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An Innovative Product Design Approach Based on TRIZ's Inventive Principles

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Abstract

A systematic design approach with effective and efficient guiding principles is pivotal for developing versatile and innovative products, which then lead to product success. This research aimed to propose an innovative product design approach that incorporates TRIZ principles. This newly proposed approach started with identifying design issues or problems by conducting a comprehensive literature review with respect to the targeted product. The revised three-step inventive problem solving procedure of Shulyak's then formulated potential design problems to generate the problem statement in a structured way. The three steps for solving an inventive problem were: determining product's characteristics that should be improved or eliminated, stating characteristics needed to be improved to locate the potential contradictions of the problems, and eliminating the contradictions by employing contradiction matrix to identify the proper inventive resolutions. The solution concepts, as suggested from TRIZ's principles, were generated after working through the procedures. They can serve as design directions to improve and re-design the original product. Case studies were conducted to demonstrate how this approach works. Study results show that the proposed approach can help product designer or relevant profession develop innovative products effectively and efficiently, resulting in gaining better competition in the marketplace.

Keywords: Innovative Product Design, Inventive Problem Solving, Systematic Innovation, TRIZ.

1. Introduction

The Product design generally determines more than 70% of the total cost in the whole product development (Boothrody, et al., 2002; Dowlatshahi, 1992; Miller, 1995; Shetty, 2002). This suggests that mistakes or successes in the conceptualization of a product often have the greatest impact throughout the product development. Furthermore, they tend to be amplified over the course of the product development. Due to the nature of the product development in the early phases, chaotic, unpredictable and unstructured activities are often expected and inevitable (Koen, et al., 2002). These typical scenarios normally post great challenges for a product to be designed and developed effectively and successfully in the end. A sound product design can then be highly rewarding, which will eventually lead to a successful product that can be producible, marketable, and profitable.

Product design can be considered as a process for problem solving (Cross, 2000). A common strategy used in this problem-solving process is random search that is generally no apparent plan. This solution search strategy is generally constraint to past experiences and own specialties and disciplines that will influence and dominate the search directions for solutions. These never-ending random trials take huge effect to locate the potential solutions, which are likely not existed in the search region. And they couldn't be very helpful to deal with uncertainties in the earlier phases of the product development and provide the needed information and responses in a timely manner. To address this issue, a systematic innovation approach is necessitated to help point out the most promising solution directions by enlarging solution search space and directing appropriate solution search across inter-disciplines.

TRIZ, a Russian acronym meaning theory of inventive problem solving, can serve as one of the promising candidates to meet this requirement. Based on analyzing numerous patents, TRIZ theory suggests that design problems can be solved in predictable ways and 95% of the inventive problems in any particular field have already been solved in some other fields (Terninko, et al., 1998). Therefore, solving design problems can be effective and efficient when the appropriate solutions are found and implemented by following TRIZ principles. However, design problems are mostly not well defined and relevant information is normally limited. The classic TRIZ theory does not provide tools to define problem situation and formulate the problem. These post the difficulties for classic TRIZ theory to deal with problem statement and situation analysis effectively (Dwyer, 2005; Terninko, et al., 1998). Teaming up with problem formulation tools, TRIZ then can serve better to offer innovative solution concepts.

The remainder of this paper is structured as follows. Firstly, TRIZ theory, as the core of the proposed approach, is introduced. This is followed by description of the TRIZ-based systematic innovation product design process in details. Thirdly, case studies are provided. Finally, conclusions are presented.

2. Introduction to TRIZ

After reviewing and analyzing more than several millions of patents, Genrich Altshuller, a former Soviet Union inventor and scientist, introduced TRIZ. In the era of cold war between east and west, TRIZ theory was regarded as the state secret of the Soviet Union all the time, the western countries knew little about it. After the fall of Soviet Union, many TRIZ researchers and practitioners have migrated to western countries such as U.S. and Europe. In addition, Kishinev School, known for its great reputation in teaching and researching TRIZ in the Soviet Union, has established branch schools in the western countries to continuously promote and develop TRIZ (Terninko, et al., 1998). TRIZ then begun to popularize and further develop in the western countries rapidly. Many international companies, such as, Ford, GM, Chrysler, and Xerox, have been sponsored the development of TRIZ and integrated TRIZ to their product design and development, resulting in gaining great benefits (Domb, 2013; Dwyer, 2005). Companies, such as Samsung from South Korea, were recovering from the verge of bankruptcies after employing TRIZ.

The main theories of TRIZ include contradiction analysis, substance-field method, ideal final result, ARIZ (algorithm of inventive problem solving), etc. (Ideation International Inc., 1999; Mann, 2007; Terninko, et al., 1998). Among them, contradiction analysis is one of the most popular ones in application. Altshuller indicated that every innovative patent was the result to solve an inventive problem, which normally contains some contradictions (Altshuller, 1998; Altshuller, 1999). Contradiction is classified into physical and technical contradictions (Altshuller, 1998; Altshuller, 1999). Physical contradiction is the conflict within the same parameter that has the opposite states co-existing at the same time. To eliminate physical contradiction, separation principles are employed (Mann, 2007; Terninko, et al., 1998). When improving one parameter is causing the deterioration of another, the conflict is named technical contradiction. To eliminate technical contradiction, contradiction matrix, made up by a 39 by 39 matrix, is utilized (Mann, 2007; Terninko, et al., 1998). An innovative problem solving method should be the one that can eliminate conflict or contradiction in a problem effectively and efficiently and help generate innovative solution. And TRIZ is the one to serve this purpose well.

3. A TRIZ-based Method

Based on the creative design approach proposed by Yang et al. (2010), this research proposed a structured and systematic innovation design process that incorporates both TRIZ principles and a revised three-step inventive problem solving procedure. Although the original three-step inventive problem solving process proposed by Shulyak (1997) is a sound problem formulation method to help solve inventive problems in conjunction with both contradiction matrix and inventive principles of TRIZ, the forms (Form F-1 & Form F-2) from the completion of the 3-step process are designed with engineering terminologies, which make them not friendly to some professions in product design and development field, such as industrial designers. To address this issue, a revised 3-step process, designed from the perspective of the product design and development, was proposed.

This research started with a comprehensive literature review on a targeted product to identify the potential problems. The revised 3-step process was then employed to translate the initial problem description into the conflict or contradiction such that the contradiction matrix of TRIZ can be introduced to resolve the problem and provide solution concepts. The revised 3-step process for solving an inventive problem is described in the following:

(1) The first step, completed by filling out the Form F-1, was to formulate the initial problem description and analyze the product to determine characteristics

that should be improved or eliminated. In this step, there are five items to work with step by step. Item one is to list the product name. Item two is to define the goal of the product and how the product is designed for. Item three is to list the main elements and their corresponding functions. Item four is to describe how to use the product. Based on the information provided above, the last item is to determine characteristics that should be improved or eliminated.

(2) By following the analysis results of the first step, the second step, completed by filling out the Form F-2, was to analyze positive or negative characteristics needed to be improved or eliminated in order to identify the potential contradictions in the problem for resolution. In this step, there are two items to work with step by step. Item one is to determine the characteristics to be improved from TRIZ's 39 generic characteristics for product improvement, based on the product's goal from Form F-1. Item two is to determine the deteriorated characteristics with respect to the characteristics to be improved.

(3) The third step, completed by filling out the Form F-3, was to eliminate the contradictions, identified from second step, by applying TRIZ's problem solving tool – contradiction matrix to locate appropriate inventive principles for resolving the problem. In this step, there are two items to work with step by step. Item one is to identify the suggested principles from TRIZ's 40 Principles, after applying contradiction matrix analysis. Item two is to determine the proper inventive principles, which are from the suggested principles of Item one, with respect to each element of the product for design improvement.

The suggested principles or solution concepts can serve as design directions to improve and re-design the original product with innovative ideas. If any of the contradictions cannot be clearly identified after the problem formulation, Liu's method (Chen & Liu, 2001; Liu & Chen, 2013) can be employed to help locate the proper solution concepts. Another approach to deal with no contradiction situation is to go through every inventive principle and choose the most desired solution concepts (Shulyak, 1997).

4. Case Studies

The daily writing instrument, such as pen and pencil, was selected as to demonstrate how this approach works. From the intensive literature review, three major issues concerning daily writing instrument design are needed to be improved. They are: assisting people to write easily and smoothly, avoiding muscle injury during the writing process, and assisting in guiding people to use the correct writing posture (Chang, et al., 2010). To deal with these issues, the revised 3-step process was applied to formulate the initial problem description and to help construct and verify the conflict or contradiction. By completing each item of Forms F-1 (shown in Table 1), the initial problem description was formulated to identify product's characteristics needed to be improved. They were core, grip, and shaft of a pen. A typical writing instrument can be improved by introducing a better core, grip, or shaft design. To promote easily and comfortably writing experience, our aim was to design a better housing or grip of the writing instrument. By completing Form F-2 (shown in Table 2), all of TRIZ's 39 characteristics were investigated one by one with respect to the design goals (item 2 from Table 1) and the product elements to be improved (item 5 from Table 1). The characteristic #12, i.e., shape, was then identified as the sole one needed to be improved, while the deteriorated characteristics were #7 (volume of a mobile), #13 (stability), #32 (manufacturability), and #35 (adaptability). Four technical contradictions were formulated as follows:

(TC-1) If the shape (characteristic #12) design of the housing or the grip can be improved by introducing a better one, then the volume of the writing instrument (characteristic #7) will get worse.

(TC-2) If the shape (characteristic #12) design of the housing or the grip can be improved by introducing a better one, then the stability of the writing instrument (characteristic #13) will get worse.

(TC-3) If the shape (characteristic #12) design of the housing or the grip can be improved by introducing a better one, then the manufacturability of the writing instrument (characteristic #32) will get worse.

(TC-4) If the shape (characteristic #12) design of the housing or the grip can be improved by introducing a better one, then the adaptability of the writing instrument (characteristic #35) will get worse.

