

In addition to the above concepts, TRIZ generates a group of innovation tools, such as Su-Field Analysis, Contradiction Matrix, Technological Evolution Trends, ARIZ, etc. Evidently, being the only technology able to overcome psychological inertia, TRIZ provides systematic approaches to formulate problems, analyze systems, generate innovative ideas, and forecast evolution trends based on the common solutions derived from intensive studies of previous inventions.

All TRIZ tools follow the general problem-solving model illustrated in Figure 2.4. Rather than directly seeking solutions to resolve current problem, TRIZ first identifies the current problem. Then, the problem must be formulated in order to link it with certain analogous standard problems which have already been solved. As a result, a set of standard solutions will be acquired from the TRIZ knowledge database. Finally, these known solutions will inspire users to find practical solutions in resolving their own problems. Some of the most important TRIZ tools are briefly introduced in the following sections.

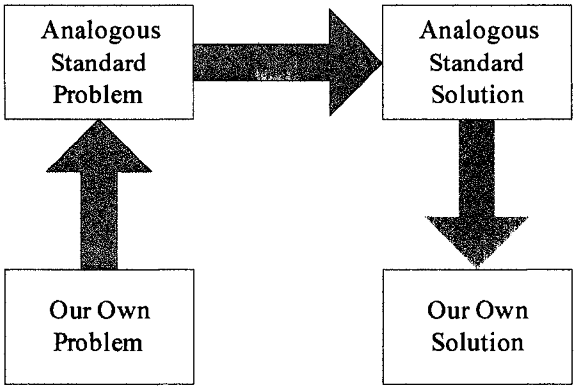

Figure 2.4: General Problem Solving Model

Contradiction Matrix and 40 Inventive Principles

Technical contradiction occurs when increasing one desirable parameter in a system leads to an increase in another less desirable parameter in the same system, or a decrease in a different desirable parameter. For instance, to improve the cleaning quality of a vacuum cleaner, we can boost its suction power; however, this will also increase the cleaner's noise and weight. Generally, conventional problem solving leads to a compromise solution, where the solution will become innovative only if it eliminates the contradiction. TRIZ has identifies 39 parameters (referred to in Appendix 1) that have often caused technical contradictions in a technical system, and develops 40 inventive principles (referred to in Appendix 2) that have been commonly utilized to solve technical contradictions occurring in different fields. To help users search for inventive principles according to certain identified contradictions, TRIZ has designed a contradiction matrix as shown in Appendix 3.

Separation Principles

Other than technical contradictions, TRIZ also defines the concept of "physical contradictions". Physical contradictions appear when the same parameter of a technical system is requested for two opposite properties. For instance, in producing a mixture, a physical contradiction might be expressed as: the mixture must have a high temperature to dissolve a compound rapidly, but it must also have a low temperature to remain homogenous. TRIZ provides methods to solve physical contradictions as follows:

1. Separate opposite properties in time: during one period an object has a property P, and during the other period it has the anti-property -P.
2. Separate opposite properties in space: part of the object provides property P, the other part of it gives the anti-property -P.
3. Separate opposite properties between the whole system and its parts: the whole system has property P while its components have the opposite property -P.
4. Separate opposite properties under different conditions: opposite properties coexist within the same system under different conditions.

Patterns of Evolution

TRIZ has also discovered that the evolution of any system follows certain objective laws rather than being randomly generated—laws which have been used in different fields in various formats for some time. Ultimately, every system evolves toward increasing its ideality, and evolution intends to consume a system's own resources in a more efficient manner. TRIZ condenses these laws into eight evolution patterns:

1. A technological system evolves through periods of infancy, growth, maturity, and decline.
2. The general direction of system development is toward increasing ideality.
3. Different components of a system reach their inherent limits at different times, resulting in contradictions.

4. A system evolution follows the increase of dynamism and controllability in order to allow for functions to be performed with greater flexibility or variety.
5. Technological systems tend to develop first toward increased complexity and then toward simplicity through integration.
6. As a system evolves, system elements are matched or mismatched to either improve performance or compensate for undesired effects.
7. Technological systems tend to transform from macro-systems to micro-systems. During this transition, different types of energy fields are used to achieve better performance or control.
8. System evolution tends to decrease human involvement and free up personnel to perform more intellectual work.

Su-Field Analysis and 76 Standard Solutions

TRIZ has defined function as the interaction between two substances and a field acting upon them. In other words, a function is the output of a substance known as the "Tool" interacting with a substance known as the "Object" within a certain field. Substances may be objects of any level of complexity, from a single item to a complex system. The field, generated by a third part, can refer to a broad spectrum including the fields of mechanics, chemistry, physics, gravity, thermal dynamics, magnetics, acoustics, etc.

The Su-Field model is a fast and simple analytical tool which can be used to identify problems within a system, and which tends to work best when applied to well-formulated problems. Normally, a technical system should be able to be symbolized as a Su-Field model. An ill system is one which creates undesired effects or in which any of the three elements is missing. Complex systems can be modeled by connecting multiple

Su-Field triangles. Once a technical system is simplified using the Su-Field model, it becomes easier to discover the system's problems by analyzing the undesired interactions resulting from the Su-Field model. In this regard, TRIZ has identified 76 standard solutions (Appendix 4) to modify and improve Su-Field models.

Although this broad field of 76 standard solutions gives users numerous choices by which to improve a Su-Field model, the solutions are complicated in their use. To respond to this issue, Chapter 4 will discuss how 76 standard solutions have been summarized into seven general principles so that users are able to carry out Su-Field analysis more efficiently.

Scientific and Technical Effects

In order to provide the means of realization, TRIZ has created an effect database in which an effect is depicted as the interaction between two or more parameters under certain operating conditions. In other words, an effect is described as a set of outcomes resulting from a set of inputs. For the case in which an inventor wants to realize a specific function, he or she can look at possible innovative solutions from broad technical or scientific areas other than his or her own field by searching the database. The effect database works extremely well in circumstances where the desired function of a Su-Field model is known but for which there is no known method by which to realize it.

Algorithm for Inventive Problem Solving (Russian Abbreviation: ARIZ)

As one of TRIZ's major analytic tools, ARIZ provides step-by-step guidance that one can follow in order to create innovation solutions using TRIZ technology. The procedure can be applied to solve complex problems using a solution for which contradictions can hardly be identified. The latest version, ARIZ-85C, includes nine steps as listed below (Apte 2005):

a. Identify and formulate the problem.
b. Make Su-Field models for the part(s) of the system for which problems have been encountered.
c. Formulate an ideal final result and define the ideality.
d. Make a list of the available resources (for the base system, sub-systems, and the super-system).
e. Look into the database of examples and find an analogous solution.
f. Resolve technical or physical contradictions using inventive or separation principles.
g. Starting from the Su-Field model, generate several solution concepts.
h. Implement solutions using only the free available resources of the system.
i. Analyze the modified system to verify that no new drawbacks have appeared.

2.4.5 TRIZ Application in Construction Industry

Although TRIZ has proven to be an effective systemic approach for solving technical problems with innovative solutions, little research has been conducted to introduce this technique to the construction industry. Without any professional experience, Mohamed (2002) used TRIZ tools such as Su-Field analysis and Contradiction Matrix to analyze a number of tunneling problems. In fact, his proposed solutions are very close to what tunnel experts have previously suggested. He therefore alleged that TRIZ has the ability to guide the problem solver towards the most effective solutions for solving a problem.

Furthermore, this guidance offered by TRIZ tools may serve to minimize the randomness in searching for solutions and force all VE team efforts in the most promising direction. He also concluded that TRIZ application could possibly lead to solutions which would be new to the construction industry but which have been widely accepted in other disciplines.

Inspired by the manner in which TRIZ's contradiction matrix consolidates and preserves high-level knowledge, Mohamed also developed a framework by which to systematically accumulate construction contractors' knowledge and experience so that it would become accessible in facilitating day-to-day construction decision-making. In addition, he developed a hybrid function-based simulation model according to TRIZ's function analysis concepts, state-based simulation concepts, and intelligent agent concepts. This framework provides a new approach to create special purpose simulation tools and build simulation models in construction.

2.5 TRIZ Integration with Value Engineering

One important feature of TRIZ is that it enables users to control the process of innovation, as TRIZ relies on technology rather than mere psychology in generating creative ideas. This characteristic of TRIZ distinguishes it from the freethinking-based creativity techniques that have been used in conventional VE exercises. In fact, some researchers believe that TRIZ has the potential to generate more innovative ideas and enhance the efficiency and effectiveness of the VE process.

Hannan (2000) has already predicted that TRIZ as a management tool will become more popular as more and more practitioners recognize its usefulness. In his view, VE is focused specifically on engineering and management, whereas TRIZ is focused generally on innovation. Hence, TRIZ should be integrated into VE and not the other way around if any form of integration is pursued. He also addressed the fact that the combination of TRIZ and VE will not be practical unless there are individuals involved who have sufficient knowledge in both areas.

Clarke (1999) discussed in his paper that problem solving is determined both by the searching process and by availability of the knowledge needed to solve the problem. Accordingly, he considered TRIZ to be an analytical and knowledge-based tool by which to enhance the effectiveness of VE process and the development of practical solutions. He suggested that the opportunity for integration between TRIZ and VE lies within the brainstorming process, where the transition is made from identified functions to concrete solutions. Because TRIZ provides a structured and systematic approach to substitute for the current creativity phase of VE, (which highly relies on the talent of the facilitator and the knowledge of the participants), it ensures that all creative abilities are invested in the right direction.

Sawaguchi (2000) has observed that it is difficult to transcend psychological inertia and come up with good ideas using brainstorming-based idea generation in conventional VE job planning. He recommended the utilization of both Innovation Guide and brainstorming for the purpose of idea generation. Here, Innovation Guide refers to a subset of the 76 standard solutions and effects.

Dull (1999) has indicated that in his opinion VE's advantage lies in its ability to foster team building, whereas the strength of TRIZ is that it is effective at offering more creative solutions than what may have originated from the VE team's collective knowledge and imagination. As a result, it is feasible to integrate the two problem-solving methodologies and obtain more comprehensive results than what would have been rendered by applying either approach individually. In addition, he also agreed with Hannan that it is easier to incorporate TRIZ into the VE job plan than vice versa. Moreover, he advised that a combined VE/TRIZ analysis would be the approach best suited to technically complex projects or manufacturing processes. His suggested combined job plan is summarized in Table 2.2.

In addition, both VE and TRIZ look for the best ratio of function to cost. According to VE, value is equal to function divided by cost. The value produced by a system can therefore be increased by either improving its function or reducing its cost. On the other hand, TRIZ follows the law of ideality, which is defined as the ratio of useful function against the summation of harmful function and cost. As harmful functions will eventually result in extra costs to overcome their negative impacts, the essential principles of value and ideality are the same. In order to improve a project's value/ideality, both techniques seek to reduce costs while maintaining the project's basic functions.

Since TRIZ has the potential to enhance the efficiency and effectiveness of the VE process, and both techniques ultimately pursue the same objective, the author proposes a framework in Chapter 5 by which to incorporate TRIZ tools into conventional VE.

Table 2.2: Modified Value Engineering Job Plan to Include TRIZ

STEP	VE PHASE	VE JOB PLAN DESCRIPTION	TRIZ ADDITION
	Information		
1		Pre-Workshop activities	
2		Issue Orientation Memorandum	
3			Issue and receive Innovative Situation Questionnaire (ISQ)
4		Project management team briefing and questions & answers	
5		Function analysis	
6			Problem formulation
	Creative		
7		Brainstorming and/or other creativity exercises	
8			Select the most promising contradictions
9			Prioritize and refine directions for innovation
10			Develop concepts for innovation
	Analysis		
11		Make the first cull, e.g., pass/fail/risks, gut feeling index, etc.	Include TRIZ concepts in the VE analysis
	Development		
12		Develop surviving ideas from the analysis phase, i.e., technical development, life-cycle cost analysis, implementation plan	
13			Use TRIZ on very promising ideas that have "unsolvable" roadblock
14		Finalization of ideas, i.e., peer review, grouping, pre-sell	
	Implementation		
15		The accepted VE proposals are incorporated into the project per the Review Board's instructions and the VE Team's plan	

2.6 Value Engineering Knowledge Management

Value engineering (VE) has been practiced for over half a century with the overall aim of producing innovative ideas and solutions by which to enhance project value. Surprisingly, little research has been conducted which investigates how to reutilize these ideas and solutions for future projects and share the VE knowledge throughout the entire company or the entire industry. VE usually starts from scratch with each application and its success relies solely on the VE team members' experience and competence. Based on the literature review, no knowledge management system has been identified by which to support VE analysis.

2.6.1 What is Knowledge and Knowledge Management?

Knowledge can be distinguished into two categories, explicit and tacit (Nonaka and Takeuchi 1995). Within the construction industry, explicit knowledge refers to documented information, such as project information, design drawings and specifications, cost reports, risk analysis results, and other information being collected, stored, and archived by a company in either paper or electronic format and made available to other users. On the contrary, tacit knowledge refers to the experience and expertise of personnel, the company culture, lessons learned, know-how, and other elusive yet extremely valuable forms of information (Lin et al. 2005).

Knowledge will not be of any value unless it is used actively. Thus, the knowledge management system plays a pivotal rule in tapping into the value of knowledge. Carrillo and Chinowsky (2006) have noted that the objective of knowledge management in the construction industry is to systematically develop and utilize a company's knowledge by arranging organizational knowledge, capturing lessons learned from finished projects, and building collaboration among departments with shared interests.

2.6.2 Importance of Knowledge Management in Value Engineering

Conducted by a multi-disciplinary project team with intensive experience and specialized knowledge during the project planning phase, VE is an engineering process by which forms of tacit knowledge, such as know-how and experience, are utilized in order to generate a large number of ideas which achieve the essential functions of a project in the most economical manner. During VE practice, significant engineering talent and efforts are invested with great cost in order to create distinctive approaches and innovative solutions to improve project value.

With the focus primarily on the stimulation of VE applications, little research has been carried out with respect to how to capture best engineering and construction practices originating from VE analysis and pass this hard-earned knowledge on to future projects, or on how to effectively and efficiently share this knowledge. Often, engineers have found themselves "reinventing the wheel", and intellectual strength of companies has deteriorated as experts move on or retire.

2.6.3 Current Research of Knowledge Management in Construction Industry

While research in the area of VE knowledge management is for the most part inactive, numerous papers have been published in the field of construction which discuss the consolidation, storage, and retrieval of constructability knowledge, construction domain-specific knowledge, and lessons-learned from the design review process.

Several researchers have attempted to create knowledge databases according to some specific type of structures or classification and to incorporate them into the design and construction phase of a project. East and Fu (1996) have argued that design reviewers have lacked the necessary time to access stand-alone repetitive deficiency checklists; therefore, they recommended a data mining tool called a lessons-learned generator by which to identify and add frequently used design review comments into the database for use in new projects. Pulaski and Horman (2005) introduced an approach to organize constructability information in accordance with the timing and levels of details required which will assist a project team in identifying and resolve constructability issues at the appropriate time. A design review checking system, called corporate lessons learned, was developed by Soibelman et al. (2003) to collect personal experiences and lessons learned on projects and incorporate these data into a corporate knowledge base. These research studies all highlighted the necessity of handling construction knowledge, and provided preliminary insights about how and when the information should be cleaned and saved into the database. Although a few concepts pertaining to data categorization have been presented in these papers, they have been too generic to be used effectively in organizing information and retrieving the desired results, a reality due in large part to their inability to break down knowledge into specific domains and narrow down the scope of the search. As a consequence, users have had to depend on their personal capability to recognize the best-fit solutions from data collection in order to solve new problems.

To overcome the randomness of knowledge extraction, a number of studies have explored the notion of automating the knowledge acquisition, representation, and retrieval processes by applying such artificial intelligence techniques as machine learning and artificial neutral networks (ANN). Skibniewski, Arciszewski and Lueprasert (1997) verified the notion of using a machine learning technique to automate the constructability knowledge acquisition process in the design of a reinforced-concrete beam. Rather than using explicit generalization rules, Knapp and Wang (1992) experimented with a neural network approach for the automatic acquisition of process planning knowledge. Both methods require a large amount of data in order to train their models. As the scope of knowledge requirement increases, the computational requirements will grow rapidly. Moreover, this process cannot feasibly depend on previous training to handle new and unforeseen cases.

Alternatively, TRIZ has been experimented with by Mohamed and AbouRizk (2005) for the purpose of managing construction knowledge. Taking into account the concepts of contradiction and inventive principles associated with TRIZ, Mohamed and AbouRizk developed a tool by which to consolidate the solutions derived for technical difficulties encountered by a major contractor in Canada. This prototype is also helpful in searching for and retrieving information to solve new problems.

The first attempt to develop a knowledge framework using TRIZ concepts was published by Mann and Hey (2003). Adopting the TRIZ concepts of functionality and contradiction, they proposed knowledge management schemas that enable storage and access of knowledge by function classification and saving and reusing of design solutions according to the design conflicts solved and principles applied. Furthermore, they concluded that a TRIZ-based knowledge management system has four advantages:

1. It is very effective at consolidating, accessing and retrieving knowledge from a database.
2. It can be easily incorporated into a company's standard problem-solving protocol, and can collect knowledge automatically throughout this ongoing process.
3. It facilitates knowledge transfer and sharing across disciplinary boundaries and therefore generates more creative solutions.
4. The effort needed to access appropriate information and techniques in solving the problem at hand will be considerably reduced.

Inspired by fellow researchers' findings and the desperate industrial demand for a knowledge management plan for VE analysis, a prototype framework to capture and retrieve knowledge generated from VE analysis has been proposed and is presented in Chapter 7.

2.7 Conclusions

VE constitutes an organized attempt to analyze the function of projects in order to achieve the essential functions at the lowest possible life cycle cost in a manner which is consistent with the required performance, reliability, quality, and safety. While this technique has been widely accepted by the construction industry over the years, there is still mixed feedback with regard to the end result of VE analysis. As mentioned above, the discussion in this chapter has indicated that the contradictory opinions observed have likely been a function of whether or not users have obtained innovative ideas that improve project value based on previous VE applications. Furthermore, this chapter has identified some of the shortcomings existing in current VE process: (1) Function analysis is not critical because the FAST diagram provides too many details upfront about lower-level project functions and thereby limits the creativity of the VE team; (2) The outcomes stemming from the creativity phase are limited by the experience, knowledge, and creativity of VE participants; (3) VE analysis is not sufficient to understand and formulate essential problems; (4) VE analysis is not sufficient to develop and evaluate alternative plans; and (5) the VE process does not fully utilize the existing resources within a project system.

To overcome these weaknesses of conventional VE and boost its creative capability, a number of studies have suggested that TRIZ should be integrated into VE as a structured and systematic approach to substitute the current creativity phase of VE. Being the only technology able to overcome psychological inertia, TRIZ provides systematic approaches to formulate problems, analyze systems, generate innovative ideas, and forecast evolutionary trends based on the common solutions derived from intensive studies of previous inventions.

In addition, VE needs to be improved in terms of its ability to capture and manage the engineering and construction knowledge obtained from VE analysis and share it efficiently within a company and across industry. During the VE process, significant engineering talents and efforts are invested at a great cost in order to come up with distinctive approaches and innovative solutions. It is worthwhile to capture and reuse these intellectual assets of companies rather than recreating them at each time when they are needed.

This chapter has thus introduced the fundamental principles and concepts of VE, TRIZ, and VE knowledge management, as well as their many current applications within construction industry. Based on the literature review, it has become obvious that the current VE process needs to be improved in order to make it more efficient and efficacious. It also seems feasible that TRIZ can not only help enhance the creative capability of VE, but can also assist in managing the knowledge originating from VE studies. Based on these findings, an enhanced VE framework (referred to as the TRIZ-enhanced-VE framework) is proposed in Chapter 5 which will incorporate TRIZ into conventional VE in order to enhance the creative capacity of the VE team. Furthermore, a prototype framework to capture and retrieve knowledge obtained from VE analysis is proposed in Chapter 7 which uses a unique knowledge classification structure inspired by TRIZ tools. Additionally, a study to condense 76 standard solutions into seven general principles for Su-Field analysis is described in Chapter 4 as one of the important contributions of this research.

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Chapter 3 - Understanding TRIZ Tools

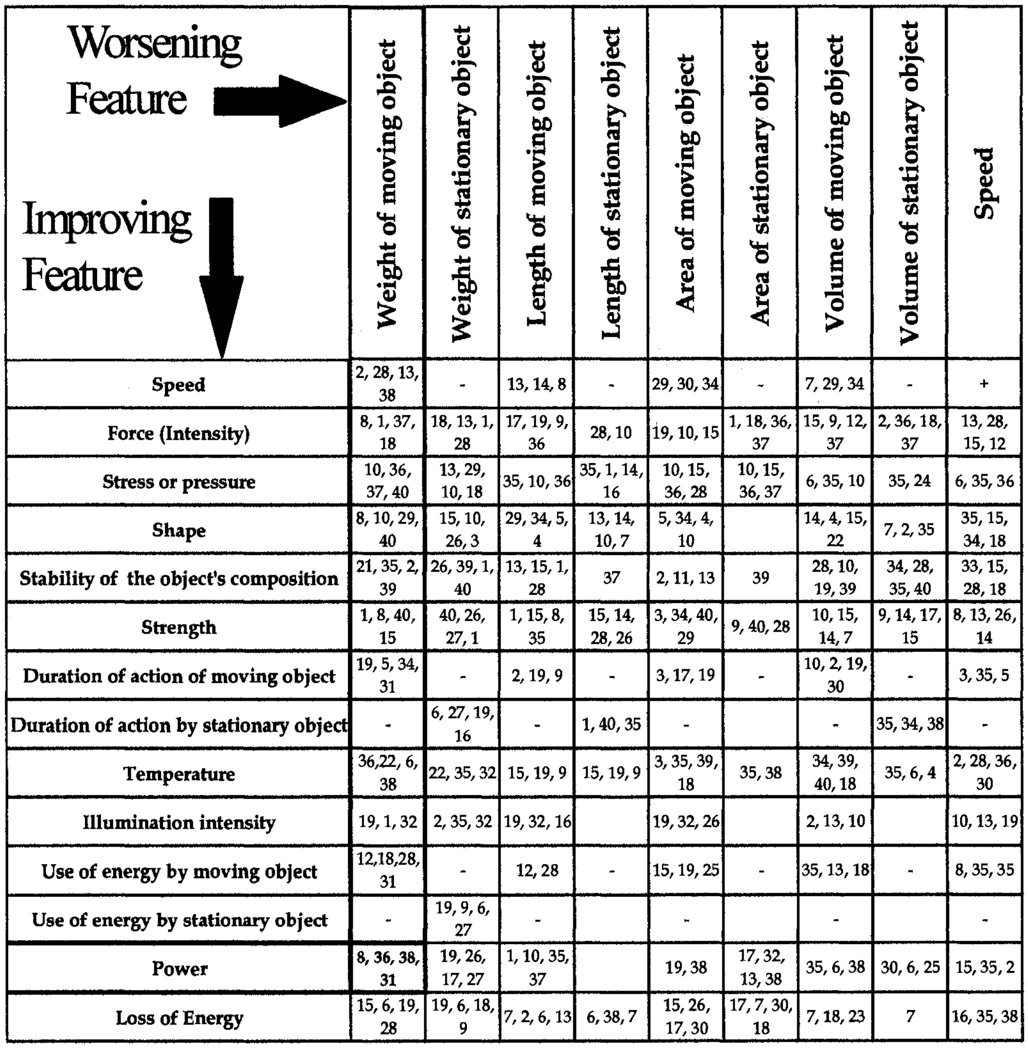
3.1 Introduction

Through intensive study, a number of TRIZ concepts and tools have been chosen to boost the creativity of conventional VE analysis. A contradiction matrix and 40 inventive principles have been selected on the basis of their ability to solve technical contradictions, whereas four separation principles have been chosen because they are able to eliminate physical contradictions. For those systems without any type of contradiction, Su-Field analysis provides a fast and simple analytic tool by means of which to identify and solve problems. Once all identified problems have been resolved, the patterns of evolution can be used to continuously increase a system's ideality.

This chapter discusses all selected TRIZ concepts and tools other than Su-Field analysis, which is discussed in Chapter 4 along with the simplification of 76 standard solutions. All standard principles are explained using engineering- and construction-related examples. Although the theory of TRIZ is new to many engineers, numerous examples indicate that the evolution and development of engineering have in fact naturally progressed in accordance with TRIZ theory for centuries.

3.2 Contradiction Matrix and 40 Inventive Principles

One of TRIZ's main strengths is its ability to solve contradictions in a system without introducing compromise (Mohamed 2002). Contradiction occurs if while attempting to improve one desirable property another desirable property deteriorates. Generally speaking, conventional problem solving leads to a compromising solution, where the solution becomes innovative as the contradiction of the technical problem is eliminated. Through his extensive patent analysis, Genrich Altshuller concluded that only 40 inventive principles are needed to resolve the technical contradictions occurring in different fields.



Worsening Feature → Improving Feature ↓	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed
Speed	2, 28, 13, 38	-	13, 14, 8	-	29, 30, 34	-	7, 29, 34	-	+
Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12
Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36
Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18
Stability of the object's composition	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18
Strength	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14
Duration of action of moving object	19, 5, 34, 31	-	2, 19, 9	-	3, 17, 19	-	10, 2, 19, 30	-	3, 35, 5
Duration of action by stationary object	-	6, 27, 19, 16	-	1, 40, 35	-		-	35, 34, 38	-
Temperature	36,22, 6, 38	22, 35, 32	15, 19, 9	15, 19, 9	3, 35, 39, 18	35, 38	34, 39, 40, 18	35, 6, 4	2, 28, 36, 30
Illumination intensity	19, 1, 32	2, 35, 32	19, 32, 16		19, 32, 26		2, 13, 10		10, 13, 19
Use of energy by moving object	12,18,28, 31	-	12, 28	-	15, 19, 25	-	35, 13, 18	-	8, 35, 35
Use of energy by stationary object	-	19, 9, 6, 27	-		-		-		-
Power	8, 36, 38, 31	19, 26, 17, 27	1, 10, 35, 37		19, 38	17, 32, 13, 38	35, 6, 38	30, 6, 25	15, 35, 2
Loss of Energy	15, 6, 19, 28	19, 6, 18, 9	7, 2, 6, 13	6, 38, 7	15, 26, 17, 30	17, 7, 30, 18	7, 18, 23	7	16, 35, 38

Figure 3.1: Sample of Contradiction Matrix

In order to assist users to track down these inventive principles based on the specific contradictions being identified, TRIZ designs a contradiction matrix, as illustrated in Figure 3.1, in which 39 parameters are listed respectively in X and Y axes as worsening features and improving features. Where a column and row intersect, the item numbers of suggested inventive principles are referenced, which enables users to improve the parameter on the vertical axis without worsening its counterpart on the horizontal axis.

For instance, increasing the **power** of a rocket (improving feature) will lead to the increase of its **weight** (worsening feature). Most likely, added weight will offset increased power. A compromised solution would be to partially increase the power of the rocket in order to decrease the negative impact. Alternatively, through checking the contradiction matrix, four inventive principles are identified that have previously proven effective in raising power without compromising weight. These principles are: (a) principle #8: Anti-weight, (b) principle #31: Porous materials, (c) principle #36: Phase transitions, and (d) principle #38: Strong oxidants.

Since the nominated inventive principles are generic solutions associated with a certain contradiction, not all ideas will be helpful to resolve a specific problem. In the above case, only principles #36 and #38 are applicable, which suggests that the rocket could use liquefied gas and pure oxygen as propellants to boost the power without precipitating a contradiction.

Given that the construction industry is exhibiting a growing need for broad knowledge and solutions, numerous examples of the use of these 40 Inventive Principles have been compiled in Appendix 5. This collection indicates that the 40 inventive principles have been widely applied in the areas of project design, construction, and management. These applications of inventive principles are gathered for the purpose of stimulating the intelligence of TRIZ rather than giving tangible solutions. As such, users' experience, knowledge, and creativity still play important roles in the process of developing practical solutions.

Table 3.1: Relationship of Principles

Principles	**Similarity**
Segmentation (1), Preliminary counteraction (9), Preliminary action (10), Beforehand cushioning (11), Dynamicity (15), Periodic action (19), Rushing through (21), Rejecting and regenerating parts (34) (Rantanen and Domb 2002)	Principles for realizing incompatible requirements in different times (**time resources**) (Rantanen and Domb 2002)
Separation (2), Local quality (3), Symmetry (4), Nesting (7), Another dimension (17), Flexible shells and thin films (30) (Rantanen and Domb 2002)	Principles for realizing incompatible requirements in different places (**space resources**) (Rantanen and Domb 2002)
Segmentation (1), Merging (5), Universality (6), Mediator (24), Composite materials (40) (Rantanen and Domb 2002)	Principles for realizing incompatible requirements at the same time in the same place (resources on the macro and micro level) (Rantanen and Domb 2002)
Use pneumatic or hydraulic systems (29), Counterweight (8), Another dimension (17), Changing the color (32)	Utilization of generally existing resources: air, fluid, space, gravity, color and others (Rantanen and Domb 2002)
Mechanical vibration (18), Periodic action (19), Continuity of useful action (20), Rushing through (21)	Actions in different formats
Parameter changes (35) Phase transition (36) Thermal expansion (37) Use strong oxidizers (38) Inert environment (39) Composite materials (40)	Characteristics created from object's chemical, physical, and parametric transformations.

Once the inventive principles for solving certain technical contradictions have been identified in the Contradiction Matrix, the user can search for examples associated with each principle. Solutions will likely emerge from application of one or more of the principles. If the identified principles are not adequate, other principles having close ties (as listed in Table 3.1) with the selected ones should be examined. If there is still no answer, then the user should work through the remaining principles. Alternatively, one can work through the 40 inventive principles directly without creating a contradiction in the contradiction matrix.

3.3 Physical Contradiction and 4 Separation Principles

Besides the technical contradiction, TRIZ has also created another concept of "physical contradiction", referring to the situation where one object must fulfill two mutually opposite requirements. The essential difference between technical contradiction and physical contradiction has been clearly illustrated in graphic form as shown in Figure 3.2 (Mann and Stratton 2000). The left-side graphic indicates an inconsistent requirement as to the physical condition of a single parameter. In contrast, the technical contradiction is described as a conflict between two parameters.

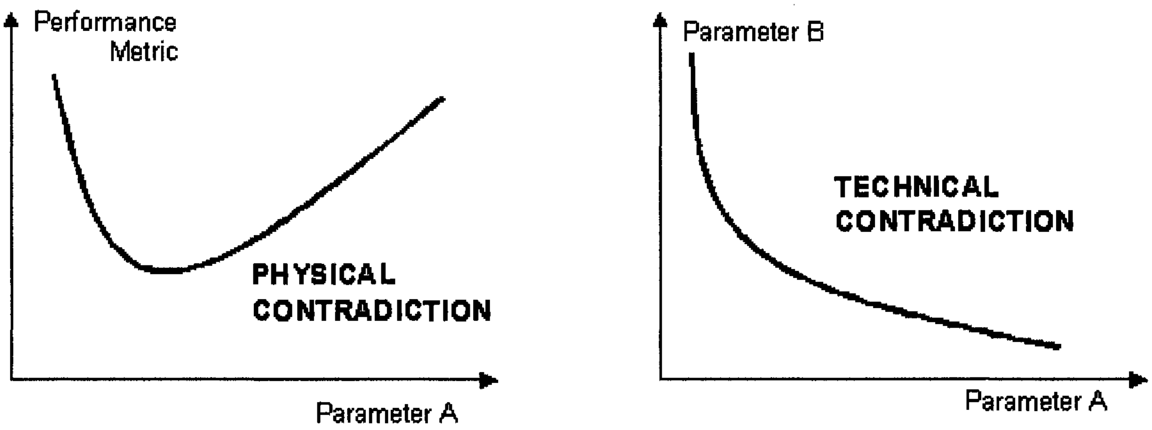


Figure 3.2: Graphical Comparison of Physical and Technical Contradictions (Mann and Stratton, 2000)

Physical contradiction indicates inconsistent requirements regarding the physical condition of the same element. To eliminate physical contradictions, Genrish Altshuller created four theoretical solutions: (1) separation in time, (2) separation in space, (3) separation between the whole system and its parts, and (4) separation based on different conditions. These solutions are intended to segment the occurrence of an element's different physical characteristics as desired.

Since each physical contradiction has a hidden root associated with certain technical contradictions, the four separation principles can somehow be linked with certain inventive principles as indicated in Table 3.2. Thus, instead of developing practical solutions directly based on the implication of separation principles, the user can first allocate an appropriate separation solution and then screen its associated inventive principles to search for ideas as to how to solve a physical contradiction.

Table 3.2: Relationship between Physical Contradiction Solution Strategies and Inventive Principles (Mann and Stratton, 2000)

Contradiction Solution Route	**Inventive Principles**
Separation in Space	1,2,3,4,7,13,17,24,26,30
Separation in Time	9,10,11,15,16,18,19,20,21,29,34,37
Separation between the whole system and its parts	1,5,6,7,8,13,14,22,23,25,27,33,35
Separation based on different conditions	12,28,31,32,35,36,38,39,40

Using brick block as an example, four separation principles are examined to demonstrate how physical contradiction can be solved, as well as to account for its connection with inventive principles.

3.3.1 Separation in Space

This solution implies the same idea embedded in inventive principle #1 – "Segmentation", meaning the separation of a unit into smaller parts. This principle suggests that brick block be reduced into small assembly pieces so that each block becomes lighter in weight and easier to handle. The major drawback of this solution, of course, is the time increase for brick installation since more blocks will be needed.

3.3.2 Separation in Time

This solution route can be directed into principle #29 – "Use pneumatic or hydraulic systems". This principle is designed to stimulate the replacement of solids with liquids or gases so that they become more flexible and can thus be more easily manipulated. According to this theory, brick block can be liquefied and pumped up to the appropriate location on a wall. In practice, this idea could be transferred into the cast-in-place pouring method. However, it might not be a cost-effective approach here, as extra formwork would be required.

3.3.3 Separation between the Whole System and Its Parts

This solution route is recommended as a means to utilizing existing resources hidden in the super- and sub-systems, and its application in the improvement of brick block leads to two more inventive principles, "Nesting" (principle #7) and "Spheroidality" (principle #14). Inventive principle #7 advises putting one element inside another one as with a Russian doll, or fitting them together in some other way. Meanwhile, principle #14 asks the user to consider the use of curves in place of rectangular shapes. These ideas, when combined, could transfer to a practical solution by which to build brick block with the desired insulation value and strength: establish nesting holes in brick block in order to utilize air as a natural insulator; and make holes in a circular shape rather than a square one in order to maintain block strength.

3.3.4 Separation based on Different Conditions

The solution route assists users in the discovery of two more inventive principles, "Use of porous materials" (principle #31) and "Composite materials" (principle #40). The first idea suggests using or adding porous substance, and the other one promotes the utilization of combined materials or synergistic effects, since the composite not only possesses different properties of all substances, but also provides better performance than does a single substance. These inventive principles may also suggest to engineers that shale and fly ash ought to be used as composite materials to make bricks.

If we combine all feasible recommendations originated from these separation principles together, then, the best practical solution appears to be making of fly ash & shale porous brick with circular holes in the middle. The new brick block will not only be stronger and lighter than ordinary bricks, but will also offer better insulation and less handling work.

As one can observe, physical contradictions can be eliminated using the ideas obtained from either a single solution route or multiple solution routes. Furthermore, different inventive principles may point to similar ideas. Overall, this practice will provide users the opportunity to generate innovative ideas in a more efficient manner.

3.4 Patterns of Evolution

Through the rigorous study of thousands of patents, Genrish Altshuller and his successors showed that all technical systems have been developed according to objective laws, and have not been generated randomly as may have once been thought. They argued that these laws have in fact been used in different fields in various formats for a considerable amount of time. However, no one had recognized their existence until TRIZ condensed them into eight evolution patterns. The essential principle of the patterns of evolution is that all systems are and should be evolving toward their ideal states over time by fully identifying and utilizing resources embedded within the given system.

Gaining a better understanding of patterns of invention enables inventors to identify and predict trends within a system. In other words, it tells inventors what the next generation of system should look like despite the fact that the solutions needed in order to reach the objective are still unknown. A subjective system improvement process is thus transformed into a search for the steps so as to fill the gap between the existing system and desired system.

The eight patterns of evolution are described below, complete with examples related specifically to construction industry.

3.4.1 Stage of Evolution

A technical system, as described in Figure 3.3, follows a life cycle of evolution which includes the following elements:

1. Envision – the desire of having a system emerges, although the preliminary conditions needed to facilitate its birth have not yet developed.
2. Birth – a new system results from the combination of conceptual ideas and obtainable technologies, but development is slow at this early stage.
3. Growth – the demand of the new system increases as its value becomes more readily recognized by society, and therefore efforts are intensively pursued to meet urgent requirements.

4. Maturity – the system exhausts all its available resources and becomes well developed. Higher-level innovative ideas are expected to lead to break-through improvements.
5. Decline – the popularity of original system fades as the next-generation system emerges, which performs the same function in a superior way. Meanwhile, the original system may co-exist with the new system in limited use until the new one becomes mature and well accepted by users.

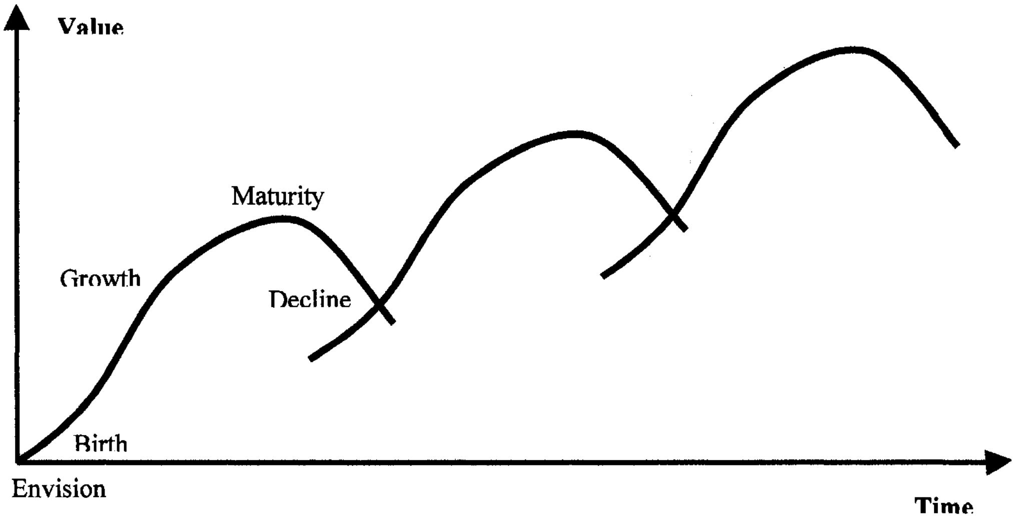


Figure 3.3: Evolution Trend of a Technical System

The life spans of all technical systems follow the above trend. As a specific example from construction, bridge evolution is summarized here as since it has been around for some time as an important field of study and has evolved over many generations.

- The reader can imagine that thousands of years ago, people wanted to build permanent overpasses on rivers, but did not know how.
- Anthropologists have presented reasonable evidence leading to the assumption that even prehistoric humans constructed bridges to facilitate their migratory activities. One can imagine that these rudimentary bridges might have consisted of stacked stone supporting a large stone slab or fallen tree which acted as a beam.

- The world's first iron bridge was built in England in 1779. However, bridge technology was not modernized until later in the eighteenth century when steel-truss structures became mature and were soon popularized.
- Some time in the later half of the nineteenth century, Thaddeus Hyatt suggested a method by which to reinforce concrete in order to alleviate stress on the beam. In 1890, one of the first early modern cantilever bridges was completed. The steel structured bridge gradually disappeared as improvements were made to concrete and composite steel and concrete design during the first half of the twentieth century.
- In the past fifty years, concrete-reinforced suspension bridges have been extensively developed. Bridges designed using modern technology can span more than two kilometers, with a higher loading capacity and wind-resistance capability than ever before. Rapidly emerging new technologies such as composite materials and innovative designs have further accelerated the pace of bridge evolution.
- As the population grows and global trade and communication become more active, the demand on bridge designers and constructors will keep growing. Consequently, technologies related to bridge construction will be increasingly pushed higher. It is foreseeable that those currently mature technologies will decline at a certain time when the know-how of the next generation appears and then evolves towards mature.

3.4.2 Systems Evolve toward Ideality

It is stated in the laws of the theory of TRIZ that a technical system evolves towards ideality by resolving its contradictions. Ideality is defined as the equation of the sum of the system's useful functions, $\sum U_{i,}$ divided by the sum of its harmful function, $\sum H_i$ (Mazur, 1995).

$$\text{Ideality} = \sum U_i / \sum H_j$$

The harmful functions in the above equation can be further split into expenses and harmful functions. In the case of a construction project, expenses represent the summation of direct and indirect costs which are spent to build the project; harmful functions include waste, pollution, and various social costs. As a result, ideality can be presented as

$$\text{Ideality} = \sum\text{Useful Functions} / (\sum\text{Expenses} + \sum\text{Harmful Functions})$$

The equation implies that in order to increase the ideality of a project, one must (Savransky 2000):

a. Increase useful functions at a faster rate than the total of the expenses and harmful functions.
b. Increase the numerator by adding useful functions or by improving the performance of the more important functions.
c. Remove unnecessary functions to reduce expenses, such that the denominator can be reduced at a faster rate.
d. Merge the sub-systems containing several useful functions into a single system in order to reduce the expenses and thereafter decrease the denominator.
e. Reduce harmful functions by increasing expenses which will not increase the denominator.

