Enhancing Value Engineering Process by Incorporating Inventive Problem-Solving Techniques

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Enhancing Value Engineering Process by Incorporating Inventive Problem-Solving Techniques

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Abstract: The creativity phase is critical to the success of a value engineering exercise, in which the brainstorming technique is deployed to generate ideas. One shortcoming of the brainstorming technique is its lack of direction in problem solving, and consequently the efficiency is low in generating innovative and useful ideas. To overcome this shortcoming, this paper has explored the possibility of incorporating the theory of inventive problem solving (TRIZ) into the workshop session of the value engineering exercise by initiating three new procedures in this session: (1) an initial design procedure to examine the functions of a proposed project; (2) a function trimming procedure to fully utilize existing resources and ensure low life-cycle cost and sustainability of the proposed project; and (3) an interaction analysis procedure to assess the proposed project in a broad perspective with social, economic, and environmental awareness. A case study has indicated the workability of the modified workshop procedures and the usefulness of TRIZ tools and techniques in efficiently and effectively creating innovative ideas.

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Introduction

Value engineering (VE) has been widely practiced in the construction industry and become an integral part in the development of many projects. The outcomes from a VE exercise often improve the value of a project without compromising its designed functions. However, the overall opinion on VE is mixed. The Engineering News Record's Web site poll has shown that about half of the respondents think that VE is a valuable constructability tool, whereas 43% of them consider it as a marketing ploy. These contradictory opinions are likely due to the mixed results of whether or not these respondents had come up with ideas in their previous VE exercises that improved the value of the corresponding projects.

The creativity phase of VE relies to a great degree on a brainstorming process. One assumption is that quantity will bring quality, i.e., the brainstorming process will generate a large number of ideas and some of these are innovative. Consequently, a substantial amount of the time and effort of the VE team is spent on free thinking in order to create as many ideas as possible. However, most of these ideas will eventually be proven useless as they are irrelevant to the problems of the project. This, in a sense, indicates a kind of waste and inefficiency in the VE exercise.

In an attempt to increase the efficiency of the VE exercise, this paper has explored the applicability of the theory of inventive problem solving (TRIZ) in VE's creativity phase through a case study. This attempt is made in view of an important feature of various TRIZ tools and techniques, which rely on technology rather than mere psychology in generating creative ideas. This feature may complement the free-thinking brainstorming process in a VE exercise to enhance the efficiency and effectiveness in generating innovative ideas.

Theory of Inventive Problem Solving

TRIZ is a Russian acronym for the "theory of inventive problem solving," which was initially developed in 1946 by Genrich Altshulle, who had studied more than 200,000 patents and found that some fundamental principles had appeared repeatedly in inventions from different industries and in different years and that the most creative patents had been embedded with solutions that satisfy contradictory requirements (Savransky 2000). He extracted and compiled these fundamental principles behind those inventions into an organized body of knowledge called TRIZ. As a knowledge-based system, TRIZ includes a set of tools and techniques, including (1) contradiction matrix and 40 inventive principles; (2) four separation principles; (3) Su-field analysis and 76 standard solutions; and (4) eight patterns of evolution. These tools and techniques can be used to analyze problems from different angles to find inventive solutions.

Contradiction Matrix and 40 Inventive Principles

Different technical parameters of a system may be in conflict with one another. This is called a technical contradiction. Solutions to a technical contradiction usually necessitate a compromise of these parameters. A solution is innovative if it eliminates this technical contradiction. TRIZ has identified 39 parameters that have often caused technical contradictions in different systems across a variety of fields and derived 40 inventive principles (see