Finally, the contradiction matrix of TRIZ was applied to eliminate the contradictions specified above and provides totally 15 inventive principles for resolving the problem (shown in Table 3).

After carefully reviewing the suggested principles with the consideration of three major design issues (item 2 from Table 1) and main product elements (item 5 from

Table 1) of writing instrument design improvement, the researchers, with the aim of designing a better housing or grip, made the judgment call to consider four of the suggested principles as the most promising ones and choose them as the re-design directions for design improvement. The chosen principles (#1, #4, #14, and #15) were employed to assess the potential improvement of daily writing instrument (shown in Table 3). Based on the product analysis from Form F-1 and previous study (Chang, et al., 2010), it was found that the shaft (or housing) of the writing instrument holds the main influence on design improvement, following by grip (or grip area) and core, which are all utilized to support writing in an easy and comfortable manner. The applicable chosen principles were assessed with respect to the components of a writing instrument mentioned above. Selected examples on applying the inventive principles to generate feasible design directions are in the following.

Table 1. Formulation of Product's Characteristic to Be Improved.

F-1: Formulation of Product's Characteristic to Be Improved	
1. State the name of the product:	
A typical writing instrument	
2. Define the goal of the product. The product is designed to:	
** Assisting people to write easily and smoothly* ** Avoiding muscle injury and writing strain during the writing process* ** Assisting in guiding people to use correct writing posture*	
3. List main elements of the product and their functions:	
Element	Function
Core	*To be applied to a surface of writing*
Grip	*To support comfortable writing*
Housing	*To be hold in writing*
4. Describe the operation of the product:	
A typical way to hold a writing instrument is three-finger grasp. The writing instrument lies on the middle finger and is controlled using the thumb and index finger.	
5. Determine the element of the product should be improved or eliminated:	
Core, Grip, or Housing (To improve the typical writing instrument by introducing a better core, grip, or housing design.)	

Table 2. Formulation of Technical Contradiction.

F-2: Formulation of Technical Contradiction		
1. State the characteristic that should be improved, based on the goal from F1:		
#12.Shape		
2. State a characteristic that is getting worse under previous conditions: (State the technical contradictions)		
Name of Technical Contradictions	Improved Characteristic	Worsen Characteristic
TC-1	*#12 Shape*	*#7 Volume of moving object*
TC-2	*#12 Shape*	*#13 Stability of object*
TC-3	*#12 Shape*	*#32 Manufacturability*
TC-4	*#12 Shape*	*#35 Adaptability*

Table 3. Formulation of Solution Concept.

F-3: Formulation of Solution Concept			
1. List suggested principles by eliminating the contradictions:			
Name of Technical Contradictions	Coordinates in the Contradiction Matrix	Suggested Inventive Principle	Name of the Principle
TC-1	*#12 x #7*	*#14*	*Spheroidality*
		#4	*Asymmetry*
		#15	*Dynamicity*
		#22	*Convert Harm into Benefit*
TC-2	*#12 x #13*	*#33*	*Homogeneity*
		#1	*Segmentation*
		#18	*Mechanical Vibration*
		#4	*Asymmetry*
TC-3	*#12 x #32*	*#1*	*Segmentation*
		#32	*Changing the Color*
		#17	*Transition Into a New Dimension*
		#28	*Replacement of Mechanical System*
TC-4	*#12 x #35*	*#1*	*Segmentation*
		#15	*Dynamicity*
		#29	*Pneumatic or Hydraulic Construction*
2. Determine the proper principles for design directions:			
#1. Segmentation , #4.Asymmetry, #14.Spheroidality, and #15.Dynamicity			

(1) Principle 1 - Segmentation

For better writing results, the core of a writing instrument can be divided into parts. The refillable pen or pencil in the marketplace, such as the one shown in Fig. 1, is a good example by applying this idea.

Fig. 1. Refillable Pencil (Pacific Writing Instrument, Inc., 2010).

(2) Principle 4 - Asymmetry

Without the proper guidance, the existing symmetrical barrel design is difficult to promote the correct writing position. We normally have to accommodate the existing design while writing, resulting in writing strain. An asymmetrical shaft design could serve as holding guidance to promote the correct writing position. Handy Birdy Minny (as shown in Fig. 2), designed by Tripod Design in Japan, is a good example by applying asymmetry principle.

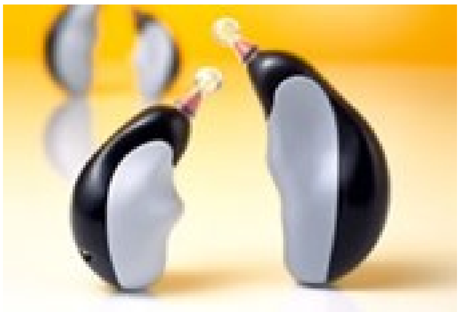

Fig. 2. Handy Birdy Minny (Tripod Design, 2013).

(3) Principle 14 - Spheroidality

The typical barrel design can be replaced with spherical shapes to provide support while holding the writing instrument in the writing process. This design should help reduce writing strain and provide better and more comfort control throughout the writing. A good example to demonstrate this idea is U-Wing Pen (as shown in Fig. 3), design by Tripod Design in Japan.

Fig. 3. U-Wing Pen (Tripod Design, 2013).

(4) Principle 15 - Dynamicity

To accommodate all users, the grip or support area can be designed to adjust for various writing positions dynamically. Yoropen (as shown in Fig. 4), designed by Yoropen Corp. in Taiwan, is a good example to demonstrate this idea.

Fig. 4. Yoropen (Yoropen, 2013).

In addition, to further demonstrate how this method could work on generating new design concepts for writing instrument, several student designers were recruited to participate in pen re-design based on the proposed approach. The design goals and the typical pen design analysis were provided and explained. The four chosen principles (#1, #4, #14, and #15) with detailed descriptions and examples were provided as the re-design directions. Student designers employed the suggested inventive principles as the stimuli to develop the design concepts. The proposed design concepts are shown in the following:

(1) Concept One

Concept one in Fig. 5 employed a combination of two principles from the chosen ones, which were #4 and #15, to re-design the typical pen. By applying asymmetry, the grip or support area was designed asymmetrically and ergonomically to direct user fitting in the more appropriated writing position and help relaxed writing comfort. The dynamicity principle was applied to develop the flexible profile on the pen shaft in order to let the pen rest well and comfortably in the hand, which can serve as both writing position guidance and relaxed writing.

(2) Concept Two

Three principles from the chosen ones, which were #4, #14, and #15, were incorporated in generating concept two (as shown in Fig. 6) to re-design the typical pen. By applying asymmetry and spheroidality, the typical grip and barrel design was replaced by asymmetrical and spherical shapes to provide optimal support for relaxed writing comfort. The dynamicity principle was also applied in this design to develop the dynamic profile for pen length adjustment, resulting in accommodating all users for various pen grapping positions.

(3) Concept Three

Instead of re-designing the whole writing instrument, concept three in Fig. 6 designed merely the extender for

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pencil by employing a combination of three TRIZ's inventive principles of #1, #4, and #15. With applying the design direction of segmentation, extender was designed for used pencils. With its asymmetrical and triangular design, the extender can also be used to hold other pens for resting comfortably in the hand and guiding the writing position. The dynamicity principle was also applied in this design to develop the retractable feature to slide the used pencil to the right place.

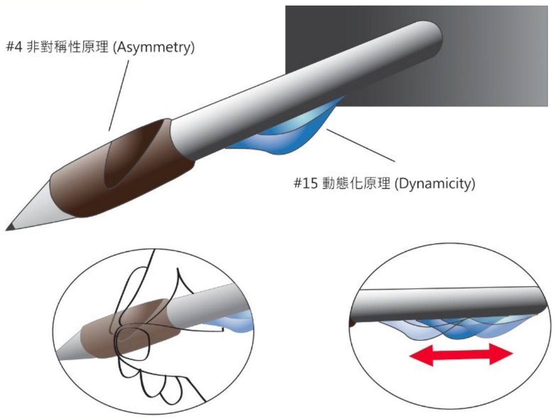

Fig. 5. Concept One.

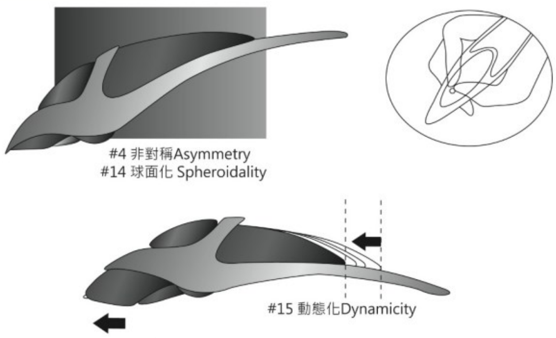

Fig. 6. Concept Two.

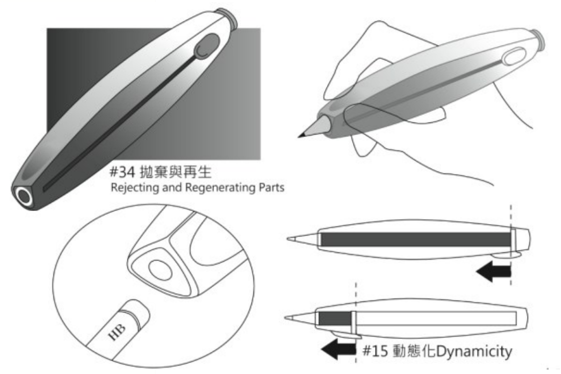

Fig. 7. Concept Three.

5. Discussions & Conclusions

By adopting the existing products as examples, the first part of case studies section demonstrated how this newly proposed approach works step by step. And it also shows that this TRIZ-based method can be used to analyze the existing products to gain some product development insights, resulting in developing new product concepts. The second part of case studies recruited student designers to practice writing instrument re-design exercises with the help of this TRIZ-based method. During the design activities, the only instruction was to ask them to employ the chosen inventive principles of TRIZ as re-design directions and stimuli to generate new design concepts of typical writing instrument. From the re-design results, it is found that the student designers tended to apply multiple inventive principles within a design concept. This compound design strategy is worth to be studied in the later research.