Theoretically, an ideal system will be the one that is able to perform its functions with zero cost and no harm. Although a technical system will never be able to reach this ideal operation, it implies a direction with respect to which a system should be analyzed toward which improvements the system should be. Spain (2004) has commented that people tend to rush in to the problem solving process by beginning from the current situation rather than starting at an ideal final solution and working backwards, a strategy which would demand much less effort.

The Ideal Final Result (IFR) has been proposed by TRIZ to represent the ideal solution for a system. IFR helps transform a subjective problem-solving process into a search for the steps to fill the gap between the existing system and the desired system. In addition, IFR facilitates working backwards, which is more appropriate than working forward as it works toward a clearer goal in guiding improvements to the system.

In the area of construction, there are many methods and systems which are continuously evolving towards ideality. For example, modern tunnel construction approaches which have used a tunnel boring machine (TBM) have been under development for almost two centuries and are still undergoing improvement.

- Sir Marc Isambard Brunel invented the first successful tunneling shield to excavate the Thames Tunnel beginning in 1825. Then, Peter W. Barlow substantially improved this design in 1870, changing the rectangular cross-section to a circular cross-section, which makes the tunnel simpler to construct and more supportive of the weight from the surrounding soil.
- Later on, two types of TBMs, open-face and close-face, were developed to suit different soil conditions. The open-face TBM is generally selected for soils with reasonable stability. On the other hand, close-face TBMs are employed for scenarios with poor soil conditions and/or a high water table. In this method, slurry is pumped into the bulkhead with a specified pressure in order to keep the excavation face stable and the tunneling process efficient.
- Over the past twenty years, the conventional slurry shielded method has gradually begun to be substituted by an Earth Pressure Balance (EPB) method, which further enhances the TBM's compatibility in poor soil conditions and results in a high performance with negligible surface settlement.
- Furthermore, as the tunnel boring mechanism improves, so are other activities related to the tunneling process. Today, for instance, manual surveys are commonly being dropped in favor of an automated guidance system, which has been widely applied in order to continuously monitor a TBM's advancement and

positioning without interrupting its progress. A mechanical arm has been invented to lift segmented liner into place so as to reduce the need for a labor-intensive process of placing the liner manually. The ideality is increased since the price paid for upgrading the TBM system is significantly less than the cost savings stemming from productivity improvement.

- As well, the micro-tunnel has been invented to suit projects where the traditional tunneling method is not deemed to be cost-effective due to the relatively small size of the tunnel.

The above evidence clearly proves that the evolution of tunneling has been aimed at pursuing ideality primarily by means of decreasing any harmful functions and increasing the useful functions of the TBM system.

3.4.3 Uneven Evolution of Systems

TRIZ recognizes that a system can be decomposed into sub-systems, and that each component of the sub-system can be further divided into sub-systems. Likewise, a system can be regarded as an element of a super-system, which may in turn be part of an upper-level super-system.

During the course of evolution of any system, users' expectations and demands for each sub-system increase unevenly with increases in their knowledge and the emergence of new technologies, which are also developed at a non-uniform pace. The evolution of a system normally occurs for those sub-systems which have an urgent need of improvement and which may be upgraded using state-of-the-art technologies with obvious social and economic benefits. As the system evolves irregularly, it causes problems, bottlenecks, and contradictions (Rantanen and Domb 2002). Thus the limitations of the overall system shift to those sub-systems which are intact, which soon become the new focus of technological enhancement and the next generation in the evolution of the system.

Computer application in engineering design is a good example of the above tendency.

- Design drawings, also called blueprints, have been made manually with pencil or ink on paper for hundreds of years. Minor changes to the print entail erasing and redrawing while major changes often mean recreating the drawing from scratch.
- The first computer graphic system was developed by MIT in the mid 1950s for the U.S. Air Force's air defense system.
- As a system comprised of two major sub-systems, software and hardware, computer graphic design was not economically utilized in engineering design until the early 1980s, when computer hardware with much more power at less cost started to appear on the market.
- In 1982, AutoCAD was designed to run on personal computer at a price of $1000, thus becoming competitive with traditional methods.
- In 1993, AutoCAD 12 was released in order to adapt to the new Windows operating system and fully employ an Intel processor powered PC.
- Although 3D graphic design started soon after 2D, it could not be operated on a PC until the later 1990s due to its massive demand of computing power. Today, 3D illustration and animation have been widely utilized in engineering design; and their applications have also been expanded into a number of non-engineering fields, including architecture, interior design, filmmaking, etc.

3.4.4 Increasing Dynamism and Controllability

A system is normally created to achieve one main objective. Once users accept its prototype, it will then begin to progress from a simple and rigid system to a system with more flexibility. In another words, the evolution of a system involves moving towards a more dynamic and controllable entity. Remote control, CD players, computer systems, mobile phones, and countless numbers of other systems have all followed this pattern over time.

A theodolite, which consists of an optical telescope mounted movably within two perpendicular axes—a horizontal and a vertical axis—is an instrument by which to measure both horizontal and vertical angles, as used in triangulation networks.

Nowadays, this system is usually equipped with integrated electro-optical distance measuring devices which allow for a reliable 3D measurement in just one iteration. The reading out of the horizontal and vertical circles is usually performed electronically. CCD sensors have also been added to the focal plane of the telescope allowing for both auto-targeting and the automated measurement of a residual offset of the target.

Moreover, an intelligent theodolite, also called a "Total Station", enables the user to save data into internal registering units or external data storage devices from which it can be retrieved via connection with a laptop or PDA.

All of the above adding features for a theodolite have been created to enhance its dynamism and controllability.

3.4.5 Increasing Complexity, followed by Simplicity through Integration

It is quite common to observe a system becoming more complex over time in order to meet the needs of users. A system at its early stage of evolution tends to increase the quality and quantity of its functions such that the system itself becomes more complicated. Once the desired functions have been achieved, attention will be focused on simplifying the system while maintaining the same level of functionality. In the evolution of a given system, the above processes can take place repeatedly in a series of cycles (where each cycle includes one deployment and one simplification). In addition, these processes can partially overlap (i.e., while the overall system is in the simplification process, its sub-systems might still be in deployment, and vice versa). Eventually these complex additions are simplified or eliminated and the system continues on its journey toward ideality.

Consider the following example: Traditionally, the global position of a new survey point has been measured using theodolite as a means of measuring vertical and horizontal angles, and a steel chain as a means of measuring the distance from a known reference spot. This process is complex and time-consuming because the surveyor needs a considerable amount of time to manually record data and conduct calculations, and because the survey must be repeated a number of times to ensure its accuracy.

Once laser-based technology had been invented and was successfully applied for measuring distance, the laser unit was soon integrated with theodolite to simplify the survey process and improve its precision.

Later on, a data collector was combined with electronic theodolite. As its name suggests, the date collector gathers information from the theodolite and stores it for later transfer to a computer. In addition, the data collector actually drives the theodolite when the system is in use and prompts it to take a reading. As a result, the entire procedure takes much less time than it had in prior usage, thus enabling the user to reach a higher level of accuracy than ever before.

3.4.6 Matching and Mismatching of Parts

Traditionally, when parts or sub-systems have been put together to form a system, there has not been much thought given to whether or not those elements would match up with each other perfectly. The objective has been simply to make the whole system work. During the course of a system's evolution, these mismatches are bound to be identified sooner or later as they invariably lead to system contradictions. At this point, counter-measures must be taken. Moreover, in some cases, a sub-system needs to become more flexible in order to adapt to changing working conditions.

For example, when an earth moving project just begins, the manager will dispatch as many trucks as he or she thinks will be necessary to operate efficiently in conjunction with the loaders. Regardless of how many years work experience he or she may have, there will always be mismatching between trucks and loaders for various reasons, including road conditions, truck travel distance, truck and loader efficiency, etc. As a result, the manager must act to balance productivity between trucks and loaders in order to increase output and lower construction operation costs. Furthermore, the earth moving process must be flexible in order to maintain its equilibrium. For example, back-up equipment will have to be available in case of equipment breakdown.

In some cases, mismatching is in fact purposely created in order to obtain additional functions from the differences. An example of this would be the use of a bimetal spring that changes spring rates when a current is applied.

3.4.7 Transition from Macro-systems to Micro-systems

Occasionally, a system can be improved by introducing changes on a micro level. During this stage, the energy field concept is applied to achieve better performance or control. For instance, heating systems have evolved from wood-burning, to coal, to gas, to electricity, each of which causes less environmental damage than the previous system. Insulation materials have moved from asbestos to fiberglass, to polyurethane foam, which can seal and fill all the tiny cracks and seams and nearly eliminate energy-wasting air filtration. Distance measurement has evolved from steel chain, to laser distance meter, to GPS. Communication method has evolved from physical shouting, to smoke signals, to wire-based telephones, to microwave towers and cell phones.

3.4.8 Decreased Human Interaction and Increased Automation

All technological systems need human intervention to facilitate inventive evolution. They then tend to evolve in such a direction as to require progressively less human interaction until ultimately they become fully automated.

Today, almost every system functions with less human intervention than it had traditionally. Concrete plants, where intensive labor was once commonplace, have automated most of the processes involved in concrete production, such as material handling, concrete mixing, and product loading. Automated welding systems have improved both welding quality and productivity significantly. Tunnel surveying has evolved from manual operations using theodolite, which halts the TBM every couple of strikes, to a fully automated laser guidance system which entails no interruptions of the TBM's operation.

3.5 Conclusions

This chapter reviewed a number of TRIZ concepts and tools that have been incorporated into TRIZ-enhanced-VE process to enhance the creativity of the process. All standard solutions have been discussed using engineering- and construction-related examples. Numerous examples indicate that the evolution and development of engineering has in fact naturally progressed in accordance with TRIZ principles for centuries even though the codified theory of TRIZ is new to many engineers.

3.6 References

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Chapter 4: Generalized Solutions for Su-Field Analysis[1]

4.1 Introduction

Su-Field analysis, one of the major contributions of TRIZ, is a useful tool to identify problems in a technical system and find innovative solutions to these problems. However, the 76 standard solutions of the Su-Field analysis make the implementation of this tool difficult as they contain repetitive information from other TRIZ tools, give special favors in utilizing certain fields, and cannot be fully explained using the Su-Field model. Consequently, users may feel frustrated and often feel inclined to give up. To help users carry out Su-Field analysis and more easily uncover the best solutions, this chapter condenses the 76 standard solutions into seven general principles with graphic demonstrations and examples. The seven generalized solutions can be deployed to fix Su-Field models for all types of relationships between substance S_1 and S_2.

4.2 What is Su-Field Analysis?

Su-Field analysis is a basic concept being used to symbolize a technical system and identify its comprehensiveness and effectiveness. Recognized as one of the most valuable contributions of TRIZ, Su-Field analysis is able to not only model a system in a simple graphical approach and identify problems, but also offer standard solutions to improve the system.

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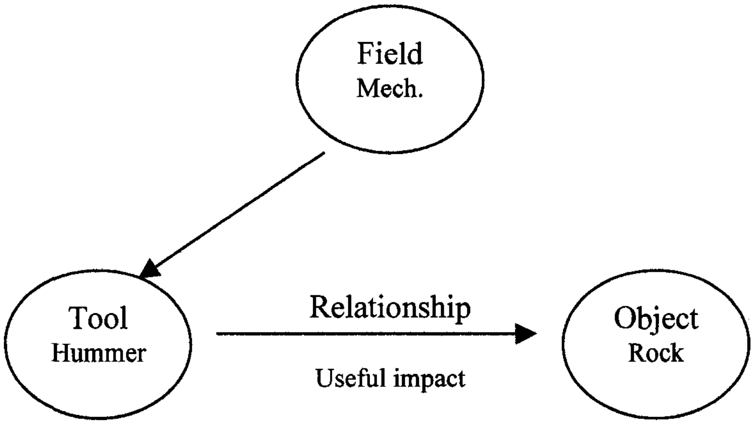
[1] A paper version of this chapter was published in the TRIZ Journal, August Issue, 2007.

According to TRIZ, the rationale for creating a Su-Field model is that a system with the ultimate objective of achieving a certain function normally consists of two substances and a field. The term S_1 is used to represent the "Object" that needs to be manipulated. The term S_2 refers to the "Tool" which acts upon S_1. Each of substances may be as simple as a single element or as complicated as a large system with many components, which can also be explained by individual Su-Field models. The "Field" is the source of energy needed to enable the interaction between the substances. According to Savransky (2000), the states of substances can be typical physical forms (e.g., gas, liquid, solid), interim forms, or composite forms (e.g., aerosol, power, porous). Likewise, the term field may refer to a broad range of energy-related fields, including mechanics, chemistry, physics, acoustics, optics and radiations.

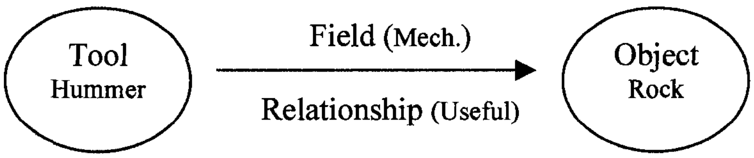
Genrich Altshuller, the inventor of TRIZ, graphically represented a Su-Field model as a triangle, which stands as a simple and ingenious way to explain a technical system. Furthermore, assuming that the field is generated by a hidden substance, the triangle can be practically simplified into a dumbbell shape with the field indicated on top of the arrow and the relationship indicated underneath the arrow, as shown in Figure 4.1. In the case of hammer crushing rock, hammer is Tool, and rock is Object. Surrounding both, it is Mechanical Field, generated by another hidden substance, that forces the hammer to act upon the rock.

There are primarily five types of relationships which may exist between the substances, namely, useful impact, harmful impact, excessive impact, insufficient impact, and transformation (Savransky 2000). Among them, useful and harmful interactions are the most common relationships.

The Su-Field model is a fast and simple analytic tool by which to identify problems in a system and provide insights toward the evolution of this system. Once a model is created, Su-Field analysis can first decipher whether or not any of the three elements of the model is missing or if there are undesired effects within the system. Then, it points out the best direction for system improvements. A complex system can be modeled using multiple connected Su-Field models. In general, there are four types of basic Su-Field models (Terninko 2000): (1) an effective complete system, (2) an incomplete system that requires completion or replacement, (3) a complete system that requires improvement to create or enhance certain useful impacts, and (4) a complete system that requires the elimination of some harmful or excessive impact.



(a) Triangle



(b) Dumbbell

Figure 4.1: Basic Su-Field Model

4.3 Problems in Current Standard Solutions

Once a technical system is simplified into a Su-Field model, its potential problems can be identified by analyzing undesired interactions resulting from the model. Problematic Su-Field models can be fixed by exploring the underlying ideas that have generated previous patents. Based on his intensive research of a huge number of patents, Genrish Altshuller identified 76 standard solutions by which to address problematic Su-Field models. These 76 solutions can be categorized into five classes (Terninko et al. 2000):

Class 1: Construct or destroy a Su-Field (13 standard solutions)

Class 2: Develop a Su-Field (23 standard solutions)

Class 3: Transition from a base system to a super-system or to a sub-system (6 standard solutions)

Class 4: Measure or detect anything within a technical system (17 standard solutions)

Class 5: Introduce substances or fields into a technical system (17 standard solutions)

Although Su-Field analysis provides a simple means to model systems and reveal their problems, the over seventy standard solutions may make users rather confused and overwhelmed in their searching for answers from these many possible solutions. This issue is discussed in greater detail below.

Firstly, many of these solutions have appeared in other contexts with regard to TRIZ, where they seem to be mixed with the patterns of evolution, inventive principles, and effects (Savransky 2000; Soderlin 2003). For example, the subclass 3.2 (transition to micro-level) may be derived from the pattern of evolution #4 (transition from macro to micro level); and the standard solution 2.2.5 (change an uncontrolled field to a field with predetermined patterns that may be permanent or temporary) may indicate the same idea as the inventive principle #19, periodic action.

Secondly, special attention has been given to promoting the application of mechanical and magnetic fields, i.e., subclasses 2.4 and 4.4. It may be improper and unnecessary to only mention a few fields, given the fact that many other fields (such as hydraulics, optics, and acoustics) are potentially capable of modifying and improving Su-Field models. Furthermore, it is suggested that standard solutions be generic in order to be widely applicable in enhancing Su-Field models amongst various fields.

Thirdly, although Su-Field models can illustrate most standard solutions, Soderlin (2003) has observed that many solutions (e.g., classes 3 and 5, subclass 4.1, 2.3.1, 2.3.3, and 4.5.1) are difficult to symbolize in a Su-Field model. In fact, these solutions are very close to other TRIZ tools. For example, solution 4.1.2 recommends measuring a copy or image for cases in which it is difficult to measure the original item. This principle is identical to inventive principle #26, copying.

4.4 Seven Generalized Solutions

Following a careful evaluation of the 76 standard solutions, the author recommends that these standard solutions be significantly reduced in order to avoid excessive redundancy and detail. In addition, the standard solutions should be depicted as general principles which are not field-specific. For those solutions provided with a certain field to improve the Su-Field model, they must be removed from the standard solutions and integrated into other TRIZ tools where they are more suitable. The standard solution should have the ability to improve all types of problematic Su-Field models, be they incomplete or models with harmful, insufficient, or excessive impact. As a result, the solutions have been condensed and generalized into seven simple and universal solutions. These seven generalized solutions are discussed in the following discussion along with several graphic demonstrations and examples. Please note that although these solutions are discussed in the context of a Su-Field model with harmful impact, they are applicable to Su-Field models with other types of problems, e.g., excessive and insufficient interactions between substances.

General solution 1: Complete an incomplete Su-Field model

Complete a Su-Field model if any of its three components is missing (Figure 4.2).

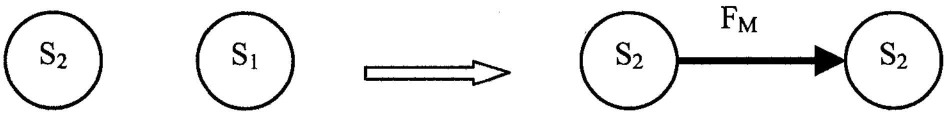


Figure 4.2: Complete a Su-Field Model

Example: A truck alone is not sufficient to complete an earth loading operation. Three components—materials for handling, a truck, and a mechanical force (produced from a loader), are required in order to conduct the loading process.

General solution 2: Modify substance S_2 to eliminate or reduce harmful impact

The physical and/or chemical characteristics of substance S_2 may be changed internally or externally, temporarily or permanently in order to eliminate or reduce harmful impact (Figure 4.3). Modification may mean changing substance S_2 into some alternate form, material, or system as long as the Su-Field system with which S_2 is associated carries out the same useful function. Additives may need to be added to the system in this modification.

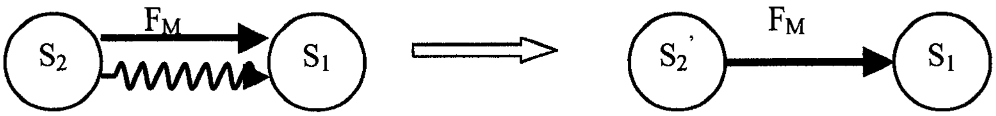


Figure 4.3: Modify Substance S2

Example: A rubber hammer is utilized to curve a metal sheet instead of a regular hammer with steel head, which could cause damage. A screwdriver is magnetized so that it can guide the screw to its proper position more easily.

General solution 3: Modify S_1 to be either insensitive or at least less sensitive to harmful impact

The physical and/or chemical characteristics of substance S_1 may be altered internally or externally so that it becomes less sensitive or becomes entirely insensitive to some harmful impact (Figure 4.4). The modification could be either temporary or permanent. Additives may be needed in this modification.

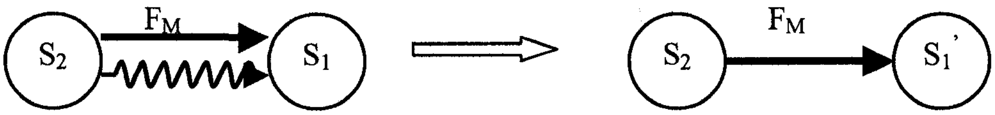


Figure 4.4: Modify Substance S1

Example: Tunneling through sandy soil is costly and has a high possibility of causing soil collapse. One method to overcoming this problem is to freeze soil prior to tunneling.

General solution 4: Change existing field to reduce or eliminate harmful impact

Changing the existing field while keeping the same substances may be a favorable option to reduce or remove the harmful impact (Figure 4.5). Changing the existing field entails either increasing or decreasing the existing field or completely removing the existing field and using another one.

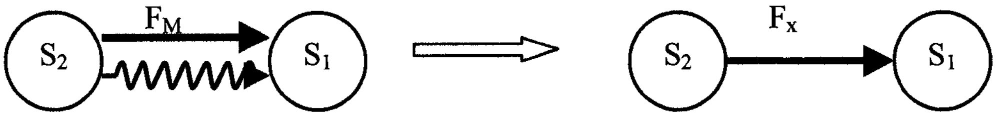


Figure 4.5: Change Existing Field

Example: During winter construction, cold temperature deteriorates construction productivity. As a countermeasure, the working area is enclosed with a heating system to increase the temperature in the working environment to an appropriate degree.

General solution 5: Eliminate, neutralize, or isolate harmful impact using another counteractive field Fx

In a system where a harmful impact exists and substances S_1 and S_2 must coexist, a counteractive field of F_X may be introduced in order to remove, neutralize, or isolate the harmful impact (Figure 4.6). Neither S_2 nor S_1 will change its physical and chemical characteristics in this solution. A third substance will be introduced in order to provide field F_X.

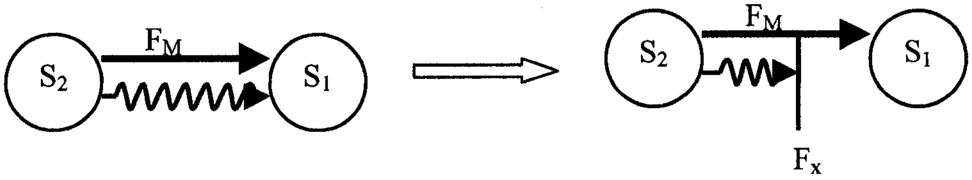


Figure 4.6: Introduce Counteractive Field

Example: Warm air temperature can reduce concrete curing time but will increase the possibility of the concrete cracking. Covering concrete with waterproof curing paper will hold in the moisture and thus help to prevent thermal cracking.

General solution 6: Introduce a positive field

Another field may be added to work with the current field in order to increase the useful effect and reduce the negative effect of the existing system while keeping all substances intact (Figure 4.7).

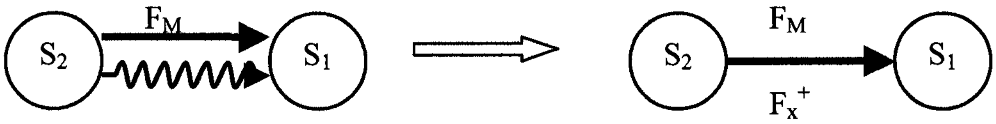


Figure 4.7: Introduce Another Positive Field

Example: Metal parts are placed in a bath of nickel salt for plating. To increase the productivity of the process, the bath is heated to a certain temperature.

General solution 7: Expand existing Su-Field model to a chain

The existing Su-Field model can be expanded to a chain by introducing a new substance S_3 to the system (Figure 4.8). Rather than directly acting upon S_1, S_2 will interact indirectly with S_1 via a medium—substance S_3.

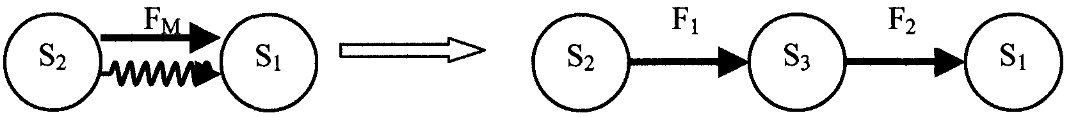


Figure 4.8: Expand the Su-Field Model to a Chain

Example: Direct communication between the project engineer and the laborers may sometimes result in misunderstanding and confusion. One favorable option is to pass the engineer's plan on to site workers through the superintendent.

Table 4.1: Breakdown Explanation to Simplify 76 Standard Solutions (Class 1, 2, 3)

Class 1. Modifying a System in order to have a Desired Outcome or to Eliminate an Underired Outcome									
1.1 Improving the performance of an inadequate system									
76 Standard Solutions	1.1.1	1.1.2	1.1.3	1.1.4	1.1.5	1.1.6	1.1.7	1.1.8	
7 Generalized Solutions	1	2, 3	2, 3	2, 3	5	Inventive Principle 16*	7	3	
1.2. Eliminating or neutralizing harmful effects.									
76 Standard Solutions	1.2.1	1.2.2	1.2.3	1.2.4	1.2.5				
7 Generalized Solutions	5	2, 3, 5	5	5	5				
Class 2. Developing the Substance-Field System									
2.1. Transition to the complex Su-Field models									
76 Standard Solutions	2.1.1	2.1.2							
7 Generalized Solutions	7	6							
2.2 Forcing the Su-Field Models									
76 Standard Solutions	2.2.1	2.2.2	2.2.3	2.2.4	2.2.5	2.2.6			
7 Generalized Solutions	4	Pattern of Evolution $6^{\#}$	2	Pattern of Evolution $7^{\#}$	Inventive Principle 19*	Inventive Principle 3,4*			
2.3 Controlling the frequency to match or mismatch the natural frequency of one or both elements to improve performance									
76 Standard Solutions	2.3.1	2.3.2	2.3.3						
7 Generalized Solutions	Inventive Principle 18*	5, 6	Inventive Principle 20*						
2.4 Integrating ferromagnetic material and magnetic fields is an effective way to improve the performance of a system									
76 Standard Solutions	2.4.1	2.4.2	2.4.3	2.4.4	2.4.5	2.4.6	2.4.7	2.4.8	2.4.9
7 Generalized Solutions	6	4, 6	6	6	2, 3	6	Inventive Principle 36*	Inventive Principle 15,23*	6
76 Standard Solutions	2.4.10	2.4.11	2.4.12						
7 Generalized Solutions	Inventive Principle 18,19*	7	Inventive Principle 35*						
Class 3. System Transitions									
3.1 Transition to the Bi and Poly-Systems									
76 Standard Solutions	3.1.1	3.1.2	3.1.3	3.1.4	3.1.5				
7 Generalized Solutions	Inventive Principle 5*	Pattern of Evolution $4^{\#}$	Pattern of Evolution $7^{\#}$	Pattern of Evolution $5^{\#}$	N/A (add in Inventive Principles)				
3.2 Transitionto the Micro-Level									
76 Standard Solutions	3.2.1								
7 Generalized Solutions	Pattern of Evolution $6^{\#}$								

* Refer to "40 Inventive Principles With Examples" (TRIZ Journal)

$^{\#}$ Refer to "Introduction to TRIZ - Innovative Problem Solving" (Apte 2005)

Table 4.2: Breakdown Explanation to Simplify 76 Standard Solutions (Class 4, 5)

Class 4. Detecting and Measuring									
4.1 Indirect Methods									
76 Standard Solutions	4.1.1	4.1.2	4.1.3						
7 Generalized Solutions	Pattern of Evolution 2#	Inventive Principle 26*	Inventive Principle 19*						
4.2. Create or synthesize a measurement sytem									
76 Standard Solutions	4.2.1	4.2.2	4.2.3	4.2.4					
7 Generalized Solutions	7	2, 3	7	7					
4.3. Enhancing the meansurement system									
76 Standard Solutions	4.3.1	5.3.2	4.3.3						
7 Generalized Solutions	7	7	7						
4.4. Measure Fe-Field									
76 Standard Solutions	4.4.1	4.4.2	4.4.3	4.4.4	4.4.5				
7 Generalized Solutions	7	2, 3	2, 3	Inventive Principle 28*	7				
4.5. Direction of Evolution of the Measuring System									
76 Standard Solutions	4.5.1	4.5.2							
7 Generalized Solutions	Inventive Principle 16*	7							
Class 5. Methods for Simplifyig and Improving the Standard Solution									
5.1. Introducing Substances									
5.1.1 Indirect ways									
76 Standard Solutions	5.1.1.1	5.1.1.2	5.1.1.3	5.1.1.4	5.1.1.5	5.1.1.6	5.1.1.7	5.1.1.8	5.1.1.9
7 Generalized Solutions	Inventive Principle 29*	Inventive Principle 28*	N/A (add in Inventive Principles)	Inventive Principle 38*	Inventive Principle 3*	2, 3	Inventive Principle 26*	2, 3	N/A (add in Inventive Principles)
76 Standard Solutions	5.1.2	5.1.3	5.1.4						
7 Generalized Solutions	Inventive Principle 1*	Inventive Principle 34*	Inventive Principle 29*						
5.2.Use Fields									
76 Standard Solutions	5.2.1	5.2.2	5.2.3						
7 Generalized Solutions	7	N/A (add in Inventive Principles)							
5.3. Phase Transitions									
76 Standard Solutions	5.3.1	5.3.2	5.3.3	5.3.4	5.3.5				
7 Generalized Solutions	Inventive Principle 35*	Inventive Principle 36*	Inventive Principle 36*	Inventive Principle 36*	Inventive Principle 36*				
5.4. Applying the natural phenomena									
76 Standard Solutions	5.4.1	5.4.2							
7 Generalized Solutions	Inventive Principle 23*	N/A (add in Inventive Principles)							
5.5. Generating higher or lower forms of substances									
76 Standard Solutions	5.5.1	5.5.2	5.5.3						
7 Generalized Solutions	Inventive Principle 38*	Inventive Principle 38*	Inventive Principle 38*						

* Refer to "40 Inventive Principles With Examples" (TRIZ Journal)

\# Refer to "Introduction to TRIZ - Innovative Problem Solving" (Apte 2005)

4.5 Relationship with Existing 76 Standard Solutions

Tables 4.1 and 4.2 indicate the relationship between the 76 standard solutions and the seven generalized solutions. According to Terninko et al. (2000), solution 5.1.1 can be decomposed into 9 sub-solutions. Therefore, there are in total 84 standard solutions.

Through careful examination and comparison, 40 of 84 standard solutions are linked to the seven general solutions. Among these 40 standard solutions, there are twelve which can be explained by more than one generalized solution. The remaining 44 of the 84 standard solutions are difficult to be interpreted using the Su-Field model. Therefore, these 44 standard solutions are connected with either the 40 Inventive Principles or the 8 Patterns of Evolution. This re-organization of the 76 standard solutions should make it easier both to teach and to learn the process of Su-Field modeling and problem solving.

Thirty-one out of the 84 solutions are identified as constituting the implementation of the existing inventive principles (Domb et al. 1999), including such principles as "1-Segmentation", "3-Local quality", "4-Asymmetry", "5-Merging", "15-Dynamism", "16-Partial or excessive actions", "18-Mechanical vibration", "19-Periodic action", "20-Continuity of useful action", "23-Feedback", "26-Copying", "28-Mechanics substitution", "29-Peeumatics and hydraulics", "34-Discarding and recovering", "35-Change parameters", "36-Phase transitions", and "38-Strong Oxidants".

Another six solutions, namely, 3.1.5 (System transition: Opposite features of the whole and parts), 5.1.1.3 (Use an external additive instead of an internal one), 5.1.1.9 (Obtain the required additive by decomposition of either the environment or the object itself), 5.2.2 (Use fields that present in the environment), 5.2.3 (Use substances that are the sources of fields) and 5.4.2 (Strengthening the output field when there is a weak input field), are recommended for consideration as new inventive principles since they cannot be explained using the Su-Field model but have the nature of inventive principles.

In addition, there are seven solutions which have originated from the patterns of evolution, including #2 (Increase ideality), #4 (Match and mismatch), #5 (Increase complexity, then follow with simplicity through integration), #6 (Transform from macro-system to micro-system) and #7 (Increase dynamism and controllability).

4.6 Conclusions

Su-field analysis is a useful tool in identifying problems in a technical system and finding solutions to these problems for the purpose of improvement of the system. Nonetheless, the 76 standard solutions seem to have some shortcomings. First, users may become confused with so many possible solutions and they may not know which to start with. Second, the basic idea behind many of these standard solutions has been repeated in other concepts of TRIZ. Third, it may be not necessary to give special attention to certain fields. Fourth, many solutions cannot be symbolized in a Su-Field model. To avoid these limitations, the author has examined the 76 standard solutions in detail and developed seven general solutions. Those standard solutions which cannot be symbolized in a Su-Field model are suggested for inclusion in those parts of TRIZ to which they are better suited. These efforts enhance the logic of TRIZ in general and facilitate the application of the Su-Field concept in particular with improved efficiency.

4.7 References

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Chapter 5 - Enhancing the Value Engineering Process by Incorporating Inventive Problem Solving Techniques

5.1 Introduction

Value engineering (VE) has been widely practiced in the construction industry, and has become an integral part of the development of many construction projects. The outcomes generated by the multi-disciplinary team during the VE process can often improve the value of the project without sacrificing the designed project functions. However, while about half of users have been impressed with effectiveness of VE, not all users are yet convinced that VE has been a useful development. These contradictive opinions may be partly a function of whether or not users have encountered innovative new ideas to improve their projects' value as a result of previous VE exercises.

Since the creativity phase of VE primarily relies on brainstorming and other freethinking-based creativity tools, the chance of generating an innovative solution in a VE exercise is limited by the participants' experience, knowledge, and creativity. Furthermore, little effort is made during a VE exercise to understand and formulate the essential problem which can guide the inspiration in the direction whereby the search for effective and robust solutions becomes optimally efficient. Rather, one assumption in the VE exercise is that quantity brings quality. As a result, a substantial amount of time during the VE exercise was spent creating a significant number of project alternatives, most of which will eventually be proven useless and eliminated since they fail to address the essential problems of the project. As such, there is a need to improve the VE process for increased efficiency in generating useful solutions.

The theory of inventive problem solving (TRIZ) is a comprehensive set of knowledge-based creativity tools. According to TRIZ, all technical systems evolve according to the laws of nature, and there are universal trends to follow in developing and improving a product, project, or system. One important feature of TRIZ is that it enables users to control the process of innovation, as TRIZ relies on technology rather than mere psychology in generating creative ideas. This characteristic of TRIZ distinguishes it from the freethinking-based creativity techniques that have been used in conventional VE exercises. Some researchers believe that TRIZ has the potential to generate more innovative ideas and enhance the efficiency and effectiveness of the VE process (Clarke 1999; Hannan 2000; Sawaguchi 2000). The various knowledge-based creativity tools of TRIZ may significantly enhance the creative power of the VE team beyond their collective knowledge and power of imagination. However, to the author's knowledge, little research has been done so far to integrate TRIZ into the VE process in order to improve the efficiency and effectiveness of VE. The author has thus conducted research in this regard. In this research, an improved VE framework has been developed which incorporates TRIZ into the VE process to enhance its creativity capability. Details of this methodology are discussed in the following sections.

This chapter focuses on introducing a TRIZ-enhanced-Value Engineering (TRIZ-enhanced-VE) framework in which the various TRIZ theories and creative tools are incorporated into the VE process to reinforce VE's creativity capability. In addition, the case study of an actual sewer delivery project is conducted to demonstrate the use of the TRIZ-enhanced-VE framework and the benefits of implementing this framework. Many of the proposed solutions derived from TRIZ seem obvious and could be created without using this process; however, this simplicity is deliberate. By providing an understandable demonstration, simple examples have been chosen to make this new approach accessible to users of disparate backgrounds.

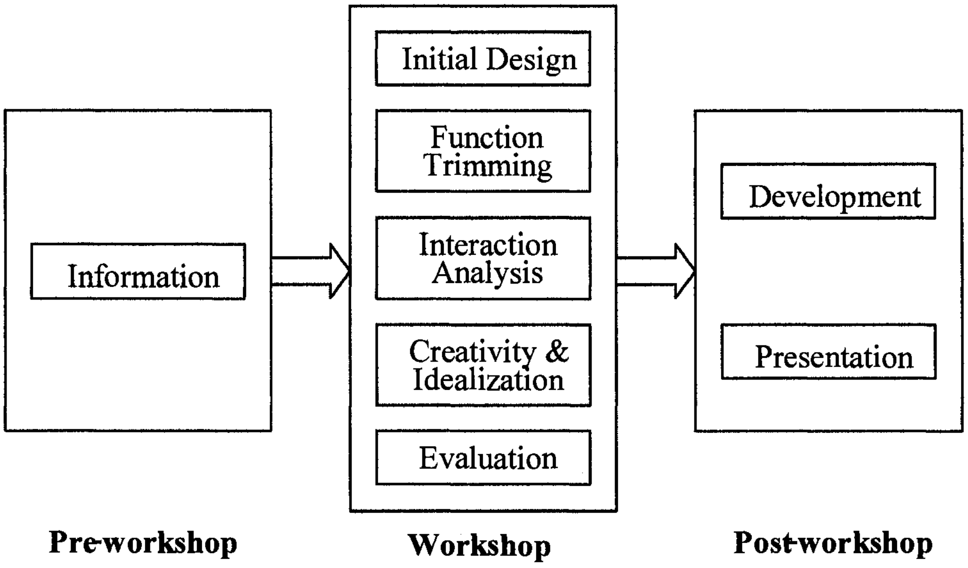

Figure 5.1: Framework of TRIZ Enhanced Value Engineering

5.2 Enhancing Value Engineer Process

As discussed in previous chapter, TRIZ may enhance the efficiency and effectiveness of the VE process. In this regard, the author has developed a framework in which TRIZ tools have been incorporated into the conventional VE process. This framework is hereafter referred to as the TRIZ-enhanced-VE framework. As illustrated in Figure 5.1, the TRIZ-enhanced-VE framework still maintains the three sessions (pre-workshop, workshop and post-workshop) of a conventional VE process. The TRIZ-enhanced-VE framework does not modify the procedures of the pre-workshop and post-workshop. However, it significantly changes the procedures of the workshop by making this session more systematic and more organized and enabling the VE team to control the creativity process. Please refer to Figure 5.2 for detailed procedures of the workshop session for the TRIZ-enhanced-VE framework.

5.2.1 Main Ideas Underlying the Enhanced Value Engineering Framework

Three main ideas underlie the TRIZ-enhanced-VE framework. First, the initial design of the proposed project alternative is based on its desired basic functions rather than being on a detailed function analysis system technique (FAST) diagram as is the case in conventional VE. This change is proposed based on the following observations: The FAST diagram contains a relationship map of multi-level functions (basic, secondary, and other lower-levels). Although all alternatives generated from a conventional VE workshop are intended to fulfill the same basic functions, other levels of functions of different alternatives may be quite different. The FAST diagram may constrain the VE team's creativity by providing too many details of the lower-level functions upfront. Second, the TRIZ-enhanced-VE framework includes a function trimming exercise at its early stage in order to ensure that the proposed alternatives produce no more than what the system's basic functions require and to fully utilize the existing resources embedded in the surrounding environment prior to the requisition of new components to the proposed project alternative. This exercise will keep the proposed project alternative simple, reduce its total life cycle cost, and enhance its sustainability. Third, the TRIZ-enhanced-VE framework invests significant team efforts in identifying the useful and harmful interactions of all project alternatives and idealizing these alternatives by eliminating and/or minimizing harmful interactions before making the final choice. It also puts the proposed project alternative in a broad social, economic and environmental perspective rather than merely tackling problems from the specific project point of view.

5.2.2 Phase 1: Initial Design

The objective of this phase is to create initial project alternatives so that the VE team can have a solid basis upon which to initiate discussions on how to improve design, enhance value, and reduce the cost of the proposed project alternative. First, the desired basic functions of the proposed project alternative must be established. Then, all existing resources in the environment of the proposed project alternative that may be utilized to achieve these basic functions need to be identified. Often, in a conventional VE exercise, a new system is proposed along with all the functions necessary to fulfill the owner's needs without seriously considering the utilization of existing resources. However, the existing resources may provide or assist some of these basic functions. Next, a number of project alternatives will be initialized by the VE team based on the team members' creativity, knowledge, and experience. In addition, details and sketches of each project alternative will be developed to facilitate further studies in the following phases.