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Worsening Feature → / Improving Feature ↓		Weight of moving object	Area of stationary object	Volume of moving object	Object-affected harmful factors	Object-generated harmful factors	Difficulty of detecting and measuring	Extent of automation	Productivity
		1	6	7	30	31	37	38	39
6	**Area of stationary object**	-	+	-	27, 2, 39, 35	22, 1, 40	2, 35, 30, 18	23	10, 15, 17, 7
7	**Volume of moving object**	2, 26, 29, 40	-	+	22, 21, 27, 35	17, 2, 40, 1	29, 26, 4	35, 34, 16, 24	**10, 6, 2, 34**
21	**Power**	8, 36, 38, 31	17, 32, 13, 38	35, 6, 38	19, 22, 31, 2	2, 35, 18	19, 35, 16	28, 2, 17	28, 35, 34
22	**Loss of Energy**	15, 6, 19, 28	17, 7, 30, 18	7, 18, 23	21, 22, 35, 2	21, 35, 2, 22	35, 3, 15, 23	2	28, 10, 29, 35
30	**Object-affected harmful factors**	22, 21, 27, 39	27, 2, 39, 35	22, 23, 37, 35	+		22, 19, 29, 40	33, 3, 34	22, 35, 13, 24
31	**Object-generated harmful factors**	19, 22, 15, 39	22, 1, 40	17, 2, 40		+	2, 21, 27, 1	2	**22, 35, 18, 39**
38	**Extent of automation**	28, 26, 18, 35		35, 13, 16	2, 33	2	34, 27, 25	+	5, 12, 35, 26
39	**Productivity**	35, 26, 24, 37	10, 35, 17, 7	2, 6, 34, 10	22, 35, 13, 24	35, 22, 18, 39	35, 18, 27, 2	5, 12, 35, 26	+

Inventive Principles	2	Extraction	22	Convert harm to benefit
	6	Universality	34	Discard and recover
	10	Prior action	35	Parameter changes
	18	Mechanical vibration	39	Inert environment

Fig. 1. Contradiction matrix

the Appendix) that have been commonly applied implicitly to solve technical contradictions. As partially demonstrated in Fig. 1, TRIZ has designed a 39×39 matrix where the 39 parameters are listed on both the x-axis in a worsening feature and on the y-axis in an improving feature. The coding number of the 40 inventive principles are placed in the grid of the column and row. The principles in the grid improve the corresponding parameter on the vertical axis without worsening its counterpart on the horizontal axis. Therefore, once a technique contradiction is defined, inventive principles to solve this contradiction can be found from this contradiction matrix.

Four Separation Principles

TRIZ also defines a concept of "physical contradiction," which refers to two opposite physical requirements of a single technical parameter (Mann and Stratton 2000). TRIZ has developed four 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.

Su-Field Analysis and 76 Standard Solutions

In a Su-Field 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. The substance may be an object at any level of complexity, from a single item to a complex system. The field, generated from a third party, may be a mechanics, chemistry, physics, gravity, thermal dynamics, magnetics, or acoustics field. TRIZ uses a graphical model as shown in Fig. 2, called a Su-field model, to represent the interaction between the tool and the object. This interaction may lead to a useful, harmful, excessive, or insufficient function (Souchkov 1999). The harmful, excessive, or insufficient function is a problem in the technical system, for which TRIZ has developed 76 standard solutions (not listed in this paper to save space) to such a problem. Therefore, once a specific problem of a particular technical system is simplified in a Su-field model, suitable solutions may be found or useful ideas generated from the 76 standard solutions to solve this problem.

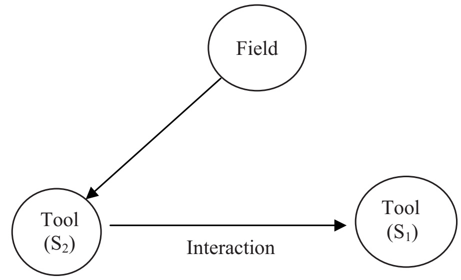

Fig. 2. Su-field model

Mao et al. (2007) have condensed the 76 standard solutions into seven general principles in order to help users carry out the Su-field analysis and easily find the appropriate problem-solving solutions. The seven general principles are outlined here:

1. Completing an incomplete Su-field model;
2. Modifying substance S_2 to eliminate or reduce the harmful impact;
3. Modifying S_1 to be either insensitive or at least less sensitive to the harmful impact;
4. Changing the existing field to reduce or eliminate the harmful impact;
5. Eliminating, neutralizing, or isolating the harmful impact using another counteractive field;
6. Introducing a positive field; and
7. Expanding the existing Su-field model to a chain.