The intensive literature review from this research helped summarize the common problems in writing (Chang, et al., 2010). Previous studies (Chang, et al., 2010) show that diameter, length, cross-section, and grip area of a writing instrument are major factors to influence writing performance. While handwriting, user has to rely on holding or grasping the shaft or housing of the writing instrument. Poor writing instrument design with respect to factors mentioned above can normally cause writing strain and performance. The design of a writing instrument, without any guidance or support to help correct finger and hand positions, can easily cause writing strain and performance. To resolve these issues, this research introduced the revised three-step inventive problem solving process to formulate the design problems and determine the conflict or contradiction. The contradiction matrix of TRIZ was then employed to eliminate the contradiction and provide solution concepts for improving the writing instrument design. By incorporating the revised three-step inventive problem solving process, this newly proposed TRIZ-based innovative product design can help product designers, product planners and relevant professionals to solve design problems and generate innovative solutions in an effective and efficient way.

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A Phenomenological Model of Parameter Growth in Engineering Systems

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Abstract

A new model for approximation and prediction of growth of the parameters of engineering systems is suggested. The model derives the rate of growth not only from the considered system itself but also from the customers' expectations that play a role similar to the "driving force" in thermodynamics. The suggested model is written in the form of the system of few differential equations that can be solved by numeric calculations, similarly to the simulation of the structural and stress relaxation phenomena in super-cooled liquids. Some examples of applications of the simplified model are presented.

Keywords: engineering system, technical system, growth, parameter, S-curve, model, relaxation

1. Background

The Theory of Inventive Problem Solving (TRIZ) believes that development of the Engineering Systems (ES) can be considered as an evolutionary process that undertakes some general laws. The term "engineering system", in our consideration, means a "population" of particular systems that satisfy a particular human need in similar way like "car" (for transfer by road), "aircraft" (for transfer by air), "photo camera" (for making a picture by using optical lens), etc.

Although exact formulations of the laws of evolution of engineering systems are not known yet, many rather common trends describing the development of multiple particular systems seem to confirm the existence of such laws. For example, various engineering systems (transport, weapons, information systems, etc.) being developed become more powerful, more "dynamic", better-controlled, less human-involved, etc. (Leon, 2006).

Multiple investigations describe the progress of particular kinds of systems in terms of the "evolution" of the "key parameters", e.g. speed and range for transport, resolution and sensitivity for photo cameras, power and weight for batteries, etc. (Martino, 1972 & Kynin, 2009). Such consideration generally leads to a concept of so-called "S-curve" (Fig. 1). There are several different kinds of concepts describe "S-like" dependences of various quantities from each other. In this paper, we will consider only one of them: the dependences of the key parameters of a system on time. This kind of dependences is often called a "life line".

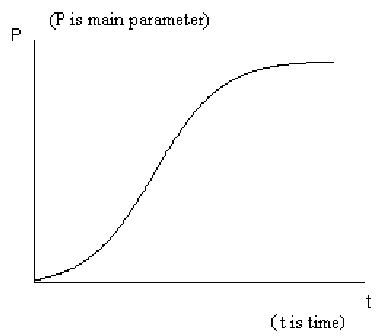


Fig. 1. Schematic view of S-curve

In the above-mentioned and other investigations, it was shown that the concept of "S-curve" can be well applied as a rough approximation of various "life lines". So, it was natural to try to describe these (generally similar) curves by some mathematical expression to be able to quantitatively predict the growth of key parameters of a system in the future. Indeed, knowing the "life line" of a system could allow developing of an ES with maximum effect for minimal cost that is a basic idea for the "Directed Evolution" concept (Zlotin, 2001).

For that, multiple approaches were proposed. Bass (1969), Kohlrausch (1863), Modis (1992) etc. described multiple more or less simple equations that can more or less correctly describe the growth of various characteristics of ES. In this way, however, serious problems appeared.

First, not all of the systems (and surely not all of their key parameters) demonstrate the S-like behavior. Kynin (2010) mentions that we considered the examples of abrupt halts and rather long delays in the "life lines" of key parameters of multiple systems. These events are usually very difficult to forecast. As a demonstrative example, we can mention serious problems of the Microsoft Corporation with the OS Windows Vista. This operating system has been developed under the assumption that the growth of the clock rate of PC processors described by nearly exact exponential curve (twice growth each ~18 months) during several decades could be extrapolated for the next few years. However, after reaching about 3 GHz, this characteristic suddenly stopped its growth, and now we mostly use the processors with virtually the same clock rate as it was 3-5 years ago. The "physical barrier" has been achieved instantly and manifested as a break point instead of expected "smooth" slowing the growth rate. As a result, the operating system optimized for 10-20 GHz did not satisfy most of customers having "slow" 2-3 GHz computers.

Second, sometimes the market seems not "to like" the improvements of the systems and does not accept the products with seemingly quite better characteristics. This situation can be considered as opposite to previous one. For example, it is easily possible to develop a locomotive with the speed of ~250 km/h able to be used in conventional railroads. These locomotives really exist and even are commercially used somewhere, e.g. on the route Moscow – St. Petersburg in Russia. However, the typical maximum speed of conventional locomotives is now nearly the same as it was half a century ago: somewhat about 120 km/h. Improvement of this characteristic is accepted by market only for the next generation of the railroad transport that uses other types of ways (Kynin, 2011). In this case, investments to a system did bring the expected technical result – but this result was not required by the infrastructure. This situation is known in the scientific world as "good enough".

Sometimes, however, the key parameters of a system which typical values did not change for long enough time (see above), suddenly start to grow again. Kynin (2011) considered several examples of this kind and concluded that such behavior can often be explained as a result of competition with a new system with potentially better characteristics.

The above-described kinds of behavior of the "life lines" seem not to be predictable by using the mentioned approaches that consider only a system itself, without its competitors and surroundings. Below we suggest a new approach that allows, at least theoretically, description of above-mentioned behavior of the "life lines". However, in the simplified model described below we consider only the "regular" case i.e. growing the main parameter of a system to some limit.

The idea of simulation is borrowed from chemical thermodynamics where any process is described in terms of current state, external conditions, target state, driving force and internal parameters ("order parameters"). Certainly, for an engineering system it is, in general, very difficult to apply this approach in its "pure" form because even if we define all required parameters of a considered system and all of its competitors it might be very difficult (if possible at all) to exactly determine their numeric values. However, there is a simulation that can quantitatively describe the behavior of complicated systems with big (or even infinite) number of "order parameters" under arbitrary external conditions. This is the simulation of structural and stress relaxation in in amorphous materials like glasses and polymers (Scherer, 1986).

Within the frames of this approach, the process in a system is described in terms of equilibrium and non-equilibrium states according to Le Chatelier's principle. The equilibrium state of a system is determined as a state having no tendency to change in time under given (constant) external conditions. Each particular combination of external conditions corresponds to one and only one equilibrium state of the system. In each particular equilibrium state, the system has constant characteristics (physical properties) that do not depend on the way of achieving it. Any change of the external conditions causes so-called relaxation process in the system that tends to come to new equilibrium state corresponding to new conditions. Multiple changes of the external conditions cause multiple responses, each of them being independent of all others (superposition of responses). Changes of multiple external conditions cause multiple responses independent of each other (superposition of excitations). Each relaxation process in the system is a linear combination of multiple "particular" relaxation processes, each of them being characterized by a single internal parameter of the system that determines the time scale of the process ("relaxation time"). Relaxation times of particular relaxation processes depend on a single integral characteristic that can be represented as a function of all internal parameters of the system (cooperative change of relaxation times). Each particular relaxation process is governed by its "driving force" determining the deviation from equilibrium state and relaxation time determining the rate ("speed") of coming to equilibrium.

2. Mathematical description of the model

2.1 Basic equations of the relaxation model

Mathematically, the model of structural relaxation can be represented as a system of the following equations:

$$\begin{cases} P = f_p(X, X_f) \cong P_0 + \alpha_f X + (\alpha_e - \alpha_f)\sum_{i=1}^{n} g_i (x_i - X); & (1) \\ X_f = \sum_{i=1}^{n} x_i g_i,\ \sum_{i=1}^{n} g_i = 1; & (2) \\ \frac{\partial x_i}{\partial t} = -\frac{X - x_i}{\tau_i}; & (3) \\ \tau_i = K_i \tau_0; & (4) \\ \tau_0 = f_\tau\left(X, \sum_{i=1}^{n} x_i g_i\right). & (5) \end{cases}$$

Here P is a characteristic (property) of the system to be measured. X is an external parameter which change (excitation) starts the relaxation process (response), and x_i are internal parameters (i is an index of a particular parameter corresponding to a particular relaxation process. n is the number of particular processes); g_i are "weight factors" of particular processes determining their contributions to the "macroscopic" state of system. t is time; τ_i are relaxation times of particular relaxation processes; τ_0 is mean ("weighted") relaxation time that can be considered as a macroscopic characteristic of the system. f_p and f_τ are some functions (in particular, they might be assumed the same that simplifies calculations). K_i are ratios of particular relaxation times to τ_0 (it is assumed that the K_i values are constants). α_e and α_f are constants determining (as a first approximation) the rate of change of the P value after very slow and very fast changing of X parameter correspondingly. In the first case, the system can be considered as approximately equilibrium, and in the second case as nearly "frozen" (that describes the indexes "e" and "f" near X).

In equilibrium state, $x_i = X$, $\partial x_i / \partial t = 0$ for all x_i, and, correspondingly, $X_f = X$; $\partial P / \partial t = 0$ for all P that means that the state and all measurable characteristics of the system are kept unchanged for unlimited time while the value of X is kept constant.