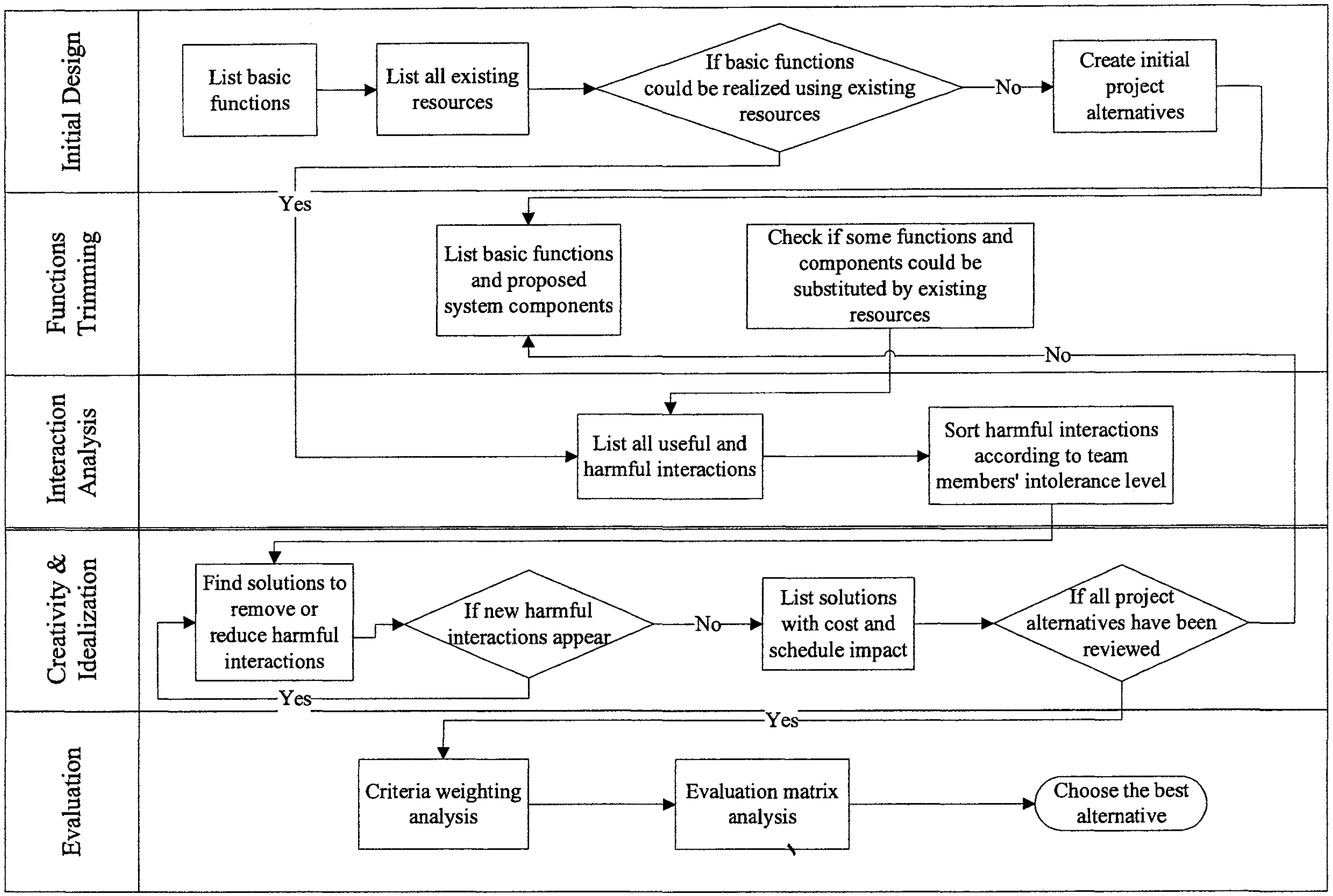

Figure 5.2: Workshop Procedure of the TRIZ-enhanced-Value Engineering Framework

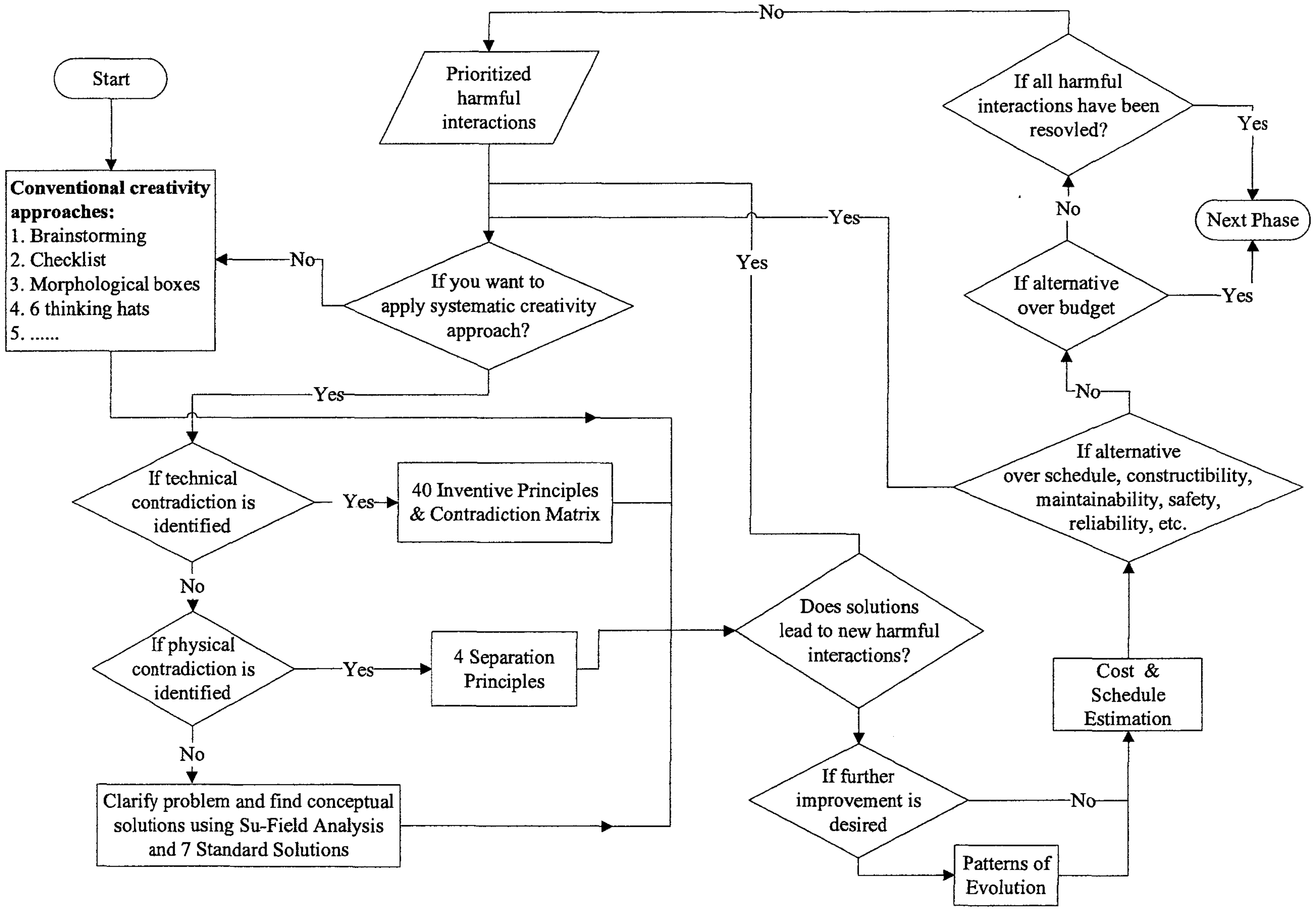

Figure 5.3: Flowchart of Creativity and Idealization Phase

5.2.3 Phase 2: Function Trimming

In this phase, the VE team needs to examine whether or not some basic functions can be realized using existing resources. Optimal utilization of existing resources will strengthen the project's cost-effectiveness, environmental friendliness, and sustainability. Only those components which explicitly serve project are included in the proposed project alternative. Function trimming also simplifies the relationship between the components and functions of the proposed project alternative without impairing its performance and quality.

5.2.4 Phase 3: Interaction Analysis

Following the function trimming phase, the remaining components of each project alternative are further examined in terms of their interactions with the setting of the surrounding environment. Useful and harmful interactions associated with each project alternative are then identified. These include interactions between the components of a project alternative and those between the system components and the existing resources in the environmental setting. Useful interactions are part of the benefits from the development of a project alternative whereas the harmful interactions are the problems that must be eliminated or minimized to a tolerable level. Harmful interactions are sorted in accordance with the VE team's level of intolerance, which is derived according to team members' gut feeling. For example, the intolerance level may be ranked from 1 to 10, with 10 representing the most intolerable level. This directs the efforts of the VE team towards focusing on harmful interactions of the highest intolerance level and reducing such interactions to a level below a specified threshold value, say 7. A project alternative will be deemed unfeasible and discarded if certain harmful interactions cannot be reduced to a level below the threshold value.

5.2.5 Phase 4: Creativity and Idealization

This is the phase where creativity tools are utilized to improve the value of each project alternative and increase its ideality, which is determined by Equation (1):

$$Ideality = \frac{UsefulFuncitons}{Cost + HarmfulFunctions} \qquad (1)$$

Several approaches may be taken to increase the ideality of a project alternative: (1) increasing useful functions, (2) reducing harmful functions, (3) reducing the cost of the project, and (4) a combination of (1), (2) and (3). In practice, since a project's basic functions are useful functions and have already been defined in the initial design phase, the approaches usually taken to improve a project alternative's ideality are (1) reducing the cost of the alternative and (2) reducing its harmful functions.

The procedures involved in the creativity and idealization phase are shown in Figure 5.3. The VE team may use either the conventional or the TRIZ-based creativity techniques to idealize project alternatives. Conventional creativity techniques include brainstorming, checklist, morphological boxes, and six thinking hats. TRIZ-based creativity techniques include the contradiction matrix, the 40 inventive principles, separation principles, and Su-Field analysis. These tools may be more efficient in generating solutions to eliminate or neutralize existing harmful interactions. However, some of these solutions may also cause new harmful interactions or worsen some other existing harmful interactions. Therefore, once a new solution is proposed, it needs to be reviewed to see whether new harmful interactions emerge as a consequence of this proposed solution. Any harmful interaction encountered need to be either eliminated or minimized to a tolerable level before carrying out the next step in the VE exercise.

It should be noted that a solution intended to eliminate or minimize a harmful interaction might incur a cost. This necessitates a quantification of the tradeoff between the increased cost and the reduced/minimized harmful functions. If there is sufficient funding, the Creativity and Idealization process will continue until harmful interactions have been resolved. However, this is usually not the case. For a project with limited budget, this process ends when the total project cost reaches its budgetary limit. If some harmful interactions cannot be eliminated or minimized to a tolerable level using the available budget, then the project is deemed unfeasible and will not be considered further unless additional funding is available. On the other hand, those project alternatives for which harmful interactions are eliminated or minimized to a tolerable level within the limited budget will be kept for further evaluation in the next phase.

To facilitate the application of TRIZ-based creativity techniques, at least one member of the VE team should be competent in TRIZ concepts and able to lead the workshop exercise. This person could either act as an independent TRIZ practitioner or carry out the tasks of both VE facilitator and TRIZ practitioner. However, it is preferable to keep the two roles separate. In this formulation, the VE facilitator focuses on the entire VE exercise and the TRIZ practitioner concentrates on conceptual development. In addition, it is important to provide basic training to the rest of the VE team members about how to apply TRIZ tools prior to their exercise for improving the initial project alternatives.

5.2.6 Phase 5: Evaluation

The purpose of the evaluation phase is to select the best from among the remaining project alternatives from the creativity and idealization phase. This evaluation phase is similar with a conventional VE exercise. A set of evaluation criteria is identified and consequently an evaluation matrix developed. The best project alternative is selected by evaluating each alternative against this evaluation matrix.

5.3 Case Study – W12 Project in Canada

A case study using the information of an actual project is presented here in order to demonstrate how to implement the TRIZ-enhanced-VE framework and how the TRIZ tools can be deployed to improve the creativity phase of the VE process. For the sake of brevity, only the workshop session of the TRIZ-enhanced-VE framework, which is significantly different from that of conventional VE, is discussed in detail in this case study.

The W12 project has been instigated by the City of Edmonton as part of the upgrading of its sewer system. It is proposed for the purpose of conveying sewage collected from the north side of a river, which flows through the center of the city, to the south side of the river, and then to connect to an operating water treatment plant which has extra capacity to treat more sewage. On the south side of the river, there is an existing shaft connected to the plant. The primary objective of the W12 project, moreover, is to deliver sewage from the north side of the river to the water treatment plant on the south side of the river.

5.3.1 Initial Design

According to the requirements of the City of Edmonton, the basic function of the project is defined as "conveying sewage to the water treatment plant." From reviewing the project documentations and visiting the project site, existing resources within the project area have been identified. These include river, air, land, sewer, park users, communities, existing shaft, water treatment plant, forest, and wildlife. Four existing resources are identified which have the potential to contribute to the achievement of the basic function:

1. River - could become the body by which to discharging sewage
2. Existing water treatment plant – has the capacity to treat more sewage
3. Riverbed - provides a space at which to build a tunnel
4. Existing shaft - provides a tie-in point at which to access to the wastewater treatment plant

However, further examination of the existing resources has led to the conclusion that the project's basic function cannot be accomplished merely using these existing resources. Therefore, there is a need to acquire additional resources in order to initiate project alternatives for further VE analysis. Two project alternatives have been proposed following an assessment of the possible relationships between the basic function of the project and the available resources: (A) building a pipe bridge to cross the river and connect to the existing shaft and (B) building a tunnel to cross underneath the river and link to the existing shaft (as shown in Figure 5.4).

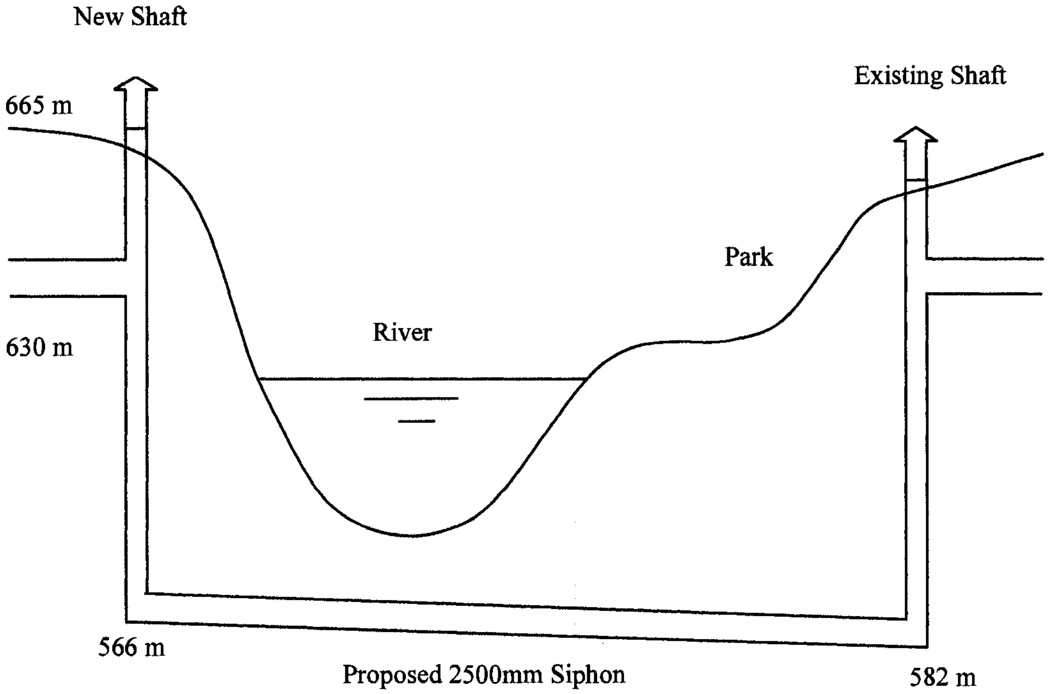

Figure 5.4: Cross Section of Alternative B

5.3.2 Function Trimming

After examining available resources, it has become clear that alternative A requires both the bridge structure and attached pipelines as project components to realize the basic function while alternative B needs to build one shaft and a tunnel to connect to the existing shaft.

5.3.3 Interaction Analysis

This phase identifies and analyzes the interactions among components of each project alternative and their interactive relationships with existing resources. For example, the useful and harmful interactions in alternative B are shown in Figure 5.5. The project components of alternative B are enclosed in a large rectangular square to create a boundary between the project and its living environment, and resources are arranged

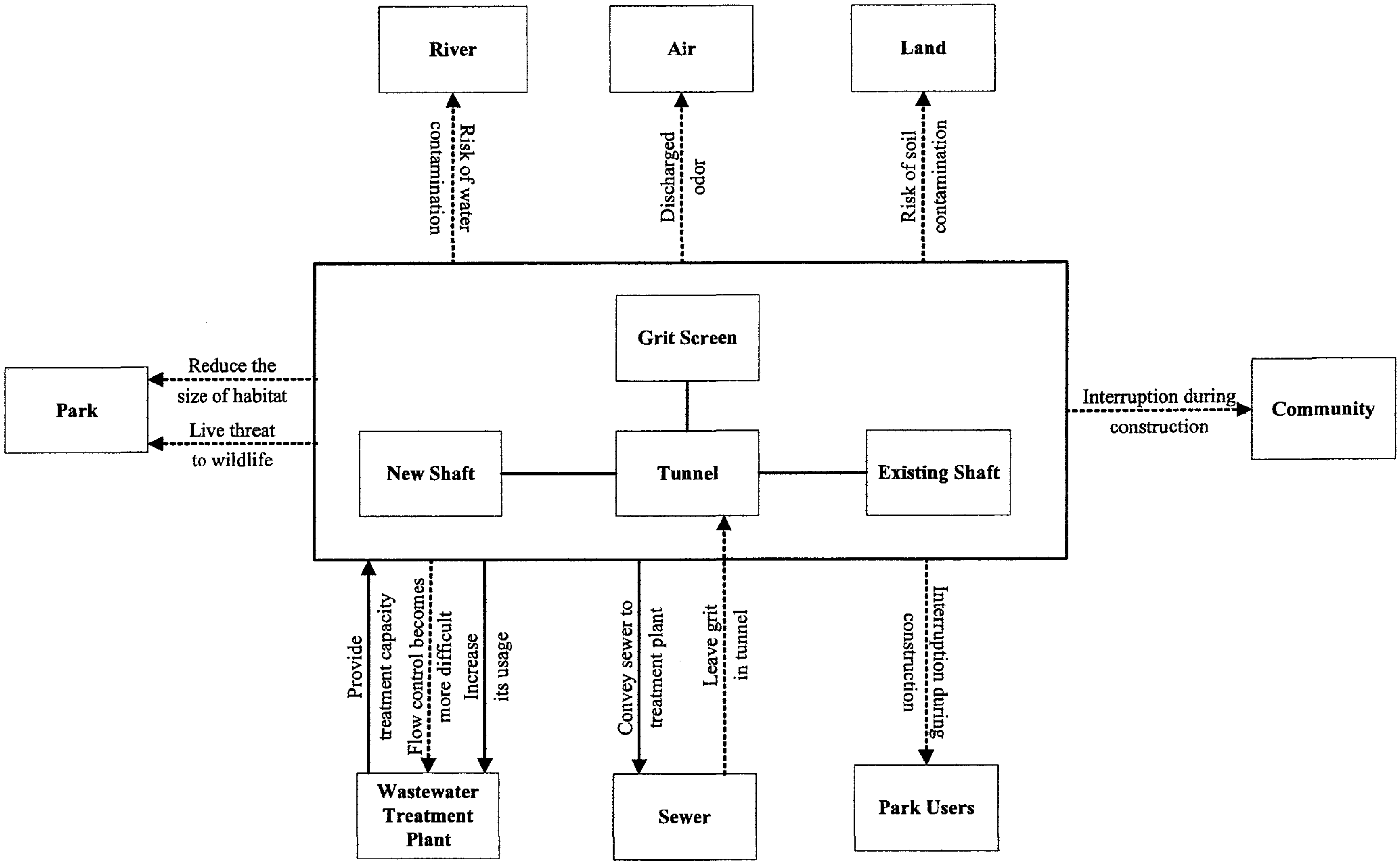

Figure 5.5: Interaction Analysis for Project Alternative B

around the square. Actions acting upon the project as a whole from existing resources are expressed by an arrow pointing to the edge of the big rectangular square. An action on an existing resource from the project as a whole or from a particular project component is expressed by an arrow pointing to the box of the existing resource. Similarly, an action on a project component from an existing resource is expressed by an arrow pointing to the box of the project component. It is possible that a project component could be associated with multiple interactions. Furthermore, the useful interaction is indicated by a solid line with an arrow pointing to the recipient of the useful effect while the harmful interaction is represented by a dashed line with an arrow pointing to the recipient of the harmful effect. The connection by a solid line with no arrow indicates an unclassified interaction. The harmful interactions of alternatives A and B are summarized in Table 5.1 in the order of descendent level of intolerance.

Please note that the components of a project alternative can be broken down into subcomponents which in turn can be decomposed into lower-levels of elements. In the same way as for the project components, interactions among subcomponents and lower level elements and those between the sub-components / lower-level elements and existing resources in the environmental setting can be identified and analyzed.

Table 5.1: Harmful Interactions Associated with Project Alternatives

Alternative	Project in General /Component	Existing Resource	Harmful Interaction	Intolerance Index
Alternative A - Pipe bridge	Pipe bridge	River	Against river bylaw	10
	System in general	Wastewater treatment plant	Increase of flow control difficulty	9
	System in general	River	Risk of water contamination	9
	System in general	Land	Risk of soil contamination	8
	System in general	Air	Odor discharge	7
	System in general	Community	Interruption during construction	6
	System in general	Park users	Interruption during construction	6
	System in general	Park	Life threat to wildlife	5
Alternative B - Tunnel	Land	Tunnel	Methane gas exposure	9
	System in general	Wastewater treatment plant	Sewage flow beyond treatment capacity	9
	Sewer	Tunnel	Grit deposition along the invert of the tunnel	9
	System in general	River	Risk of water contamination	9
	System in general	Land	Risk of soil contamination	8
	System in general	Air	Odor discharge	7
	System in general	Community	Interruption during construction	6
	System in general	Park users	Interruption during construction	6
	System in general	Park	Life threat to wildlife	5
	System in general	Park	Reduced size of habitat	4

5.3.3.1 Harmful Interaction 1 - Methane Gas Exposure

According to the geotechnical report, there is evidence of methane gas under pressure in test holes at the elevations where the cross-river tunnel is proposed to be built. Being lighter than air, colorless and odorless, methane gas is frequently encountered in underground mining. Methane gas may leak and accumulate in the tunnel during the tunneling operation. An electronic instrument often mounted on a piece of mining equipment can detect and measure the methane content in the air. If the content of methane gas in the air exceeds a certain threshold, it can impair the health of construction personnel and even result in an explosion. This hazard can also have negative impacts on the cost, time, and quality of the tunnel construction, To solve the problem of methane gas exposure, the TRIZ tool of 40 Inventive Principles and Contradiction Matrix may be applied. Two contradictions are found from the contradiction matrix—the first between Parameter #7 – Volume of Moving Object and Parameter #39 – Productivity (In the context of tunnel construction, it is further expressed as "the tunneling productivity is decreased while the volume of methane gas increases".), and the second between Parameter #31 – Object Generated Harmful Effects and Parameter #39 – Productivity. This latter contradiction is further expressed as "methane gas generates harmful effects that reduce the tunneling productivity."

After examining the eight listed inventive principles (#2, #6, #10, #18, #22, #34, #35, and #39) in the contradiction matrix as shown in Appendix 3, it has been found that four of the eight inventive principles have the potential to resolve the two contradictions. Please note that not all inventive principles will lead to feasible solutions to a particular contradiction, as they are merely a collection of generalized countermeasures to address harmful interactions embedded in similar contradictions. The four inventive principles, their general solutions as provided by TRIZ, and the particular potential solutions to the two contradictions as provided by the author based on the four inventive principles and their general solutions are all provided in Table 5.2. In summary, it is suggested that decision makers opt to install a system to which either reduced or separated methane gas in order to minimize its accumulation inside the tunnel working area. The use of a ventilation system—a traditional mechanism for improving air condition inside the tunnel—is certainly an option here. Alternatively, it is suggested that project planners search for a device which can collect or neutralize the methane gas.

Table 5.2: Inventive Principles Applicable to Harmful Interaction 1 - Methane Gas Exposure

Contradiction	**Inventive Principle**	**TRIZ General Solution**	**Recommended Solution**
Contradiction 1: the tunneling productivity is decreased while the volume of methane gas increases	#2. Extraction	a. Separate an interfering part or property from an object. b. Single out the only necessary part (or property) of an object	Separate methane gas from air inside the tunnel. This is possible since methane gas is only half the weight of air.
	#10. Prior Action	a. Perform, before it is needed, the required change of an object (either fully or partially). b. Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.	Circulate air in the tunnel using a ventilation system in order to prevent the density of methane gas from reaching a level that can cause health and safety problems.
Contradiction 2: methane gas generates harmful effects that reduce the tunneling productivity	#22. Convert harm into benefit	a. Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect. 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.	Methane gas is dangerous for tunnel construction. However, it is a clean nature fuel. Instead of ventilating methane gas and discharging it into the environment, which can cause ten times climate warming effect as that of the carbon dioxide, methane gas can be collected and used as an energy resource.
	#35. Parameter changes	a. Change an object's physical state (e.g. to a gas, liquid, or solid). b. Change the concentration or consistency. c. Change the degree of flexibility d. Change the temperature e. Change the pressure	Reduce the concentration of methane gas inside the tunnel in order to maintain a safe working environment. This can be realized using an air ventilation system or a methane gas neutralizer.

5.3.3.2 Harmful Interaction 2 – Sewage Flow beyond Wastewater Treatment Capacity

The existing wastewater treatment plant's capacity to treat wet weather sewage flow is 15m^3/s. Due to the limit of this treatment capacity, it is estimated that in peak periods of wet weather, 5.1m^3/s of sewage flow will be discharged into the river without treatment.

This constitutes a harmful interaction – whereby the sewage flow in peak periods is beyond the wastewater treatment plant's capacity.

To reduce this harmful interaction, a solution must be found such that all wet weather sewage flow can be treated at the wastewater treatment plant. Increasing the treatment capacity of the plant is also an option here. However, this alternative entails an enormous investment to expand the plant and a significant increase in the long-term operation and maintenance costs of the expanded plant. Given the fact that wet weather sewage flow over 15m^3/s only occurs a few times each year, the expansion of the wastewater treatment plant may not be an economically prudent option. Instead, it may be better to search for a solution that reduces this harmful interaction without expanding the capacity of the wastewater treatment plant.

The four separation principles of TRIZ are applied here to find a solution to the insufficient wastewater treatment capacity problem. This problem is expressed as a physical contradiction as follows: The wastewater treatment plant's capacity should be increased for complete wet weather sewage flow treatment and the capacity of the plant should not be increased to avoid a large investment in expanding the plant capacity only for infrequent usage. The separation principle applicable to handle this physical contradiction is "separation in time." In the context of this particular problem, this separation principle may be expressed as "treating sewage overflow in the non-peak period when the plant has enough capacity." It is suggested that sewage overflow be temporarily contained during peak periods somewhere within the sewer system and released after the peak period for treatment. Practically, this may be achieved by either building a new sewage storage tank or installing a new sewage pipeline with a larger diameter. These two options also involve significant investment. However, they are expected to involve a cost smaller than that of expanding the wastewater treatment plant.

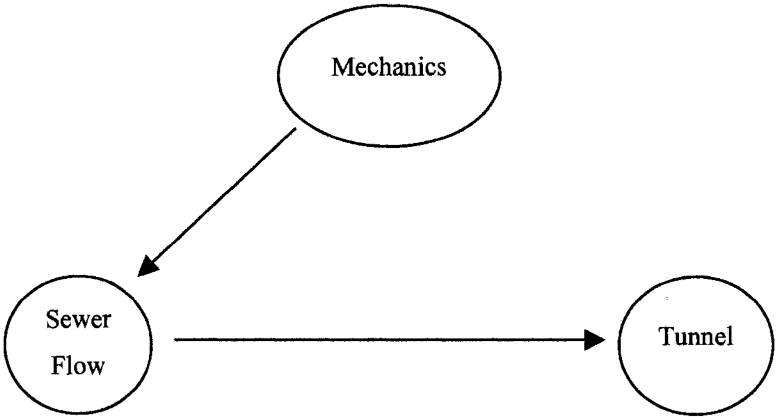

Figure 5.6: Su-Field Model

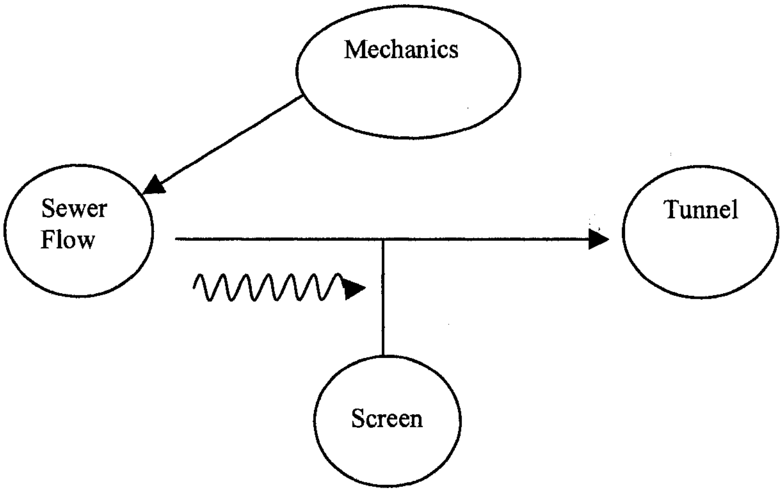

Figure 5.7: Transformed Su-Field Model

5.3.3.3 Harmful Interaction 3 – Grit Deposition along the Invert of Tunnel

Grit carried by the wastewater will be deposited along the tunnel invert as the sewage flow in the siphon diminishes at the conclusion of a storm event. Over time, if the grit deposits are not removed, they will build up in the invert and consequently reduce the capacity of the siphon and cause operational problems.

The interaction between the sewage flow and the tunnel can be analyzed in a Su-Field model as shown in Figure 5.6. The sewage flow as a tool acts upon the tunnel as an object, using a mechanical force. While this interaction is useful in conveying sewage through the tunnel, it also causes harm, i.e., grit deposition along the invert of the tunnel, due largely to the diminishing of the sewage flow at the end of the tunnel. The seven general principles for the Su-Field analysis discussed may be applied here in order to generate a solution which addresses the harmful effect. For example, according to general principle (5), it is suggested that this harmful effect be eliminated by introducing a counteractive field (as shown in Figure 5.7). One method to achieve this is to install a steel mesh screen right in front of the siphon to prevent grit from entering the tunnel. Alternatively, based on general principle (2), the harmful effect may be minimized by applying an additional mechanical force to increase the flowing speed of the sewage in the invert section of the tunnel and thus to reduce the settlement of grit. However, the introduction of additional mechanical force to increase the flow speed may be very costly.

The eight general patterns of evolution may also be applied to improve the solutions originated from the Su-Field analysis. As discussed in a previous section, the eight general patterns of evolution may provide insights regarding the evolutionary trend of a particular system and thus facilitate inventors in the search for measures to fill the gap between the existing system and the desired system. A preliminary discussion is presented below which addresses how to generate ideas from general patterns of evolution to further improve the solution "to install a steel mesh screen right in front of the siphon to prevent grit from entering into the tunnel":

1. ***Adding a mesh screen cleaning system.*** This idea may be prompted by pattern of evolution #2 – systems evolving toward ideality. After being used for a certain period, the mesh screen must be cleaned in order to keep it functioning properly. A screen-cleaning system will enhance the mesh screen's ideality.

2. ***Upgrading the material of the steel screen.*** This idea may be prompted by pattern of evolution #3 – uneven evolution of system components. Corrosion is the major concern for the steel screen. A seriously rusted steel screen must be replaced to ensure proper operation of the tunnel. To reduce the frequency of screen replacement and minimize interruptions to the operation of the tunnel, alloy materials, such as stainless steel, may be used to provide corrosion protection, strength, and durability.

3. ***Increasing the dynamism and controllability of the mesh screen.*** This idea may be prompted by pattern of evolution #4 – increasing dynamism and controllability. Making the aperture of the mesh screen adjustable in such a way as to best match grits with different sizes will enhance the mesh screen's controllability.

4. ***Automating the whole screen system.*** This idea may be prompted by pattern of evolution #8 – decreased human interaction and increased automation. The automation of the screen system will increase the efficiency and effectiveness of the operation and management of the tunnel.

Table 5.3: Harmful Interactions, Intolerance Levels, Proposed Solutions and their Effects, Cost and Schedule Consequences (Alternative B)

Harmful Interaction	**Intolerance Level**	**Solution**	**Effect of Solution**	**Cost Increase**	**Time Increase**	**Total Project Cost**	**Total Project Duration**
Methane gas exposure	9	Install ventilation system	Problem removed	$50,000	None	$24,050,000	220 days
Sewage flow beyond treatment capacity	9	Increase the diameter of sewer pipe	Problem removed	$530,000	30 days	$24,580,000	250 days
Grit deposition along the invert of the tunnel	9	Install stainless mesh screen right in front of the siphon	Problem removed	$12,000	None	$24,592,000	250 days
Risk of river contamination	9	Use bolted segment liner with sealant on joints	Problem mitigated	$210,000	8 days	$24,802,000	258 days
Risk of land contamination	8	Use bolted segment liner with sealant on joints	Problem mitigated				
Odor discharge	7	Mix odor with aroma	Problem mitigated	$20,000	None	$24,822,000	258 days
Interruption to community during construction	6	Change working schedule and reduce construction noise	Problem mitigated	$56,000	10 days	$24,878,000	268 days
Interruption to park users during construction	6	Minimize construction site and build bypass	Problem mitigated	$34,000	5 days	$24,912,000	273 days
Life threat to wildlife	5	Minimize the access and footprint of project	Problem mitigated	$1,000,000	30 days	$25,912,000	303 days
Reduced size of habitat	4	Reduce the size of facilities and hide them under the ground	Problem mitigated				

Total project cost increase is $1,912,000, and total project schedule increase is 83 days.

Note: Initial total project cost is $ 24,050,000 and initial total project duration is 220 days.

5.3.4 Evaluation

5.3.4.1 Summarization of Results from Previous Phases

Once the first four phases (i.e., initial design, function trimming, interaction analysis, and creativity & idealization) of the workshop session have been conducted, the results from these four phases are summarized for each project alternative for further evaluation. These results include: (1) harmful interactions, (2) intolerance levels of harmful interactions, (3) solutions proposed to remove/minimize harmful interactions, (4) effects of proposed solutions, and (5) cost and schedule consequences of proposed solutions. For example, the results for project alternative B are summarized in Table 5.3.

5.3.4.2 Evaluation Criteria and their Relative Importance

A set of evaluation criteria must be established for the evaluation of the project alternatives. Based on the experience and expertise of its members, the VE team has determined the following evaluation criteria: budget, schedule, meeting objectives, constructability, environmental impact (long term), environmental impact (short term), functionality, reliability, safety, and durability. As shown in Table 5.4, pair comparison is used to determine the relative importance of each criterion. The relative importance of one criterion over another is categorized into one of four levels—major, medium, minor and equally important. This means that if criterion X is "major" in importance compared to criterion Y, it is symbolized as X-3, indicating that criterion X is assigned a score of 3; if criterion X is "medium" in importance, it is symbolized as X-2, indicating that criterion X is assigned a score of 2; if X is "minor" in importance, it is symbolized as X-1, indicating that criterion X is assigned a score of 1; and if criteria X and Y are "equally important", they are symbolized as X/Y, indicating that both X and Y are to be assigned a score of 1.

Table 5.4: Evaluation Matrix for W12 Project

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Total Score**	**Standardized Weight**
A		A-2	A/C	A-2	A-1	A-2	A-3	A-3	A-1	A-2	17	10
B			B-3	D-2	E-2	F-2	B-2	B-3	B-1	J-1	9	5
C				C/D	C-1	C-2	C-3	C-3	C-1	C-2	14	8
D					D-1	F-1	D-2	D-3	D-1	J-2	10	6
E						E-1	E-2	E-3	E-1	E-1	10	6
F							F-2	F-3	F-1	J-1	9	5
G								G-2	I-2	J-1	2	1
H									I-3	J/H	1	1
I										J-1	5	3
J											7	4

Note: 1. Evaluation criteria:

A: Budget
B: Schedule
C: Meeting Objectives
D: Constructability
E: Environmental Impact River & Valley (long term)
F: Environmental Impact River & Valley (short term)
G: Functionality
H: Reliability
I: Safety
J: Durability

2. Relative importance of two criteria X and Y:

X-1 Major
X-2 Medium
X-3 Minor
X/Y Equally important

As shown in Table 5.4, the total score of each criterion is calculated by adding all scores assigned to this criterion in its comparison with other criteria. For example, the total scores of the criteria "budget" and "schedule" are 17 and 9, respectively. The relative importance of each criterion is measured by the "standardized weight", which is derived by standardizing the total score of each criterion to the scale of 1 to 10, where 10 is assigned to the criterion with the highest total score (i.e., budget, with a total score of 17) and 1 to the criterion with the lowest total score (i.e., durability, with a total score of 1). Please refer to Table 5.4 for the standardized weights of other criteria.

Table 5.5: Comparison Results between Alternatives A and B

Criteria	**Standardized weight**	**A**					**B**				
	WT	5	4	3	2	1	5	4	3	2	1
Budget	10	E	VG	**G**	F	P	E	**VG**	G	F	P
Schedule	5	E	VG	G	**F**	P	E	VG	G	**F**	P
Meet objectives	8	E	**VG**	G	F	P	E	**VG**	G	F	P
Constructability	6	E	VG	G	**F**	P	E	VG	G	**F**	P
Environmental impact (long term)	6	E	VG	**G**	F	P	E	VG	**G**	F	P
Environmental impact (short term)	5	E	VG	G	F	**P**	E	VG	G	**F**	P
Functionality	1	E	VG	**G**	F	P	E	VG	**G**	F	P
Reliability	1	E	VG	G	**F**	P	E	VG	**G**	F	P
Safety	3	E	VG	**G**	F	P	E	VG	**G**	F	P
Durability	4	E	VG	G	**F**	P	E	VG	G	**F**	P
Total weighted score		129					145				
Rank		1					2				

Note: E - excellent, VG - very good, G - good, F - fair, P - poor

5.3.4.3 Evaluation of Project Alternatives

Project alternatives A and B are evaluated against each evaluation criterion. In this evaluation, each alternative is ranked as either E (excellent), VG (very good), G (good), F (fair) or P (poor) for a particular evaluation criterion, as highlighted in bold text in Table 5.5. E, VG, G, F, P are assigned numerical scores of 5, 4, 3, 2, 1, respectively. The total weighted score of each project alternative is calculated by adding up the weighted score of each criterion, a value which is equal to the product of the score assigned to this criteria and its corresponding standardized weight. The alternative with the higher total weighted score (i.e., alternative B) will be selected.

5.4 Conclusions

The TRIZ-enhanced-VE framework proposed in this chapter significantly improves the procedures and methodologies of the workshop session from the VE exercise, and the case study demonstrates the applicability and benefits of implementing this framework. Although the most of the solutions proposed in this chapter was obvious and would likely have been identified without using TRIZ. It is meant to demonstrate how TRIZ can be applied to a project that can be generally understood by a wide range of people with construction and engineering interests. This new approach is not a replacement of current VE. Instead, it follows the essence of conventional VE with a number of improvements, which enable to improve the logic, practicability, and creativity of the existing practice. Compared with conventional VE, the TRIZ-enhanced-VE framework makes the following improvements:

(1) It makes the workshop session more systematic and better organized, incorporating five phases—initial design, function trimming, interaction analysis, creativity and idealization, and evaluation.

(2) It enhances the creative capacity of the VE team and their effectiveness in conducting the VE exercise by incorporating inventive problem-solving techniques such as the contradiction matrix & 40 inventive principles, separation principles, patterns of evaluation, and Su-Field analysis. During creativity phase, both TRIZ based creativity tools and brainstorming can be applied to create new solutions. It depends on VE team's preference as well as the complexity of problems.

(3) It increases the likelihood of realizing project sustainability, environmental friendliness, and cost-effectiveness by incorporating a function trimming exercise and an interaction analysis in order to fully utilize existing resources and minimize the harmful impacts of the proposed project on its environment.

(4) It makes the VE exercise more objective-oriented and more problem-specific by replacing the development of detailed FAST diagrams with a focus on basic functions and the need to utilize existing resources within a limited budget to reduce harmful interactions and generate the best project alternative to effectively and efficiently provide the required functions.

However, there may be some difficulties in the application of the TRIZ-enhanced-VE framework. For example, it will be challenging to transform the generic principles of TRIZ into domain-specific solutions to the specific problems of a particular construction project. The general principles of TRIZ only indicate the direction in which the main thrust of development should be based on where the most effective solutions may exist. To a great extent this depends on the ability of the problem solver to successfully find the potential solutions. In this regard, it is suggested that a knowledge base of previous engineering solutions which have been innovatively created based on TRIZ tools be built. This knowledge base will enhance the VE team's analogical capabilities and increase the opportunity to generate creative ideas. In addition, the development of a right contradiction or Su-Field model may not be an easy assignment for new users. When a number of contradictions or Su-Field models can be formed for the same problem, trials and errors become necessary in order to properly formulate the problem and identify a generic solution. It is recommended that an introductory workshop on basic TRIZ concepts and tools be provided for reference to first-time users.