Eight Patterns of Evolution

A technical system is developed according to objective laws rather than random generation. 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 macrosystems to microsystems; and (8) decreased human interaction and increased automation. The essential idea in these patterns of evolution is that a system evolves toward its ideality over time through full identification and utilization of the resources embedded in the system's environment. These patterns of evolution enable inventors to predict trends and what the next-generation system should look like despite the fact that solutions to the desired system are still unknown. Therefore, these patterns of evolution transform a subjective system improvement process into a search for the innovations to fill the gap between an existing system and its desired form.

Enhancing Value Engineering Process

Value Engineering

VE is a process whereby team efforts are made to understand the functions of a system in order to realize the essential functions of that system at the lowest possible life-cycle cost (Younker 2003). As a definitive tool to improve the value of a system, VE has been widely used by government agencies, financial institutions, manu-

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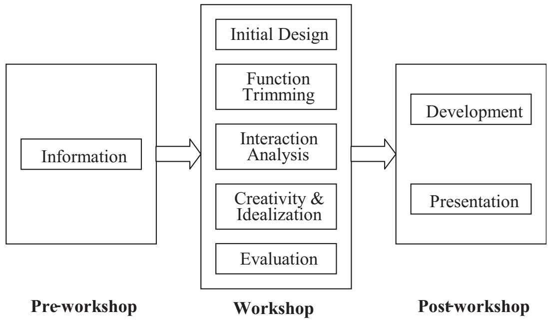

Fig. 3. Modified workshop session

facturers, construction designers, and contractors. A VE process contains three sections, preworkshop, workshop, and postworkshop. During the VE process, a multidisciplinary team reviews the project plan and assesses the possibility of improving the project value. In the construction industry, VE is normally conducted at the early design stage. However, VE should not be ruled out at the construction stage as the contractor's practical experience and expertise, innovative construction plan and construction methods, and improved construction logistics management can also lead to substantial cost savings, better quality, and earlier project completion.

The key stage of the VE process is the workshop session, which includes information and function analysis phase, creativity phase, and evaluation phase. The creativity phase is the most decisive stage, in which the brainstorming technique is usually applied to generate innovative ideas for enhanced project functions and reduced project costs.

Modified Workshop Session

To improve efficiency and effectiveness, the workshop session of VE is significantly modified by incorporating TRIZ tools and techniques, whereas the preworkshop and postworkshop remain the same as in a conventional VE process. As illustrated in Fig. 3, the modified workshop session consists of five phases: initial design, function trimming, interaction analysis, creativity and idealization, and evaluation. For detailed procedures of the modified workshop session please refer to Fig. 4.

Case Study: W12 Inverted Siphon Project

As discussed in previous sections, the difference in the modified VE process from that of the traditional VE process lies in the workshop session. To save space, only the procedures in the workshop session are discussed in this case study to demonstrate how to conduct the modified workshop session in a VE exercise.

Project Background

The W12 Inverted Siphon Project (hereinafter referred to as the W12 project) is located in Edmonton, Canada. It is proposed as part of the expansion of Edmonton's sewer system. The main purpose of the project is to convey sewage collected from the north side of the North Saskatchewan River to the south side of the river, and then connect to an existing water treatment plant that has extra capacity to treat more sewage.

Initial Design

The main objective of this phase is to create initial project alternatives. According to the requirements of the City of Edmonton, the basic function of the W12 project is stated as "conveying sewage to water treatment plant." After reviewing the project documentation and visiting the project site, the VE team has identified a number of resources existing in the project area: North Saskatchewan River, air, land, sewer, park users, communities, water treatment plant on the south side of the river, shaft on the