If the system is in equilibrium state and then at the moment $t=t_0$ the X value instantly changes from X_1 to X_2 and then is kept constant (i.e. $X = X_1$ at $t<t_0$; $X=X_2$ at $t \ge t_0$) the relaxation process in the system begins at t_0. According to Eq. (3) it is assumed that particular relaxation processes at constant values of X and τ_0 can be described by exponential equations:

$$x_i(t) = X_2 + (X_1 - X_2)\exp\left(-\frac{t - t_0}{\tau_i}\right). \quad (6)$$

Accordingly, the P value (i.e. the characteristic that we are interested in) changes as

$$P(t) = P_0 + \alpha_f X_2 + (\alpha_e - \alpha_f)\sum_{i=1}^{n} g_i (x_i - X_2) =$$

$$= P_0 + \alpha_f X_2 + (\alpha_e - \alpha_f)\sum_{i=1}^{n} g_i (X_1 - X_2)\exp\left(-\frac{t - t_0}{\tau_i}\right). \quad (7)$$

According to principle of superposition of responses, gradual change of X can be approximately presented as a series of "instant" changes and consequent time intervals where the X value remains unchanged. Thus, it is possible to calculate the value of P for any "profile" of changing of X with time by using numerical methods.

2.2 Relaxation model for engineering systems

Now let us try to find the equivalents of the parameters of structural relaxation model in the development of engineering systems. The general scheme of the considered factors is shown in Fig. 2. Here P is the main parameter of the system (to be predicted), and X value corresponds to the "equilibrium state" (the value that could completely satisfy the customers).

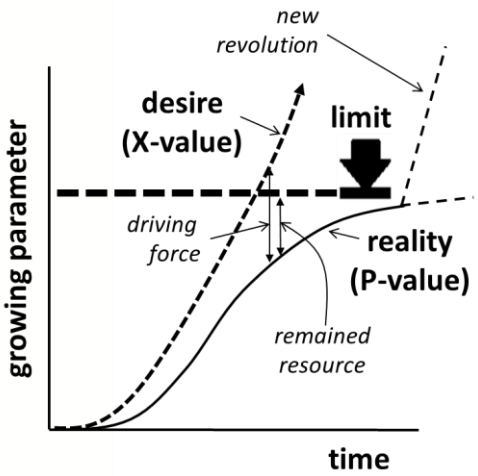


Fig. 2. Schematic view of factors considered by the model

We do not know exactly which characteristic can be considered as the main parameter for a given system. In terms of TRIZ, this characteristic can be presented as an analog of "ideality" that is determined as a ratio of "sum of profits" to "total cost" where the latter one includes cost and harmful side effects caused by the development, production, use and utilization of the system. It is also possible to consider the reciprocal characteristic: acceptable cost of a unit of the main parameter of the system. Thus, the X value can be represented as AC/MP or MP/AC where AC is Acceptable Cost and MP means the value of the Main Parameter of the system. For example, if the main parameter of a digital camera is its resolution (that was actual few years ago) then X value would be determined as acceptable cost of the resolution of 1 pixel of a picture, or as the number of pixels acceptable for 1 dollar of the cost of camera. It is also possible to use the logarithmic scale, namely:

$$P \equiv \log(MP / AC) = \log(MP) - \log(AC) . \quad (8)$$

To judge if this assumption is correct or not we need additional investigations. However, even without clarification of this or other choice, we can assume that *some external characteristic* plays the role of *X*-value. Thus, we can try to fit this value and its growth empirically without loss of generality of the model.

The sense of the "internal" parameters of the system (x_i) is most difficult to realize in the structural relaxation model. No exact meaning of these parameters exists. The structure relaxation model does not require ascribing exact sense to these parameters: it is quite satisfactory to determine them empirically as "something in the system".

Now let us focus at the relaxation times τ_i. These parameters determine the time required for decreasing the *F* value for *e* times ($e \cong 2.718$ is the base of natural logarithms) under the constant *X* value, i.e., in our case, increasing the main parameter of the system for *e* times. It is known that in some practical cases this value is approximately constant for rather long time. For example, for various characteristics of computers (clock rate of main processor, RAM memory size, typical capacity of the hard drive, etc.) this situation was observed during about half a century, from 1950th to the beginning of 2000th (the so called Moore's law); the typical τ values were about 2-4 years all this time. However, for particular engineering systems this characteristic is usually not constant and tends to increase with time. According to Leon (2006), exponential growth is only an extreme scenario of evolution that is normally observed only in the beginning of the system evolution. As far as the system comes nearer to its physical limit of growth, the "normal" relaxation time increases, with a tendency to infinity when this limit is achieved. So, let us suggest the simplest equation that describes this behavior:

$$\tau_i = \frac{K_i}{\log(X_{i,\max} / X_i)} = \frac{K_i}{\log X_{i,\max} - \log X_i} \quad (9)$$

where K_s is normally a constant for a given system, and X_{max} is the limit (or barrier) for the *X* value.

It is known however that big enough investments can greatly accelerate the progress of the system, i.e. to reduce the relaxation time τ_0. Let us implement a new term ω to Eq. (9) to consider the effect of investments:

$$\tau_i = \frac{K_i}{\left(\log X_{i,\max} - \log X_i\right)^{\omega}} . \quad (10)$$

The quantity ω should demonstrate the following behavior:

$$\begin{cases} \omega \approx 1 \text{ at no special investment;} \\ \omega \to 0 \text{ at maximum possible investment.} \end{cases}$$

This means that at normal investment we have "natural" growth curve (with decreasing the rate with time), and at maximal investment the growth rate is kept nearly constant, only slightly depending on the difference between *X* and X_{max}. The simplest expression having these properties is

$$\omega(t) = \frac{k_{\omega}}{\exp\left(dI / dt\right)} , \quad (11)$$

where dI/dt is the invest to the considered system per a unit of time, and k_ω is a constant. However, for short enough periods of time, we can neglect the time dependence of ω considering it as a constant for a given system.

Then we have to specify the expression for K_i. From very general consideration, we know that normally the rate of technical progress exponentially increases with time (Wikipedia, 2014). In terms of our model, it means that the values of K_i can be considered as functions of the total time starting from the first (working) appearance of the system:

$$K_i = \exp\left(-\frac{\Delta t_i}{K_s}\right), \tag{12}$$

where Δt_i is the time difference between the moments when the system itself and a given kind of this system appeared, and K_s is a constant for the system. For example, in a system with $K_s = 1$ year the relaxation time of each new "generations" will be diminished for e times every year.

3. Simplified model and its practical application

3.1. Simplification of the model

The above-described model is able (at least, in principle) to describe various complex scenarios of the development of Engineering Systems. For that, one needs to determine the parameters that describe the considered system itself, its competitors and the surroundings.

However, we consider it reasonable to start the verification of the model with the simplest (but important for practice) case of behavior: monotonic growth without halts as depicted in Fig. 2. We believe that if a model of some phenomena is correct then the simplest behavior should be properly described by the simplest case of the model. So, let us try to simplify the model in maximum possible extent and then try to apply it to the description and prediction of monotonic growth of the engineering systems.

The main simplification is to drop multiple relaxation processes off and to consider only one of them. This simplification turns the system of equations (1-5) to the following form (as far as we have only one relaxation process, the indexes i are also dropped):

$$\begin{cases} P = P_0 + \alpha_f X + (\alpha_e - \alpha_f)x; & (13) \\ \dfrac{\partial x}{\partial t} = -\dfrac{X - x}{\tau}; & (14) \\ \tau = \dfrac{K_s}{(\log x_{\max} - \log x)^{\omega}}. & (15) \end{cases}$$

Then let us consider the P value being the main parameter of the system, without its attribution to cost. This simplification is equivalent to the assumption that the cost of the unit of the main parameter changes much slower than this parameter itself.

Next, let us assume that $\alpha_f \ll \alpha_e$, i.e. that the changes of x-value in the "frozen" state are negligible. This assumption allows dropping the X-value from Eq. (13):

$$P = P_0 + \alpha_f x. \tag{16}$$

Correspondingly, the X-value becomes some external function that can be considered independently of other characteristics describing the system itself. We can assume that for the systems demonstrating similar behavior, the time dependences of X-values would also be similar. As far as we postulate this similarity, it becomes natural to reduce them to some universal "master curve". For that, we consider it reasonable to introduce some "reduced parameters" t_r and P_r instead of time t and growing parameter P:

$$t_r = (t - t_0) / K_s; \tag{17}$$

$$P_r = (P - P_0) / (P_{max} - P_0); \tag{18}$$

$$\tau_r = \tau / K_s, \tag{19}$$

where t_0 is the moment of time when the system was appeared, P_0 is the value of P-parameter at this moment, and P_{max} is the maximum value of P (i.e. the limit of the development).

Last, as far as we consider the P value proportional to x there is no more need to use the last value. We can rewrite all equations directly substituting P_r for x. After all mentioned substitutions we finally have:

$$\begin{cases} \dfrac{\partial P_r}{\partial t} = -\dfrac{X - P_r}{\tau_r}; & (20) \\ \tau_r = \dfrac{1}{(-\log P_r)^{\omega}}. & (21) \end{cases}$$

After reduction, the model can be presented as shown in Fig. 3.

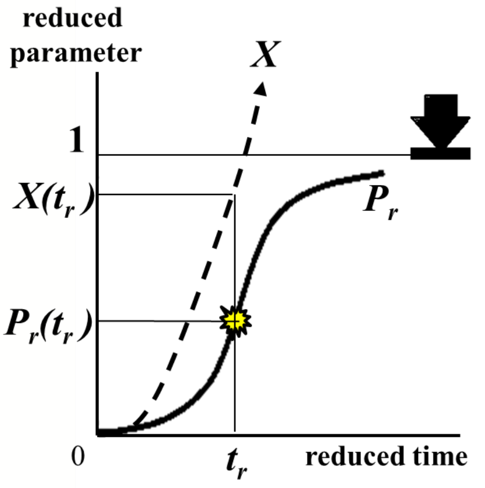


Fig. 3. Schematic view of the reduced model

The difference ($X - P_r$) corresponds to the "driving force" of the relaxation process, and the difference ($1 - P_r$) describes the remained resource of the main parameter's growth.