5.5 References

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Chapter 6: The Application of TRIZ-enhanced-Value Engineering Analysis

6.1 Introduction

This discussion is intended to assess the logic and practicality of TRIZ-enhanced-VE analysis. This novel approach was introduced to senior-level engineering students at both the University of Alberta and Hong Kong University of Science and Technology parallel to the introduction of conventional VE analysis. Students in both universities were required to conduct their term projects using the TRIZ-enhanced-VE analysis. In addition, the students in Hong Kong University of Science & Technology were invited to complete a survey designed to elicit their opinions about the performance of the enhanced VE approach against traditional VE practice. The survey measured four areas of students' satisfaction with regards to the performance of: (1) TRIZ-enhanced-VE, (2) Function trimming phase, (3) FAST diagram, and (4) Su-Field analysis and its seven generalized solutions. Both student applications and survey results indicate the acceptance of TRIZ-enhanced-VE approach as a value-adding tool to substitute for conventional VE analysis. Nevertheless, the results of the survey have also revealed that more training is needed to assist users to understand the procedures and benefits of this new approach. As well, further analysis is suggested in order to address the discrepancies and questions generated by this survey.

6.2 Student Application in the University of Alberta

In the winter term of 2006, the TRIZ-enhanced-VE analysis was introduced to fourth-year civil engineering students at the University of Alberta as part of the introduction to

VE analysis in a course on project management (Civ E 409). The author of this thesis was invited to the class to give a lecture about the basic idea of improving the current VE method as well as the concepts and procedures of the new approach. One student-group was chosen to use the TRIZ-enhanced-VE to conduct their term project, a value engineering exercise intended to identify optimal project solutions for the so-called 19th avenue underpass project. Their outcomes were evaluated against the other eight teams' results obtained using conventional VE analysis.

The final reports of the term project are attached in Appendices 6 and 7. Appendix 6 originated with an application of the TRIZ-enhanced-VE process in which students reported their analysis in the standardized forms provided as part of the enhanced VE package. These forms cover the five phases of the VE workshop, including initial design, function trimming, interaction analysis, creativity and idealization, and evaluation. Additionally, one analysis report resulting from the conventional VE analysis is attached in Appendix 7 for the purpose of comparison.

In comparing the two reports, it seems that the procedures and standardized forms of TRIZ-enhanced-VE allow VE participants to work around the project's primary functions, make reasonable efforts to develop project alternatives and gain understanding of their pros and cons, integrate and idealize project options before making a decision, and evaluate project plans based upon both quantitative (cost and schedule) and qualitative (weighted project score) evidence. As the students concluded in their report: "TRIZ-enhanced-VE process is an effective alternative to value engineering and can save money and time for a project if done correctly." On the other hand, it was observed that students assigned to the conventional approach did not include their FAST diagram in the report, which is normally utilized to assist with function analysis. Further research has shown that there is no FAST diagram in any of the eight groups' reports. This fact is likely due to the reality that students have a difficult time creating FAST diagrams and often choose to give up, which may serve to verify that VE analysis can be successfully conducted even without the assistance of FAST diagram.

Although the findings from students' applications appear to support the author's arguments about the weakness of conventional VE analysis and the objectives of the new approach, any findings identified in this study ought to be understood to carry a certain level of inaccuracy and inconclusiveness because there was only one group of students engaged in the pilot approach. Consequently, the results of this study have encouraged the author to conduct full-scale exploration along with a survey in order to truly assess the new approach.

6.3 Student Survey at the Hong Kong University of Science and Technology

In the spring term of 2007, the TRIZ-enhanced-VE analysis was taught during the course of CIVL300R (Project Management for Civil Engineers) in parallel with the introduction of conventional VE analysis. Offered by the Department of Civil Engineering of the Hong Kong University of Science and Technology, this course is designed to help senior civil engineering undergraduate students understand the basic methods, tools and techniques involved in managing capital construction projects. Both conventional VE and TRIZ-enhanced-VE processes were introduced during the class. The students' term project was to use the TRIZ-enhanced-VE process in order to identify the best project option for a real-life project. The objective of this experiment is to test the overall logic and practicality of the new VE approach as well as the performance of Su-Field analysis and its seven generalized solutions. The students' feedback concerning the enhanced VE method was collected through questionnaires immediately after they had presented their term projects during the final class. Out of the 24 students who had participated in the term project, a total of 20 valid responses were received.

To minimize the author's influence upon interviewees' opinions, questionnaires were handed out by the instructor, acting as a third party. Furthermore, it was clearly stated in the questionnaire that students' comments would not affect their grades.

6.3.1 Survey Methodology

The survey was developed to elicit feedback from the students who had had opportunities to use the TRIZ-enhanced-VE approach. A total of eleven questions were asked: one with multiple choices as well as ten questions which each required a single non-multiple-choice response. This questionnaire was designed to measure respondents' perception of how easy the TRIZ-enhanced-VE is to use in comparison with conventional VE, whether or not TRIZ-enhanced-VE can create more innovative project plans than does conventional VE, how Su-Field analysis and its seven standard solutions can benefit the creativity phase of VE, what is the cause of the difficulty encountered in implementing the function analysis of VE, whether or not the FAST diagram can bring significant value to VE, etc. (see Appendix 8 for a complete version of the questionnaire).

In the questionnaire, the first question asked for user feedback regarding the advantages of the improved TRIZ-enhanced-VE in comparison with conventional VE. Respondents were allowed to check multiple choices from six answers, including (1) Leads to a more social, economic, and environmentally-friendly project plan, (2) Can better utilize existing resources, (3) Improves the ideality of a project plan, (4) Simplifies the function analysis phase, (5) Provides more detailed and step-by-step guidance in searching for better project alternatives, and (6) The process is easy to follow. The remaining ten questions are Likert scale questions with five default choices—namely, strongly agree, agree, neutral, disagree, and strongly disagree.

Respondents were only allowed to select a single answer for each question, except the first one. Below each question, a one-line space was given to allow respondents to provide additional feedback. Respondents were also encouraged to freely express frustrations that they may have encountered in implementing this new approach.

6.3.2 Survey Results Analysis

As illustrated in Figure 6.1, in response to the statement of question #1, "What is the improvement of TRIZ-enhanced-VE in comparison with conventional VE?", 3 out of 20 respondents agreed that the new approach improves the ideality of a project plan, simplifies function analysis phase, and better utilizes existing resources. 6 out of 20 respondents accepted the fact that the enhanced VE process is easy to follow and may be expected to generate more social, economic and environmentally-friendly project plans. Moreover, 15 out of 20 answerers strongly believed that the proposed method is able to search for better project alternatives in a systematic and comprehensive manner.

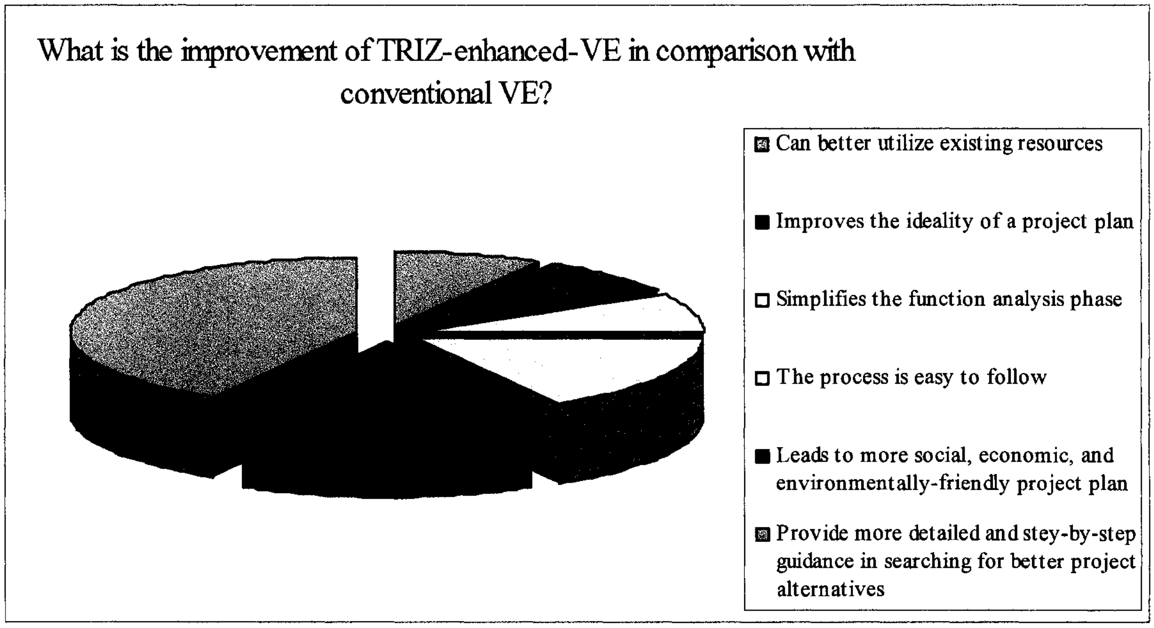


Figure 6.1: Answer Summary for Question #1

Table 6.1: Summary of Survey Results

Questions		Strongly Agree & Agree	Neutral	Strongly Disagree & Disagree	Mean
2	TRIZ-enhanced-VE practice is based upon a well-defined procedure and guideline.	75%	20%	5%	4.1
3	The implementation of TRIZ-enhanced-VE analysis at engineering stage can produce more environmental and social friendly project plan.	55%	40%	5%	3.6
4	The specific procedure and premade forms of TRIZ-enhanced-VE are easy to employ.	40%	55%	5%	3.5
5	Function trimming phase is a necessary step to ensure there is no more or less functionalities being produced by proposed project alternative.	65%	30%	5%	3.8
6	FAST diagram cannot bring significant value to VE analysis.	15%	40%	45%	2.8
7	It is difficult to develop a FAST Diagram.	70%	20%	10%	3.3
8	The difficulty of implementing Function Analysis of VE is due to the complexity of developing FAST diagram.	60%	35%	5%	3.6
9	7 standard solutions for Su-Field analysis can empower creativity phase of VE to generate more innovative solutions.	60%	35%	5%	3.7
10	Su-Field analysis can generate more creative ideas than brainstorming.	40%	50%	10%	3.3
11	Su-Field analysis can tackle the essence of a problem and accelerate the speed of discovering proper solution.	55%	45%	0%	3.6

The survey results for questions #2 to #11 are summarized in Table 6.1. In general, students appeared to be satisfied with their experiences of implementing the TRIZ-enhanced-VE analysis. However, the high level of neutrality with regard to some questions reveals that additional instruction and training may be necessary in order to help users become more familiar with the proposed new VE approach.

Mean satisfaction scores for each question have also been calculated and are presented in the table. The mean scores reveal that respondents were most satisfied with the statement that TRIZ-enhanced-VE analysis is a thoughtful and well-established procedure. The comparison of these mean values also indicates that students are least satisfied with the statement that the FAST diagram cannot bring considerable value to VE analysis. However, it should also be noted that across the board a great number of respondents (60% to 70%) admit that the FAST diagram is difficult to develop and therefore causes problems at the function analysis phase.

In response to the statement, "TRIZ-enhanced-VE practice is based upon a well-defined procedure and guideline.", 75% of respondents answered affirmatively (strongly agree, agree), 20% expressed neutrality (neutral), and 5% expressed disagreement (disagree, strongly disagree). This highly positive result shows strong overall support for this enhanced VE process.

In response to the statement, "The implementation of TRIZ-enhanced-VE analysis at the engineering stage can produce a more environmentally-friendly and socially-sound project plan.", 55% of respondents answered affirmatively (strongly agree, agree), 40% expressed neutrality (neutral), and 5% expressed disagreement (disagree, strongly disagree). Although large percentages of students were satisfied with this statement, a significant percentage (40%) of them expressed neutrality, suggesting that there is either a lack of understanding of the new approach's ability to address the environmental and social issues of a proposed project plan, or TRIZ-enhanced-VE in need of more in-depth enhancements in order to tackle these issues.

In response to the statement, "The specific procedure and pre-made forms of TRIZ-enhanced-VE are easy to employ," 40% of respondents answered affirmatively (strongly agree, agree), 55% expressed neutrality (neutral), and 5% expressed disagreement (disagree, strongly disagree). While 40% of students were satisfied with the statement, a high level of neutral responses here suggests a lack of understanding of the procedures and templates specifically prepared for the enhanced VE process. Therefore, it is suggested that more instructions about how to use TRIZ-enhanced-VE be given in the future.

In response to the statement, "Function trimming phase is a necessary step to ensure there is no more or less functionalities being produced by proposed project alternative," 65% of the respondents answered affirmatively (strongly agree, agree), 35% expressed neutrality (neutral), and 5% expressed disagreement (disagree, strongly disagree). Overall agreement about this statement indicates the usefulness of this phase. Similarly, the fact that 40% of respondents expressed either neutrality or disagreement shows that students need more training in order to understand how to trim unnecessary functions at this phase.

In response to the statement, "FAST diagram cannot bring significant value to VE analysis," 15% of respondents answered affirmatively (strongly agree, agree), 40% expressed neutrality (neutral), and 45% expressed disagreement (disagree, strongly disagree). The high level of disagreement here indicates that respondents still consider the FAST diagram to be a value-added step for VE analysis. However, the author is led to conclude based on answers to both questions #7 and #8 that most respondents agree that FAST diagrams are difficult to create and therefore obstruct the use of function analysis.

In response to the statement, "It is difficult to develop a FAST Diagram," 70% of respondents answered affirmatively (strongly agree, agree), 20% expressed neutrality (neutral) and 10% expressed disagreement (disagree, strongly disagree). With the second-highest level of agreement, the feedback from this question confirms the author's supposition that developing a FAST diagram is not an easy task. Although it is a useful tool as confirmed by the answers given to question #6, the development of FAST diagram must either be simplified or substituted by another approach so that the function analysis phase can more easily proceed.

In response to the statement, "The difficulty of implementing Function Analysis of VE is due to the complexity of developing FAST diagram," 60% of respondents answered affirmatively (strongly agree, agree), 35% expressed neutrality (neutral), and 5% expressed disagreement (disagree, strongly disagree). Consistent with previous findings, 6 out of 10 respondents agreed that the FAST diagram likely makes the function analysis more difficult.

In response to the statement, "7 standard Su-Field analysis formulas can empower creativity phase of VE to generate more innovative solutions," 60% of respondents answered affirmatively (strongly agree, agree), 35% expressed neutrality (neutral), and 5% expressed disagreement (disagree, strongly disagree). The reasonable level of satisfaction with this statement supports the notion that Su-Field analysis combined with the seven generalized formulas can boost the creative power of VE at its creativity phase. Additional analysis found the answers to be slightly inconsistent with those for question #3, which may imply that respondents need extra training and practice to understand both conventional and enhanced VE processes and thus provide more consistent feedback.

In response to the statement, "Su-Field analysis can generate more creative ideas than brainstorming," 40% of respondents answered affirmatively (strongly agree, agree), 50% expressed neutrality (neutral), and 10% expressed disagreement (disagree, strongly disagree). Although only 10% of respondents disagreed or strongly disagreed with the statement, the answers for this question still show inconsistency with those for previous questions since 50% of respondents expressed neutrality toward this statement. Further comparative analysis between these two creativity tools is suggested. In addition, it might be worthwhile to ask users if Su-Field analysis can generate the same ideas in a more efficient and systematic manner than does brainstorming.

In response to the statement, "Su-Field analysis can tackle the essence of a problem and accelerate the speed of discovering proper solution," 55% of respondents answered affirmatively (strongly agree, agree), 45% expressed neutrality (neutral), and 0% expressed disagreement (disagree, strongly disagree). The answers for this question are two-fold in nature. More than half of responses agreed that Su-Field analysis is effective at disclosing and resolving problems. On the other hand, 45% answered that they are not concerned about this aspect, which indicates a lack of concern about the importance of Su-Field analysis. Again, more training is recommended to help users become more familiar with Su-Field analysis.

6.3.3 Survey Summaries

In general, most students expressed satisfaction with their experimental application of TRIZ-enhanced-VE. They strongly believe that the new approach provides detailed and systematic guidance in searching for optimal project alternatives, places the project value assessment within a broad social, economic and environmental perspective, and is easy to apply. Nevertheless, additional training and instruction are recommended to assist users in familiarizing themselves with the proposed new value management approach.

About 75% of respondents recognized that TRIZ-enhanced-VE analysis is a well-defined procedure and guideline. Findings from the survey also indicate that the new approach should be readily utilized during the engineering stage in order to create a more social and environmentally friendly project plan. Meanwhile, respondents do not seem to be entirely satisfied with the procedure and pre-made forms, given that nearly 55% of respondents expressed neutrality on this matter, a statistic which serves to implies that there may be opportunities to further improve upon them.

With respect to the function trimming phase, the majority of respondents appear to agree that it is a critical step toward ensuring that only preferred functions remain as project objectives. Furthermore, results show that a fair amount of respondents still believe that the FAST diagram is important to VE analysis. However, about 60% to 70% of respondents have indicated that it is not easy to create FAST diagrams, and that this reality results in considerable difficulty implementing the function analysis.

Author also came across some interesting observations regarding the use of Su-Field analysis as well. About 55% to 60% of respondents consider Su-Field analysis and its simplified solutions to be effective tools by which to drive VE's creativity phase. On the other hand, 60% of respondents do not agree that Su-Field analysis can do a better job than does brainstorming. Further and more focused investigations into this finding might be necessary to determine which creativity tool is better.

6.4 Conclusions

The primary objective of the student survey and application with respect to the TRIZ-enhanced-VE analysis has been to identify its practicality and investigate its limitations for the purpose of initiating further improvement. Both assessment approaches reflect the acceptance of the enhanced VE approach. The positive results reported in this study have provided a sound basis for further development aimed toward improving this new approach's performance and eventually making it widely available for the analysis of project value in construction. For future studies, it is recommended that VE professionals become involved in order to assist researchers seeking to elicit expert opinions and conclusive evaluations about this new approach. Furthermore, certain statistical measures are suggested in order to make survey analysis more accurate.

Chapter 7: Developing a Knowledge Management System for Improved Value Engineering Practices in the Construction Industry

7.1 Introduction

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

Surprisingly, little research has been conducted on how to reutilize the ideas and solutions generated through VE for future projects. The construction industry is still practicing VE in the same fashion as when it was introduced over fifty years ago. Each VE study starts from scratch and its success relies solely on the VE team members' experience and competence. Past experience shows that VE has led to cost savings of 5 to 10% for a wide range of construction projects. However, there has been no significant result from the VE study in a number of other construction projects.

Moreover, there has been increasing demand for a knowledge management system (KMS) to improve the efficiency of VE. The author has thus conducted research and consequently developed a VE knowledge management system (VE-KMS) for VE knowledge acquisition, representation, and retrieval. In this system, the theory of inventive problem solving (TRIZ) is applied to the creativity phase of the VE study to make this phase more systematic and better organized, enabling the VE team to control the creativity process. In specific, TRIZ is a comprehensive set of knowledge-based creativity tools which consolidates the talent and experience of the world's most ingenious inventors. It is believed that the incorporation of TRIZ tools in the VE process will significantly enhance the creative power of the VE team beyond their collective knowledge and power of imagination and improve the efficiency and effectiveness of VE in generating more innovative and practical ideas and solutions to the problems with the project under consideration.

7.2 Knowledge Management in the Construction Industry

There are two basic categories of knowledge, explicit and tacit (Nonaka and Takeuchi 1995). Within the construction industry, explicit knowledge refers to documented information such as project information, design drawings and specifications, cost reports, risk analysis results, and other information being collected, stored, and archived in paper or electronic format and available to other users. Tacit knowledge is the experience and expertise contained within the construction professional's mind, the company culture, lessons learned, know-how, and other elusive yet valuable information (Lin et al. 2005).

Knowledge will not bring any value unless it is used actively, and in this regard a KMS is particularly useful in actively using existing knowledge (whether explicit or tacit) to create value. Knowledge management is a process by which to create, secure, capture, coordinate, combine, retrieve, and distribute knowledge (Lin et al 2005). The effective application of existing knowledge can create innovation and improve business performance and client satisfaction whereas the failure to capture and reuse the knowledge kept in previously accomplished projects will increase the likelihood of "reinventing the wheel", and will consequently lead to a waste of resources and profit loss (Kamara et al. 2002a; 2002b).

Knowledge management is particularly important in the construction industry. First, the construction industry is extremely competitive due to tight construction schedules, low profit margins, considerable complexity, diversity, and non-standardized production of projects. Effective knowledge management will facilitate the generation of new technologies and processes, which in turn will improve the industry's productivity, profitability, and competitiveness (Clough et al. 2000; Pathirage et al. 2006). This has been confirmed by Carrillo and Chinowsky (2006) in their survey on contractors in the United Kingdom, which indicated that the application of a KMS had resulted in new technologies and processes. Second, the construction industry is a project-based industry, much more fragmented than many other industries. The formation of a project team (including engineering, procurement, and construction professionals) is temporary and project-specific. Without a KMS, it is difficult to reuse a professional's knowledge if he or she leaves the company or if he or she is not a team member of the project.

7.3 TRIZ Based Problem-Solving Model

Rather than directly seeking solutions to the current problem, this study suggests to follow the general problem-solving model of TRIZ as demonstrated in Figure 7.1. The TRIZ based model first identifies the current problem in the system. Then, this particular problem is abstracted into one of three types of standard problems: (1) a Su-field model, (2) a physical contradiction, and (3) a technical contradiction. Next, a few standard solutions may be found for this particular problem by examining all the standard solutions provided by TRIZ for that type of standard problem. For example, there are seven standard solutions to a Su-field problem, 40 inventive principles to solve the technical contradiction problem, and four separation principles to solve the physical contradiction problem. After that, the standard solutions are evaluated against the eight technological evolution patterns in order to further enhance the ideality of the standard solutions. Finally, the problem solver will come up with a solution that is practical and relevant to the particular problem based on his or her experience and expertise.

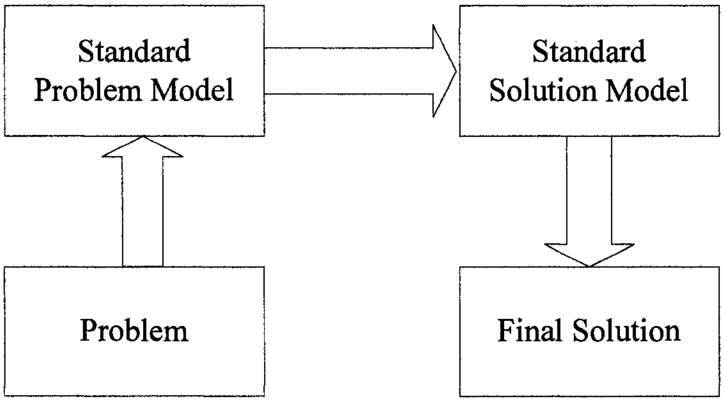


Figure 7.1: General Problem-Solving Model of TRIZ

The biggest challenge here lies in the transformation of the generic principles/solutions of TRIZ into domain-specific solutions. As Mohamed (2002) has stated, those generic principles/solutions merely indicate the directions in which the most effective solutions could possibly exist, but the successful identification of a practical solution depends mainly on the ability of the problem solver. Moreover, by capturing innovative solutions to various problems from previous VE studies in a knowledge database, the author hopes to facilitate VE team members to efficiently and effectively find practical solutions.

7.4 Improving Value Engineering

7.4.1 The Value Engineering Process

The VE study is normally conducted by a team of members with multi-disciplinary experience and expertise. The VE team analyzes the functions of a project against their costs in an attempt to find innovative solutions (which could be a new material, creative design, or construction method) in order to achieve the necessary functions at the lowest possible life cycle cost. In specific, the main objectives of the VE study are to improve quality, minimize costs, reduce construction time, simplify the construction process, ensure safety, and meet environmental goals.

A VE study includes three sessions—pre-workshop, workshop and post-workshop, and each session can be further divided into phases. For example, the workshop session includes three phases: an information and function analysis phase, a creativity phase, and an evaluation phase. It is generally recognized that the creative phase of the workshop is the critical phase determining the success or failure of the VE study because it is in this phase that creativity techniques are applied to generate innovative ideas for enhanced project functions and reduced project costs.

7.4.2 Shortcoming of Traditional Value Engineering Studies

The traditional VE study mainly relies on free-thinking techniques such as the brainstorming technique to generate creative ideas and solutions, and it usually starts from scratch without adequately utilizing the knowledge and results generated from previous VE studies because the lack of a KMS. Obviously, the chance of generating an innovative solution is limited by the current VE team members' experience, knowledge and creativity. Furthermore, in a traditional VE study, little effort is made to understand the essential problems of a project. Therefore, there is no guidance on the direction in which the search for effective and robust solutions is efficient. To overcome these shortcomings, it is proposed in this chapter to incorporate the TRIZ tools in the creativity phase of the VE study to make this phase more systematic and more organized and enables the VE team to control the creativity process. This attempt will significantly enhance the creative power of the VE team beyond their collective knowledge and imagination power, which is confirmed by Clarke (1999), Hannan (2000) and Sawaguchi (2000) who believe that TRIZ has the potential to generate more innovative ideas and enhance the efficiency and effectiveness of the VE study.

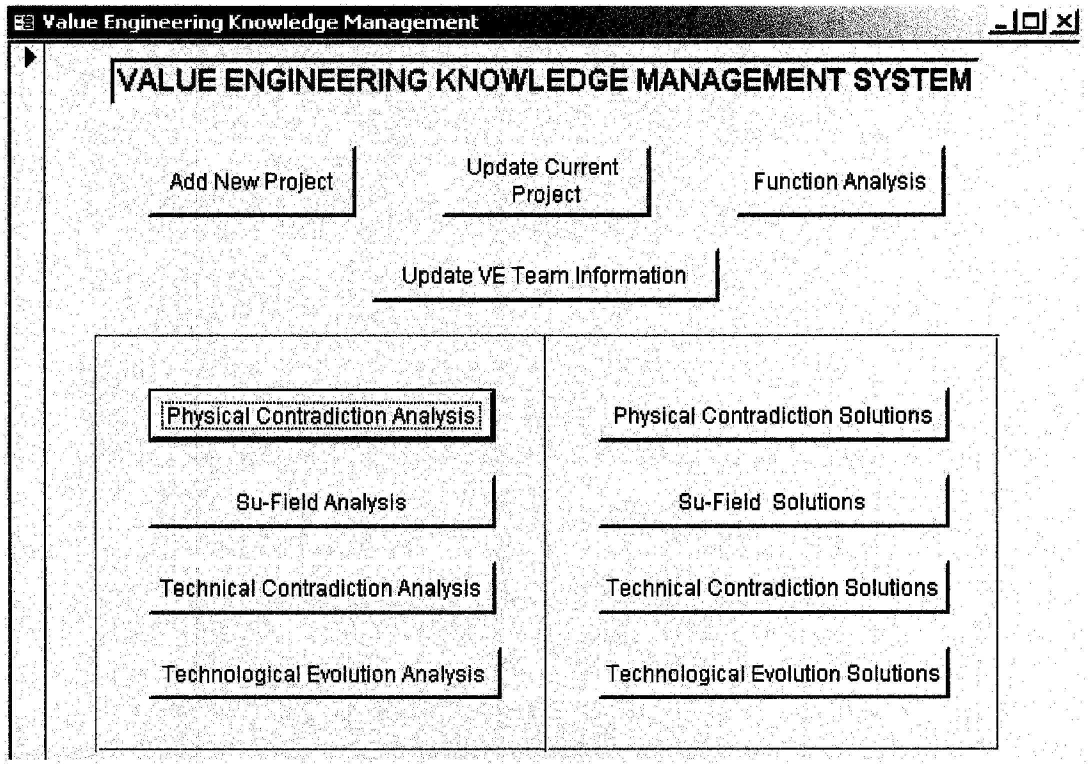


Figure 7.2: Interface of Proposed Value Engineering Knowledge Management System

7.4.3 Value Engineering Knowledge Management System

As shown in Figure 7.2, the VE-KMS is developed by integrating TRIZ tools into the creativity phase of the VE process for improved efficiency and effectiveness of VE studies. The TRIZ tools incorporated in the VE-KMS include (1) physical contradiction analysis, (2) Su-field analysis, (3) technical contradiction analysis, and (4) technological evolution analysis.

The VE-KMS enables VE team members to capture, extract, and convert their engineering experience, expertise, innovative ideas and solutions into explicit knowledge, store it in the database of the system in the process of the current VE study, and to continuously consolidate and update the knowledge database over time. VE team members can use this platform to retrieve previous innovative solutions, which may either be reutilized as direct solutions for a new project or provide more discipline-related insights for the generation of new ideas to solve the problems of the new project. Alternatively, VE team members may choose to generate innovative solutions themselves by systematically applying the TRIZ tools. Essentially, the two approaches share the same logic of TRIZ's general problem-solving methodology as shown in Figure 7.1.

Details of the VE-KMS are discussed in the following sections.

7.5 Architecture of the VE-KMS

7.5.1 Previous Construction Knowledge Management Systems

A number of researchers have conducted studies on knowledge management in the construction industry which provide insight into the development of the VE-KMS proposed in this chapter. For example, Assaf et al. (2000) developed a computerized system for the application of the VE Methodology. Mohamed (2002) developed a TRIZ-based framework for systematic improvement of construction systems. Mann and Hey (2003) proposed a knowledge management schema based on TRIZ concepts to store and access design solutions based design conflicts solved and principles applied. Soibelman et al. (2003) developed a data mining system to collect and store frequently used design review comments, personal experiences, and lessons learned on projects. Pulaski and Horman (2005) proposed to organize constructability information in accordance with the timing and levels of details required in order to assist a project team to identify and resolve constructability issues at the appropriate time. Zanni and Rousselot (2006) addressed the challenge of how to use TRIZ to formalize innovative designs.

7.5.2 Architecture of the VE-KMS

The architecture of the VE-KMS is presented in Figure 7.3. The major component of this architecture is the data warehouse, which contains three types of information: VE team information, project explicit knowledge, and project tacit knowledge. VE team information includes VE team members' contact information, expertise, and their specific contributions to particular projects. This information will help VE team members to seek support directly from these experts in case the knowledge expressed in the database is not sufficient to solve the current problems. Project explicit knowledge covers project drawings, specifications, records, and other related documentation. This information provides background information related to the project so that VE team members can better understand the project and its associated problems for which the solutions are being sought. It also enables VE team members to quickly locate relevant lessons from previous projects. Project tacit knowledge consists of know-how, expert suggestions, and innovations originating from the current VE study.

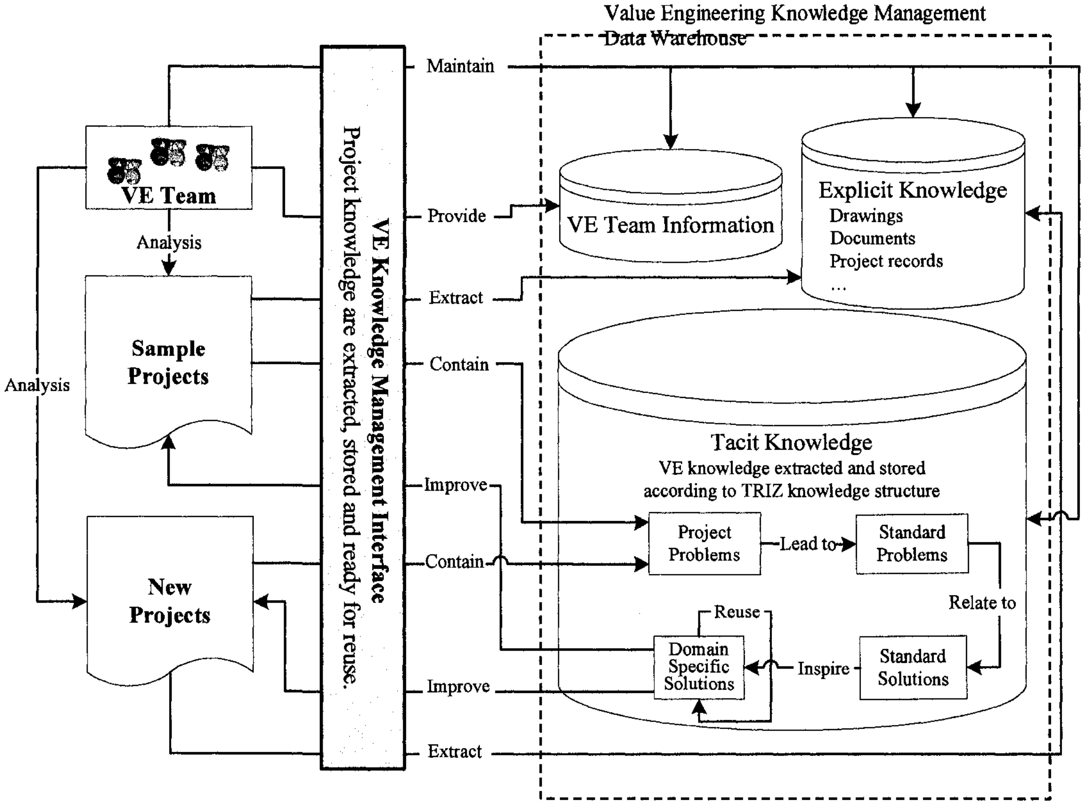


Figure 7.3: Architecture of Proposed Value Engineering Knowledge Management

7.5.3 Knowledge Extraction and Coding in the Database

Extracting construction knowledge related to specific subject matter or from a field expert is the most challenging step involved in developing a knowledge base (Kartam 1996). Without having the core knowledge of construction practices captured and stored in an orderly and retrievable format, it will be time-consuming to find useful information and difficult to apply it in solving future problems encountered in new projects. This is partly due to the fact that every construction project is unique because of variations in the scope of work, specifications, geographic location, and disciplinary requirements.

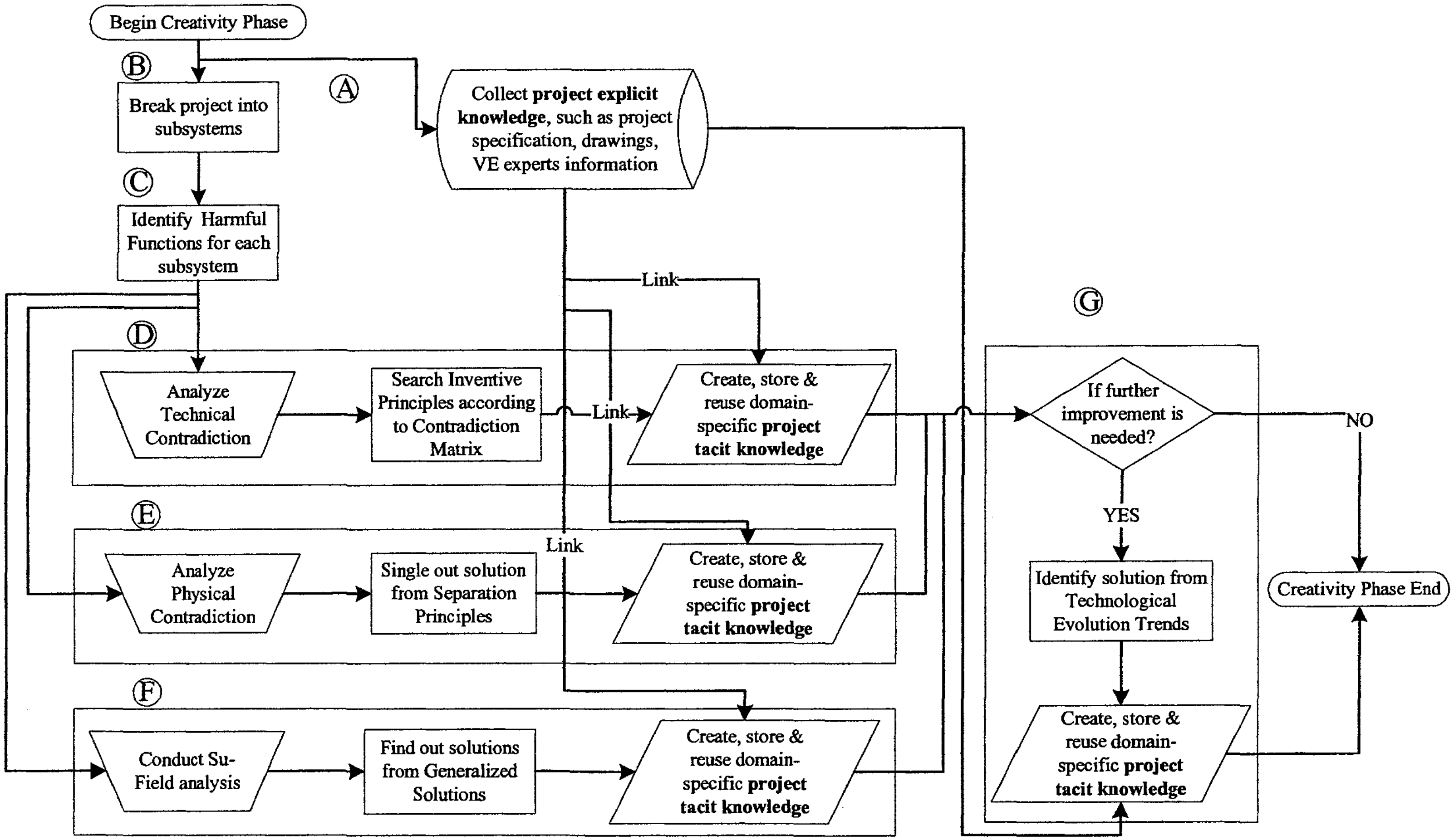


Figure 7.4: Procedures of the Creativity Phase of TRIZ-enhanced-Value Engineering

The knowledge obtained from the VE study is extracted and stored in the central database according to the following knowledge classification structure of TRIZ: (1) eight technological trends, (2) 40 inventive principles for technical contradictions, (3) four separation principles for physical contradictions, and (4) seven generalized principles for Su-field analysis. This means that the knowledge obtained from the VE study and the resultant solutions are consolidated and stored in the database according to the TRIZ tools to which the knowledge and solutions mainly belong. In addition, the knowledge and solutions are coded according to their field of discipline, a process which can serve to narrow down the search for useful knowledge in subsequent VE studies.

7.6 Procedures of the Improved Value Engineering Creativity Phase

As discussed in previous sections, TRIZ concepts and tools are incorporated into the VE-KMS to enhance the creativity phase of the VE process. The procedures followed to conduct this improvement of the creativity phase are shown in Figure 7.4 and the details are discussed in the sections below.

Step A: Collect Project Explicit Knowledge and VE Team Information

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

Step B: Break Project into Sub-systems

According to TRIZ, a project consists of a group of sub-systems which provide various functions. This step decomposes a project into sub-systems down to a level at which project functions can be sufficiently identified and properly analyzed. This can be accomplished based on a certain kind of hierarchical formation. For example, a building project can be broken down either based on the discipline (e.g. structural, mechanical, plumbing, and electrical components) or based on the physical nature of the project (e.g., foundation, floor, wall, and roof). This step facilitates the categorization of various solutions into specific domains in order to make the knowledge retrieval process more efficient and effective.

Step C: Identify Harmful Functions in Each Sub-system

Each sub-system may be associated with a number of harmful functions. This step identifies these harmful functions and ranks them in accordance with the VE team's level of intolerance. The intolerance level may be a value ranging anywhere from 1 to 10, with 10 representing the most intolerable level. This ranking directs the attention and focus of the VE team toward the most intolerable harmful functions. As will be discussed in steps D to F, TRIZ tools will be deployed in order to generate technical solutions to remove the harmful functions or minimize them to a level which is below a certain threshold of intolerance, say 7. Different technical solutions will incur different costs, and the solutions with the highest benefit/cost ratios will be selected. Here benefit refers to a reduction in the intolerance level based on a particular solution.

Step D: Identify and Solve Technical Contradictions

A technical contradiction occurs when improving one parameter of a sub-system worsens another parameter. This means that the measures taken to remove/minimize one harmful function will worsen other functions. A conventional approach to solve this dilemma is to seek the best compromise between the two parameters. However, this is not an ideal solution. To find better solutions, TIRZ has identified 39 engineering parameters and 40 inventive principles, based on which a 39x39 contradiction matrix has been developed. In this matrix, the 39 parameters are listed on the horizontal axis in a worsening feature and on the vertical axis in an improving feature, and some of the 40 inventive principles are located at the intersecting points of columns and rows. These inventive principles solve the contradiction represented by the parameters on the corresponding vertical and horizontal axis. In specific, the corresponding principles improve the parameter on the vertical axis without worsening its counterpart on the horizontal axis. For a particular sub-system, once a pair of contradicted parameters is identified, the corresponding inventive principles can be obtained from the contradiction matrix. These principles will guide the direction of the search toward the most innovative solutions to this contradiction.