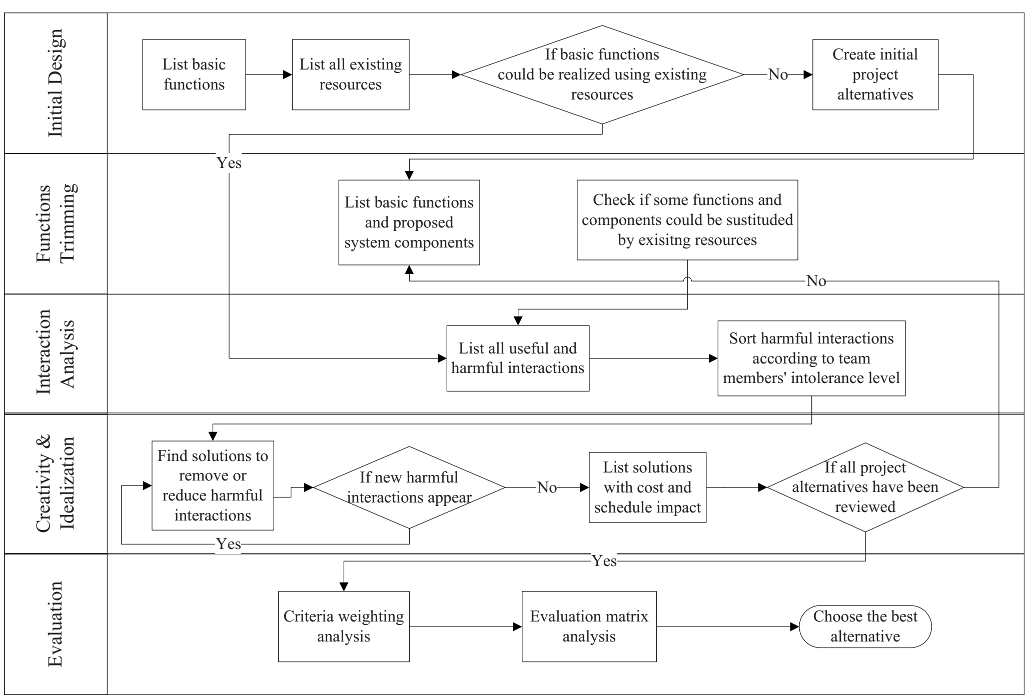

Fig. 4. Procedures of the modified workshop session

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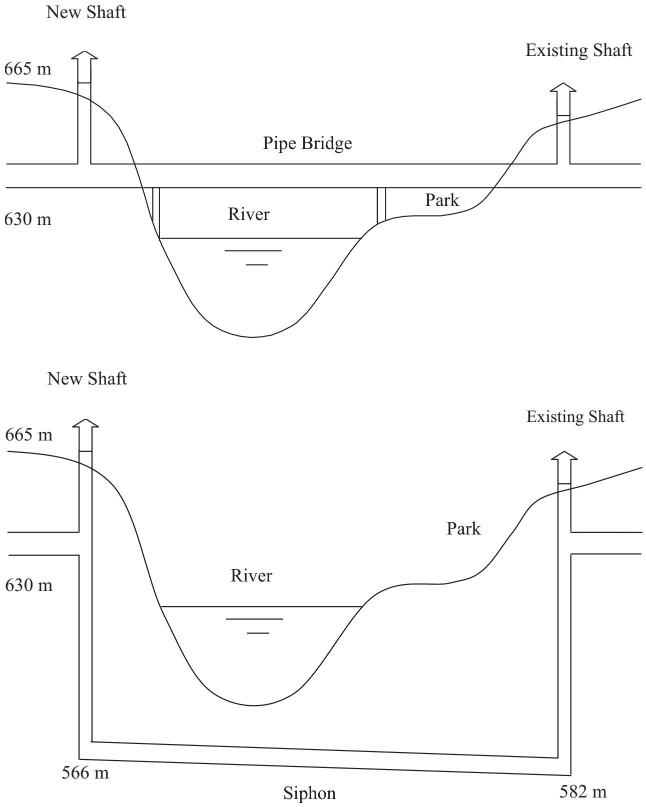

Fig. 5. Cross sections of Alternatives A and B

south side of the river, forest, and wildlife. Then, through further analysis, the VE team has concluded that (1) the project's basic function cannot be accomplished by merely utilizing the existing resources; (2) additional resources are needed in order to initiate project alternatives; and (3) four existing resources have the potential to contribute to the basic project function:

1. North Saskatchewan River—could be the place to which sewage is discharged;
2. Water treatment plant—has the capacity to treat more sewage;
3. Riverbed—provides a space to build an underground tunnel; and
4. Existing shaft—provides a tie-in point to access to the existing wastewater treatment plant.

The VE team has proposed two project alternatives (as shown in Fig. 5) following an assessment of the relationships between the project basic function and the obtainable resources (including existing resources):

- Alternative A—building a pipe bridge to overpass the river and connect to the existing shaft and
- Alternative B—building a tunnel to underpass the river and link to the existing shaft.