The S-shaped form of the curve calculated by the model is caused by the specific change of the derivative $\partial P_r/\partial t$ according to Eqs (20) and (21): both the numerator and denominator of Eq. (20) continuously grow with time but the growth curves are different as shown in Fig. 4.

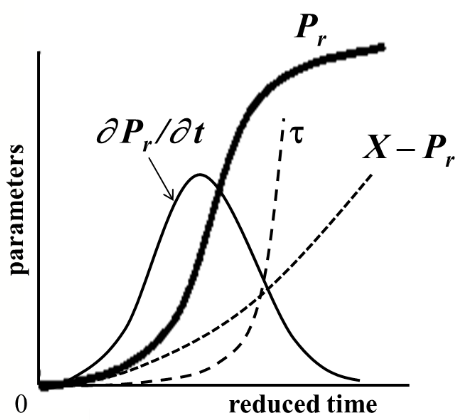


Fig. 4. Schematic explanation of S-shaped growth

Thus, we only need to determine the function $X = f(t_r)$ to be able to perform practical calculations.

After some trials, we came to conclusion that for most practical S-curves, one of the following two equations for X-function is applicable:

$$X(t_r) = t_r \quad \textbf{(22)}$$

or

$$X(t_r) = \exp(2t_r - 3.67). \quad \textbf{(23)}$$

The functions (22) and (23) describe the S-curves with fast and slow starting parts correspondingly.

The equations (17-23) allow calculation of the growth curve for an arbitrary growing variable P for which the following values are known:

- P_0 and P_{max}: minimum and maximum values (in practice, the P_0 value can often be considered as zero);
- t_0: moment of time when the considered system appeared;
- K_s and ω: parameters of the model;
- Kind of X-function: either (22) or (23).

Detailed description of the calculation algorithm is presented in the Appendix 1.

3.3. Data processing

When applying the model, three questions arise: (1) how to find the main parameter of the system, which is usually a complex parameter, i.e. some relationship of particular parameters of the system (Kynin, 2009). (2) how to determine the limit of growth P_{max} in advance, and (3) how to determine the model parameters K_s and ω.

Our approach determines the main (complex) parameter of the system (Priven, 2011 & 2012). Shortly, as far as we consider the main parameter as *something that customers are ready to pay for*, it is natural to expect significant positive correlation of this parameter with the total cost of the system. In a particular case when the major constituent of the total cost is the cost of the product, we can expect significant positive correlation between the values of the main parameter and the market prices of best-selling items. An example of such correlation for laser printers is presented in Fig.5. (We consider only mid-price range: for the cheapest printers the market price cannot be considered as a main constituent of the total cost whereas the most expensive printers are not in competition with considered ones.) Some other requirements to complex parameter are considered in Priven's work (2011).

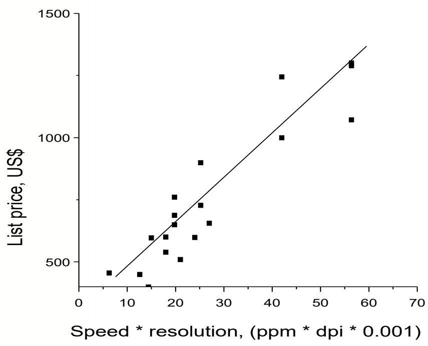


Fig. 5. Correlation between the main parameter of laser printers and market price (for the range from 400 to 1500$) of the best items according to five independent consumers' and experts' ratings (see refs in Priven, 2011 & 2012).

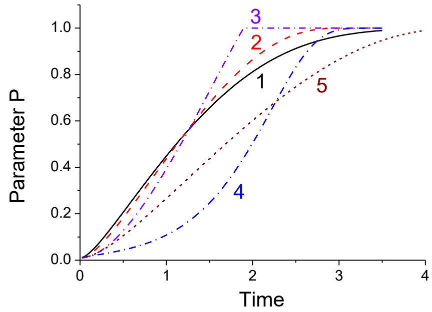


Fig. 6. Results of simulation by the suggested simplified model with different values of parameters:
1: $X = t$; ω = 1; 2: $X = t$; ω = 0.7; 3: $X = t$; ω = 0.1; 4: $X = \exp(-3.7 + 2\,t)$; ω = 1; 5: $X = t$; ω = 0.7. In all cases, we set $K_s = 1$, $\alpha_f = 0$; $\alpha_e = 1$; $x_{1,max} = 1$; $P_0 = 0$.

The limit of growth P_{max} can be determined in two ways: as one of the fitting parameters of the model or from some external reasoning, such as physical limits for a given operation principle. Detailed consideration of the problem requires a special publication. Shortly, as far as the model contains only two fitting parameters it is possible to add P_{max} as the third fitting parameter and find its value together with K_s and ω, e.g. by least square method.

After the complex parameter of the system is found and the parameters of the model are determined, it is possible to perform the calculations as described above.

3.4. Examples of practical application

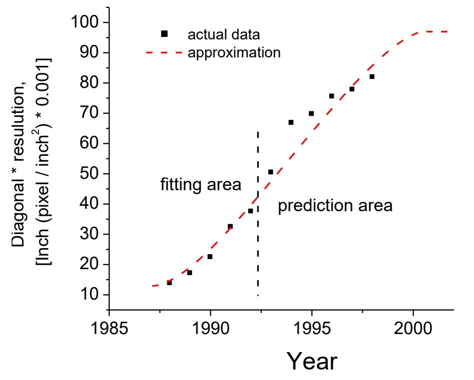
In Fig. 6, the results of numerical simulation with five combinations of parameters ω and $X = f(t)$ are presented. Below we consider some practical situations where the "life lines" have shapes of these curves.

From this picture, we can see that the model, even after drastic simplification, is able to describe various forms of the growth curves including such effects as diverse asymmetry, fast and low start, abrupt stopping the growth, etc.

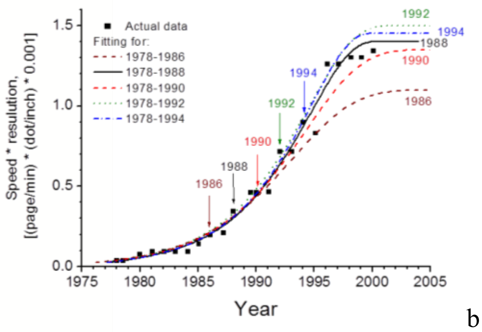
Below we demonstrate some examples of comparison of the model with factual data (Sood, 2005&2009, Tsao, 2004, Intel, 2011, Brodrick, 2013), the data shows the development several systems. The source data are presented in the Appendix 2.

In Fig. 7, growth curves of the key parameters of CRT monitors (product of diagonal size and resolution) and dot matrix printers (product of printing speed and resolution) are presented. These variables were selected as complex parameters describing the most important characteristics of corresponding systems, which are the Main Parameters of Value in terms of TRIZ (Efimov, 2011).

The considered systems were selected as far as their evolution is now virtually completed (they exist only in the narrow market niches), so that it is possible to overview the whole curves. However, for determination of the model parameters, we used only the starting (left) parts of both curves; the right parts were used for model validation. The value of P_{max} was considered in this case as a fitting parameter; in Fig. 7b, we demonstrate several variants of such fitting for several different starting segments of the curve. As we can see from the figure, the results of calculation (presented the Table 1 of the Appendix 2) are in good accordance with actual data.



a



b

Fig. 7. Growth of the key parameters of CRT monitors (a) and dot matrix printers (b) (Sood, 2009).

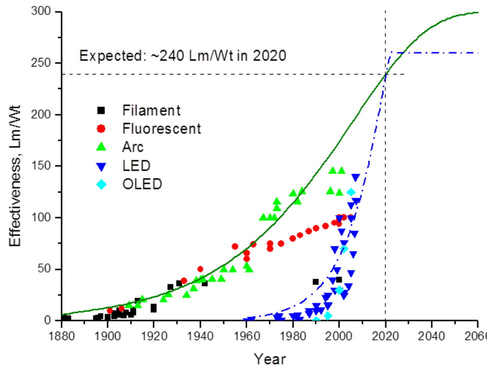


Fig. 8. Growth of the effectiveness of the electric lamps (Tsao, 2004)

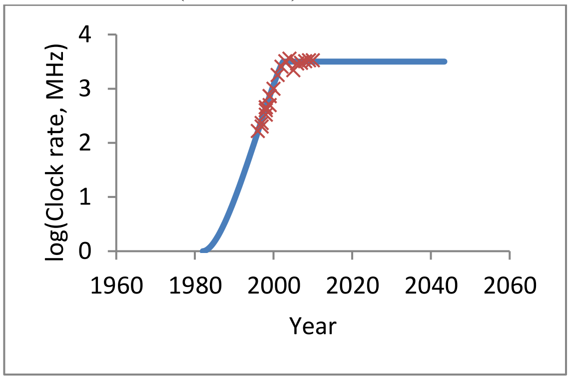


Fig. 9. Growth of the clock rate of personal computers (in semi-logarithmic scale) (Intel, 2011)

In Fig. 8, we made some prognosis for the growth of the effectiveness of the electric lamps.

Like previous picture, markers mean actual data and curves show the results of simulation. Judging from our modeling, we expect maximum effectiveness of lamps come to approximately 240 Lm/Wt in 2020.

3.4. Specific case: simulation of the "Moore's law"

In Fig. 9 we consider growing the clock rate of processors of personal computers (PC) starting from the appearance of Pentium processor. In this case, we used logarithmic scale that is only available for prediction in the case when a well-developed system continues huge growth. In this case, the model predicts abrupt stopping the growth. The exact value at which the growth is to be stopped is not predictable by the model; however, the model properly predicts that no "precursors" of such behavior occur (see above). The actual data are in good accordance with this prediction.

Let us describe this example in more detail. As it was stated above, this engineering system demonstrated exponential growth of their characteristics that is often called "the Moore's law" (Hutcheson, 2005):

$$\frac{dP}{dt} = k\ P;\ P \sim \exp(t - t_0)\,. \qquad (24)$$

Considering the fact that the average cost of personal computers very slightly changes with time (a contemporary notebook with middle characteristics costs nearly the same as PC XT twenty years ago), we can conclude that the "life line" shown in Fig. 5 can be applied to the acceptable cost as well. Let us remind that the P value in this case means the *logarithm* of the clock rate.