Step E: Identify and Solve Physical Contradictions

A physical contradiction appears when one parameter must be modified in two opposite directions in order to remove or minimize a harmful function. This does not occur as frequently as the technical contradiction. Although a physical contradiction in some cases may be converted to a technical contradiction, it is differentiated as a separate stream for the purpose of improved knowledge management. TRIZ provides four general separation principles to solve physical contradictions: (1) separation in time, (2) separation in space, (3) separation between the whole system and its parts, and (4) separation based on different conditions. These principles guide the search for a solution to a particular physical contradiction.

Step F: Conduct Su-field Analysis

Su-field analysis is often used when a harmful function cannot be explained by a technical or physical contradiction. In this analysis, a function is defined as the result of the interaction between two substances (i.e. a "tool" and an "object") with the assistance of a field, where the substance may be an object at any level of complexity. The field, generated from a party other than the tool or object refers to a broad sense, may be mechanics, chemistry, physics, gravity, thermal dynamics, magnetics, or acoustics, for example. There are useful functions and harmful functions, but the objective of a Su-field analysis is to maintain/strengthen the useful functions and eliminate/minimize the harmful functions. TRIZ provides 76 standard solutions for Su-field analysis. To facilitate Su-Field analysis and increase efficiency, Mao et al. (2007) have condensed the 76 standard solutions into seven general Su-field analysis principles: (1) completing an incomplete Su-field model, (2) modifying the tool to eliminate or reduce the harmful function, (3) modifying the object to be insensitive or less sensitive to the harmful function, (4) changing the existing field to reduce or eliminate the harmful function, (5) eliminating, neutralizing, or isolating the harmful function using another counteractive field, (6) introducing a positive field, and (7) expanding the existing Su-field model to a chain.

Step G: Improve the Project According to Technical Development Trends

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

7.7 Data Warehouse Development

7.7.1 Entity Relationship Diagram for Designing the Database

The development of a valid information schema is critical to successful knowledge management. The information schema addresses how the comprehensive information repository is organized and formalized on the storage medium for effective and efficient knowledge development (Wang and Ariguzo 2004). The entity relationship diagram (ERD) is a simple semantic network model by which to design a database. The ERD, in turn, should be designed in accordance with some understandable classification or framework of information (Kazi and Hannus 2002). The ERD for the VE-KMS (developed in Microsoft® Access) is shown in Figure 7.5. Enclosed by the dashed line, the entities and relationships are grouped into five blocks corresponding to the five primary components of the VE-KMS: (1) project information collection and function analysis, (2) technological evolution analysis, (3) physical contradiction analysis, (4) technical contradiction analysis, and (5) Su-field analysis. The project information collection and function analysis component decomposes a project into sub-systems and identifies their harmful functions. The other four components collect the creative ideas and solutions according to the specific TRIZ tools involved. The creative ideas and solutions generated from a number of sample VE studies were extracted and stored in the database to test the validity of the ERD.

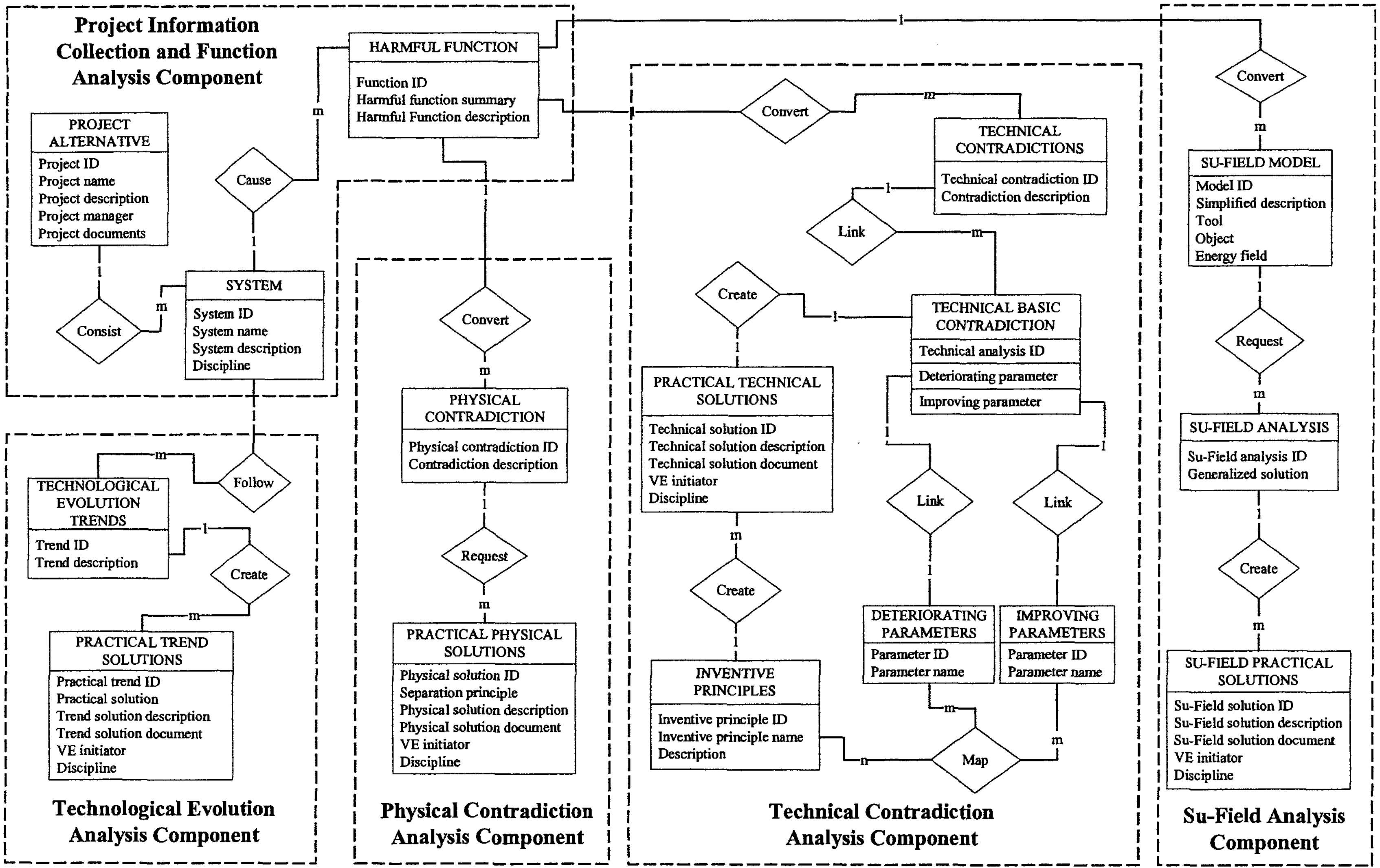


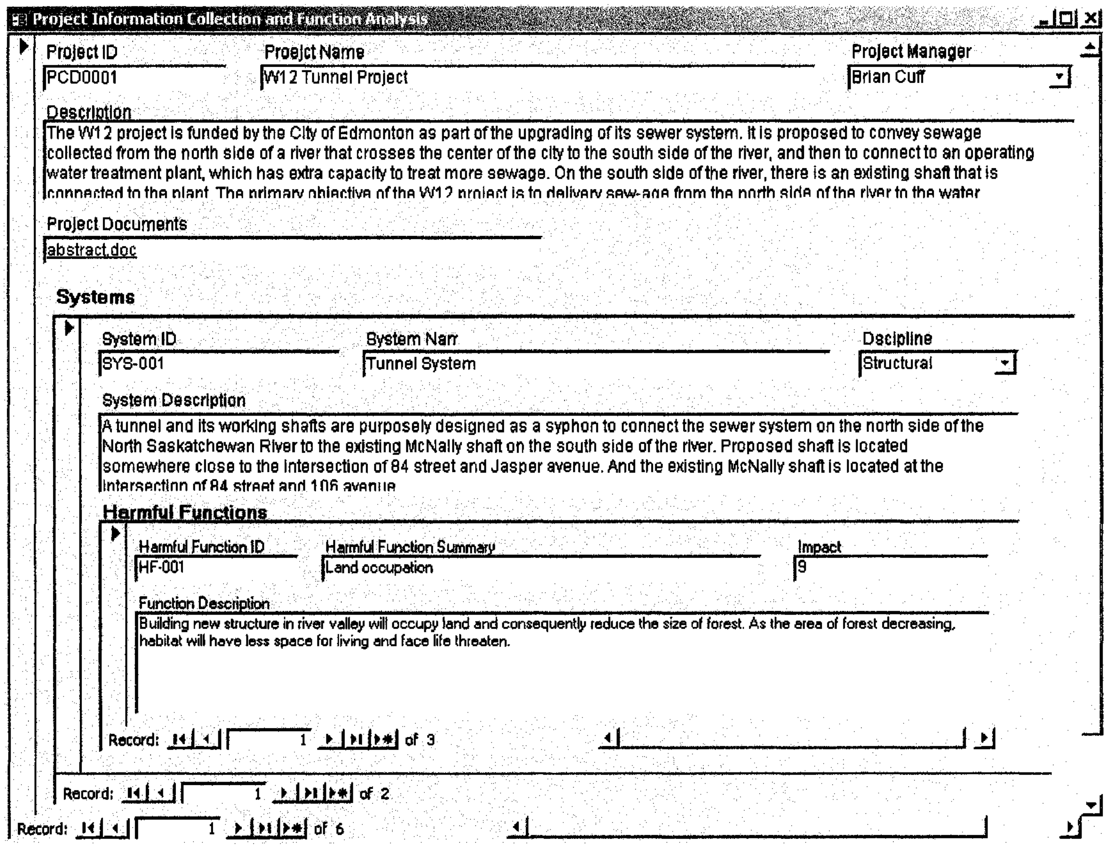
Figure 7.5: Entity Relationship Diagram

7.7.2 Coding of Domain Knowledge in the Database

The strength and utility of a KMS depend largely upon the quality and scope of the domain knowledge coded into the knowledge base (Lu 1987). Reflecting the importance of the domain knowledge, all tables of the database in the VE-KMS, which store practical solutions from VE studies, have two common fields—the VE initiator and the domain. The VE initiator documents the name and relevant information of the person who leads the development of the solution to ensure that his or her expertise is accessible in future VE studies. The domain documents the discipline of the solution. In this regard, the author has categorized construction knowledge into ten disciplines: civil, structural, architectural, piping, mechanical, process, electrical, instrumentation, chemical, and material. The two fields of knowledge allow for the search to be done by the domain, the initiator, or a combination of both.

7.7.3 Some Interfaces of the Database

A few database interfaces are provided here to help readers better understand the VE-KMS. Figure 7.6 shows the interface in which the information on a project and its sub-system, and the harmful functions of each sub-system, are recorded. The solutions to these harmful functions generated from individual TRIZ tools are documented using separate interfaces. For example, as demonstrated in Figure 7.7, this interface collects the solutions and other supporting knowledge from the Su-field analysis. The database also enables VE team members to use a query to retrieve existing knowledge and solutions to previous problems in their efforts to solve a new problem. As shown in Figure 7.8, all previous solutions to physical contradictions using the principle "separation based on different conditions" can be retrieved by querying this principle.



Project ID: PCD0001

Proejct Name: W12 Tunnel Project

Project Manager: Brian Cuff

Description: The W12 project is funded by the City of Edmonton as part of the upgrading of its sewer system. It is proposed to convey sewage collected from the north side of a river that crosses the center of the city to the south side of the river, and then to connect to an operating water treatment plant, which has extra capacity to treat more sewage. On the south side of the river, there is an existing shaft that is connected to the plant. The primary objective of the W12 project is to delivery sew-age from the north side of the river to the water

Project Documents: abstract.doc

Systems

System ID: SYS-001

System Narr: Tunnel System

Dscipline: Structural

System Description: A tunnel and its working shafts are purposely designed as a syphon to connect the sewer system on the north side of the North Saskatchewan River to the existing McNally shaft on the south side of the river. Proposed shaft is located somewhere close to the intersection of 84 street and Jasper avenue. And the existing McNally shaft is located at the intersection of 84 street and 106 avenue

Harmful Functions

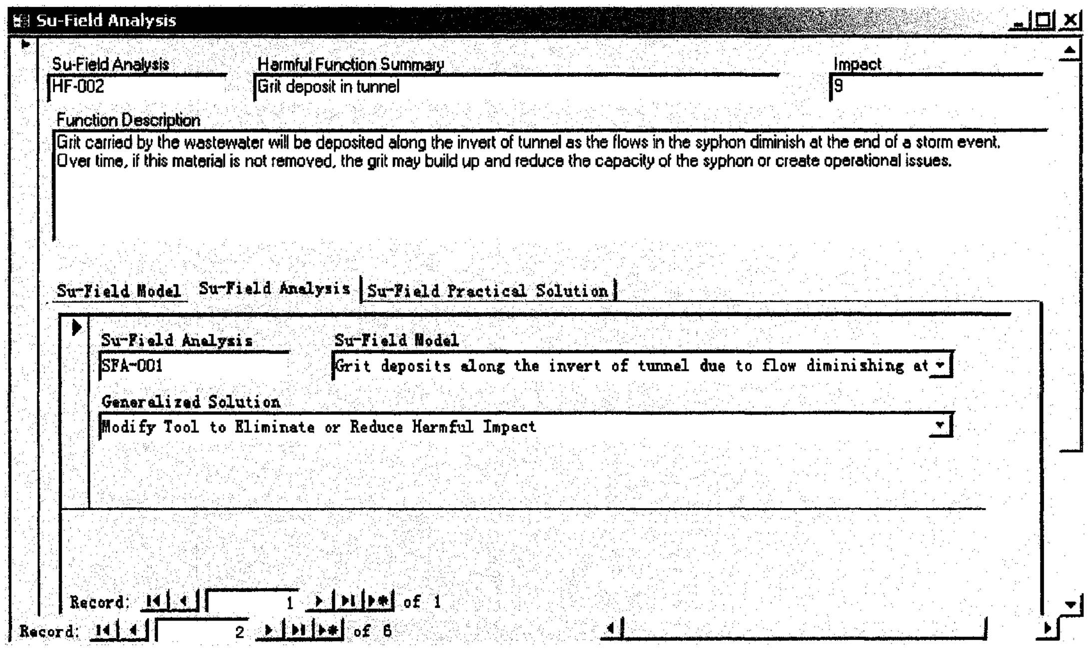
Harmful Function ID: HF-001

Harmful Function Summary: Land occupation

Impact: 9

Function Description: Building new structure in river valley will occupy land and consequently reduce the size of forest. As the area of forest decreasing, habitat will have less space for living and face life threaten.

Figure 7.6: Database Interface for Project Information Collection and Function Analysis



Su-Field Analysis: HF-002

Harmful Function Summary: Grit deposit in tunnel

Impact: 9

Function Description: Grit carried by the wastewater will be deposited along the invert of tunnel as the flows in the syphon diminish at the end of a storm event. Over time, if this material is not removed, the grit may build up and reduce the capacity of the syphon or create operational issues.

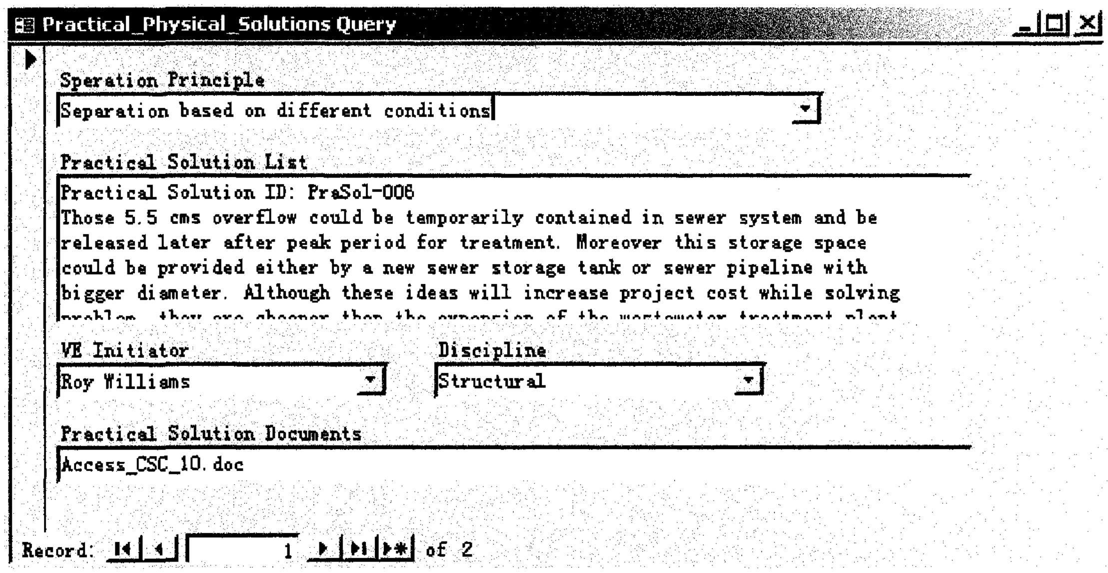
Su-Field Analysis: SFA-001

Su-Field Model: Grit deposits along the invert of tunnel due to flow diminishing at

Generalized Solution: Modify Tool to Eliminate or Reduce Harmful Impact

Figure 7.7: Database Interface for Su-Field Analysis

In addition, the name of the VE initiator and the attached documentations assist VE team members in gaining a deeper understanding of the solution, and they are also allowed to contact the corresponding experts when needed. If the dropdown list of the "Discipline" is clicked, the search will be narrowed such that only those solutions found within that domain will be presented.



Sperations Principle: Separation based on different conditions

Practical Solution List:
Practical Solution ID: PraSol-006
Those 5.5 cms overflow could be temporarily contained in sewer system and be released later after peak period for treatment. Moreover this storage space could be provided either by a new sewer storage tank or sewer pipeline with bigger diameter. Although these ideas will increase project cost while solving

VE Initiator: Roy Williams

Discipline: Structural

Practical Solution Documents: Access_CSC_10.doc

Figure 7.8: Database Interface for Knowledge Retrieval

7.8 Case Study

An interchange project is used to demonstrate the application of the proposed VE-KMS. For the sake of brevity, only the part of the VE study related to the protection of the existing pipelines underneath the soil of the project area is presented in the following sections.

7.8.1 Background of the Interchange Project

The City of Edmonton, Canada, has experienced a significant increase in population due to rapid economic growth in recent years. This has been one of the primary causes of the severe traffic congestion encountered during rush hour at the intersection of Calgary Trail and 23rd Avenue, which has raised serious safety concerns. To solve these problems, the City of Edmonton has decided to build a grade separated interchange as shown in Figure 7.9. This interchange project would allow easy access to surrounding commercial and residential areas and create a free flow of traffic on Gateway Boulevard and the connecting primary provincial highway, the Queen Elizabeth II Highway.

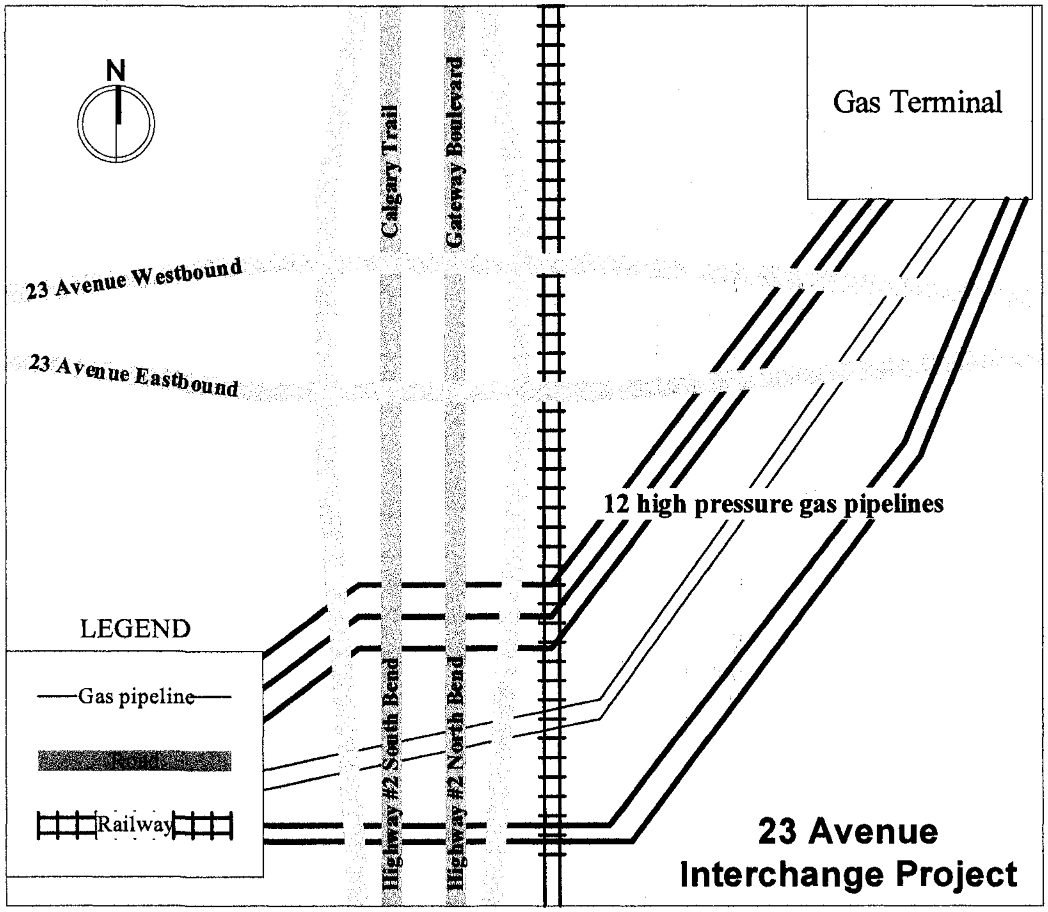


Figure 7.9: 23 Avenue Interchange Project

One pipeline corridor crosses the project area, which poses a challenge to the interchange project. This pipeline corridor contains 12 high-pressure gas lines ranging from 50 to 600mm in diameter, all of which had been installed between the early 1950s and the 1980s. Unfortunately, there is no detailed information available on the precise condition of their coating systems. Most of the pipelines have bends, which likely were made with some sort of fittings. These fittings represent the weak points in the pipelines. Furthermore, the soil overburden depths of these pipelines vary from 1.2 to 3.5 m., and these pipelines will be buried under the embankment fills of the new interchange with heights ranging from 1 to 6.8 m. above the existing grade. A differential settlement will take place near the interface between the soil under the ramp/retaining wall and the soil outside of the ramp/retaining wall area. This differential settlement can also cause significant stress along the pipelines (Bobey and Tweedie 2004). The lack of detailed information on the existing pipelines together with the stress of the pipelines caused by the differential settlement may result in some significant design and construction problems. The following sections discuss the matter of how to apply the VE-KMS to find solutions to these problems.

7.8.2 Function Analysis

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

1. The pressure and differential settlements from the high soil overburdens pose stress on the pipelines as the pipelines are buried under embankment fills with variable heights.
2. Differential settlement will take place near the interface between the soil under the ramp and that outside of the ramp area, resulting in significant stress on the pipelines.
3. Differential settlement could break pipelines at the bend areas because these fitting-connections represent the weak points in the pipelines.
4. Traffic load causes pressure on the pipelines where the overburden is shallow.

5. The retaining wall could damage the pipelines because of the differential settlement between the retaining wall and the pipelines crossing the wall.
6. It is difficult to inspect the corrosive condition of the buried pipelines.
7. Future replacement of the pipelines using an open-cut method could significantly interrupt the traffic flow in the interchange area.
8. Pipeline failures will interrupt gas transportation, and it will be difficult and time-consuming to repair buried pipelines.
9. Vibration compaction during ramp construction could damage the pipelines.

7.8.3 Knowledge Creation, Extraction and Reutilization

Once the harmful functions are identified, the previously discussed procedures for the enhancement of the creativity phase are followed in order to generate ideas and solutions to overcome these harmful functions. Consequently, the ideas and solutions generated from each TRIZ creativity tool are abstracted and recorded in a corresponding table of the VE-KMS database. For each problem, the TRIZ tool applied, its particular principle used, and the solutions generated from the TRIZ tool for each harmful function are listed in Table 7.1. It can be seen from Table 7.1 that a given harmful function can be solved using a number of different TRIZ tools. Furthermore, in some cases different TRIZ tools may lead to similar solutions.

In the following discussion, one solution generated from each TRIZ tool is discussed in order to demonstrate how to apply the TRIZ tools to solve harmful functions.

Su-field Analysis for Harmful Function #5 – Retaining Wall May Damage Pipelines: The first step in the Su-field analysis is to create a Su-field model, in which this particular problem is modeled as the retaining wall (the tool) acting on the pipeline (the object) using a mechanical force. On the one hand, the retaining wall provides support to the pipelines by holding fills. On the other hand, the retaining wall may damage the pipelines due to the differential settlement between the retaining wall and the pipelines. The second step is to identify a general principle to remove/minimize the harmful function. In this case, general principle #2, modifying the tool to eliminate or reduce the harmful impact, seems to be the most applicable. The third step is to develop a domain-specific solution under the guidance of the selected general principle. Since the maximum ground settlement is about 64 mm., a hole made on the retaining wall which has a diameter of 130 mm. greater than the diameter of the pipelines will provide enough space to tolerate the settlement variance between the retaining wall and the pipelines. The void space between the pipeline and retaining wall could be stuffed with compressive materials. Following completion of the Su-field analysis, the details of the case are captured in a corresponding sub-form of the VE-KMS database as illustrated in Figure 7.7. Moreover, this solution is linked to the generalized principle #2 under the discipline "Civil". VE team members may review this solution when they choose the same general principle to solve a new Su-field model within the same discipline.

Technical Contradiction Analysis for Harmful Function #2 – Differential Settlement at Ramp Interface May Cause Stress on Pipelines: The first step in the technical contradiction analysis is to identify the parameter which needs to be enhanced and the parameter which must be weakened. In this example, the length of the pipeline needs to be extended to cross the areas with different overburdens whereas the stress of the pipeline needs to be reduced. The variance of overburdens leads to differential soil settlements and consequently increases the pipeline stress at the transitional areas where the depth of the embankment changes. Obviously, the length of the pipeline and the stress of the pipeline constitute a technical contradiction. The second step is to search the contradiction matrix for possible inventive solutions. Two inventive principles, "segmentation" and "transformation of properties," are identified as having the potential to solve the above contradiction. "Segmentation" may prompt the VE team to increase the degree of fragmentation in order to accommodate the differential settlement while "transformation of properties" may stimulate the team to change the degree of the pipeline's flexibility. One solution possibly resulting from the two inventive principles is the use of flexible joints to connect the segmented pipelines buried under different depths of soil. This is a practical solution as many manufacturers make flexible joints for different purposes such as compensating for expansion contraction, rotation, bending, and settlement.

Physical Contradiction Analysis for Harmful Function #8 – Pipeline Repair May Interrupt Gas Transportation: The purpose of solving this problem is to minimize the interruption to gas transportation due to maintenance and repair of pipelines. After evaluating the four separation principles for physical contradiction analysis, it is found that the principles of "separation in time" and "separation in space" may be applied here to solve the problem. Based on these two principles, it is suggested that spare pipelines be built underneath the interchange area to back up the lost capacity encountered when some existing pipelines are out of service. The number of spare pipelines available may be determined by means of a probabilistic analysis.

Technological Trend Analysis for Harmful Function #6 – It is Difficult to Inspect the Corrosion Condition of Buried Pipelines: Assessing the state of corrosion of inaccessible underground coated pipelines has long been a problem. Buried pipelines are traditionally inspected by digging the test area over the pipeline, removing the pipeline's coating, and visually inspecting the bare steel surface. This approach is expensive, destructive, and time-consuming. In this respect, one technological evolution trend is "system evolving towards ideality." This trend advises the VE team to seek non-destructive solutions. Consequently, one possible solution is to use the electrical polarization technique to assess the state of corrosion of the buried pipelines.

7.9 Conclusions

Effective knowledge management will facilitate the generation of new technologies and processes and consequently improve business performance and client satisfaction. This is all the more important in the construction industry, which is project-based, much more fragmented than many other industries, and one in which the multiple parties involved in each project are temporary. Without a knowledge management system, a construction company may lose its intellectual strength and competitiveness when its experts move on or retire.

The value engineering knowledge management system (VE-KMS) proposed in this chapter makes the creativity phase of the VE process more systematic, better organized, and more objective-oriented by incorporating the creativity tools from the theory of inventive problem-solving (TRIZ). This endeavor significantly enhances the creative power of the VE team beyond their collective capability and consequently enhances the efficiency and effectiveness of the VE exercise. The case study of an interchange project in Edmonton, Canada, demonstrates the usefulness and applicability of the VE-KMS.

The VE-KMS facilitates automatic knowledge collection in conjunction with ongoing and effective retrieval and consolidation of knowledge from the database, and also facilitates cross-disciplinary knowledge transfer and sharing. VE team members can use the VE-KMS to retrieve previous hard-earned knowledge, which may either be reutilized as direct solutions for a new project or provide more discipline-related insight for the generation of new ideas to solve the problems encountered in a new project. Alternatively, team members may choose to generate innovative solutions themselves by systematically applying the TRIZ tools integrated in the VE-KMS.

Table 7.1: VE Analysis Results Summary

TRIZ Enhanced VE				
No.	**Harmful Function**	**TRIZ Tool**	**Principle**	**Practical Solution**
1	Soil pressure and soil settlements produce stress on pipelines.	Su-Field Analysis	#2: Modifying Tool to eliminate or reduce the harmful impact	1. Build an arch to cover pipes. 2. Install casing pipe on existing pipes.
		Technical Contradiction Analysis	#29: Pneumatic of hydraulic construction #35: Transformation of properties #22: Convert harm into benefit	1. Cover pipelines with lightweight materials, such as cellular concrete to reduce external pressure on pipe. 2. Increase embankment fills to optimal depth because soil pressure decreases when its depth increasing.
2	Differential settlement at ramp interface cause stress on pipelines.	Technical Contradiction Analysis	#35: Transformation of properties #1: Segmentation	Segment pipeline buried under different depths of soil with flexible joints, which compensate for expansion, bending and settlement of pipelines.
3	Differential settlement could break pipelines at bend areas	Su-Field Analysis	#2: Modifying Tool to eliminate or reduce the harmful impact	Cover pipelines with lightweight materials, such as cellular concrete to reduce external pressure on pipe.
4	Traffic load causes pressure on pipelines	Su-Field Analysis	#4: Changing the existing field to reduce or eliminate harmful impact	Bury pre-cast concrete slab in embankment to even pressure.
5	Retaining wall damages pipelines	Su-Field Analysis	#2: Modifying Tool to eliminate or reduce the harmful impact	Increase the diameter of hole to tolerate settlement.
6	Difficult to inspect the corrosion condition of buried pipelines.	Technological Trend Analysis	#8: Decreased human interaction and increased automation	Monitoring corrosion status of inaccessible pipes using electrical polarization technique.
7	Find alternative to replace pipeline rather than using open-cut method	Technical Contradiction Analysis	#7: Nesting	Build new pipe within existing pipe.
8	Pipe reparation will stop gas transportation for a significant time.	Physical Contradiction Analysis	#1: Separation in space #2: Separation in time	Build spare pipe to provide temperate service when needed.
9	Compacting soil without using vibration	Technological Trend Analysis	#2: Systems evolving toward ideality	Fill embankment on top of pipeline area with sands and condense sands with water.

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Chapter 8 – General Discussions and Conclusions

8.1 Research Summary

The research presented in this thesis mainly focuses on enhancing the creative power of the VE team beyond their expertise and experience and consequently improving the efficiency and effectiveness of conventional VE. In order to achieve the above objectives, this research has been conducted in the following three major areas: (1) review TRIZ concepts and tools in order to understand whether or not they are applicable to the construction industry and how they could potentially be utilized within the VE process; in addition, efforts have been made to simplify the 76 standard solutions of Su-Field analysis, which are too complicated to be used by general users; (2) develop the framework for a TRIZ-enhanced-VE approach in which inventive problem-solving techniques are incorporated into the creativity phase of a conventional VE approach; and (3) develop a VE knowledge management system so that knowledge originating from the VE study can be live captured and reused effectively in future VE project analysis.

This thesis began by reviewing a large volume of literature concerning the current VE practice and its limitations, the concepts and tools of TRIZ, the feasibility of integrating TRIZ with VE, and knowledge management in construction. It became obvious through this exercise that the current VE process must be improved in order to make it more efficient and effective. In this regard, it seems that it would be helpful to integrate TRIZ concepts and tools into VE since TRIZ can not only help enhance VE's creativity power, but can also help manage the knowledge obtained from VE.

Following the literature review, a number of TRIZ tools, including a contradiction matrix, 40 inventive principles, physical contradiction, 4 separation principles, and 8 patterns of evolution were examined in Chapter 3 in order to better understand their theories, interrelationships, and applications in construction.

Su-Field analysis and the simplification of its 76 standard solutions were then discussed in Chapter 4. As the major contribution of TRIZ, Su-Field analysis is a powerful tool by which to identify problems in a technical system and find corresponding innovative solutions from a solution pool. Despite its strength, the 76 standard solutions of the Su-Field analysis make the implementation of this tool difficult as they contain repetitive information from other TRIZ tools, give special favors in utilizing certain fields, and cannot be fully explained using the Su-Field model. In order to circumvent these shortcomings while making Su-Field analysis more effective, this research condensed 76 standard solutions into seven general principles. As a result, the logic of TRIZ in general is improved and the application of Su-Field analysis becomes more efficient.

Although VE has become an integral part of the development of many construction projects, its usefulness is still questioned by some practitioners due largely to a number of limitations existing in the conventional VE process: (1) function analysis is difficult to apply and may restrain the VE team's creativity; (2) VE's creativity is limited by individual VE team members' experience, knowledge, and creativity; (3) there has been a lack of effort made toward understanding and identifying essential problems, and (4) there has been a lack of effort in developing and evaluating alternative plans. To overcome these shortcomings, an enhanced VE framework was proposed in Chapter 5 which incorporates TRIZ concepts and tools in order to increase the creative capability of the VE team and guide the VE process towards innovative solutions. Compared with the process of a conventional VE exercise, the new framework entails the following improvements: (1) making the workshop session more systematic and better organized; (2) enhancing the creative capacity of the VE team and their effectiveness in conducting the VE exercise; (3) increasing the potential to realize project sustainability, environmental friendliness, and cost-effectiveness; and (4) making VE exercises more objective-oriented. These benefits were demonstrated through a case study based upon the parameters of an actual sewer delivery project.

In order to further validate the applicability and enhancement of the enhanced VE process, this new approach, as well as conventional VE analysis, was introduced to senior-level engineering students at Hong Kong and Canadian universities. Students at the two universities were required to conduct their term projects using the TRIZ-enhanced-VE analysis. Additionally, the students in Hong Kong were invited to complete a survey designed to elicit their opinions about the performance of the enhanced VE approach against traditional VE practice. Both sets of student applications and survey results indicate the acceptance of TRIZ-enhanced-VE approach as a value-adding tool to substitute for conventional VE analysis. Nevertheless, the results of the survey have also revealed that more training is needed to assist users in understanding the procedures and the benefits of this new approach.

One challenge identified from the application of the TRIZ-enhanced-VE framework is the difficulty involved in transforming the generic principles of TRIZ into domain-specific solutions to the specific problems of a particular construction project. The general principles of TRIZ only indicate the directions in which the most effective solutions may possibly exist. To a considerable extent, this depends on the problem solvers' abilities to successfully find potential solutions. Moreover, VE study usually starts from scratch without adequately utilizing the knowledge generated from previous VE exercises, which leads to the likelihood of "reinventing the wheel" and consequently the waste of resources. To respond these issues, a VE knowledge management system was developed in Chapter 7 to facilitate the creativity phase of VE by live capturing, extracting, and reusing the best engineering and construction knowledge obtained from this stage. The architecture of the proposed database for VE knowledge management also deals with the workflow of the creativity phase of the TRIZ-enhanced-VE study. This knowledge management system helps VE practitioners convert tacit knowledge in their minds into explicit project solutions, to capture them in a structured format within the VE exercise, and to facilitate cross-disciplinary knowledge transfer and sharing. Furthermore, it helps VE team members to retrieve hard-earned previous knowledge, which may either be reutilized as direct solutions for a project or may provide more discipline-related insights for the generation of new ideas to solve the problems of the new project.

8.2 Research Contributions

The research efforts outlined in this thesis contain a number of contributions to the research of TRIZ, TRIZ application, and current VE practice in construction. In particular, the major contributions of this thesis are as follows:

1. Simplification of standard solutions for Su-Field analysis

Su-Field analysis is a very effective tool by which to model a technical system and identify its problems. However, the 76 standard solutions associated with this tool could make users frustrated in searching for proper answers. The tremendous reduction of the 76 standard solutions into seven general principles may add considerable value to Su-Field analysis by making its application more efficient. Moreover, it improves the logic of TRIZ in general.

2. Improvement of conventional VE analysis

The framework of TRIZ-enhanced-VE is the first experiment toward the integration of TRIZ with VE. Although some previous researchers had addressed that TRIZ has the potential to generate more innovative ideas and enhance the efficiency and effectiveness of the VE process, this thesis developed the prototype by which to incorporate various TRIZ theories and creative tools into the conventional VE process. The case study demonstrated the applicability of the framework as well as the benefits of implementing this framework. Compared with the process of conventional VE, the proposed framework makes the VE study more systematic, better organized, more creative, and more objective-oriented. In general, this research constitutes one of relatively few attempts which have sought to revise and improve conventional VE, which has been practiced for half a century without any major enhancements.

3. Pioneer study of VE knowledge management system

The research presented in this thesis is the first attempt to develop a knowledge management system for VE analysis. It provides a new approach to enhance the creative power of VE by automatically collecting knowledge on an ongoing basis and effectively consolidating and retrieving knowledge from the database. The positive research conclusions indicate the necessity and value of the development of a knowledge management system for VE. It is expected to trigger a number of successive studies with respect to managing the knowledge obtained from VE study and reusing it in future VE analyses.

8.3 Recommendations for Future Work

As the preliminary initiative to conduct research in the previously mentioned areas, this thesis is certainly not a final and conclusive study through which the objectives of improving current VE practice, integrating VE with TRIZ, developing a knowledge management for VE analysis, and applying TRIZ in construction have been achieved or finalized. It is recommended that additional investigations, studies, and developments should be continued in the following areas:

1. Practicing TRIZ-enhanced-VE in real projects. Although the proposed framework has been reviewed by some VE experts and has been implemented by engineering students at both the University of Alberta and Hong Kong University of Science and Technology with very positive results, this approach needs to be applied by experienced VE practitioners through real-life VE exercises in order to further demonstrate its applicability and improve its logic.
2. Evaluating the effectiveness of the TRIZ-enhanced-VE using simulation techniques. Testing VE-improved engineering concepts and construction plan in a real project environment could be costly, risky, and, in many cases, impossible. As such, it would be preferable to validate the benefits of the newly proposed ideas prior to their execution. In this regard, computer simulation techniques provide an ideal platform by which to quantify the improvements resulting from TRIZ-enhanced-VE analysis and identify the areas where further improvements are needed.

3. Expanding upon the VE knowledge management research begun in this research. Studies could be carried out either by enhancing the current VE-KMS framework or choosing other, entirely different approaches. The key to formulating a successful knowledge management system is to find an appropriate data structure or classification system by which to consolidate obtained information and retrieve certain results efficiently when they are desired. Therefore, additional studies ought to be conducted to test different knowledge classification structures with the combination of various TRIZ creativity tools. These potential classifications could be categorized according to different phases of the project life cycle, various physical project components, relevant disciplines, or various types of projects.
4. Improving the VE-KMS in order to make it more robust and user-friendly. The knowledge management model being presented in this thesis is intended to test the feasibility of managing and reusing the knowledge created during VE study. Further research will be necessary in order to fully automate the application of this framework. These efforts could be focused on integrating automated knowledge acquisition techniques into the current conceptual model, allowing user access through a web-based interface, etc.

Appendix 1: The 39 Features of Altshuller's Contradiction Matrix

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The contradiction matrix, one of the first tools of TRIZ, remains one of the most popular. (Ref.1) The matrix itself, and the 40 principles of problem solving to which it refers can be downloaded from the July, 1997, issue of the TRIZ Journal. The same issue has a tutorial article on how to use the matrix and the 40 principles. (Ref. 2)

One barrier to using the matrix has been the very brief statement of the features that are the lists of improving and worsening features. The following expanded list was prepared by comparing several different translations (ref. 3, 4, 5) and has proven useful in several test classes.