Phase 2: Function Trimming

In this phase, the VE team reviews preliminary project alternatives in order to (1) eliminate undesirable functions and unnecessary project components; (2) utilize existing resources; and (3) determine new (additional) resources that are required by each alternative. After examining available resources, it is concluded that to realize the basic function, Alternative A requires building a new bridge structure and attaching new pipelines to the bridge structure, whereas Alternative B needs to build an additional shaft and a new tunnel, for which the existing shaft can be used.

Phase 3: Interaction Analysis

The main objective of this phase is to identify both useful and harmful functions associated with a project alternative. The results of the interaction analysis for Alternatives A and B are summarized in Table 1, in which harmful interactions of both alternatives are listed in the order of descending level of intolerance (10 representing the most intolerable level). Harmful interactions are the problems that must be eliminated or minimized to a tolerable level. A project alternative will be deemed unfeasible and discarded if certain harmful interactions cannot be mitigated to a level that is below a preset threshold value.

Table 1. Harmful Interaction 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	Interuption during construction	6
	System in general	Park users	Interuption during construction	6
	System in general	Park	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 depositing 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	Threat to wildlife	5
	System in general	Park	Reduced size of habitat	4

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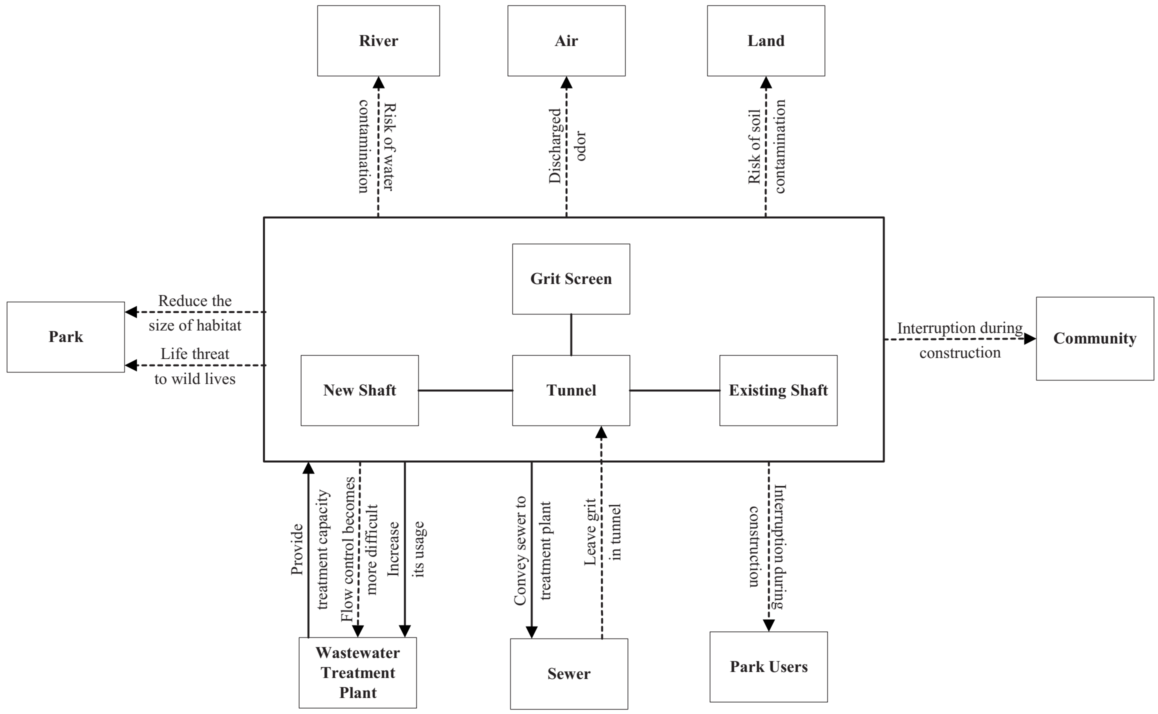

Fig. 6. Interaction analysis for Project Alternative B

A graphical representation is quite helpful in interaction analysis. To demonstrate this point, the case of Alternative B is provided as shown in Fig. 6. The project components of Alternative B are enclosed in a large rectangular square, which creates a boundary between the project and its environment setting. Existing resources are arranged around the square. An action from an existing resource that has an impact on the whole project is expressed by an arrow pointing to the edge of the big rectangular square. An action on a project component from an existing resource is expressed by an arrow pointing to the box of the project component. Similarly, 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. A project component or an existing resource can be associated with multiple interactions. Further, a useful interaction is indicated by a solid line with an arrow pointing to the recipient of the useful effect, whereas a 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.