Such behavior can be simulated by the suggested model (again, with a single relaxation process) in the case when the relaxation time τ_0 and the term $(X - P_r)$ in Eq. (20) remains constant, regardless of the distance from the current P_r value to the limit ($P_{r,max} \equiv 1$). The latter feature corresponds to $\omega \cong 0$ in Eq. (21). This specific situation means that whatever the value of the main parameter of the system would be, the surroundings (customers, infrastructure, etc.) requires its further growth, regardless of the cost of its improvement. In fact, this situation is close to the struggle against a global threat when to survive is much more important than to save cost. Indeed, we can observe such situation in the history of wars.

However, the above-described situation can also be made artificially, without any external threat. For that, we only should assume that the system, for some reason, has unlimited resources. Now let us ask ourselves a question that is commonly used in so-called "failure analysis approach" (Kaplan, 1999) widely known in TRIZ: how to force the environment (i.e. human society including manufacturers, buyers, governments etc.) not to spare the resources for a system? As far as we formulate this question, the answer becomes obvious: somebody in the surroundings should get benefits that grow with growing the key parameter of a system. In essence, it means the positive feedback between the activity of the system and the environmental benefits; in other words, there must be a couple of synergists that amplify each other as a result of their activity.

If we consider development of personal computers from this viewpoint, we can easily find that the growth of the key parameters of computers really gets additional benefits to the computer industry, and the software developers play the role of synergists for hardware producers. Indeed, the more resources the hardware gives the more complicated – and more convenient – new software can be developed for this hardware. This stimulates the further growth of the characteristics of the hardware in turn. Realizing this situation, the software developers did the next step: they artificially stimulated hardware producers to increase the resources more and more to accelerate the "aging" of the software. This meant that the computer programs that essentially satisfy most of customers *do not work* in new computers because of the lack of resources. Thus, the customers who want to use the contemporary (the most convenient) software are forced to update the hardware, after which they need new version of the software in turn. Actually, the cost of the R&D in the computer industry ceased to play a role of the "bottleneck", i.e. the hardware developers had virtually "infinite" resources for improving the hardware.

If we now return to Eq. (21) above then we come to a conclusion that as far as the main parameter of a system approaches to its limit the base of the denominator of the right part of this equation tends to zero: $\left(\log P_{r,\max} - \log P_r\right) \to (\log 1 - \log 1) = 0$, and even small power index ω cannot prevent fast growth of the relaxation time τ. In other words, the growing process should be rapidly stopped near to the mentioned limit.

The Fig. 5 shows that this is exactly what we observe: the growth of the clock rate rapidly stopped near 3 GHz after exponential growing during more than 20 years.

4. Relaxation model and Synergetics

Now it is common knowledge that the evolution of self-developing systems can be described within the frames of synergetics. This branch of knowledge has been first developed by Ilia Prigogine and its coworkers. (Prigogine, 1969) The "synergetic" ideas are now widely used for descriptions of evolution in various kinds of natural and artificial systems. We believe that the basic concepts of the synergetic theory can be applied to the evolution of the engineering systems as well.

In this connection, we have to note that the structural relaxation model that we used as a base for the suggested model uses the concepts that are essentially similar to synergetics. Volkenstein (1956) & Mazurin (1986) mention the structural relaxation was considered within the frames of thermodynamics. From these works, one can conclude that the phenomenon of structural relaxation simulated by this model concerns essentially the same kind of behavior as synergetics does: thermodynamically non-equilibrium state.

In our previous paper (Priven, 1987), it was shown that under some external conditions the structural relaxation demonstrates the behavior which is similar to the synergetic systems: in particular, it becomes difficult to exactly predict because of appearance of positive feedback between excitation and response. In the present model, such positive feedback also can appear that we showed in the last example.

Above we showed that multiple features that can be observed in the "life lines" of real engineering systems can be easily simulated by using an essentially very simple model that is based on very common assumptions (such as superposition, equilibrium, relaxation, etc.). We believe that the further development of the model would help to describe and predict multiple features of behavior of engineering systems that are now very difficult to simulate and properly predict.

5. Conclusion

A new model of evolution of engineering systems is suggested on the base of a known model that describes the phenomenon of structural relaxation in amorphous physicochemical systems. This model uses the concepts of equilibrium and non-equilibrium states of a system, Le Chatelier's principle of tending of a system to equilibrium, multiple particular (elementary) processes impacting the "visible" results, superposition and cooperation of these processes.

The model is (at least, in principle) able to explain some specific behavior of engineering systems that has been observed in practice and (in our opinion) unlikely can be properly described within any of existing models and approaches taken one by one.

To compare the model predictions with actual data we considerably simplified the model. Although the simplified model cannot predict all possible cases of behavior of the growing system, it is considerably more flexible than the known simple models. At that, the simplified model contains only three fitting parameters. One of them is the maximum value of the growing variable that can be either used from external data or fitted as a model parameter. In the first case, the number of fitting parameters reduces to two that is the same as in the mentioned models. However, containing only two fitting parameters our models is able to properly describe and predict various cases of growth curves, including different asymmetry and different shapes of starting and ending parts. In particular, the model properly predicted the fact of abrupt stopping the growth of the clock rate of the processors of personal computers after long years of exponential growth, without any "precursors" of such behavior.

We believe that the suggested approach could be helpful for forecasting the evolution of engineering systems including specific cases which are difficult to explain and simulate by using the known approaches.

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APPENDIX 1: Algorithm of calculation

Step-by-step calculation

As mentioned above, the calculations are performed step by step. Each step consists of instant growth of X value followed by the relaxation process at which the internal parameter x (that was reduced to the P_r value) gradually comes to the equilibrium.

Our practice showed that the optimal value of the time step is

$\Delta t = 0.01\ K_s$,

which corresponds to the step of the t_r value equal to $\Delta t_r = 0.01$.

The calculation procedure consists of the following parts:

(1) We postulate some initial conditions;
(2) We make the first step by a simplified algorithm;
(3) We make the next steps by using normal algorithm;
(4) We exit calculations when the P value becomes close to saturation.

Below these parts are considered in more details.

Initial conditions

On start ($t = t_0$), we accept the following values of variables:

$t_r = 0$; $P_r = 0.0001$; $P = P_0 + 0.0001\ (P_{max} - P_0)$.

The value $P_r = 0.0001$ instead of 0 is accepted for simplicity of further calculations. This does not affect the final result as far as the error of calculation is anyway much greater than 0.01%.

First step of calculation

Below, the subscript "1" means that the corresponding values concern the end of the first step, i.e. the moment of time corresponding to $t_r = 0.01$; $t = t_0 + 0.01\ K_s$. At this moment, we have:

$t_{r,1} = 0.01$;
$P_{r,1} = 0.0001$;
$t_1 = t_0 + \Delta t = t_0 + 0.01\ K_s$;
$P_1 = P_0 + 0.0001(P_{max} - P_0)$.

Next steps of calculation

Below, the formulas for the next steps are presented. All values concern the end of the corresponding step of calculation; the number of step is specified as "i":

$X_i = X(t_{r,\ i-1})$;
$\tau_i = (-1/\ln P_{r,\ i-1})^{\omega}$;
$(dP_r/dt_r)_i = -(X_i - P_{r,\ i-1}) / \tau_i$;
$P_{r,i} = P_{r,\ i-1} + (dP_r/dt_r)_i\ \Delta t_r$;
$t_i = t_{i-1} + \Delta t = t_{i-1} + 0.01\ K_s$;
$P_i = P_0 + P_{r,i}\ (P_{max} - P_0)$.

Exit of calculation procedure

The calculations stop when the P_r value becomes greater than 0.99. This means that the growing variable came to 99% of saturation. Further calculations are surely senseless because of the model error.

APPENDIX 2: Source data tables

1. **Complex parameter of dot matrix printers: speed (page/min) * resolution (dpi) * 10-3**

Year	CP (actual)	Model
1977	-	0
1978	0.036	0.012
1979	0.037	0.017
1980	0.073	0.023
1982	0.092	0.045
1983	0.092	0.062
1984	0.092	0.085
1985	0.09	0.11
1986	0.14	0.15
1987	0.20	0.20
1988	0.21	0.26
1989	0.34	0.33
1990	0.46	0.41
1991	0.46	0.50
1992	0.46	0.60
1993	0.71	0.70
1994	0.71	0.81
1995	0.90	0.91
1996	0.83	1.01
1997	1.26	1.10
1998	1.26	1.17
1999	1.30	1.24
2000	1.30	1.30
2001	1.34	1.34

Data source: [15]

2. **Complex parameter of CRT monitors: diagonal (inch) * resolution (pixel/inch^2) * 10^{-3}**

Year	CP	Year	CP
1988	14	1994	67
1989	17	1995	70
1990	22	1996	76
1991	32	1997	78
1992	38	1998	82
1993	50		

Data source: [15]

3. **Maximum clock rate of Intel CPU for PC**

Year	F, MHz	Year	F, MHz
1971	0.108	1996	2000
1972	0.2	1997	300
1974	2	1998	450
1978	10	1999	1200
1979	8	2000	2000
1982	12	2001	3060
1985	32	2002	2530
1988	32	2003	3200
1989	50	2004	3600
1990	25	2005	2200
1991	33	2006	2930
1992	50	2007	3000
1993	200	2008	3200
1994	100	2009	3330
1995	200	2010	3330

Data source: [17]