Table 1: Explanation of the 39 Features of the Contradiction Matrix

No.	Title	Explanation
	Moving objects	Objects which can easily change position in space, either on their own, or as a result of external forces. Vehicles and objects designed to be portable are the basic members of this class.
	Stationary objects.	Objects which do not change position in space, either on their own, or as a result of external forces. Consider the conditions under which the object is being used.
1	Weight of moving object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension.
2	Weight of stationary object	The mass of the object, 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	Any one linear dimension, not necessarily the longest, is considered a length.
4	Length of stationary object	Same.
5	Area of moving object	A geometrical characteristic described by the part of a plane enclosed by a line. The part of a surface occupied by the object. OR the square measure of the surface, either internal or external, of an object.
6	Area of stationary object	Same
7	Volume of moving object	The cubic measure of space occupied by the object. Length x width x height for a rectangular object, height x area for a cylinder, etc.
8	Volume of stationary object	Same

9	Speed	The velocity of an object; the rate of a process or action in time.
10	Force	Force measures the interaction between systems. In Newtonian physics, force = mass X acceleration. In TRIZ, force is any interaction that is intended to change an object's condition.
11	Stress or pressure	Force per unit area. Also, tension.
12	Shape	The external contours, appearance of a system.
13	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability.
14	Strength	The extent to which the object is able to resist changing in response to force. Resistance to breaking.
15	Duration of action by a moving object	The time that the object can perform the action. Service life. Mean time between failures is a measure of the duration of action. Also, durability.
16	Duration of action by a stationary object	Same.
17	Temperature	The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate of change of temperature.
18	Illumination intensity * (jargon)	Light flux per unit area, also any other illumination characteristics of the system such as brightness, light quality, etc..
19	Use of energy by moving object	The measure of the object's capacity for doing work. In classical mechanics, Energy is the product of force timing distance. This includes the use of energy provided by the super-system (such as electrical energy or heat.) Energy required to do a particular job.
20	Use of energy by stationary object	same
21	Power * (jargon)	The time rate at which work is performed. The rate of use of energy.
22	Loss of Energy	Use of energy that does not contribute to the job being done. See 19. Reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category.
23	Loss of substance	Partial or complete, permanent or temporary, loss of some of a system's materials, substances, parts, or sub-systems.
24	Loss of Information	Partial or complete, permanent or temporary, loss of data or access to data in or by a system. Frequently includes sensory data such as aroma, texture, etc.
25	Loss of Time	Time is the duration of an activity. Improving the loss of time means reducing the time taken for the activity. "Cycle time reduction" is a common term.
26	Quantity of substance/the matter	The number or amount of a system's materials, substances, parts or sub-systems which might be changed fully or partially, permanently or temporarily.
27	Reliability	A system's ability to perform its intended functions in predictable ways and conditions.
28	Measurement	The closeness of the measured value to the actual value of a property of

	accuracy	a system. Reducing the error in a measurement increases the accuracy of the measurement.
29	Manufacturing precision	The extent to which the actual characteristics of the system or object match the specified or required characteristics.
30	External harm affects the object	Susceptibility of a system to externally generated (harmful) effects.
31	Object-generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of the object or system. These harmful effects are generated by the object or system, as part of its operation.
32	Ease of manufacture	The degree of facility, comfort or effortlessness in manufacturing or fabricating the object/system.
33	Ease of operation	Simplicity: The process is NOT easy if it requires a large number of people, large number of steps in the operation, needs special tools, etc. "Hard" processes have low yield and "easy" process have high yield; they are easy to do right.
34	Ease of repair	Quality characteristics such as convenience, comfort, simplicity, and time to repair faults, failures, or defects in a system.
35	Adaptability or versatility	The extent to which a system/object positively responds to external changes. Also, a system that can be used in multiple ways for under a variety of circumstances.
36	Device complexity	The number and diversity of elements and element interrelationships within a system. The user may be an element of the system that increases the complexity. The difficulty of mastering the system is a measure of its complexity.
37	Difficulty of detecting and measuring	Measuring or monitoring systems that are complex, costly, require much time and labor to set up and use, or that have complex relationships between components or components that interfere with each other all demonstrate "difficulty of detecting and measuring." Increasing cost of measuring to a satisfactory error is also a sign of increased difficulty of measuring.
38	Extent of automation	The extent to which a system or object performs 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 re-program 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 a system per unit time. The time for a unit function or operation. The output per unit time, or the cost per unit output.

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Appendix 2: 40 Inventive Principles

Principle 1. Segmentation

A. Divide an object into independent parts.
B. Make an object easy to disassemble.
C. Increase the degree of fragmentation or segmentation.

Principle 2. Taking out

A. Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.

Principle 3. Local quality

A. Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.
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.

Principle 4. Asymmetry

A. A. Change the shape of an object from symmetrical to asymmetrical.
B. If an object is asymmetrical, increase its degree of asymmetry.

Principle 5. Merging

A. Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.
B. Make operations contiguous or parallel; bring them together in time.

Principle 6. Universality

A. Make a part or object perform multiple functions; eliminate the need for other parts.

Principle 7. "Nested doll"

A. Place one object inside another; place each object, in turn, inside the other.
B. Make one part pass through a cavity in the other.

Principle 8. Anti-weight

A. To compensate for the weight of an object, 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).

Principle 9. Preliminary anti-action

A. If it will be 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 beforehand stresses in an object that will oppose known undesirable working stresses later on.

Principle 10. Preliminary action

A. Perform, before it is needed, the required change of an object (either fully or partially).
B. Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.

Principle 11. Beforehand cushioning

A. Prepare emergency means beforehand to compensate for the relatively low reliability of an object.

Principle 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).

Principle 13. 'The other way round'

A. Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).
B. Make movable parts (or the external environment) fixed, and fixed parts movable).
C. Turn the object (or process) 'upside down'.

Principle 14. Spheroidality - Curvature

A. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; 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.

Principle 15. Dynamics

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.

Principle 16. Partial or excessive actions

A. If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.

Principle 17. Another dimension

A. To move an object in two- or three-dimensional space.
B. Use a multi-story arrangement of objects instead of a single-story arrangement.
C. Tilt or re-orient the object, lay it on its side.
D. Use 'another side' of a given area.

Principle 18. Mechanical vibration

A. Cause an object to oscillate or vibrate.
B. Increase its frequency (even up to the ultrasonic).
C. Use an object's resonant frequency.

D. Use piezoelectric vibrators instead of mechanical ones.
E. Use combined ultrasonic and electromagnetic field oscillations.

Principle 19. Periodic action

A. Instead of continuous action, use periodic or pulsating actions.
B. If an action is already periodic, change the periodic magnitude or frequency.
C. Use pauses between impulses to perform a different action.

Principle 20. Continuity of useful action

A. Carry on work continuously; make all parts of an object work at full load, all the time.
B. Eliminate all idle or intermittent actions or work.

Principle 21. Skipping

A. Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.

Principle 22. "Blessing in disguise" or "Turn Lemons into Lemonade"

A. Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.
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.

Principle 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.

Principle 24. 'Intermediary'

A. Use an intermediary carrier article or intermediary process.
B. Merge one object temporarily with another (which can be easily removed).

Principle 25. Self-service

A. Make an object serve itself by performing auxiliary helpful functions
B. Use waste resources, energy, or substances.

Principle 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 or ultraviolet copies.

Principle 27. Cheap short-living objects

A. Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).

Principle 28 Mechanics substitution

A. Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.
B. Use electric, magnetic and electromagnetic fields to interact with the object.
C. Change from static to movable fields, from unstructured fields to those having structure.
D. Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.

Principle 29. Pneumatics and hydraulics

A. Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).

Principle 30. Flexible shells and thin films

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.

Principle 31. Porous materials

A. Make an object porous or add porous elements (inserts, coatings, etc.).
B. If an object is already porous, use the pores to introduce a useful substance or function.

Principle 32. Color changes

A. Change the color of an object or its external environment.
B. Change the transparency of an object or its external environment.

Principle 33. Homogeneity

A. Make objects interacting with a given object of the same material (or material with identical properties).

Principle 34. Discarding and recovering

A. Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
B. Conversely, restore consumable parts of an object directly in operation.

Principle 35. Parameter changes

A. Change an object's physical state (e.g. to a gas, liquid, or solid).
B. Change the concentration or consistency.
C. Change the degree of flexibility.
D. Change the temperature.

Principle 36. Phase transitions

A. Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).

Principle 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.

Principle 38. Strong oxidants

A. Replace common air with oxygen-enriched air.
B. Replace enriched air with pure oxygen.
C. Expose air or oxygen to ionizing radiation.
D. Use ionized oxygen.
E. Replace ozonized (or ionized) oxygen with ozone.

Principle 39. Inert atmosphere

A. Replace a normal environment with an inert one.
B. Add neutral parts, or inert additives to an object.

Principle 40. Composite materials

A. Change from uniform to composite (multiple) materials.

Appendix 3: TRIZ Standard Contradiction Matrix

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	35,32,26,28	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	39,2,13,11	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
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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
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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	26,28,10	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
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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	29,28,16,13	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

	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	37,36,3,24
2	28,27,2,11	29,19,15	39,28,10,1	26,25,17,15	35,26,2	35,28,15,1
3	28,10,1	16,15,14,1	28,24,19,1	35,28,24,1	28,24,17,16	4,29,28,14
4	3	35,1	26,1	28		7,31,28,14
5	15,13,10,1	30,15	14,13,1	36,28,2,18	30,28,23,14	34,26,2,10
6	18	16,15	36,18,1	35,30,2,18	23	7,17,15,10
7	10	29,15	26,1	4,29,28	35,34,24,16	6,34,2,10
8	1		31,1	28,2,17		37,35,2,10
9	34,28,27,2	28,15,10	4,34,28,10	34,3,27,16	18,10	
10	15,11,1	20,18,17,15	35,28,18,10	37,38,19,10	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	34,28,17,10
13	35,2,16,10	35,34,30,2	35,28,22,2	36,29,23,22	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	26,2,18
19	28,17,16,1	17,16,15,13	29,28,27,2	38,35	32,2	35,28,12
20				35,25,19,18		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	35,28,23,10
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	9,35,26,11,1	2,15,13	27,28,1	6,28,11,1	8,28,1	35,28,10,1
33	32,28,12,1	34,16,15,1	32,28,17,12		34,3,12,1	28,16,1
34		7,4,16,1	35,26,13,11,1		7,35,34,13	32,10,1
35	7,4,16,1		37,29,28,15	1	35,34,27	6,37,35,26
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 4: 76 Standard Solutions

TRIZ Standard Solution represents a frequently used solution for a specific type of problem. Standard Solutions are based on the best inventors' experience, Genrish Altshuller with co-workers identified and documented seventy-six Standard Solutions and organized them into following 5 classes (see below):

1. Su-Fields creation/destruction.
2. Su-Fields development.
3. Super-system/ micro-systems transition.
4. Su-Fields for measurement.
5. Rules for Standards application

To use this tool one identifies (based on a model obtained as a result of Su-Field Analysis) the class of a problem and then chooses a set of Standard Solutions for that type of problem. The Standard Solution is a recommendation of how to transform the system in order to eliminate the problem. Standard Solutions (and Principles as well) are not related to specific areas of technology and, together with analogical thinking, help transfer effective solutions from one branch of technology to another.

Each Standard has confirmed by a great number of strong inventions. Many Standard Solutions reflect the Laws of Technical System Evolution.

Altshuller's Standard Solutions of Invention Problems

Class 1. CONSTRUCTION AND DESTRUCTION OF SU-FIELD SYSTEMS

1.1. Synthesis of Su-Fields
    1.1.1. Making Su-Field
    1.1.2. Inner complex Su-Field
    1.1.3. External complex Su-Field
    1.1.4. External environment Su-Field
    1.1.5. External environment Su-Field with additives
    1.1.6. Minimal regime
    1.1.7. Maximal regime
    1.1.8. Selectively maximal regime
1.2. Destruction of Su-Fields
    1.2.1. Removing of harmful interaction by adding a new substance

- 1.2.2. Removal of harmful interaction by modification of the existing substances
- 1.2.3. Switching off harmful interaction
- 1.2.4. Removal of harmful interaction by adding a new field
- 1.2.5. Turn-off magnetic interaction

Class 2. DEVELOPMENT OF SU-FIELDS

- 2.1. Transition to complex Su-Fields
  - 2.1.1. Chain Su-Field
  - 2.1.2. Double Su-Field
- 2.2. Forcing of Su-Fields
  - 2.2.1. Increasing of field's controllability
  - 2.2.2. Tool fragmentation
  - 2.2.3. Transition to capillary-porous substances
  - 2.2.4. Dynamization (Flexibility)
  - 2.2.5. Field organization
  - 2.2.6. Substances organization
- 2.3. Forcing of Su-Fields by fitting (matching) rhythms
  - 2.3.1. Field - Substances frequencies adjustment
  - 2.3.2. Field - Field frequencies adjustment
  - 2.3.3. Matching independent rhythms
- 2.4. Transition to Su-M_Field systems
  - 2.4.1. Making initial Su-M_Field (or "proto-Su-M_Field")
  - 2.4.2. Making Su-M_Field
  - 2.4.3. Magnetic liquids
  - 2.4.4. Capillary-porous Su-M_Field
  - 2.4.5. Complex Su-M_Field
  - 2.4.6. Environment Su-M_Field
  - 2.4.7. Usage of physical effects
  - 2.4.8. Su-M_Field dynamization
  - 2.4.9. Su-M_Field organization
  - 2.4.10. Matching rhythms in Su-M_Field
  - 2.4.11. Su-E_Fields
  - 2.4.12. Electrorheological suspension

Class 3. TRANSITION TO SUPER-SYSTEM AND TO MICROLEVEL

- 3.1. Transition to bi-systems and poly-systems
  - 3.1.1. Creation of bi-systems and poly-systems
  - 3.1.2. Development of links
  - 3.1.3. Increase of difference between system's elements
  - 3.1.4. Convolution
  - 3.1.5. Opposite properties
- 3.2. Transition to micro-level
  - 3.2.1. Shift to micro-level

Class 4. STANDARDS FOR SYSTEM DETECTION AND MEASUREMENT

- 4.1. Roundabout ways to solve problems of detection and measurement
  - 4.1.1. Change instead to measure
  - 4.1.2. Copying
  - 4.1.3. Sequential detection
- 4.2. Synthesis of Su-Field measurement systems
  - 4.2.1. Creation of measurable Su-Field
  - 4.2.2. Complex measurable Su-Field
  - 4.2.3. Measurable Su-Field at environment
  - 4.2.4. Additives in environment
- 4.3. Forcing of measuring Su-Fields
  - 4.3.1. Physical effects applications
  - 4.3.2. Resonance
  - 4.3.3. Resonance of additives
- 4.4. Transition to Su-M_Field systems
  - 4.4.1. Measurable proto-Su-M_Field
  - 4.4.2. Measurable Su-M_Field
  - 4.4.3. Complex measurable Su-M_Field
  - 4.4.4. Environment measurable Su-M_Field
  - 4.4.5. Physical effects related to magnetic field
- 4.5. Direction of measuring system evolution
  - 4.5.1. Measurable bi- or poly-systems
  - 4.5.2. Evolution line

Class 5. STANDARDS FOR USING STANDARDS

- 5.1. Adding substances at construction, reconstruction, and destruction of Su-Fields.
  - 5.1.1. Roundabout ways:
    - 5.1.1.1. "Emptiness" instead of substance.
    - 5.1.1.2. Field instead of substance.
    - 5.1.1.3. External addition instead internal one.
    - 5.1.1.4. Particularly active addition in very small doses.
    - 5.1.1.5. Substance in very small doses.
    - 5.1.1.6. Addition is used for a while.
    - 5.1.1.7. A copy instead of a sub-system.
    - 5.1.1.8. Chemical compound.
    - 5.1.1.9. Addition is obtained from the sub-system itself
  - 5.1.2. Substance(s) separation
  - 5.1.3. Substance(s) dissipation
  - 5.1.4. Big additives
- 5.2. Adding fields at construction, reconstruction, and destruction of Su-Fields
  - 5.2.1. Using existing fields
  - 5.2.2. Fields from environment
  - 5.2.3. Substances as fields sources
- 5.3. Phase transitions
  - 5.3.1. Change of the phase state

  - 5.3.2. Second type phase transition
  - 5.3.3. Phenomena coexist with phase transition
  - 5.3.4. Two-phase state
  - 5.3.5. Interaction between phases
- 5.4. Application peculiarities of physical effects
  - 5.4.1. Self-driven transition
  - 5.4.2. Increase of output field
- 5.5. Creation of particles
  - 5.5.1. Substance destroying
  - 5.5.2. Integration of particles
  - 5.5.3. How to use Standards 5.5.1 and 5.5.2

Appendix 5: Inventive Principles with Examples

Principle 1. Segmentation

A. Divide an object into independent parts.

- Each ring of tunnel liner consists of several prefabricated steel and concrete panels.
- Breakdown a large project into several manageable subprojects.
- Separately produce architectural, structural, electrical, and HVC designs for a project.
- Five steps of '5S' technique for continuous improvement: sort, set in order, shine, standardize, sustain [3]
- Replace a large truck by a truck and trailer. [1]
- Dual circuit wiring to provide back-up when failure occurs in one circuit [1]
- In factory design separate the office accommodation and manufacturing facility [1]
- In hotel design separate the bedroom block from public areas [1]
- Design against progressive structural collapse. [1]

B. Make an object easy to assemble or disassemble.

- Prefabricated steel structure
- Modulized rail climbing frame applied in falsework of high-rise buildings (http://www.xingheren.com.cn/products/cpjs_en.htm)
- Decompose spiral stair into treads sleeves, tread coverings, balusters, handrails, handrail caps, column caps, and well enclosure. (http://www.salterspiralstair.com/steel.htm)
- Prefabricated buildings in galvanized cold-rolled steel (http://www.frisomat.com/companyeng1.htm)
- Ready-to-assemble furniture
- Wood floor
- Concurrent engineering team [3]
- Partition walls [1]
- Dry construction instead of wet [1]
- Quick disconnect joints in plumbing [2]

C. Increase the degree of fragmentation or segmentation.

- The segmentations of Chinese garden using bush and trails to make it roomy
- Garage door
- Water-mist extinguisher [7]
- Break down strategic quality goals into tactical goals. [3]
- Project milestones. [3]
- Affinity diagram – breaking down complicated issues into easier to understand categories and patterns [3]
- Break down work into simple and repetitive tasks. [3]
- Work breakdown structure for projects. [3]
- Tree diagram [3]
- Multi-pane windows [1]
- Replace solid shades with Venetian blinds. [2]

- Use powdered welding metal instead of foil or rod to get better penetration of the joint. [2]

Principle 2. Taking out/Removal/Extraction

A. Separate an interfering part or property from an object.

- Subcontract
- Outsourcing [3]
- Lean manufacturing – elimination of non-value added activities [3]
- Root cause analysis [3]
- Removal of defective parts at screening inspection. [3]
- Locate noisy equipment (air-conditioning plant, etc) outside a building. [1]
- Placing of quiet and meeting areas in places of work [1]
- Non-smoking areas in restaurants or in public buildings [1]
- Outside meters avoid need for utility companies to have access to property [1]
- Glass (noise-proof) partitions in office buildings [1]
- Utility room/pet-room/garage [1]
- Guttering takes rainwater away from structure of building [1]
- Exterior fire escape or lift do not interfere with plan [1]
- Bell-tower - needs height and also reduces noise and vibration effects [1]
- Pedestrian/vehicle segregation [1]
- Lightning conductor [1]
- Central vacuum cleaning system [5]
- Air Conditioning in the room where you want it with the noise of the system outside the room (The contradiction here is noise vs. coolness- the cooler it gets the noisier it gets- this solves the contradiction by putting the noise elsewhere) [4]

B. Single out the only necessary part (or property) of an object

- A conventional water mist protection systems only leave sprinkler underneath roof.
- Electronic candle
- Welding gun connected with propane and oxygen cylinders through pipelines.
- Bury electrical wires into wall and only leave outlet box visible.
- Use fiber optics or a light pipe to separate the hot light source from the location where light is needed. [2]
- Use the sound of a barking dog, without the dog, as a burglar alarm. [2]

Principle 3. Local quality

A. Change an object's structure from uniform to non-uniform

- Customize project design to fit client' demand.
- The drawers of toolbox have various sizes.
- Stove burners with two different sizes.
- Texture-finish building materials [1]
- Material surface treatments/coatings - self-cleaning paint, etc [1]
- Increased wall thickness at the base of buildings relative to higher up to accommodate greater structural loads [1]

- Location features on roof-tiles [1]
- Compound facade constructions [1]
- High-friction compounds and/or visibly stand-out features on stair edges [1]
- Non-homogenous distribution of rebar in concrete gives tailored strength properties [1]
- Low-emissivity film glass [1]
- Black dots at the edges of windows serve to improve appearance (blending between transparency and solid structure) - as used in car windscreens [1]
- Lotus Effect - self-cleaning paint [1]
- Weakened/thinner break glass points on window-units [1]
- Reinforcement of openings [1]
- Arch in masonry [1]
- Vary standard of insulation [1]
- Movement joints [1]
- Molded hand grips on tools [4]
- Material surface treatments / coatings - plating, [4]
- Erosion / corrosion protection, case hardening, non-stick, etc [4]
- Dual-Layer Tread Tire has two kinds of rubber in the tread. As the tread wears down, the underneath layer with higher grip rubber is exposed to help minimize the effects of wear and reduce noise. [6]

B. Change an external environment (or external influence) from uniform to non-uniform.

- Make allowances for temperature, density, or pressure gradient instead of constant temperature, density or pressure when examining effects of local environment on airflows around (high-rise) buildings. [1]
- Bias towards South-facing windows [1]
- Greater standard of security for ground floor windows [1]
- Different security arrangements for front and back of shop [1]
- Introduce turbulent flow around an object to alter heat transfer properties. [4]
- Take account of extremes of weather conditions when designing outdoor systems. [4]

C. Make each part of an object function in conditions most suitable for its operation.

- An apartment consists of living room, bedroom, kitchen, storage room, etc.
- Different shaped rooms for different functions - plumbed and non-plumbed, for example [1]
- Incorporation of a pantry room on externally placed walls to achieve lower temperature than living spaces [1]
- In low energy design locate rooms with low design temperatures and buffer spaces to the north; locate large rooms with high design temperatures to the south [1]
- Night-time adjustment on a rear-view mirror [4]
- Lunch box with special compartments for hot and cold solid foods and for liquids [4]

D. Make each part of an object fulfill a different and complementarily useful function.

- Multi-plier
- Mobile crane
- Self-unloaded truck
- Structural transparency tiles [1]
- Ventilation tiles on a roof [1]
- Gravel provides security as well as a ground surface finish [1]
- Fire-retarding paint [1]
- Hammer with nail puller [2]

Principle 4. Asymmetry

A. Change the shape or properties of an object from symmetrical to asymmetrical.

- Each prong of a receptacle has unique shape to ensure proper connection with plug.
- Introduce a geometric feature which prevents incorrect usage/assembly of a component (e.g. earth pin on electric plug) [1]
- Corner bricks [1]
- Coated glass or paper [1]
- Introduction of angled or scarfed geometry features on component edges [1]
- Non-circular section chimneys reduce drag against prevailing wind direction [1]
- Sloped roofing [1]
- Single-drainer sink unit [1]
- High-flow gutter uses asymmetry to better control entry flow of rainwater from roof into down-pipe (30% more flow for a given entry area) [1]
- "Modern" planning as opposed to classical planning [1]
- Tongued and grooved flooring [1]
- T beam floor construction [1]
- Double doors where one leaf is wider than the other [1]
- Asymmetrical mixing vessels or asymmetrical vanes in symmetrical vessels improve mixing (cement trucks, cake mixers, blenders). [2]
- The Nikon's square-shaped COOLPIX SQ is convenient to carry. Yet, it incorporates a swivel lens that is integral to its overall design statement and optical precision. [6]
- By changing the fibers from a straight stem to a bone with an asymmetrical form, it gives the fibers the ability to hold the concrete together, giving it much higher strength and toughness. [7]

B. Change the shape of an object to suit external asymmetries (e.g. ergonomic features)

- Computer mouse
- Human-shaped seating, etc [1]
- Take account of differences between left/right handed, male/female users. [1]
- Finger and thumb grip features on objects [1]
- Pull-handles versus push-plates on doors [1]
- Aerofoil sections with different top and bottom surface geometries [1]
- Passive solar house design [1]
- Site Planning to respect an individual site [1]

- Change from circular O-rings to oval cross-section to specialized shapes to improve sealing. [2]
- Use astigmatic optics to merge colors. [2]

C. If an object is asymmetrical, increase its degree of asymmetry.

- Compound/multi-sloped roofing [1]
- Cable assisted cantilever roofs [1]
- Folding doors [1]
- Use of variable control surfaces to alter lift properties of an aircraft wing [4]
- Special connectors with complex shape/pin configurations to ensure correct assembly [4]
- Introduction of several different measurement scales on a ruler [4]

Principle 5. Merging

A. Bring closer together (or merge) identical or similar objects or operations in space; assemble identical or similar parts to perform parallel operations.

- Dimmer switch
- Cooling and heating system share the ductwork.
- Value engineering committee
- Constructability team
- Group brainstorming
- Double/triple glazing [1]
- Double panel radiators [1]
- Sprinkler systems offers centralized 'fire-management' capability [1]
- Networked neighborhoods - permit load sharing between multiple properties [1]
- Multi-purpose halls [1]
- Sandwich panels [1]
- Personal computer in a network [2]
- Thousands of microprocessors in a parallel processor computer [2]
- Electronic chips mounted on both side of a circuit board or subassembly [2]
- Strips of staples [4]
- A high efficiency cooling device of the notebook computer in the brand name of SONY V505 combines all radiators using heat conduction pipe. Then fan extracts the heat that comes out from all radiators. [6]

B. Make objects or operations contiguous or parallel; bring them together in time.

- Engineering-procurement-building method for construction.
- Standardize tunneling process to make it to be a continuous operation
- High-rise building is built with the aid of automatic self-climbing systems with wall formwork elements suspended from the platform. This makes it possible to concrete the entire core, slabs, and facade walls in a single pour, saving valuable time and manpower. (http://www.findarticles.com/p/articles/mi_m0NSX/is_7_48/ai_106389510)
- Concurrent engineering [3]

- Co-location of services - gas, cable, electricity, water, etc - minimizes underground disruption [1]
- Mixer taps [1]
- Prefabrication [1]
- "Partnering" - co-operative team based approach to construction reduces conflict, litigation and claims [1]
- Link slats together in Venetian or vertical blinds. [2]
- Medical diagnostic instruments that analyze multiple blood parameters simultaneously [2]
- Manufacture cells [4]
- Grass collector on a lawn-mower [4]
- Pipe-lined computer processors perform different stages in a calculation simultaneously [4]

Principle 6. Universality

A. Make a part or object perform multiple functions; eliminate the need for other parts.

- Project engineering also acts as a safety inspector.
- A total station has multiple functions as distance measurement, electronic leveling, built-in laser plummet, and full alphanumeric keyboard. (http://www.pentaxcanada.ca/products/sgps/r300n_series.php)
- A multiple skilled operator is trained to drive truck, dozer, backhoe, and other equipment on site.
- Universal remote control
- Home Depot supplies one-stop-shopping.
- Fire glass - glass with steel wire re-enforcement that prevents release of broken glass upon breakage. [1]
- Built-in wardrobes/cupboards/etc [1]
- Velux windows - provide illumination, heat insulation, ventilation and weather-proofing [1]
- Water tanks on top of buildings provide insulation and head for water supply [1]
- Use power cables as a communication medium (e.g. control signals for 'central locking' system for house. [1]
- Gargoyle eliminates the need for downpipe [1]
- Thermostatic radiator valves, shower mixers, etc [1]
- Combined doorbell and smoke alarm [1]
- CD used as a storage medium for multiple data types [4]
- Cordless drill also acts as screwdriver, sander, polisher, etc [4]
- Solar-energy tempered glass road marker combines solar-powered battery and high strength glasses together. [6]

B. Use standardized features.

- Construction module concept
- Construction procedure and specification
- Inspection and test procedure
- Specification form incoming, in-process and final quality inspection [3]

- International standard [3]
- Standard record form [3]
- Template [3]
- Use of Standards in e.g. safety regulations [1]
- Corporate-branded architecture for franchise or chain buildings [1]
- Cavity walls with standard dimensions for masonry, insulation, cavity trays and wall ties [1]
- Proprietary cladding systems with specified performance [1]

Principle 7. Nesting

A. Place one object inside another

- Install wires, pipes and ducts in wall and roof.
- Tripod for survey setup
- Cavity wall
- Hierarchy of ISO 9000 standards – 9001 embraces 9002 which in turn embraces 9003. [3]
- Organization structure – several levels with several people within each organizational unit. [3].
- Match personalities when assembling a team. [3]
- Place a safe inside a wall or under floorboards [1]
- Introduce voids into 3D structures [1]
- Injected cavity-wall insulation [1]
- Dry-lining [1]
- False ceilings [1]
- Under-floor 'trench' heating [1]
- Place electrical wiring inside architraving/dado rails/etc. [1]
- Roller shutters [1]
- Sound isolation of concert hall [1]
- Russian dolls [2]
- Double hull in oil tankers. [5]
- Telescoping structures (umbrella handles, radio antennas, pointers) [5]
- File directory structure in the Windows computer operation system. [5]
- Instead of open trench excavation to fix or replace of another object damaged pipes, run a pipe-bursting mole through the old pipe which will break and expand the old infrastructure, allowing for the new pipe which is trailing the mole to be set in place. [7]

B. Place each object, in turn, inside the other.

- Crane boom
- Fishing stick
- Stacking chairs [1]
- Multi-layer erosion/corrosion coatings [1]
- Integration of services [1]
- Ducts for pipes, wiring etc. [1]
- Franchises (e.g. car rental offices and shops in airports and railway stations) [1]

C. Make one part pass (dynamically) through a cavity in the other.

- Elevator
- Retractable seating in auditoria [1]
- Services pass through the structure of a building [1]
- Use circulation space as the return route with warm air heating systems [1]
- Retractable loft stairs [1]
- Adjustable floor levels and/or seating arrangements in theatres [1]
- Sliding doors [1]
- Seat belt retraction mechanism [2]
- Retractable aircraft landing gear stow inside the fuselage. [2]
- Telescopic car aerial [4]
- Retractable power-lead in vacuum cleaner [4]
- Tape measure [4]

Principle 8. Counterweight

A. To compensate for the weight of an object, merge it with other objects that provide lift.

- Counterweight of elevator
- Floating floor [1]
- Use of counterweights in lifts and sash windows [1]
- Inject foaming agent into a bundle of logs, to make it float better. [2]
- Lifting bodies – the shape of the fuselage acts like a wing and generate lift. Used in both aircraft and ship design.
- Air tanks in submarine vessels [5]
- Companies increase flagging sales by making connection with other rising products. [5]
- Business analogies: compensation for the heavy organization pyramid with project organization, process organization, temporary organization and other less hierarchical systems "life" the heavy structure. [5]
- The continental AG's run-flat tire system can fit into a standard rim together with a standard tire. In case of air loss, the new system carries the load and fixes the tire bead on the rim. [6]

B. To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).

- Caisson construction. As the form rises, the base of the platform lowers, partially submerging the caisson and relieving the platform of its weight. (http://www.tritonsa.gr/caissons.htm)
- A float controls the valve for filling toilet tank. The float rises on the incoming water and triggers the valve to shut off when the float reaches certain point.
- Design a building to float using a tanked basement. [1]
- Location of circulation pump in hot-water heating systems [1]
- Passive solar heaters use natural convection currents to circulate water [1]

- Aircraft wing shape reduces air density above the wing, increases density below wing, to create lift. (This also demonstrates Principle 4, Asymmetry.) [2]
- Make use of centrifugal forces in rotating systems (e.g. Watt governor). [4]
- Maglev train uses magnetic repulsion to reduce friction [4]

Principle 9. Preliminary Counteraction

A. If it will be necessary to perform an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.

- Cover all fixtures before starting to paint a room.
- Safety inspection
- Equipment maintenance
- Proactive approach [3]
- Failure analysis and prevention techniques – FMEA, FMECA, FTA. [3]
- Sustainable design [1]
- Dust removal from power tools [1]
- Minimize entropy increases. [1]
- Use recycled materials. [1]
- Use renewable energy. [1]
- Use an electric heater to preheat the car engine before starting in the winter in northern regions. Damage to the engine from running with frozen oil is prevented, fuel is saved and air pollution decreased. [5]
- Masking objects before harmful exposure: use a lead apron for X-rays, use masking tape when painting difficult edges etc. [4]
- Wire receiving device consists of an elastic mechanism and a container. When a person wants to use the wire, he could draw the wire and then, when finished, the wire can be automatically rolled up and stored in the container due to the elasticity of the spring. [6]

B. Create beforehand actions in an object that will oppose known undesirable working stresses later on.

- Formwork oil - it assists in reducing surface tension at the interface between the concrete and the formwork, ensuring the optimum of release and quality concrete finish. (http://www.pickquick.co.uk/logformoil.htm)
- Concrete curing compounds - designed to provide a fast drying, flexible, tough and impervious membrane that protects the concrete from rapid water evaporation during the initial curing stages
- Bentonite and polymer based drilling fluids are used to minimize the penetration of the solids into the side of the wellbore. (http://www.hddwell.com/HDD_installation/drillingfluid.htm)
- Self-assessment, correction of non-conformances before starting ISO 9000 registration process [3]
- Design verification and validation. [3]
- Pre-stress rebar before pouring concrete. [1]
- Pre-stressed bolts [1]
- Vapor-permeable paint helps prevent rot in wood [1]

- Prevent electrolytic corrosion by separating dissimilar metals [1]
- Masking anything before harmful exposure: Use a lead apron on parts of the body not being exposed to X-rays. Use masking tape to protect the part of an object not being painted [2]
- Changes and innovations usually meet resistance in an organization. Get the affected people involved so they can participate in the planning of changes and don't feel threatened. [5]
- Use customer trials to launch high-risk new products. [5]
- Focus on pro-action instead of reaction in maintenance. [5]
- Decompression chamber to prevent divers getting the bends. [4]

Principle 10. Preliminary action

A. Perform, before it is needed, the required change of an object (either fully or partially).

- Dust control on construction site
- Preliminary engineering design.
- Pipeline pressure test
- Mulching to reduce the speed of storm water runoff over an area
- Pre-fabricated window units, bathrooms and other structures [1]
- Pre-fabricated buildings [1]
- 'Design for re-cyclability' [1]
- Ready-mix concrete [1]
- Copper pipe connections pre-filled with solder [1]
- Double-glazing with vacuum or inert gas [1]
- Night storage heater [1]
- Pre-pasted wall paper [2]
- Self-adhesive stamps [4]
- Holes cut before sheet-metal part formed [4]
- Pre-impregnated carbon fiber reduces lay-up time and improves "wetting" [4]
- A flashlight without batteries and bulbs just needs15-30 seconds of shaking for providing up to 5 minutes of continuous bright light. Electromagnetic energy is generated by shaking and then stored in the flashlight. Moreover, the bulb is replaced by the super bright blue LED, which makes the flashlight more robust and enduring. [6]

B. Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.

- Project scheduling
- Audubon Society HQ building features integral recycling chutes allowing pre-sort of different materials by individuals within the building [1]
- Piped water and other services especially in hospitals [1]
- Central vacuum cleaning [1]
- Sprinkler systems for fire [1]
- Pre-payment machines in car-parks [1]
- Pre-compressed sealing tape [1]

- Standardized objects with known specification [1]
- Kanban arrangements in a Just-In-Time factory [2]
- Flexible manufacturing cell [2]
- Workers arrange their workspace so the most frequently used tools (either physical, paper or electronic) are the easiest to reach. [5]
- Car jack, wheel brace, and spare tyre stored together [4]

Principle 11. Beforehand cushioning

A. Prepare emergency means beforehand to compensate for the relatively low reliability of an object ('belt and braces')

- Fall arrest protection during construction: guardrails, protective coverings, travel-restraint system, fall-restricting system, fall-arrest system, safety belt and safety net.
- Project contingency planning [3]
- Excess inventory [3]
- Troubleshooting [3]
- Second source suppliers [3]
- Back-up power generator [3]
- Emergency circuit lighting [1]
- Dual channel control system [1]
- Mask borders of objects to be painted, use stencils [1]
- Emergency stairways/fire-escapes [1]
- Lightning rods [1]
- Safety measurement [1]
- Overflows [1]
- Magnetic strip on photographic film that directs the developer to compensate for poor exposure [2]
- Multi-channel control system [4]
- Pressure relief valve [4]
- Automatic save operations performed by computer programs [4]
- Crash barriers on motorways [4]
- "Self Cleaning" kitchen exhaust hood is not based on the insertion of traditional filters, but rather employs the natural air-cleansing method of rain by actively deploying water vapor to "intercept" the oil and dust in the exhaust before it reaches the interior of the hood. [6]
- Adding a damper to building structures will reduce the effect of seismic and wind loadings. [7]

Principle 12. Remove Tension (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).

- Resource leveling at project management – smoothing peaks and valleys, minimizing effect of conflict in demand for the same resources. [3]

- Counter-balance elevators [1]
- Inclusion of an inspection pit inside a garage eliminates the need to raise and lower the car during maintenance [1]
- Bungalows have only one floor [1]
- Use cleaning platforms to clean large objects. [1]
- Add electrically grounded surfaces in electronic component manufacture facilities. [1]
- Ramps for wheelchairs [1]
- Pressure equalized facades [1]
- Spring loaded parts delivery system in a factory [2]
- Locks in a channel between 2 bodies of water (Panama Canal) [2]
- Descending cable cars balance the weight of ascending cars. [4]

Principle 13. Inversion

A. Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).

- Monitor construction progress through web camera instead of visiting site.
- To loosen stuck parts, cool the inner part instead of heating the outer part. [1]
- Self-service stores [1]
- Tilt and turn windows can be cleaned from the inside. [1]
- Instead of providing more and more car parking, provide NO car parking. [1]
- Test pressure vessel by varying pressure outside rather than inside. [4]
- Test seal on a liquid container by filling with pressurized air and immersing in liquid; trails of bubbles are easier to trace than slow liquid leaks. [4]
- Reverse osmosis filter system uses a process known as cross-flow to allow the membrane to continually clean itself. As some of the fluid passes through the membrane the rest continues downstream, sweeping the rejected species away from the membrane. [6]

B. Make movable parts (or the external environment) fixed, and fixed parts movable.

- Wind tunnels [1]
- Moving sidewalk with standing people [1]
- Drive through restaurant or bank. [1]
- Instead of people's having to come to hospital use traveling medical facilities [1]
- Rotate the part instead of the tool. [2]

C. Turn the object (or process) 'upside down'.

- Lloyds building places pipes and services outside rather than inside the building [1]
- Most architectural structures rely on compressive forces, use of tension wires/tensegrity structures permits construction of lighter structures with greater internal space [1]
- Downstairs bedrooms (cooler); upstairs living rooms (better view) [1]
- Houses constructed from the inside out [1]
- Auxetic (negative Poisson Ratio) foams and structures [1]

- Pedestrians streets [1]
- Turn an assembly upside down to insert fasteners (especially screws). [2]
- Empty grain from containers (ship or railroad) by inverting them. [2]
- Instead of utilizing conventional scaffolding, which needs to be anchored to the ground, use a set of cables that will anchor the working platform to the bridge. This method will eliminate any potential disturbance to traffic under the bridge, while essentially allowing workers to work from ground level. [7]

Principle 14. Spheroidality - Curvature

A. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.

- The cross section of a tunnel; mostly choose ovoid, horseshoe, and round shapes instead of square shape.
- Water pipe use round shape.
- Smoothing technique for conflict resolution – emphasizing areas of agreement, de-emphasizing areas of disagreement, seeking a joint problem solving opportunity. [3]
- Use arches and domes for strength. [1]
- Introduce fillet radii between surfaces at different angles. [1]
- Introduce stress relieving holes at the ends of façade and other structures. [1]
- Curved driveways improve aesthetics [1]
- Port-hole windows [1]
- Circular-section buildings - light-houses, towers, etc [1]
- Geodesic structures - maximum space coverage with minimum material usage [1]
- Circular-section pillars and columns [1]
- Architraving - blends join between wall and ceiling [1]
- Curved floor edges make bathroom/changing-room floors more easy to clean [1]
- Rounded edges soften appearance of electrical sockets and switches [1]
- Curved roof shape avoids the need to construct a ridge [1]
- Use curved retaining walls for extra strength. [1]
- Use monocoque construction for better strength to weight ratio. [1]
- Change curvature on lens to alter light deflection properties. [4]
- Washing machine using centrifugal force and rotating waterfalls. During the wash cycle, the motor spins the drum at high speeds, creating a powerful water whirl. Next, the centrifugal force pushes the clothing against the stainless steel tub. Water is driven through the clothing fibers, penetrating and forcing stains and dirt out of the clothing fibers. [6]

B. Use rollers, balls, spirals, domes.

- Loop for a process
- Quality circle [3]
- Archimedes screw pumps concrete/sealants/etc into cavities [1]
- Domed roofs [1]
- Spiral plan for an infinitely extending museum [1]

- Spiral gear (Nautilus) produces continuous resistance for weight lifting. [2]
- Archimedes screw [4]

C. Go from linear to rotary motion (or vice versa)

- Team leadership rotation. [3]
- Revolving doors help keep heat inside a building [1]
- Rotating observation tower on top of tall buildings [1]
- Linear city design maximizes access to transport corridors [1]
- Use shot-bolt fixings instead of drilled. [1]
- Produce linear motion of the cursor on the computer screen using a mouse or a trackball. [2]
- Rotary actuators in hydraulic system. [4]
- Push/pull versus rotary switches (e.g. lighting dimmer switch). [4]

D. Use centrifugal forces.

- Centrifugal casting for even wall thickness concrete structures [1]
- Radius of gyration affects stability during earthquakes. [1]
- Spin components after painting to remove excess paint. [4]
- Separate chemicals with different density properties using a centrifuge. [4]

Principle 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.