Phase 4: Creativity and Idealization

This is the phase in which TRIZ tools are deployed to remove or minimize harmful functions in order to increase the ideality of each project alternative. Due to space limits, the applications of TRIZ tools and techniques in creating ideas and idealizing the project alternatives are demonstrated through resolving one of the harmful interactions either in Alternative A or B.

Contradiction Matrix and 40 Inventive Principles—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. Methane gas may leak and accumulate in the tunnel during the tunneling operation. If the content of methane gas in the air exceeds a certain threshold, it impairs the safety and health of construction personnel and may even result in an explosion. This hazard also has negative impacts on the cost, time, and quality of the tunnel construction.

To solve the problem of potential methane gas exposure, two contradictions are found from the contradiction matrix. The first contradiction is between Parameter 7 (i.e., Volume of Moving Object) and Parameter 39 (i.e., Productivity). In the context of tunnel construction, this contradiction is further expressed as “the tunneling productivity is decreased while the volume of methane gas increases.” The second contradiction is between Parameter 31 (i.e., Object-Generated Harmful Factors) and Parameter 39. In the context of tunnel construction, this contradiction is further expressed as “methane gas generates harmful effects which reduce the tunneling productivity.”

As shown in bold text in Fig. 1, the contradiction matrix provides four inventive principles (2, 6, 10, and 34) to solve contradiction one and four inventive principles (18, 22, 35, and 39) to solve contradiction two. After examining these inventive principles, it is realized that four of them, 2, 10, 22, and 35, may have the potential to resolve the two contradictions. Table 2 provides the possible solutions to the two contradictions as provided by the writers based on the four inventive principles, which are compared to the general solutions as provided by TRIZ for the four inventive principles. In summary, it is suggested to install a system to either reduce or separate methane gas in order to minimize its accumulation inside the tunnel working area. In this regard, a ventilation system, a traditional mechanism for improving air condition inside tunnel, is certainly an option. Alternatively, a device that can either collect or neutralize the methane gas may be applied.

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Table 2. Inventive Principles Applicable to Harmful Interaction 1—Methane Gas Exposure

Contradictions	Inventive principles	TRIZ general solutions	Recommended solutions
Contradiction 1: tunneling productivity is decreased whereas the volume of methane gas increases	2. Extraction	• Separate an interfering part or property from an object • 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	• Perform, before it is needed, the required change of an object (either fully or partially) • Prearrange 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 tunneling productivity	22. Convert harm into benefit	• Use harmful factors (particularly, harmful effects of the environment or surrounding) to achieve a positive effect • Eliminate the primary harmful action by adding it to another harmful action to resolve the problem • 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	• Change an object's physical state (e.g., to a gas, liquid, or solid) • Change the concentration or consistency • Change the degree of flexibility • Change the temperature • 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.

Four Separation Principles—Sewage Flow beyond Wastewater Treatment Capacity

The existing wastewater treatment plant's capacity to treat wet weather sewage flow is 15 m^3/s. It is estimated that in the peak period of wet weather, 5.1 m^3/s of sewage flow will have to be discharged into the river without treatment. This constitutes a harmful interaction—the sewage flow in the peak period is beyond the wastewater treatment plant's capacity. Therefore, a solution is needed to eliminate this harmful interaction so that all wet weather sewage flow can be treated at the wastewater treatment plant.

Increasing the treatment capacity of the plant is an option, which entails considerable 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 15 m^3/s occurs only a few times a year, the plant expansion may not be economical.

To find a better option, the four separation principles of TRIZ are applied. First, the harmful interaction is expressed as a physical contradiction—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, which is only for infrequent usage. Second, after examining the four separation principles, it is realized that the principle of "separation in time" is applicable in solving this contradiction. Third, in the context of this particular problem, this separation principle is further stated as "treating sewage overflow in the nonpeak period when the plant has enough capacity." This prompts the idea that the sewage overflow may be temporarily contained somewhere in the sewer system in the peak period and released after the peak period for treatment. Finally, two practical options are found—building a new sewage storage tank or installing a new sewage pipeline. These two options also involve significant investment. However, it is expected that they are less costly than expanding the wastewater treatment plant.