4. Efficacy of electric lamps

Filament			Fluorescent			Arc		
Year	E, Lm/W	Ref.	Year	E, Lm/W	Ref.	Year	E, Lm/W	Ref.
1880	1.5	[2]	1901	10	[2]	1909	15	[25]
1880	2.3	[25]	1906	12	[2]	1913	15	[25]
1881	3.9	[25]	1933	39	[2]	1915	20	[25]
1883	2.5	[16]	1955	72	[2]	1924	20	[25]
1895	2.5	[2]	1960	60	[16]	1926	26	[25]
1896	3.1	[25]	1963	74	[2]	1934	25	[25]
1897	4.0	[2]	1970	70	[16]	1937	31	[25]
1897	4.7	[25]	1975	75	[24]	1938	39	[25]
1900	3.5	[16]	1980	80	[24]	1941	41	[25]
1903	4.7	[25]	1983	83	[24]	1945	41	[25]
1903	7.0	[2]	1987	87	[24]	1949	41	[25]
1903	5.5	[25]	1990	90	[24]	1950	50	[25]
1905	6.0	[2]	1994	92	[24]	1954	50	[25]
1905	10.0	[2]	1998	95	[24]	1960	53	[19]
1907	5.5	[25]	2000	98	[24]	1961	50	[25]
1908	7.8	[25]	2000	100	[16]	1967	100	[25]
1910	6.0	[16]	2005	100	[24]	1972	100	[25]
1911	7.8	[25]	OLED			1973	109	[25]
1911	10.0	[2]	1990	0.5	[24]	1973	116	[25]
1911	10.9	[25]	1995	5	[24]	1980	123	[19]
1913	19.5	[2]	2000	30	[24]	1982	116	[25]
1920	11.0	[16]	2002	70	[24]	1984	126	[25]
1927	32.5	[2]	2005	125	[24]	1996	126	[25]
1931	36.0	[2]				1997	145	[25]
1942	36.0	[2]				2001	145	[25]
LED								
Year	E, Lm/W	Ref.	Year	E, Lm/W	Ref.	Year	E, Lm/W	Ref.
1960	0.1	[16]	1990	10	[24]	2000	100	[16]
1961	0.4	[16]	1992	11	[16]	2001	87	[24]
1975	1	[16]	1994	23	[16]	2002	28	[24]
1982	1.8	[16]	1995	25	[24]	2004	34	[24]
1983	2	[24]	1995	15	[16]	2005	100	[24]
1983	2	[16]	1998	70	[24]	2005	47	[24]
1987	7.5	[24]	1998	30	[16]	2006	65	[24]

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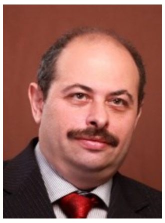

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TRIZ Supporting the Project Management Effectiveness

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Abstract

The project management (PM) techniques were created during the 1950s in the United States to increase the probability of success in large military projects and have been developed and applied in other areas since then. The Russian scientist Heinrich Altshuller and colleagues have been developing TRIZ (Theory of Inventive Problem Solving) since the 1940s to create a method to find innovative solutions for technical problems. In an organization already using a standard project management procedure to deliver quality projects but having still been missing the planned schedules in a higher rate than desirable, the TRIZ tools were used to improve those results. This paper shows how to apply a structured version of TRIZ to a typical PM procedure bringing innovative alternatives to solve the hidden contradiction that is how to accelerate projects without compromising the delivered systems quality. TRIZ supports the practitioner to go beyond the standard project risk analysis, offering innovative solutions focused not only on threats and opportunities but mainly on the contradiction elimination, increasing the probabilities of delivering projects in time and with quality.

Keywords: contradiction, effectiveness, inventive, problem solving, project management, TRIZ

1. Introduction

The Guide to the Project Management Body of Knowledge (PMBOK), organized by the Project Management Institute (PMI, 2013) is among the most effective standard procedures to plan and execute any kind of project. It covers several processes to manage a project, like scope, time, cost, human resource, quality, risk, communication, integration and so on. The guide is focused on delivering the planned scope with the specified quality in the time and costs proposed that is delivering projects with high efficacy. The reference scenario in this article considered there is a standard PM procedure based on the PMBOK and a team able to deliver the systems with the quality needed in an industrial environment. However, some projects have been running late in a higher rate than the desirable one. That is, despite a good PM maturity level has been achieved, there is an opportunity related to time and quality managements to explore, reason why an additional method was used. According to the Pulse of Profession Report (PMI, 2013), the best performing organizations (with high PM maturity level and training along the projects execution) have only reached limited percentage of successful projects among the completed ones: met the goals=66%, within budget= 62% and on schedule= 58%. For each project not reaching the goals in time there are opportunities not converted in value or problems not solved, draining value from any system. The reported limited achievement average percentages in time (58%) and quality (66%) are already enough to demonstrate the real importance of looking for additional support to improve the results.

Based on extensive analysis of a patents collection, the scientist Heinrich Altshuller and colleagues tried to identify a method for sustainable and innovative solutions related to technical problems, called TRIZ (Altshuller, 1999). With the political events in the former Soviet Union, part of the research group moved to Europe and USA spreading the TRIZ knowledge since 1990. TRIZ is based on the pursuit of ideality (higher availability of functions with the lowest resource use) and is supported on five conceptual pillars: contradictions, ideality, functionality, resources and time / space (Mann, 2010). As illustrated in Fig. 1, the method translates the "specific problem" in a more general manner ("a problem like mine"), enabling the use of solution patterns ("generic solutions") identified by Altshuller in similar problems. Among these generic solutions, the ones capable of solving the specific problem ("specific solution") will be selected, avoiding the usual trial and error and non-focused brainstorming approaches. TRIZ operates by identifying the contradiction associated with the problem under evaluation offering a shortcut to find alternative solutions in different knowledge areas than those immediately related to the problem (Silverstein, Decarlo and Slocum, 2008). For that purpose, one may use several available tools. Some of them are Identification of available resources, Thinking in Time and Space, Ideal Final Result, Contradiction Matrix & 40 Inventive Principles, Size-Time-Cost, Function Analysis, 76 Standard Solutions and the 8 Trends of Evolution.

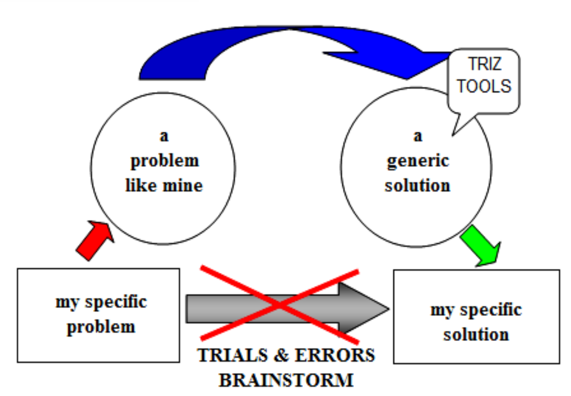

Fig. 1. TRIZ Basic Method (Mann, 2010)

Among the mentioned tools, the Matrix Contradictions is considered the first stage tool by the ease of use treating the technical contradictions (when one tries to improve a feature, there is a second independent feature/parameter that gets worse). Therefore, at least two features (the one we need to improve and the one getting worse with our attempt to improve the first) express each identified technical contradiction. According to Altshuller´s research (1999), for each combination, a number of suggested inventive principles that have already solved the same contradiction in other fields of knowledge are available. The traditional list contains 39 parameters and 40 inventive principles combined in a matrix. Originally focused on technical issues, the use of TRIZ also expanded to the management area. Through additional research, Darrell Mann has developed a similar matrix focused on managerial issues, the Business Contradiction Matrix (Mann, 2009), which we will use in this paper. To enrich the proposed alternatives, additional TRIZ tools will be used. The whole group has been integrated to facilitate the use by beginners (Fig. 3). Although there are other different integrated views, the applied approach was based on the proposals by Mann (2010) and Gadd (2011).

The link between the PMBOK and TRIZ has already been considered through the risk management process. Such a process includes the analysis to identify potential threats and opportunities, generating preventive actions to improve the probability of success for the projects (Wideman, 1992; Smith and Merit; PMI, 2013). Some of the TRIZ tools have been proposed to be applied directly to the project risk management trying to modify and boost this specific process (Barsano, 2008). In this article, the TRIZ tools were used in a different way, focusing on an existing PM procedure facing a specific problem related to projects delays. The several tools were taken as an additional support to the PM procedure, searching for new solutions, always based on the schedule's perspective. In that sense, the TRIZ tools were used in a reactive mode not intending to modify the risk management process but trying to eliminate the speed x quality contradiction. They add a specific solutions package to the PM procedure to treat an existing schedule problem. If incorporated to the PM procedure, such a package may be used in a preventive way on future individual projects, reinforcing the standard risk management to search for improvement in the success rates in time and quality. Considering the limited success rates reported in the Pulse of Profession Report (PMI, 2013), the TRIZ tools might be used in other projects environments like a support to the PM procedure to eliminate the hidden contradictions that keep organizations with lower achievements.

It is relevant to mention that one of the key attractiveness for using TRIZ on such a delicate situation is the basic concept associated to this method in which no compromise will be accepted to solve the problem. That is, the hidden conflict is identified and it guides the search for inventive solutions.

2. Context

The project management current practice applies most of the processes in the Guide to the Project Management Body of Knowledge (PMI, 2013) and has progressive decision stages (Fig. 2). In the first stages until the Filter 3, alternatives are evaluated with the selection of one of them to move forward to the detailing in order to support the final decision. At Filter 3, with no doubts left and all data available, the decision to implement the project until the delivery and results review it is confirmed.

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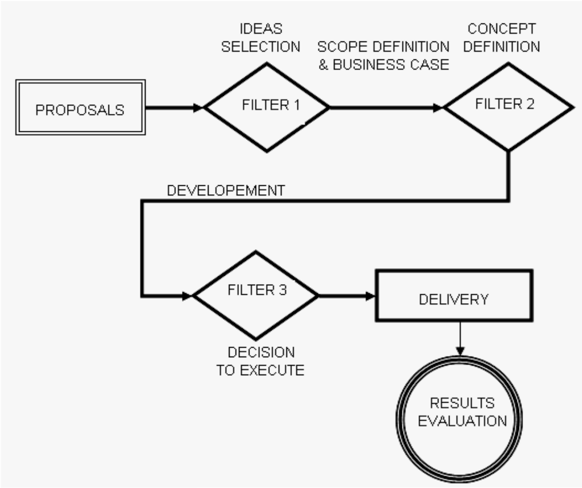

Fig. 2 Simplified Summary of Current Practice

Theoretically, the higher the effort applied to the stages before Filter 3, the higher likelihood of a good quality result. However, getting deeper in these first stages consumes financial resources and mainly takes time, exposing the basic contradiction through the TRIZ lenses: how to speed up the whole project while maintaining the desired final quality?