- Adjust TBM advancing rate based upon soil conditions.
- Change speed limitation on highway according to weather conditions.
- Flash traffic light
- Thermo- or Photo-chromic glass [1]
- Shape memory alloys/polymers [1]
- Flexible office layouts [1]
- Moveable insulation [1]
- Adjustable steering wheel (or seat, or back support, or mirror position...) [2]
- Smart traffic lights help drivers to arrive when the lights are green and discourage frequent starts and stops. [5]
- Flexible manufacturing systems (FMSs) are increasingly used in industry. [5]
- Racing car suspension adjustable for different tracks and driving techniques [4]
- Telescopic curtain rail - "one size fits all" [4]
- Trucks used to only be able to deliver shipments at a fixed temperature. A new way allows a larger container to hold some smaller ones while filling the space between two layers of the case of the smaller containers with eutectic material. [6]
- When FRP (Fiber Reinforced Plastic) is applied to the exterior of the concrete it is soft and moldable, after its application is begin to gain strength and stiffen until stage of operation final strength is reached. [7]

B. Divide an object into parts capable of movement relative to each other.

- Articulated piles allow pile to be sharp (for ease of driving in to the ground) and blunt (to create a positive location once in place) [1]
- Roofing slates [1]
- Movement joints [1]
- The "butterfly" computer keyboard, (also demonstrates Principle 7, "Nested doll".) [2]
- Bifurcated bicycle saddle [4]
- Articulated lorry [4]
- Folding chair/mobile phone/laptop/etc [4]
- Collapsible structures [4]

C. If an object (or process) is rigid or inflexible, make it movable or adaptive.

- Retractable roof structures [1]
- Flexible joint [1]
- Floating floors [1]
- Multi-purpose halls [1]
- Use escalators instead of stairs. [1]
- Structural and other redundancies allow future changes [1]
- The flexible sigmoidoscope, for medical examination [2]
- Bendy drinking straw [4]

D. Increase the degree of free motion

- 'Moving internal wall' systems allow house layout to be changed to suit evolving needs of occupants [1]
- Demountable structures [1]
- Telemedicine facilities [1]
- Loose sand inside truck type gives it self-balancing properties at speed. [4]
- Add joints to robot arm to increase motion possibilities. [4]

Principle 16. Partial or excessive actions

A. If 100% of a solution is hard to achieve, then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.

- Internal inspection requirements are higher than external ones.
- Dewatering to lower the ground water table to provide a stabilized area for construction
- Safety margins [3]
- Tolerance – permitted range of deviation from standard [3]
- Measurement accuracy – indication of closeness to the true value [3]
- Over spray when painting, then remove excess. [1]
- Over fill holes with plaster and then rub back to smooth [1]
- Over designing floor joists results in negligible deflection [1]
- Use skilled craftsmen on site to complete prefabricated work. [1]
- Design for say 95% of requirement is often the practical solution for e.g. heating systems, car parking [1]

- Use of Pareto analysis to prioritize actions when not all can be achieved with the available resources. [1]
- 'Roughing' and 'Finish' machining operations [4]
- BMW's valvetronic engine system minimizes pumping loss by reducing valve lift and the amount of air entering the combustion chambers. Thus it reduces maintenance costs, improves cold start behavior, lowers exhaust emissions, and provides a smoother running engine. [6]

Principle 17. Another dimension

A. To move an object in two- or three-dimensional space.

- Shafts for tunnel construction
- Tower crane transfer two-axis transport to three-dimensional transport.
- Underground facilities (e.g. parking lots, shopping centers)
- Overpass
- 3D computer visualization
- Multi-disciplinary cross-functional teams [3]
- Use of triangles (cross-members, etc) improve strength/stability of frame structures [1]
- Bay windows [1]
- Frank Lloyd Wright 'Fallingwater' house blends architecture with natural slope of landscape [1]
- Pyramidal structures (non-vertical walled structures) [1]
- Indirect lighting [1]
- Stair lifts [1]
- Slotted fixings [1]
- A curve at the base of a roof slows down the rainwater [1]
- Spiral staircase uses less floor area [1]
- Corrugated roofing materials offer high stiffness and low weight [1]
    - Introduction of down and up slopes between stations on railway reduces train acceleration and deceleration power requirements [1]
- Score key-slots into a wall before plastering improves adhesion of plaster [1]
- 'Round-the-corner' windows provide better views and cross-ventilation [1]
- Curved or profiled roofing materials have superior spanning capabilities [1]
- Shell and monocoque construction [1]
- Curved bristles on a brush [4]
- ShinMaywa's mechanical parking equipment adopts vertical parking mode to reduce the use of plan parking space in crowed cities. The equipment can be easily installed in buildings. Due to the smaller size of the equipment, the construction time can be shortened. Further, the parking equipment is flexible for different vehicle heights. [6]

B. Use a multi-storey arrangement of objects instead of a single-storey arrangement.

- Multi-storey office blocks or car-parks [1]
- Automated parts warehouses [1]
- Multi-use buildings e.g. shopping centers [1]

- Cars on road transporter inclined to save space [4]
- Player with many CD's [4]
- Stacked or multi-layered circuit boards [4]

C. Tilt or re-orient the object, lay it on its side.

- Tilt-up construction.
- Hang a mirror with corners (rather than edges) top and bottom to cater for greater variety of user heights for a given size of mirror [1]
- Take a door off its hinges to plane top and bottom surfaces to size. [1]
- Vertically mounted radiators (use less floor space) [1]
- Angled glazing/tilting windows [1]
- Modern kitchen overlooks street/front [1]

D. Use 'another side' of a given area.

- 'Invisible' door hinges [1]
- Hydrostatic pressure keeps waterproofing layer attached to outer face of basement wall [1]
- Stack microelectronic hybrid circuits to improve density. [2]

Principle 18. Mechanical vibration

A. Cause an object to oscillate or vibrate.

- Use vibrator to consolidate pavement.
- Vibration exciter removes voids from poured concrete. [1]
- Use non-parallel walls to prevent acoustic standing waves. [1]
- Use radius of gyration for earthquake design. [1]
- Electric carving knife with vibrating blades [2]
- Shake/stir paint to mix before applying. [4]
- Hammer drill [4]
- Vibrate during sieving operations to improve throughput [4]
- Vibration instead of sound to alert someone for incoming call. [5]
- Ultrasonic wave replaces the movement energy to take off dirt on fabrics without any detergent. Due to this new way of removing dirt, it needs only the least amount of water necessary to soak the laundry. The purified water that comes out after washing can be used for rinsing or for other purposes. These functions with no use of detergent could be useful in keeping our environment safe from water pollution. The flexible material used for folding tub was adapted to save the room for storing washing machine. [6]
- Using a high frequency hydraulic vibrator, allows for sheet piles to be driven into almost any soil condition. [7]

B. Increase its frequency (even up to the ultrasonic).

- Use white noise to disguise conversation. [1]
- Ultrasonic cleaning [1]
- Non-destructive crack detection using ultrasound [1]
- Distribute powder with vibration. [2]

- Dog-whistle (transmit sound outside human range) [4]

C. Use an object's resonant frequency.

- Use resonance to speed the flow of concrete from hopper. [1]
- Destroy gallstones or kidney stones using ultrasonic resonance. [2]
- Bottle cleaning by pulsing water jet at resonant frequency of bottles [4]
- Increase action of a catalyst by vibrating it at its resonant frequency. [4]

D. Use piezoelectric vibrators instead of mechanical ones.

- Piezoelectric vibrators improve fluid atomization from a spray nozzle [1]
- Quartz crystal oscillations drive high accuracy clocks. [2]
- Optical phase modulator [4]

E. Use combined ultrasonic and electromagnetic field oscillations.

- Geo-physics techniques to aid identification of sub-soil structures [1]
- Crack detection using ultrasound [1]
- Mixing alloys in an induction furnace [2]
- Ultrasonic drying of films – combine ultrasonic with heat source [4]

Principle 19. Periodic action

A. Instead of continuous action, use periodic or pulsating actions.

- Take break during construction work.
- Periodical project reviews [3]
- Take account of day/night temperature and light difference effects when designing thermal/illumination management systems. [1]
- Spot welding [1]
- Use railings or bollards instead of walls. [1]
- Pile drivers and hammer drills exert far more force for a given weight. [4]
- Pulsed bicycle lights make cyclist more noticeable to drivers. [4]
- Pulsed vacuum cleaner suction improves collection performance. [4]
- Pulsed water jet cutting [4]
- ABS car braking systems [4]
- Instead of continuous light signal, a flashing light is often used for information, advertising and warning. [5]
- Dayok Electrical Company applied the variable frequency technique to the new products, the inverter welders that have the following features: 1. Power consumption only half compared with traditional types; 2. More stable arc and strong penetration; 3. They are 1/3 weight compared with traditional types. [6]

B. If an action is already periodic, change the periodic magnitude or frequency.

- Replace a pulsed siren with sound that changes amplitude and frequency. [1]
- Column frequency [1]
- Vary column spacing. [1]
- Tartan grids [1]
- Use Frequency Modulation to convey information, instead of Morse code. [2]

- Replace a continuous siren with sound that changes amplitude and frequency. [2]
- Using a high cycle vibrator will allow the concrete periodic, change its frequency placement to be uniform, and will remove unwanted air bubbles (Not air entrained bubbles). [7]

C. Use pauses between actions to perform a different action.

- Conduct survey during TBM static period.
- Clean barrier filters by back-flowing them when not in use. [1]
- Use of energy storage means - e.g. batteries, fly-wheels, etc. [1]
- Multiple conversations on the same telephone transmission line [4]

Principle 20. Continuity of useful action

A. Carry on work continuously; make all parts of an object work at full load or optimum efficiency, all the time.

- Three 8-hour shifts being arranged on construction site
- Improve composting process by continuously turning material to be composted. [1]
- Multi-function spaces and personnel [1]
- Flywheel (or hydraulic system) stores energy when a vehicle stops, so the motor can keep running at optimum power. [2]
- Run the bottleneck operations in a factory continuously, to reach the optimum pace. (From theory of constraints, or take time operations). [2]
- Continuous glass or steel production. [4]
- Correction tape devices are used to cover erratum on papers with adhesive correction material. Unlike liquid correction pens, this device requires no waiting time for solidification, and words can be directly written down on the tape. Due to use of non-toxic materials, users are safe when they correct errors. Furthermore, the shell can be refilled when the tape is used. [6]

B. Eliminate all idle or intermittent actions or work.

- Get rid of non value-adding activities in a construction process.
- Preventive and predictive maintenance [3]
- Self-cleaning/self-emptying filter eliminates downtime. [1]
- Rapid-drying paint [1]
- Reduce or eliminate circulation space. [1]

Principle 21. Rushing through

A. Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.

- Cut plastic faster than heat can propagate in the material, to avoid deforming the shape. [1]
- Continuous pouring of concrete [1]

- Large sheets of roofing material allow quick erection enabling other trades to work under cover. [1]
- Mitsubishi's newly developed high-pressure swirl injectors provide the ideal spray pattern to match each engine operational modes. And at the same time by applying highly swirling motion to the entire fuel spray, they enable sufficient fuel atomization. [6]

Principle 22. Convert harm into benefit

A. Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.

- Ground freezing method
- Use explosive compaction in soil improvement. (http://www.extenza-eps.com/extenza/loadPDF?objectIDValue=52223)
- Use customer complaints as opportunities for improvement. [3]
- Use waste heat to generate electric power. [1]
- Composting toilets [1]
- Secure piles by exploding a cavity around the base and then pouring concrete into the cavity. [1]
- Double-glazing [1]
- Recycle scrap material as raw materials for another – e.g. chipboard [4]
- Vaccination [4]

B. Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.

- Use toxic chemicals to protect timber from infestation and rot. [1]
- Add a buffering material to a corrosive solution. (e.g. an alkali to an acid, or vice versa) [2]
- Use a helium-oxygen mix for diving, to eliminate both nitrogen narcosis and oxygen poisoning from air and other nitrox mixes. [2]
- Use gamma rays to detect positron emissions from explosives. [4]

C. Amplify a harmful factor to such a degree that it is no longer harmful.

- Fully glazed conservatories maximize solar gains, but cannot waste heat because they are not heated artificially [1]
- Use a backfire to eliminate the fuel from a forest fire. [2]
- Use explosives to blow out an oil-well fire. [4]
- Laser-knife cauterizes skin/blood vessels as it cuts [4]

Principle 23. Feedback

A. Introduce feedback (referring back, cross-checking) to improve a process or action.

- Survey during tunneling operation
- Corrective actions and follow-up [3]
- Quality audit and reviews [3]
- Prototype testing [3]
- Periodical reliability testing [3]

- Motion sensitive lighting/toilet flush/etc systems [1]
- Thermostatic temperature controls [1]
- Heat/smoke sensors used to detect fire [1]
- Glass doors and breast-high partitions allow people on either side see when there is someone on the other side [1]
- Automatic volume control in audio circuits [2]
- Signal from gyrocompass is used to control simple aircraft autopilots. [2]
- Statistical Process Control (SPC) -- Measurements are used to decide when to modify a process. (Not all feedback systems are automated!) [2]
- Budgets --Measurements are used to decide when to modify a process. [2]
- Engine management system based on exhaust gas levels is more efficient than carburetor [4]
- Feedback turns inaccurate op-amp into useable accurate amplifier [4]
- Active noise control system is used to suppress noise on vehicle. It can reduce use of sound insulation material. The idea works on the principle of destructive interference between the sound fields generated by the original primary sound source and that due to other secondary sources, whose acoustic outputs can be controlled. [6]
- Introducing a video camera mounted at the crane bottom will allow the crane operator to get a real-time view of the loads, this will improve productivity because it will act as a quick check with the signal craftsmen, plus allow the operator to view things that might be out to the craftsmen's line of sight. [7]

B. If feedback is already used, change its magnitude or influence in accordance with operating conditions.

- Incoming, in-process and final quality inspection and testing [3]
- Change sensitivity of a thermostat when cooling vs. heating, since it uses energy less efficiently when cooling. [1]
- Fuzzy-logic thermostats [1]
- Involve manufacturers during early design stages. [1]
- Increase frequency and/or detail of inspection for certain site operations. [1]
- Change sensitivity of a thermostat when cooling vs. heating, since it uses energy less efficiently when cooling. [2]
- Change a management measure from budget variance to customer satisfaction. [2]

Principle 24. Mediator

A. Use an intermediary carrier article or intermediary process.

- Mediation
- Lead-flashing forms leaf-proof seal between external wall and attached structures. [1]
- Skirting boards protect delicate plaster from damage by vacuum cleaners, etc. [1]
- Fly-screen door [1]
- Small ceramic tiles and woodblock flooring power supplied stuck to a disposable sheet. [1]
- Pipe lagging [1]

- Carpenter's nailset, used between the hammer and the nail. [2]
- Play a guitar with a plectrum. [4]
- Use a chisel to control rock breaking/sculpting process. [4]
- Dwell period during a manufacture process operation [4]
- In Casio's high-performance fuel cell, a reformer produces hydrogen from fuel or alcohol such as methanol, and electric energy is generated from the hydrogen through a generating cell. The reformer, so-called a unique micro-reactor formed on a silicon wafer causes chemical reaction to reform methanol to hydrogen gas in the presence of catalyst at a reforming rate of more than 98%. [6]

B. Merge one object temporarily with another (which can be easily removed).

- Use arbitrator for sensitive discussion. [3]
- Hire temporary employees. [3]
- Abrasive particles enhance water jet cutting. [1]
- Demountable insulating window shutters [1]
- Pot holder to carry hot dishes to the table [2]
- Joining papers with a paper clip [4]
- Introduction of catalysts into chemical reaction [4]

Principle 25. Self-service

A. Make an object serve or organize itself by performing auxiliary helpful functions

- User guide to teach how to operate and maintain construction tools and machines.
- Self-learning program
- On-line registration
- Self-inspection [3]
- On-site water purification plant. [1]
- Use building contours to channel wind energy towards wind-turbine. [1]
- Earth covered roofing 'maintains' itself [1]
- 'Self-cleaning' guttering - prevents blockage by leaves, etc. [1]
- Self-latching locks [1]
- To weld steel to aluminum, create an interface from alternating thin strips of the 2 materials. Cold weld the surface into a single unit with steel on one face and copper on the other, then use normal welding techniques to attach the steel object to the interface, and the interface to the aluminum. (This concept also has elements of Principle 24, Intermediary, and Principle 4, Asymmetry.) [2]
- Self-aligning / self-adjusting seal [4]
- Self-cleaning oven / glass / material [4]
- In a tire that repairs itself, liquids are sprayed inside the tire. When the tire is punctured, the liquid fills the hole. When it contacts the outside air, it solidifies, forming a permanent repair. [5]
- TOTO's aqua auto faucet features a non-contact design that switches on the water flow when the hands are brought near it, and switches off the water when the hands are removed. The absence of handles keeps the area around the basin clean, and the faucet cannot be left running, making it both hygienic and economical. TOTO upgraded the original battery-powered type to a water-powered type. This

eliminates the need for installing a power supply or changing batteries, and saves on electricity costs. [6]

- Using Stay in Place (SIP) formwork will eliminate the disadvantages related to conventional formwork such as (disassembly, cleaning, transportation, and storage). The SIP will not only act as formwork, but will also provide cladding once the concrete has been cured. [7]

B. Use waste resources, energy, or substances.

- Recycle
- Use heat from a process to generate electricity: "Co-generation". [1]
- Grey water recycling systems [1]
- Solar panels/collectors to heat water or generate electrical power [1]
- Heat exchanger takes heat from waste hot water. [1]
- Use waste heat from internal equipment (e.g. from computer rooms, heavy machinery) to generate thermal gradients to drive 'natural' ventilation systems. [1]
- Geothermal energy [1]
- Brick rubble used for hardcore [1]

Principle 26. Copying

A. Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.

- Construction simulation
- Virtual mock-ups/electronic pre-assembly modelling [1]
- Cast-concrete 'sculpture' [1]
- Multimedia presentations for tourism, training etc [1]
- Virtual reality via computer instead of an expensive vacation [2]
- Listen to an audiotape instead of attending a seminar. [2]
- Make measurements from an image instead of directly. This includes a wide spectrum of technologies, from satellite photographs of farm and timber resources to ultrasonic images of fetus in the womb. [5]
- Use prototypes for testing new systems so that any harm is detected early. [5]
- Use video-conferencing instead of travel. [5]
- Use virtual reality to test new processes or to train people to do work in difficult situations. [5]
- Scan rare historic books, documents, etc., so they can be made visible to all, while the original remains protected. [5]
- VKB has developed a highly efficient method for projecting an optical image of a keyboard onto a surface. Using laser technology, a bright red image of a keyboard is projected from a device such as a handheld. All that is necessary to use the keyboard is a flat surface. In addition, VKB has developed a detection method through several proprietary developments for the accurate and reliable detection of user interaction, such as typing or cursor control functions. [6]

B. Replace an object, or process with optical copies.

- Video-conferencing instead of physical travel [3]

- Do surveying from aerial photographs instead of on the ground. [1]
- Measure an object by measuring the photograph [1]
- Color prints of paintings [1]
- Mural "views" [1]
- Imitation wood grain veneers [1]
- Do surveying from space photographs instead of on the ground. [2]
- Make sonograms to evaluate the health of a fetus, instead of risking damage by direct testing. [2]

C. If visible optical copies are already used, move to infrared or ultraviolet copies.

- Make images in infrared to detect heat sources, such as diseases in crops, or intruders in a security system. [1]
- Use UV as a non-destructive crack detection method. [1]
- Detect heat losses through facades using infrared photography. [1]
- Use X-rays to detect structural faults. [1]
- UV light used to attract flying insects into trap. [4]

Principle 27. Inexpensive short life

A. Replace an expensive object with a multiple of inexpensive objects, compromising certain qualities (such as service life, for instance).

- Disposable doormats [1]
- Regular painting to protect otherwise non-durable surfaces [1]
- Plastic one-piece chairs [1]
- Use disposable paper objects to avoid the cost of cleaning and storing durable objects. Plastic cups in motels, disposable diapers, many kinds of medical supplies. [2]
- Matches versus lighters [4]
- Throw-away cigarette lighters [4]
- Sacrificial coatings/components [4]
- Hop-on wireless Inc. produces disposable and recyclable cell phone. The price of the phone reflects a competitive calling rate, so there is virtually no investment in the phone itself. When the minutes are used up, one can add more minutes, discard the phone, or return it to Hop-on for an US$5 rebate certificate. Hop-on will melt down the case and recast it, recharge the phone with calling minutes, and send it back out to the marketplace. The process is easy, inexpensive, and environmentally friendly. [6]
- Imbedding a sacrificial metal beside rebar, will in effect protect the reinforcing steel from corrosion, and ones, forgoing properties (e.g. extend the life of the structure). [7]

Principle 28. Replacement of a mechanical system

A. Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.

- Readable barcode systems

- Scanner
- Motion-sensitive switches remove need for occupant having to locate mechanical switch [1]
- Light-locks [1]
- Wireless data transmission between computer systems [1]
- Electro-opaque glass eliminates the need for curtains [1]
- Use a bad smelling compound in natural gas to alert users to leakage, instead of a mechanical or electrical sensor. [2]
- Finger-print/retina/etc scan instead of a key [4]
- The just-in-time manufacturing systems use Kanban cards or objects such as portable bins to indicate visibly when supplies are needed. [5]
- Toyota developed new vehicle hybrid system, THSII, to replace traditional petrol engines. The system is low noise, low exhaust pollution and low energy consumption. The system consists two kinds of motive power sources, a high-efficiency gasoline engine as well as a permanent magnet AC synchronous motor with 1.5 times more output, together with a generator, a hybrid specific high-performance nickel-metal hydride (Ni-MH) battery and a power control unit. [6]
- Instead of physically trenching and draining saturated concrete, apply a pulsating electric field that is able to push the penetrating water out towards the exterior. [7]

B. Use electric, magnetic and electromagnetic fields to interact with the object.

- Walk through metal detector
- Touch screen
- Electric lock 'keys'/swipe keys [1]
- Electromagnetic stays hold fire doors open, released by fire alarm [1]
- Electric fence
- To mix 2 powders, electrostatically charge one positive and the other negative. Either use fields to direct them, or mix them mechanically and let their acquired fields cause the grains of powder to pair up. [2]
- Electrostatic precipitators separate particles from airflow [4]
- Improve efficiency of paint spraying by oppositely charging paint droplets and object to be painted. [4]
- Magnetic bearings [4]
- Field activated switches [4]

C. Change from static to movable fields, from unstructured fields to those having structure.

- Intelligent lock 'keys' - unique signal attached to each key permits increased flexibility of use - e.g. only allowed at certain times of day [1]
- Zoned heating systems [1]
- Occupant-adjustable color lighting in hotel rooms [1]
- Early communications used omnidirectional broadcasting. We now use antennas with very detailed structure of the pattern of radiation. [2]
- Magnetic Resonance Imaging (MRI) scanner [4]

D. Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.

- Heat a substance containing ferromagnetic material by using varying magnetic field. When the temperature exceeds the Curie point, the material becomes paramagnetic, and no longer absorbs heat. [1]
- Radiopaque powders placed inside cement in critical regions in order to enable integrity by x-ray analysis [1]
- Magneto-theological effect – uses ferromagnetic particles and variable magnetic field to alter the viscosity of a fluid [4]
- Ferro-magnetic catalysts [4]
- Ferro-fluids – e.g. Magnetic oil – stay attached to surfaces requiring lubrication [4]

Principle 29. Use pneumatics and hydraulics systems

A. Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).

- Flexible (fluid) organization structure versus fixed hierarchical structure [3]
- Hydraulic elevator systems replace mechanical drives. [1]
- Use internal water features to assist climate control. [1]
- Use water level to ensure flat surface for foundations. [1]
- Warm air heating systems [1]
- Natural ventilation and stack effect [1]
- Store energy from decelerating a vehicle in a hydraulic system, then use the stored energy to accelerate later. [2]
- Gel filled saddle adapts to user [4]
- Inflatable houses and inflatable boats [5]
- Air cushion enable movement of heavy objects using very little energy. [5]
- Replacing a physical cutting blade with water jet. [5]
- Isuzu's 4-bag air suspension has more longevity and recyclability. The suspension system is composed of (1) V-shaped rod, (2) shock absorber, (3) air spring and (4) stabilizer bar. By adopting air-suspension on all axles, rear body vibration is significantly reduced in comparison to vehicles with air-suspension only on rear axles. As a result, full air-suspension prevents cargo damages and decreases tire wear, thereby reducing insurance costs and saving money. [6]
- Instead of using solid excavation equipment (conventional excavator) to dig a trench, which might be dangerous when working near sensitive areas use air or hydrostatic cushions (utilities, cables), try using an air pump and vacuum system. [7]

Principle 30. Flexible shells and thin films

A. Use flexible shells and thin films instead of three-dimensional structures

- Use inflatable (thin film) structures. [1]
- I, C or U beams instead of solid section beams [1]
- Webbed structures [1]
- Honeycomb door in-fill gives strength with lightness [1]
- Intumescent paint protects steel structures against fire [1]

- Use inflatable (thin film) structures as winter covers on tennis courts. [2]
- Taut-liner trucks [4]
- Tarpaulin car cover instead of garage [4]
- Instead of using 3-D based structures for building insulation, which take up space and effort to be easily applied to any exterior or interior wall. The new product "SUPER THERM" has two reflective ceramics to reflect sunlight and radiant heat while the third ceramic compound works to stop heat and/or conduction through the coating film. This material may be applied to almost any surface, and since it is water based, it is easy to handle and clean, along with its environmentally friendly aspects. [7]

B. Isolate the object from the external environment using flexible shells and thin films.

- Bubble-wrap [1]
- Egg-box [1]
- Draft proofing [1]
- Float a film of bipolar material (one end hydrophilic, one end hydrophobic) on a reservoir to limit evaporation. [2]
- Bandages/plasters [4]
- Tea bag [4]

Principle 31. Use of porous materials

A. Make an object porous or add porous elements (inserts, coatings, etc.).

- Weeping tile
- Porous Pavement
- Geo-textile
- Drill holes in a structure to reduce the weight. [1]
- Breeze block [1]
- Air-bricks [1]
- Cavity wall insulation [1]
- Extruded foam under-floor insulation [1]
- Passive stack ventilation systems [1]
- Transpiration film cooled structures [1]
- Foam metals [1]
- Use sponge-like structures as fluid absorption media. [1]
- "Breathable" membranes [1]
- Pressure equalized cladding systems [1]
- Micro-fibers with small pores prevent water from passing through, but allow moisture to evaporate. [5]
- Citizen uses special filters that allow a wide range of dial colors and styles. In fact, the dial is the filter that is a micro-porous structure. The dial plays a critical rule that can make any light passes through it. A solar cell beneath the dial converts any form of light into electrical energy to power the watch. With regular exposure to light, Eco-Drive continuously recharges itself for a lifetime of use. [6]

B. If an object is already porous, use the pores to introduce a useful substance or function.

- Use a porous metal mesh to wick excess solder away from a joint. [1]
- Desiccant/pest repellent in cavity wall insulation [1]
- At night pass air through hollow structure to cool it [1]
- Store hydrogen in the pores of a palladium sponge. (Fuel "tank" for the hydrogen car--much safer than storing hydrogen gas) [2]
- Desiccant in polystyrene packing materials [4]

Principle 32. Changing the color

A. Change the color of an object or its external environment.

- Antifreeze/coolants come in many colors and each signifies a purpose.
- Electro or photo-chromic glass [1]
- Camouflage [1]
- Use lighting effects to allow occupants to interactively 'change the color' of a room. [1]
- Employ interference fringes on surface structures to change color (as in butterfly wings, etc) [1]
- Use color-changing thermal paint to measure temperature. [4]
- Plastic spoon which changes color when hot - for baby food [4]
- Temperature-sensitive dyes used on food product labels to indicate when desired serving temperature has been achieved. [4]
- Sunglasses change the amount of light blocked, depending on the brightness of the environment. [5]
- Using lighting effects to change the mood in a room or office. [5]

B. Change the transparency of an object or its external environment.

- Put glass in doors on corridors so that users can see if someone is on the other side [1]
- Light-sensitive glass [1]
- Electro-chromic glass allows occupant to vary transparency [1]
- Deciduous trees give shade in summer but let sunlight pass through in winter [1]
- Use photolithography to change transparent material to a solid mask for semiconductor processing. Similarly, change mask material from transparent to opaque for silkscreen processing. [2]

C. In order to improve observability of things that are difficult to see, use colored additives or luminescent elements

- Fluorescent safety markings help guide people out of a building after power failure [1]
- Use opposing colors to increase visibility - e.g. butchers use green decoration to make the red in meat look redder. [1]
- Specify undercoats to be different shades to help inspection [1]
- Fluorescent additives used during UV spectroscopy [4]
- UV marker pens used to help identify stolen goods [4]

D. Change the emissivity properties of an object subject to radiant heating

- Use of light and dark colored panels to assist thermal management in building spaces. [1]
- Use of parabolic reflectors in solar panels to increase energy capture. [1]
- Paint object with high emissivity paint in order to be able to measure it's temperature with a calibrated thermal imager [1]
- Low emissivity glass [1]
- Use of parabolic reflectors in solar panels to increase energy capture. [4]

Principle 33. Homogeneity

A. Make objects interacting with a given object of the same material (or material with identical properties).

- Hire local people to acquire cultural knowledge of local customers. [3]
- Make the container out of the same material as the contents, to reduce chemical reactions [1]
- To avoid cracking make sure that abutting materials have similar coefficients of expansion [1]
- Ensure that adjacent metals are similar in order to avoid electrolytic corrosion [1]
- Friction welding requires no intermediary material between the two surfaces to be joined. [4]
- Join wooden components using (wood) dowel joints. [4]

Principle 34. Rejecting and regenerating parts

A. Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.

- Eliminate duplicated, redundant and non value-added activities (lean manufacturing, cycle time reduction) [3]
- Ice structures: use water ice or carbon dioxide (dry ice) to make a template for a rammed earth structure, such as a temporary dam. Fill with earth, then, let the ice melt or sublime to leave the final structure [1]
- Reusable formwork for concrete [1]
- Pour concrete directly into trenches (no form-work needed) [1]
- Bio-degradable containers, bags, etc. [4]
- Pentel's new correction ball pen has a new type replaceable ink. Users just push the upper button and the correction ink would stir automatically. The output of correction ink also adjusts a suitable amount by the correction ball pen itself. [6]

B. Conversely, restore consumable parts of an object directly in operation.

- Grey-water recycling systems [1]
- Heat exchanger recovers lost heat from (for example) water emptied from a bath [1]
- Self-sharpening lawn mower blades [2]

- Automobile engines that give themselves a "tune up" while running (the ones that say "100,000 miles between tune ups") [2]

Principle 35. Parameter changes

A. Change an object's physical state (e.g. to a gas, liquid, or solid).

- Frozen ground is nearly twice as strong as concrete, essentially impermeable, and in many cases, is competitive with conventional shoring methods. And it could apply to all soil types (running sand, cobbles, peat, clay, bedrock).
- Patching plaster
- Metal vs. alloy
- Adhesives instead of mechanical joining methods [1]
- Use injected (liquid) silicon rubber sealants. [1]
- Liquid plastic, paint-on roofing top-coats [1]
- Pouring concrete [1]
- Transport oxygen or nitrogen or petroleum gas as a liquid, instead of a gas, to reduce volume. [2]
- Sanyo's new age IH type electric rice cooker with variable pressure boiling can make rice three times sweeter than the early IH type. The rice can expand itself under 1.2 atm and 105 degrees centigrade; simultaneously, the rice in all parts of the container can be cooked thoroughly. Saccharification caused by higher boiling temperature makes the rice to have more glucose, therefore taste sweeter. Moreover, this function also can make the cooker reduce electric energy consumption. [6]

B. Change the concentration or consistency.

- Change aggregate mix in concrete to alter properties. [1]
- Dilute paint to achieve 'wash' effects. [1]
- Different grades of MDF [1]
- Liquid hand soap is concentrated and more viscous than bar soap at the point of use, making it easier to dispense in the correct amount and more sanitary when shared by several people. [2]
- Liquid soap [4]
- Abradable linings used for gas-turbine engine seals [4]

C. Change the degree of flexibility.

- Use adjustable dampers to provide active vibration damping in buildings. [1]
- Rubber-mounted windows improve vibration damping [1]
- Flexible service run pipes [1]
- Vulcanize rubber to change its flexibility and durability. [2]
- Compliant brush seals rather than labyrinth or other fixed geometry seals [4]

D. Change the temperature.

- Climate control [1]
- 'Thermal curtain' (blown warm air) used in doorways of public building [1]

- Use natural thermal gradients to create natural convection heat management in tall buildings. [1]
- 'Thermal mass' used to store thermal energy [1]

E. Change the pressure.

- Use vacuum suction to improve flow of concrete/sealants/etc into awkward shaped cavities. [1]
- Set prefabricated structures under loads that will mimic installed loads [1]
- Use barometric pressure gradients to improve ventilation in tall buildings. [1]
- Electron beam welding in a vacuum. [4]
- Vacuum packing of perishable goods [4]

F. Change other parameters

- Shape memory alloys/polymers - self regulating window hinges [1]
- Use Curie point to alter magnetic properties - thermal switching. [1]
- Shape memory alloys/polymers [4]
- Thixotropic paints/gels/etc [4]
- Use high conductivity materials – e.g. carbon fiber. [4]

Principle 36. Phase transitions

A. Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).

- Heat pipes [1]
- Use a phase change to store energy - e.g. store energy as ice, or, where heating is the issue use sodium acetate to store heat energy. [1]
- Refrigeration plant [1]
- Store thermal energy using phase transition materials (e.g. sodium sulphate). [1]
- Use melting ice as a way of gently lowering heavy structures. [1]
- Heat pumps use the heat of vaporization and heat of condensation of a closed thermodynamic cycle to do useful work. [2]
- Latent heat effects in melting / boiling. [4]
- Soak rocks in water, then freezing causes water to expand – thus opening fissures in rock, making it easier to break. [4]
- Volume expansion during water-to-steam transition [4]
- Superconductivity [4]
- Thermal inkjet uses vaporization to force ink out of the nozzle. [5]
- Tonghai Home Care Company's magical ice bag contains granular cryogen and an internal bag that holds water. When a user presses the internal bag and the water drains out, then the water and the cryogen cause a chemical reaction. The cryogen can be dissolved and rapidly cool. [6]
- In order to demolish concrete or rock without causing noise, shockwaves, or fly rock, SCDA's (Soundless Chemical Demolition Agents) are used. These chemicals are mixed with water and inserted via borehole, into the object. Through the hydration and crystallization process, enough internal pressures are created to silently explode the object. [7]

Principle 37. Thermal expansion

A. Use thermal expansion (or contraction) of materials.

- Use bimetallic plates to control windows. The change of temperature bends the plates, causing the window to open or close.
- Fit a tight joint together by cooling the inner part to contract, heating the outer part to expand, putting the joint together, and returning to equilibrium. [1]
- Through-bars help straighten buckling walls in old buildings [1]
- Expansion joints [1]
- Metal tie-bars used to straighten buckling walls on old buildings. [4]
- Shape memory alloys/polymers. [4]
- A Taiwan company developed heat-sinking rooftop to cool down internal temperature of factories. Due to heat convection and thermal expansion of air, the hot air first enters into the gaps, and then climbs and passes through the channel between the upper rooftop and the lower rooftop, finally exits from the heat-sinking gaps. All the actions do not need energy consumption, and can make the interior of the factory nice and cool. [6]

B. If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.

- Bi-metallic strips used for thermostats, etc [1]
- Shape-memory blind fasteners [1]
- Bi-metallic (or shape memory) hinges offer self-opening windows/ventilators in order to regulate climate inside building (e.g. industrial greenhouse) [1]
- The basic leaf spring thermostat: (2 metals with different coefficients of expansion are linked so that it bends one way when warmer than nominal and the opposite way when cooler.) [2]
- Two-way shape memory alloys. [4]
- Passive blade tip clearance control in gas turbine engines. [4]
- Combine materials with positive and negative thermal expansion coefficients to obtain alloys with zero (or specifically tailored) expansion properties – e.g. cerro-tru alloy used in the mounting and location of fragile turbine blade components during manufacture operations [4]

Principle 38. Use strong oxidizers

A. Replace common air with oxygen-enriched air.

- Place plants in living spaces. [1]
- Place asthmatic patients in oxygen tent. [4]
- Nitrous oxide injection to provide power boost in high performance engines [4]
- Metal active gas welding (MAG) [5]
- Sanyo achieved the world's first electrolyzed water powered "non-detergent course" washing machine. The washing machine uses electrolyzed water power produced using electrodes placed on the side of the wash basin that produce active oxygen and hypochlorous acid that work to dissolve organic dirt such as sweat on

items like bath towels, undershirts, pajamas, and T-shirts etc. Electrolyzed water combined with the ultrasonic waves provides all the cleansing power with no detergent. [6]

B. Replace enriched air with pure oxygen.

- Cut at a higher temperature using an oxy-acetylene torch. [1]
- Treat wounds in a high-pressure oxygen environment to kill anaerobic bacteria and aid healing. [2]
- Control oxidation reactions more effectively by reacting in pure oxygen [4]

C. Expose air or oxygen to ionizing radiation.

- Positive ions formed by ionizing air can be deflected by magnetic field in order to (e.g.) reduce air resistance over an aerodynamic surface [4]
- Irradiation of food to extend shelf life [4]
- Use ionized air to destroy bacteria and sterilize food. [4]

D. Use ionized oxygen.

- Ionize air to trap pollutants in an air cleaner. [2]
- Speed up chemical reactions by ionizing the gas before use. [4]
- Separate oxygen from a mixed gas by ionizing the oxygen. [4]

E. Replace ionized (or ionized) oxygen with ozone.

- Speed up chemical reactions by ionizing the gas before use. [2]
- Oxidization of metals in bleaching solutions to reduce cost relative to hydrogen peroxide [4]
- Use ozone to destroy micro-organisms and toxins in corn. [4]
- Ozone dissolved in water removes organic contaminants from ship hulls [4]

Principle 39. Inert environment

A. Replace a normal environment with an inert one.

- Treat flammable materials with inter gas during its transportation.
- Creation of 'calm' spaces into office buildings [1]
- Helium filled double-glazing units [1]
- Sealed museum displays [1]
- Clean rooms for silicon chip manufacture [1]
- Fire extinguishing systems [1]
- Prevent degradation of a hot metal filament by using an argon atmosphere. [2]
- MIG/TIG welding [4]
- Electron beam welding conducted in a vacuum [4]
- Vacuum packaging [4]
- Foam to separate a fire from oxygen in air [4]
- Shin Ding Painting Company developed a new paint that can insulate heat transfer. The heat insulation paint contains many vacuum capsules. After painting on the roof of a building, it may be likened to constructing a heat insulation layer on the roof. Through proof, the room temperature can be reduced 5 to 7 degrees

centigrade, and the internal surface temperature can be decreased 20 degrees centigrade or more. [6]

- Creating a vacuum in order to provide insulation has been proven to achieve better results than air or material filled insulation. [7]

B. Add neutral parts, or inert additives to an object.

- Non-flammable additives into cavity wall foams [1]
- Dampers [1]
- Sound absorbing panels [1]
- Timber treatments for pest control [1]
- Aggregate in concrete [1]
- Hollow block floors [1]
- Add fire retardant elements to titanium to reduce possibility of titanium fire [4]

Principle 40. Composite materials

A. Change from uniform to composite (multiple) materials where each material is tuned to a particular functional requirement.