Su-Field Analysis—Grit Deposition along the Invert of Tunnel

Some grits carried by the wastewater deposit along the tunnel invert. If the grit deposit is not removed, grits will build up in the invert over time. This will reduce the capacity of the siphon and cause operational problems. To solve this problem, the interaction between the sewage flow and the tunnel is represented in a Su-field model as shown in Fig. 7. The sewage flow (the tool) acts upon the tunnel (the object) using a mechanical force. Although this interaction is useful in conveying sewage through the tunnel, it also causes harm, i.e., grit deposition along the invert of the tunnel. To remove this harm, a counteractive field may be introduced (as shown in Fig. 8), for example, by installing a steel mesh screen right in front of the siphon to prevent grit from entering the tunnel.

Eight Patterns of Evolution—Grit Deposition along the Invert of Tunnel

As discussed in a previous section, the eight general patterns of evolution may provide insights on the evolutionary trend of a particular system and thus facilitate inventors in the search for

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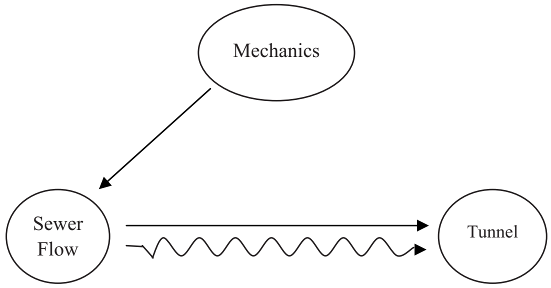

Fig. 7. Su-field model for grit deposition along the invert of tunnel

measures to fill the gap between the existing system and the desired system. Therefore, the eight patterns of evolution may be applied to improve the solutions originated from other TRIZ tools and techniques. The following provides an example of how to deploy the patterns of evolution to improve the solution from the Su-field analysis as discussed previously—"installing a steel mesh screen right in front of the siphon to prevent grit from entering 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 needs to be cleaned in order to keep it functioning properly. A screen-cleaning device 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 interruption to tunnel operation, corrosion-protective alloy materials such as the stainless steel may be used to enhance the durability of the screen.
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 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 enhance the efficiency and effectiveness in operating the tunnel.

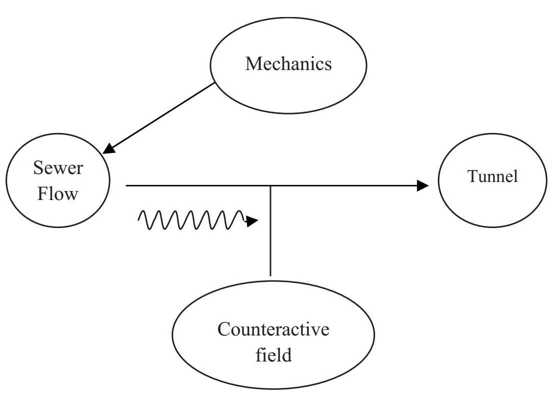

Fig. 8. Transformed Su-field model for grit deposition along the invert of tunnel

Phase 5: Evaluation

The objective of the evaluation phase is to select the best from all project alternatives. A set of evaluation criteria is identified first and then an evaluation matrix is developed. The best project alternative is selected by evaluating all alternatives against this evaluation matrix.

Evaluation Criteria

It is necessary to establish a set of evaluation criteria to assess project alternatives. Based on the experience and expertise of its members, the VE team has determined the following evaluation criteria for the W12 project: budget, schedule, meeting objectives, constructability, long-term environmental impact, short-term environmental impact, functionality, reliability, safety, and durability.

Relative Importance of Evaluation Criteria

As shown in Table 3, 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 the 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.