- Value Engineering team
- Fly ash brick
- Combine high risk and low risk investment strategy. [3]
- Multi-disciplinary cross-functional teams [3]
- Concrete aggregate. [1]
- Rebar re-enforced concrete [1]
- Glass-re-enforced plastic [1]
- Fiber re-enforced spray/paint-on roofing treatments [1]
- Fire-glass [1]
- Hard/soft/hard multi-layer coatings to improve erosion, etc properties [1]
- Straw and pressed earth building materials [1]
- Mixed fiber carpets [1]
- Composite epoxy resin/carbon fiber golf club shafts are lighter, stronger, and more flexible than metal. Same for airplane parts. [2]
- Fiberglass surfboards are lighter and more controllable and easier to form into a variety of shapes than wooden ones. [2]
- Aircraft structures where low weight and high strength are required [4]
- Composites in golf club shaft [4]
- Glass-reinforced plastic [4]
- Fiber-reinforced ceramics [4]
- Combined high-risk and low-risk investment [5]
- Flammable polyurethane coated with fire-resistant Kevlar, e.g., in airplane seat cushions. [5]
- Misawa developed a novel long-life building materials 'M-Wood' for environmental consciousness, which can almost replace all traditional wood building materials. The waste of conifer from works is gathered and crushed to powder; next added resin to synthesize the "M-Wood Raw Powder"; then the " M-Wood Raw Powder" can be made all styles of building materials. M-Wood is

very like real wood including color and grain; furthermore, its strength and durability are much higher. [6]

- By using composite pipes for offshore facilities rather than traditional steel pipes, corrosion, weight, and costs are lowered, while ease of fabrication, handling and life cycle are increased. [7]

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Appendix 6: Student Project Using TRIZ-enhanced-VE Analysis

CIV E 409

VALUE ENGINEERIN EXERCISE

GROUP 6

ACCESS FROM CALGARY TRAIL TO SOURTH EDMONTON COMMON VIA 19 AVENUE

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TRIZ-enhanced-VE Analysis

The purpose of this project is to achieve project objectives while maintaining system balance with the least cost. Our group was selected to evaluate TRIZ-enhanced-VE, vs. Value Engineering, by completing the case study regarding providing access from Calgary Trail to South Edmonton Common via 19 Avenue. Three alternatives considered, first being a tunnel under Calgary Trail from 23 Avenue to 19 Avenue, second being an overpass from 23 Avenue to 19 Avenue over Calgary Trail, and third being a traffic circle at the intersection of Calgary Trail/Gateway Boulevard and 19 Avenue. The different criteria considered for this project were:

- Impact to users
- Environment
- Ability to expand
- Ability to handle drainage
- Constructability
- Traffic Constriction
- Impact to existing structures

The effective components for the initial design phase included:

- Access to Gateway Boulevard northbound Access from 99 Street
- Access from 23 Avenue
- Anthony Henday
- Land
- Cars

Other components included:

- CP Rail impact
- Residential area
- Commercial area
- Pipeline impact
- ACTO Gas regulatory station
- Pedestrian impact
- Sewer impact
- Environmental green area

Following the initial phase design, charts for the function and components trimming as well as system interaction analysis were completed. Using the results from the system interaction analysis harmful interactions for each alternative were listed and their intolerance rated.

The harmful outcomes were evaluated for the traffic circle option and solutions were developed for each problem, as well total project costs and schedule were calculated. Refer to attached sheets for the initial design, function and component trimming, system and interaction analysis, and harmful interactions registration charts.

A weighted evaluation matrix was completed using the GFI (Gut Feeling Index). Using the results of the evaluation matrix a results of alternative comparison chart was developed for each of the three project alternatives. Refer to attached sheets for the completed charts.

Using the results of the alternative comparison chart, the traffic circle proved to be the best alternative taking the previously listed impacts into consideration with a total score of 134 compared to 109 (tunnel) and 95 (overpass). It should be noted that cost estimates may not be accurate due to our lack of knowledge in this field, and therefore budget estimates may not be accurate. Common sense tells us that the traffic circle option is not the most practical solution due to safety and the volume of traffic.

In conclusion TRIZ-enhanced-VE process is an effective alternative to value engineering and can save money and time for a project if done correctly.

Chart for Initial Design

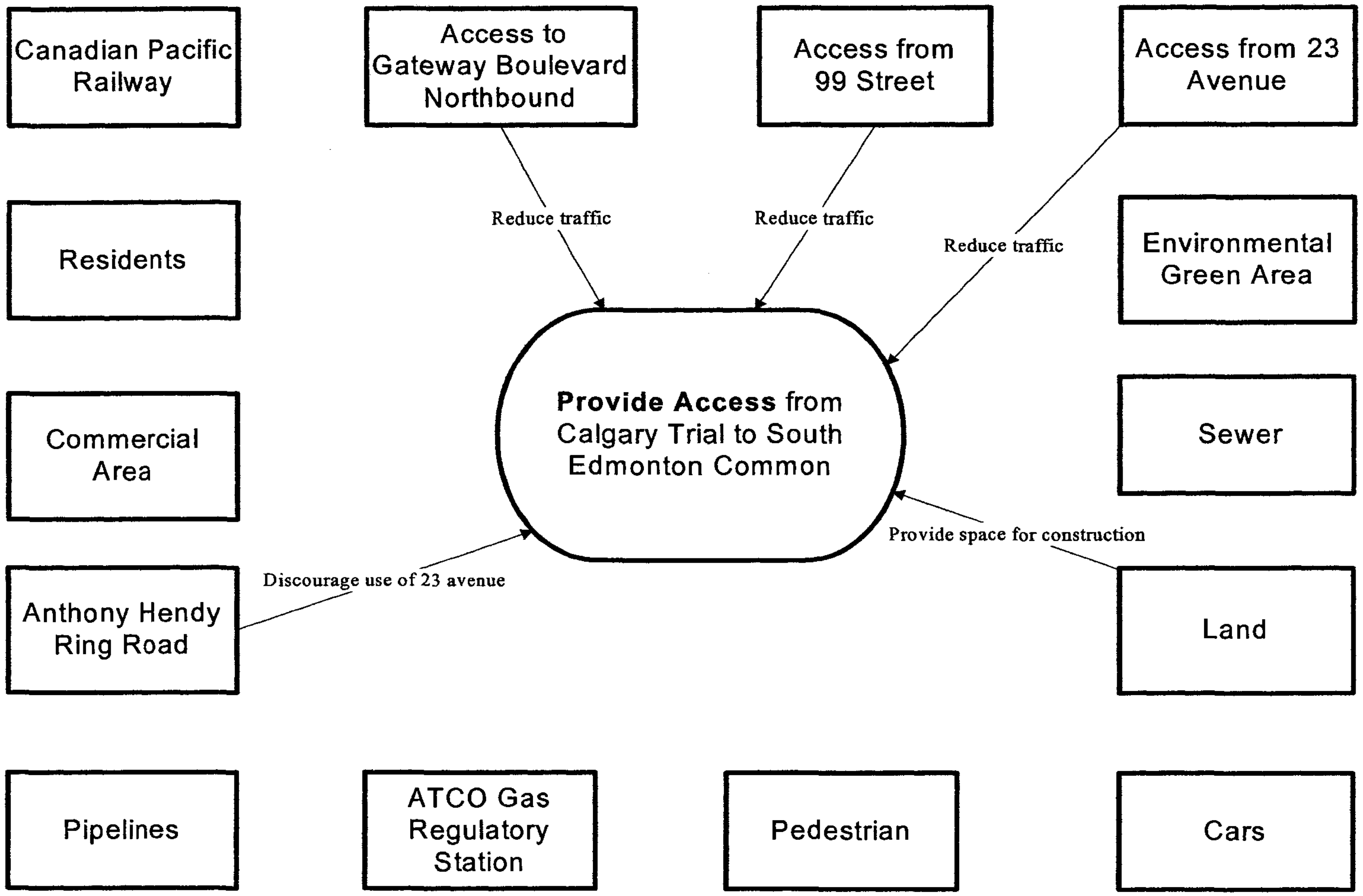


Chart for Function Trimming – Alternative 1 Tunnel

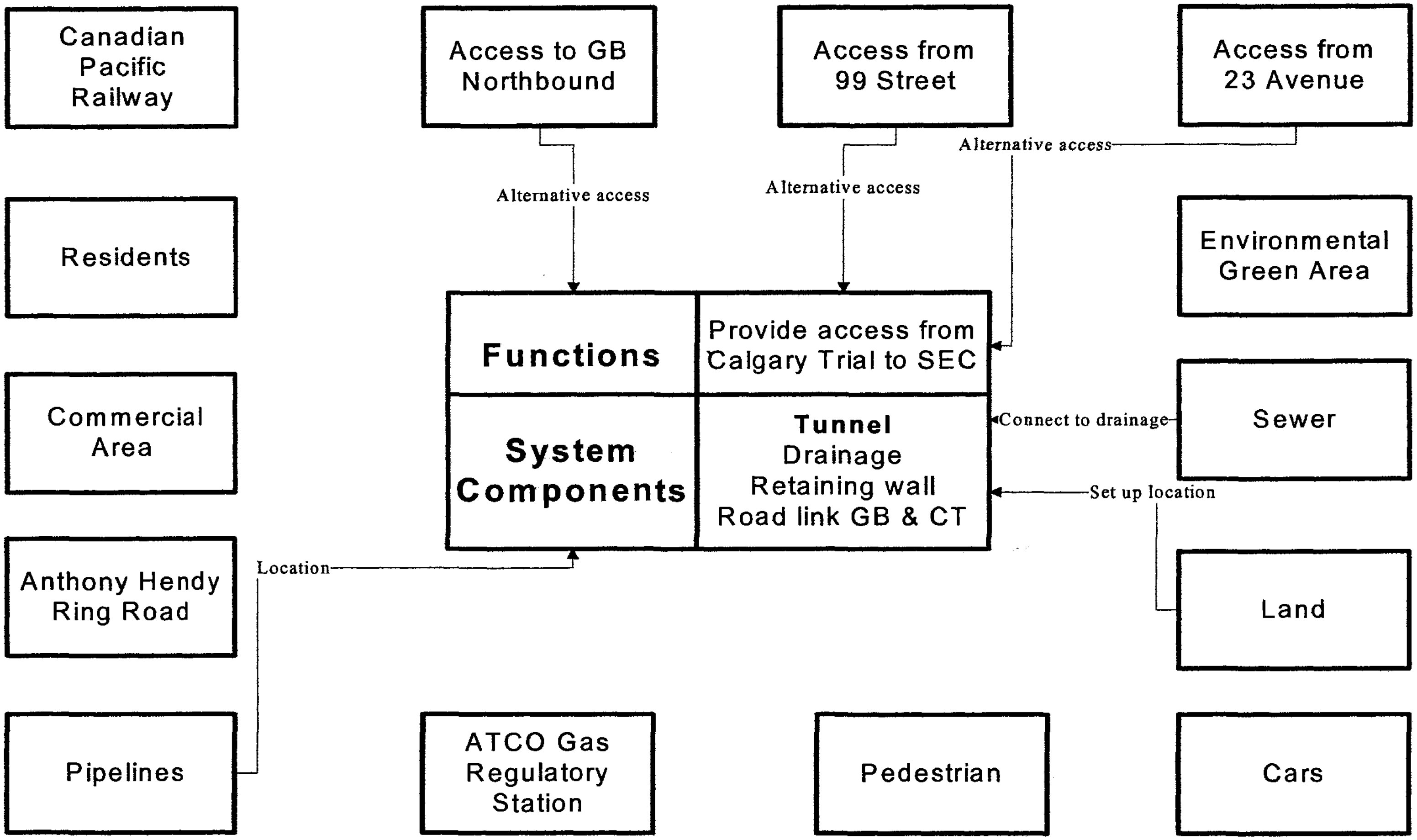


Chart for System Interaction Analysis – Alternative 1 Tunnel

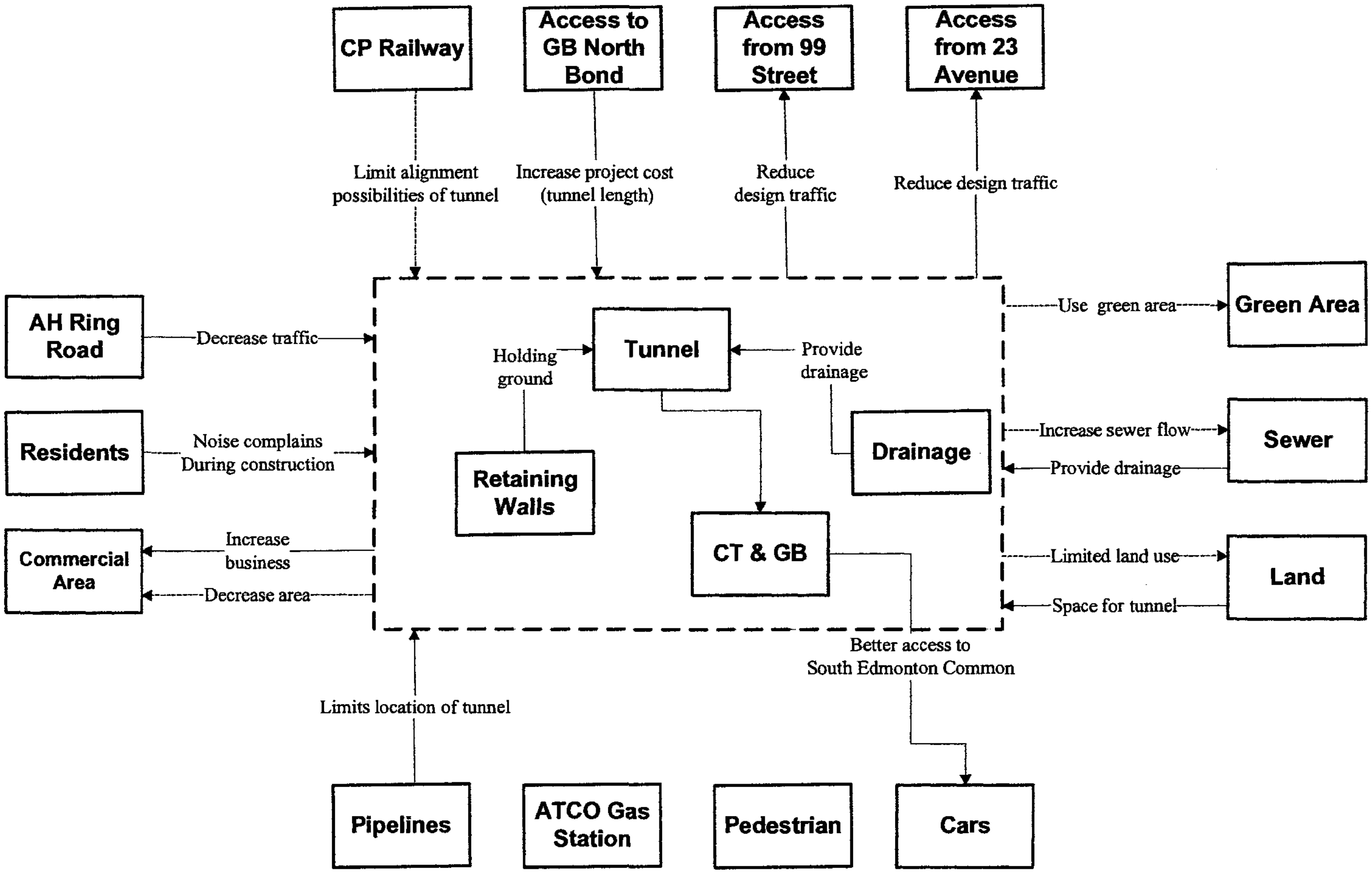


Chart for Function Trimming – Alternative 2 Overpass

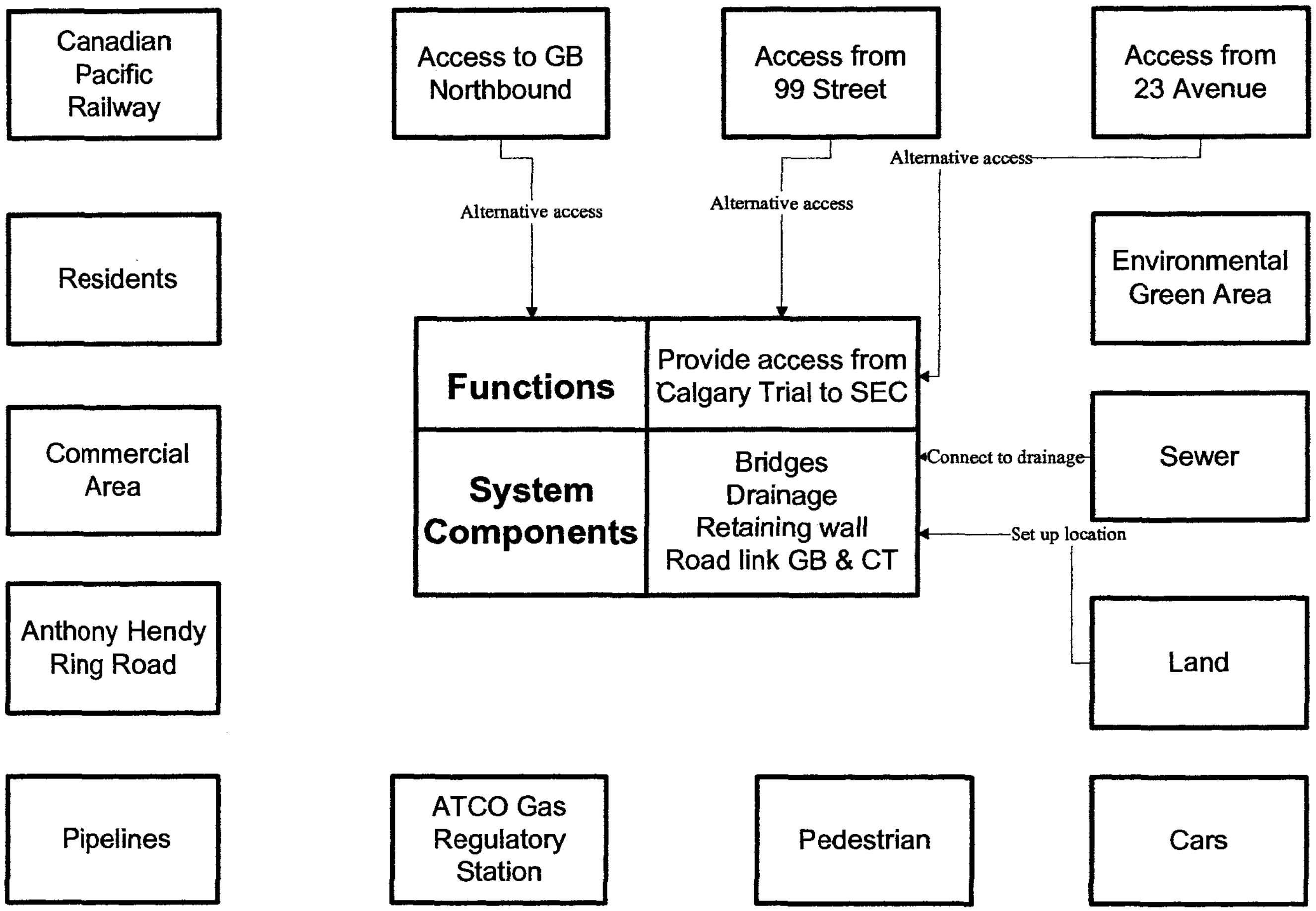


Chart for System Interaction Analysis – Alternative 2 Overpass

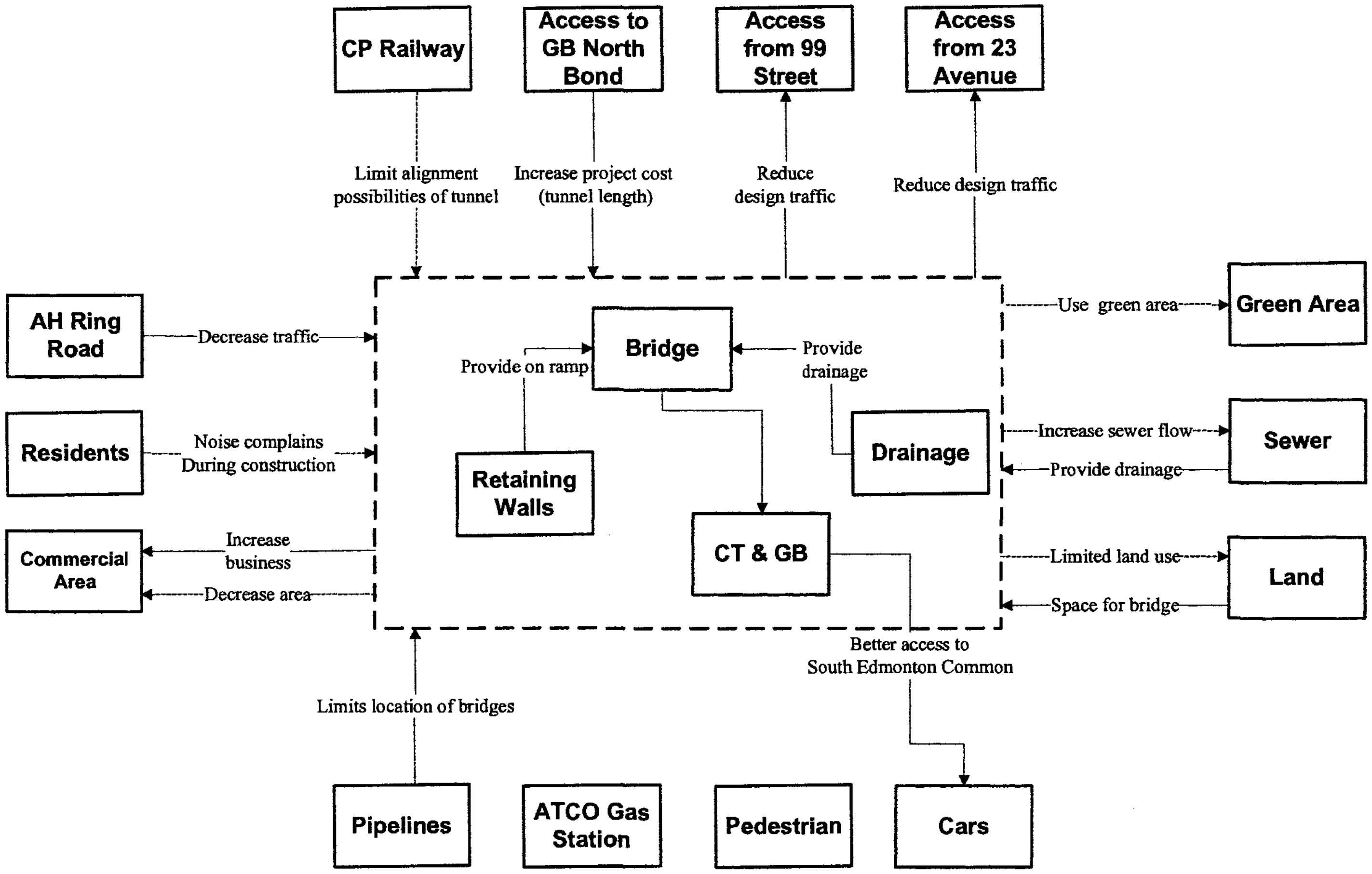


Chart for Function Trimming – Alternative 3
Traffic Circule

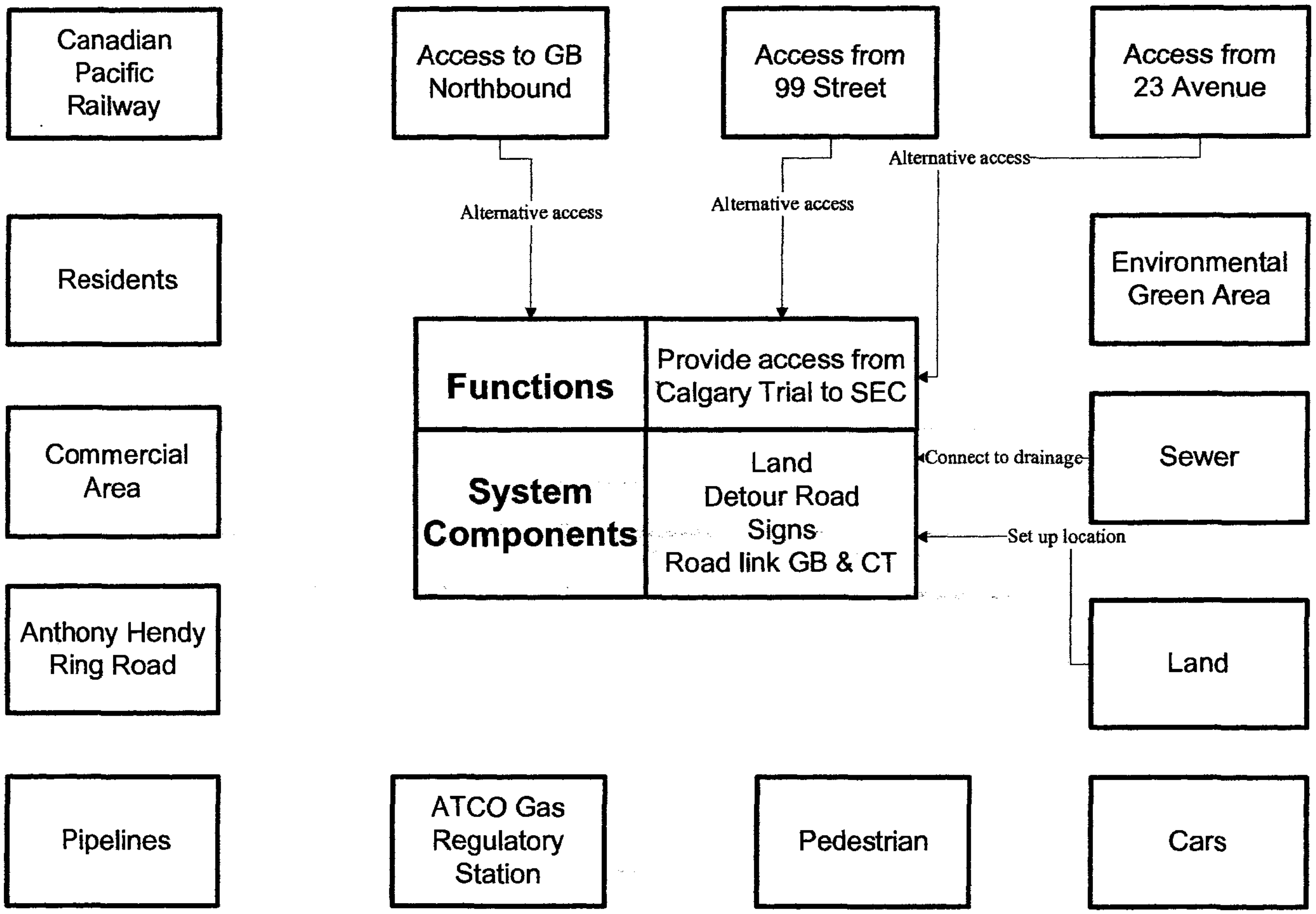
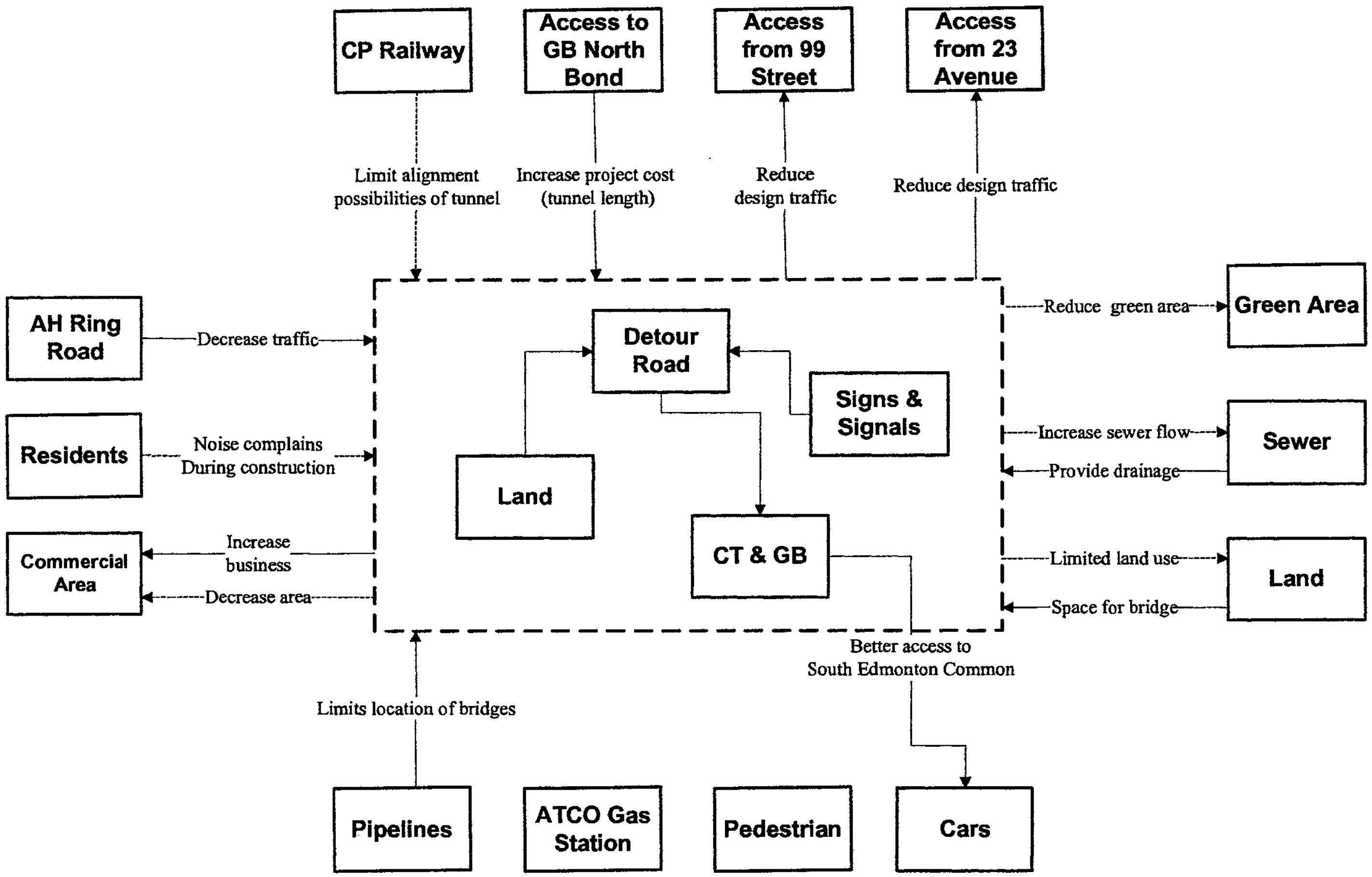


Chart for System Interaction Analysis – Alternative 3
Traffic Circle



Harmful Interactions Registration

Project Option	Contributor	Recipient	Explanation	Intolerance Index
Alternative 1: Tunnel	Tunnel	Pipeline	Limit location of tunnel	8
	Tunnel	Land	Limit use of space	7
	Tunnel	Residents	Noise complaint	4
	Tunnel	Commercial area	Decrease area	4
	Tunnel	Sewer	Increase flow	2
	Tunnel	CP railway	Limit alignment	8
	Tunnel	Access to gateway boulevard	Increase project cost	9
	Tunnel	environment	Taking green area	4
Alternative 2: Overpass	Overpass	Pipeline	Limit location of bridge	8
	Overpass	Commercial area	decrease area	6
	Overpass	Residents	Noise , a	10
	Overpass	environment	Reduce green area	4
	Overpass	Sewer	Increase flow	2
	Overpass	Land	Limit use of space	8
Alternative 3: Traffic Circle	Traffic Circle	Commercial area	Decrease area	5
	Traffic Circle	Residents	Noise complaint	10
	Traffic Circle	Environment	Reduce green area	4
	Traffic Circle	Land	Limit land use	8
	Traffic Circle	Cars	Knowledge of use	5

Results of Project Alternative Idealization Estimation (Traffic Circle)

Harmful Outcomes	Intolerance Level	Solutions	Result	Cost Variations	Schedule Variations	Total Project Cost	Total Project Schedule
Noise complaints	10	Sound barriers around circle and barriers	solved	$50,000	0	$1,000,000	120 days
Limited land use	8	Negotiate and buy from current owners	solved	$1,000,000	0	$6,000,000	120 days
Decrease commercial area	5	Rezone land	solved	$10,000	0	$6,010,000	120 days
Cars-traffic circles	5	Lots of signs, driver education	problem reduced	$50,000	0	$6,060,000	120 days
Reduce environmental green area	4	Build a park in the center of circle, rezone land	solved	$1,000,000	30 days	$7,060,000	150 days

Weighted Evaluation Matrix

	A	B	C	D	E	F	G	Total Score	Weighted Score
A		A2	A1	A1	E2	AF	A1	5	**6**
B			C2	D3	E3	F3	G2	0	**0**
C				C1	C1	F1	C2	6	**8**
D					E1	F2	G1	3	**4**
E						F1	E2	8	**10**
F							F2	4	**5**
G									**1**

A: Impact to users
B: Environment
C: Ability to expand
D: Ability to handle drainage
E: Constructability
F: Traffic congestion
G: Impact to existing structure

A-1	**Minor**
A-2	**Medium**
A-3	**Major**
A/B	**None**

Resuls of Alternatives' Total Score

Project Alternative	**Evaluation Criteria**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Total Score**	**Rank**
	Gut Filling Index	**6**	**0**	**8**	**4**	**10**	**5**	**1**		
Tunnel	**Excellent**	5	5	5	5	5	5	5	**109**	**2**
	Very Good	**4**	**4**	4	4	4	**4**	4		
	Good	3	3	3	3	**3**	3	**3**		
	Fair	2	2	**2**	**2**	2	2	2		
	Poor	1	1	1	1	1	1	1		
Overpass	**Excellent**	5	5	5	5	5	5	5	**95**	**3**
	Very Good	**4**	4	4	4	4	4	4		
	Good	3	**3**	3	**3**	**3**	3	**3**		
	Fair	2	2	**2**	2	2	**2**	2		
	Poor	1	1	1	1	1	1	1		
Traffic circle	**Excellent**	5	**5**	**5**	**5**	**5**	5	5	**134**	**1**
	Very Good	4	4	4	4	4	4	4		
	Good	3	3	3	3	3	3	3		
	Fair	**2**	2	2	2	2	**2**	**2**		
	Poor	1	1	1	1	1	1	1		

Appendix 7: Student Project Using Conventional VE Analysis

CIV E 409

VALUE ENGINEERIN EXERCISE

GROUP 3

19TH AVENUE UNDERPASS

Prepared by:
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Value Engineering Exercise

1) Introduction

This project was a Value Engineering exercise involving the proposed 19th Avenue underpass below Calgary Trail entering South Edmonton Common. Through our discussion the group came up with five alternatives which are evaluated throughout this report.

2) Purpose of the Project

Make safe free flow connection from Calgary Trail and 23rd Avenue to South Edmonton Common.

3) Criteria Selection

As a group six criteria were defined and are as stated below:

- Impact to user
- Environmental
- Constructability
- Ability to expand
- Storm water drainage
- Traffic congestion

4) Function Analysis

Below are the verb noun relationships that we found most relevant to our project.

Verb	Noun	Rating
Convey	Traffic and Goods	B
Protect	Lanes	S
Provide	Access	S
Improve	Safety	HO
Develop	Land	S
Maintain	Environment	S
Meet	Regulations	S
Support	Future Demands	S
Save	Time	HO
Increase	Capacity	B
Decrease	Stress	S

B - Basic
S - Secondary
HO- High Order

5) Criteria Weights Evaluation

	A	B	C	D	E	F
A		3A	2A	1A	1A	1F
B			1B	2D	2E	3F
C				2D	1C	2F
D					1D	1F
E						3F
F						

TOTAL WEIGHTS	
7	27%
1	4%
1	4%
5	19%
2	8%
10	38%
26	100%

A IMPACT TO USER
B ENVIRO
C ABILITY TO EXPAND
D CONSTRUCT ABILITY
E HANDLE STORM DRAINAGE F TRAFFIC
CONGESTION

6) Creativity Phase

See Figure A.

7) Evaluation of Alternatives

	RANKING ALTERNATIVE	FUNCTION	VALUE
1	At grade intersection at 19th Ave	70.3	20.1
2	Interchange at Anthony Henday	98.3	15.1
3	Overpass at 19th Ave	155.0	13.5
4	Open Excavation across Calgary Trail	110.0	6.5
5	Tunnel Boring at 19th Ave	131.0	6.0

Based on the information above, it is shown that the highest value option is the at grade intersection. However this option has the lowest function therefore it is not a viable option. Thus the two most successful options were the interchange at Anthony Henday and the overpass at 19th avenue.

Interchange at Anthony Henday (Function: 98.3, Value: 15.1)

Description: Traffic exits Calgary Trail South by utilizing the existing Anthony Henday overpass to merge onto Calgary Trail North and enter South Edmonton Common via 19th Avenue entrance.

Pros:

- Low capital cost (utilizing existing interchange) Minimal traffic disruptions
- Easily constructed
- Short construction period

Cons:

- No free flow traffic

- Long travel time
- Hard to expand

Sketches:
See Figure B.

Cost:
Our estimated final cost based on similar projects and limited knowledge was approximately $6.5 million.

Value Index:
As shown above the value index for this option is 15.1.

Overpass at 19th Avenue (Function: 155, Value: 13.5)

Description: Traffic exits Calgary Trail South using the new 23rd Avenue interchange and travels further south crossing Calgary Trail at 19th Avenue by a new overpass.

Pros:

- Free flow
- Short travel time
- Could be engineered to be easily expandable
- Rain water drainage will not be an issue

Cons:

- Not aesthetically pleasing
- Noise
- Long construction period
- Possible road closures and traffic delays

Sketches:
See Figure B.

Cost:
Our estimated [mal cost based on similar projects and limited knowledge was approximately $11.5 million.

Value Index:
As shown above the value index for this option is 13.5.

8) Development of Recommended Options

In comparison of the two options the overpass option has a significantly higher function and cost but marginally lower value. We placed a higher emphasis on function because of uncertainties in cost estimations. The overpass has free flow traffic, short travel time, and can be easily expandable. Therefore this option best meets the criteria of this value engineering session.

9) Other Design Suggestions

Another option will be open excavation which would require to excavate across Calgary Trail and to divert traffic.

Tunnel boring across Calgary trail at 19th avenue would be the highest cost alternative but traffic may not have to be diverted.

10) Conclusion

After analyzing the five alternatives to the originally purpose underpass, we recommend that 19th avenue overpass option as the most viable and efficient.

Figure A: Alternative Evaluation Matrix

ALTERNATIVE EVALUATION MATRIX

1	Overpass at 19th Ave
2	Tunnel Boring at 19th Ave
3	At grade intersection at 19th Ave
4	Interchange at Anthony Henday
5	Open Excavation across Calgary Trail

			1		2		3		4		5	
CRITERIA	EVALUATION CRITERIA	WEIGHT	RATING	SCORE	RATING	SCORE	RATING	SCORE	RATING	SCORE	RATING	SCORE
A	IMPACT TO USER	27%	9	243	8	216	2	54	5	135	7	189
B	ENVIRO	4%	8	32	7	28	9	36	8	32	6	24
C	ABILITY TO EXPAND	4%	8	32	4	16	8	32	7	28	4	16
D	CONSTRUCTABILITY	19%	9	171	8	152	8	152	7	133	3	57
E	HANDLE STORM DRAINAGE	8%	9	72	4	32	9	72	9	72	4	32
F	TRAFFIC CONGESTION	38%	10	380	9	342	2	76	5	190	9	342
				930		786		422		590		660

FUNCTION	155.0	131.0	70.3	98.3	110.0
COST (MILLIONS $)	11.5	22	3.5	6.5	17
VALUE = FUNCTION / COST	13.5	6.0	20.1	15.1	6.5

RANKING	ALTERNATIVE	FUNCTION	VALUE
1	At grade intersection at 19th Ave	70.3	20.1
2	Interchange at Anthony Henday	98.3	15.1
3	Overpass at 19th Ave	155.0	13.5
4	Open Excavation across Calgary Trail	110.0	6.5
5	Tunnel Boring at 19th Ave	131.0	6.0

Appendix 8: A Survey for TRIZ-enhanced-VE Analysis

Thank you very much for taking the time to complete this survey. This survey is designed to obtain the feedback from TRIZ-enhanced-VE users in order to evaluate the performance of TRIZ-enhanced-VE approach in helping project team create a project alternative with high value and low cost. Your responses will be used to improve and guide the future application of the TRIZ-enhanced-VE. Responses will be kept anonymous and will not affect your grade in the course.

Survey Questionnaire

1. What is the improvement of TRIZ-enhanced-VE in comparison with conventional VE? (Multiple choices)

☐ Leads to a more social, economic, and environmentally-friendly project plan,
☐ Can better utilize existing resources,
☐ Improves the ideality of a project plan,
☐ Simplifies the function analysis phase,
☐ Provides more detailed and step-by-step guidance in searching for better project alternatives,
☐ The process is easy to follow.

Other Comments:

---

2. TRIZ-enhanced-VE practice is based upon a well-defined procedure and guideline.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

3.The implementation of TRIZ-enhanced-VE analysis at engineering stage can produce more environmental and social friendly project plan.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

---

4. Function trimming phase is a necessary step to ensure there is no more or less functionalities being produced by proposed project alternative.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

---

5. The specific procedure and pre-made forms of TRIZ-enhanced-VE are easy to employ.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

---

6. FAST diagram cannot bring significant value to VE analysis.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

---

7. It is difficult to develop a FAST Diagram.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

---

8. The difficulty of implementing Function Analysis of VE is due to the complexity of developing FAST diagram?

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

9. 7 standard Su-Field analysis formulas can empower creativity phase of VE to generate more innovative solutions?

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

10. Su-Field analysis can generate more creative ideas than brainstorming.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

11. Su-Field analysis can tackle the essence of a problem and accelerate the speed of discovering proper solution.

☐ Strongly Agree identify
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

Other Comments:

Please send the compiled questionnaire to your instructor.
Thank You Very Much!