For example, the scores assigned to Criterion F (short-term environmental impact) in comparison with other criteria are highlighted in bold text in Table 3. The total score of each criterion is calculated by adding all scores assigned to this criterion. For example, the total score of criterion F is calculated as follows:

$$(F-2)+(F-1)+(F-2)+(F-3)+(F-1)$$
$$=2+1+2+3+1=9 \text{ points}$$

The relative impotence of each criterion is measured by the "standardized weight," which is derived by standardizing the total score of each criterion to the scale of 1–10, 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 3 for the standardized weights of other criteria.

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 4. E, VG, G, F, and P are assigned numerical scores of 5, 4, 3, 2, and 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 criterion and its corresponding standardized weight. The alternative with the higher total weighted score (i.e., alternative B) will be selected.

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Table 3. 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=long-term environmental impact; F=short-term environmental impact; G=functionality; H=reliability; I=safety; and J=durability. 2. Relative importance of two criteria X and Y: X-1=major; X-2=medium; X=3=minor; and X/Y=equally important. Boldface indicates scores assigned to Criterion F.

Table 4. Evaluation of Alternatives A and B

Criteria	Standardized weight	A					B				
		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
Long-term environmental impact	6	E	VG	**G**	F	P	E	VG	**G**	F	P
Short-term environmental impact	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		2					1				

Note: E=excellent; VG=very good; G=good; F=fair; and P=poor. Boldface indicates scores assigned to Alternative A or B.

Conclusions

The traditional VE process has been in use for half a century without any major improvement in the way the process is implemented. There is a mixed public opinion of the usefulness of VE. This research attempts to improve the traditional VE process for enhanced efficiency and effectiveness in creating innovative ideas by initiating three new procedures in the workshop session: (1) an initial design procedure to examine the functions of a proposed project; (2) a function trimming procedure to fully utilize existing resources and ensure low life-cycle cost and sustainability of the proposed project; and (3) an interaction analysis procedure to assess the proposed project in a broad perspective with social, economic, and environmental awareness. The significant changes in the procedures of the workshop session and integration of TRIZ tools and techniques into the creativity phase can enhance the creativity capacity of the VE team and enable it to generate more focused and innovative solutions to the problems of a project. A case study based on an actual project has been conducted to demonstrate the proposed workshop procedures and the application of the TRIZ tools and techniques. This case study indicates the workability of the modified workshop procedures and the usefulness of TRIZ tools and techniques in efficiently and effectively creating innovative ideas.

Appendix. 40 Inventive Principles

Identification	Name of principle
1	Segmentation
2	Extraction
3	Local quality
4	Asymmetry
5	Consolidation
6	Universality
7	Nesting
8	Counterweight
9	Prior counteraction
10	Prior action
11	Cushion in advance
12	Equipotentiality
13	Do it in reverse
14	Spheroidality
15	Dynamicity
16	Partial or excessive actions
17	Transition into new dimension
18	Mechanical vibration
19	Periodic action
20	Continuity of useful action
21	Rush through
22	Convert harm into benefit
23	Feedback

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Identification	Name of principle
24	Mediator
24	Self-service
26	Copying
27	Dispose
28	Replacement of mechanical system
29	Pneumatics and hydraulics
30	Flexible shells and thin films
31	Porous materials
32	Change color
33	Homogeneity
34	Discarding and recovering
35	Parameter changes
36	Phase transitions
37	Thermal expansion
38	Accelerated oxidation
39	Inert environment
40	Composite materials

References

Mann, D., and Stratton, R. (2000). "Physical contradictions and evaporating clouds." *TRIZ Journal*, ⟨http://www.triz-journal.com/archives/2000/04/b/⟩ (Mar. 17, 2006).

Mao, X., Zhang, X., and AbouRizk, S. M. (2007). "Generalized solutions for Su-Field analysis." *TRIZ Journal*, August, ⟨http://www.triz-journal.com/archives/2007/08/03/⟩ (Oct. 23, 2007).

Savransky, S. D. (2000). *Engineering of creativity: Introduction to Triz methodology of inventive problem solving*, CRC, Boca Raton, Fla.

Souchkov, V. (1999). "TRIZ: a systematic approach to innovative design." *Knowledge base: Articles*, ⟨http://www.insytec.com/TRIZApproach.htm⟩ (Jul. 5, 2005).

Younker, D. L. (2003). *Value engineering analysis and methodology*, Marcel–Dekker, New York.

J. Constr. Eng. Manage., 2009, 135(5): 416-424