In that context, the TRIZ tools are not applied to the projects individually but only once to the PM current procedure and to the environment in which the projects are managed. They allow identifying harms and opportunities related to the mentioned conflict. The most effective proposed reactions/solutions should be incorporated to the PM procedure as support for all future projects in that environment.

3. Development

Regarding the TRIZ application to the PM procedure and its managing environment, it will be used the integrated sequence in Fig. 3 (adapted from Gadd, 2011 & Mann, 2010) that illustrates the problem definition and the progressive use of several TRIZ tools.

The workflow in Fig. 3 is divided in convergent and divergent stages, according to their nature, broadening the evaluation and generating alternatives or focusing and selecting the best ones. The whole flow starts with listing all preliminary ideas (first to come, with no critics) to solve the identified problem. It consists of four steps:

a. Define the problem (the real situation)

The real situation is checked using the six critical questions (What is the problem? Why is there such a situation? Why is it a problem? Why is it necessary to solve it? What do we really want-What is our ideal? What is holding us to solve the problem?). The context is expressed in the time and space diagram (9 boxes). A map of the available resources is prepared (9 boxes). The ideal outcome is clearly defined (What do we really want?). The gap between the real and the ideal situations is explored. A first evaluation of the preliminary ideas can be performed to identify harmful aspects. The function analysis can be performed in this stage or after the contradiction identification, as considered in this article.

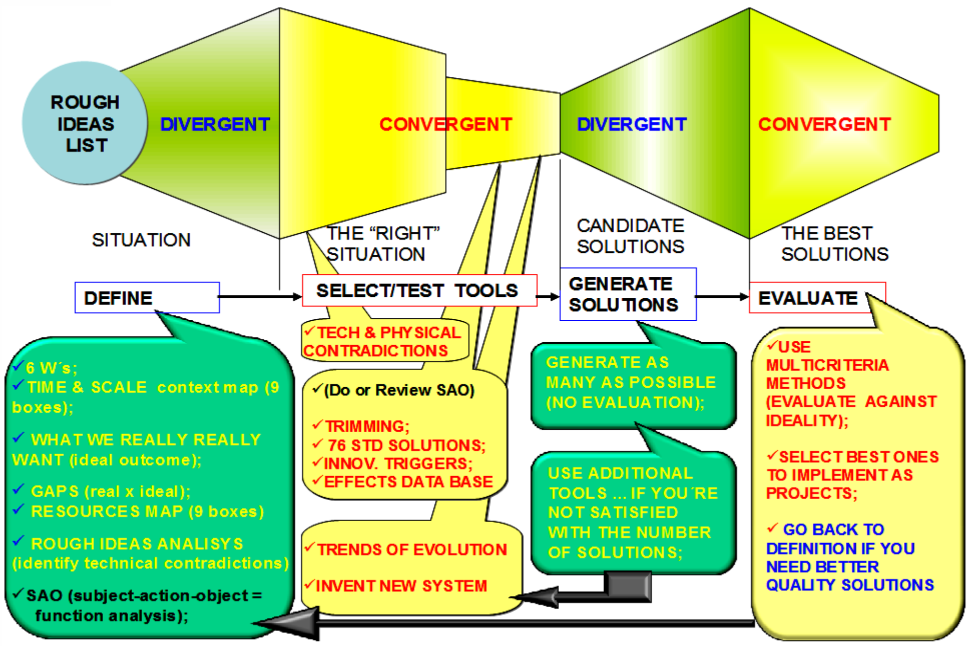

Fig. 3 TRIZ Integrated Workflow

b. Select tools to use (the right situation)

This stage is divided in other two parts. The first is the basic one in which the basic tools can be applied (contradictions). The second one must follow the function analysis and will enable additional tools, if the practitioner thinks they are necessary. The tools application starts by the technical contradiction identification and treatment with the inventive principles. The physical contradiction identification and treatment is done in the sequence, completing the first part. The function analysis and the subject-action-object list can be prepared now. With the analysis completed, the trimming and 76 standard solutions can be applied. Additionally, the innovative triggers (X-Factor; Life and Death analogies; Smart Little People; Time-Size-Cost; Subversion), the effect database and the trends of evolution may be tested. Inventing new systems is only used in specific cases.

c. Generate solutions (candidate ones)

Using the selected tools, all possible candidate solutions are generated.

d. Evaluate solutions (the best ones)

Those solutions that fit the better to the ideality criteria are selected (multi-criteria selection to support the decision-making). The criteria and their weights can be adjusted to the user's need.

This cycle can be repeated, if necessary, and establishes a way for anyone (or any organization) to contribute systematically to solve complex problems and to develop new products and systems (develop anything through identifying and breaking its hidden contradictions). How deep one should go to find alternative solutions will certainly depend on the type of problem being treated and on the practitioner needs. More than that, Fig. 3 shows a big picture of the available tools and a suggested workflow that helps TRIZ beginners to find their own way and gain confidence in the method.

4. Applying the TRIZ workflow to the problem

The TRIZ tools were applied treating the problem as any other but using the business & management adaptation (Mann, 2009). The workflow itself is a structure adapted from two authors' contribution in their published books and papers (Gadd, 2011 and Mann, 2009). For the case under focus, there are two main groups of processes: the development of information and details until the authorization to execute and the execution itself. The solution proposals were generated covering both groups.

4.1 Preliminary Ideas (spontaneous)

10 solution proposals were listed.

INCREASE THE PROJECT MANAGERS TEAM
INCREASE THE FIELD SUPERVISING TEAM
HAVE 2 ASSEMBLY CONTRACTORS AVAILABLE
HAVE 2 CIVIL CONSTRUCTION CONTRACTORS AVAILABLE
INCREASE THE PROJECT ENGINEERS TEAM
HAVE AN ENGINEERING DESIGN CONTRACTOR NEAR THE PLANT
PERFORM THE PRELIMINARY SCHEDULE RISK ANALYSIS & SIMULATION
HAVE A BUYERS TEAM DEDICATED TO THE PROJECTS
HAVE A SCAFFOLDING CONTRACTOR DEDICATED TO THE PROJECTS
HAVE A SAFETY TECHNICIAN SUPPORTING ALL WORK PERMITS TO PROJECTS

Fig. 4 Preliminary Ideas List

4.2 Definition

-Description of the problem

Projects are delivered late against the planned finish date, causing potential additional costs and delays in the expected results. When trying to accelerate the execution there is a risk to lose quality.

(As the problem and its consequences were completely clear, the 6W´s were not detailed)

-Main desired result

Systems are delivered early or on schedule and with the desired quality and specifications demanded by customers.

-Ideal Final Result (what they really want)

Critical (must have)
-Finish projects in the planned month
-Get the procurement activities done as scheduled
-Have effective field supervision during execution
-Have effective frame contracts
-List of pre-approved suppliers
-Work permits released until 9 AM daily
-Effective continuous work permits
-Costs fully managed and controlled.

Desirable (nice to have)
-Have a schedule risk simulation done before the project approval
-Have certified project managers
-Dedicated procurement team
-Scaffolding contract dedicated to the projects
-Do not depend on a single engineering support contractor

-Have at least one engineering support contractor near the plant

-Do not depend on a single assembly contractor

-Do not depend on a single civil construction contractor.

-Problem Context Map

The Fig. 5 shows a typical 9 boxes diagram with the problem context.

TIME	-2 YEARS	TODAY	+2 YEARS
ENVIRONMENT / CONTEXT	PROCUREMENT TEAM NOT STRUCTURED	STRUCTURED PROCUREMENT TEAM	PROCUREMENT TEAM DEDICATED TO PROJECTS
	CONTRACTS EXTREMELY SLOW	TIME TO SIGN THE CONTRACTS STILL TOO LONG	STANDARD CONTRACTS PRE APPROVED BY LEGAL TEAM
	MANY CRITICAL TASKS DEPENDING ON PROCUREMENT AND LEGAL TEAMS	MANY CRITICAL TASKS DEPENDING ON PROCUREMENT AND LEGAL TEAMS	NO DELAY DUE TO PROCUREMENT AND LEGAL TASKS
	NO FRAME CONTRACTS AVAILABLE	PRESSURE TO REDUCE COSTS LEAD TO NOT WELL STRUCTURED SUPPLIERS	FRAME CONTRACTS WITH GOOD QUALITY SUPPLIERS
	CAPEX MANGT PROCEDURE UNDER TRAINING	CAPEX MANGT PROCEDURE STILL NEEDS SUPPORT	CAPEX MANGT PROCEDURE COMPLETELY UNDER USE
	NO SCAFFOLDING CONTRACT	SCAFFOLDING CONTRACTOR NOT ABLE TO SUPPORT ALL DEMANDS	SCAFFOLDING CONTRACT SPECIFIED TO SUPPORT THE PROJECTS
	MAXIMUM PRIORITY FOR SAFETY NOT CLEAR	HIGH PRIORITY TO SAFETY	TOTAL PRIORITY TO SAFETY
PROBLEM		PROJECTS ARE DELIVERED WITH DELAY AGAINST THE PLANNED DATE	
	SCHEDULES NOT PROPERLY PREPARED	LOW SKILL TO DEAL WITH SCHEDULES	MS PROJECT SW FULLY APPLIED
	NO RISK ANALYSIS / SIMULATION FOR THE SCHEDULE	NO QUANTITATIVE SIMULATION FOR THE SCHEDULE	USING RISK SIMULATION FOR THE BIGGER PROJECTS
	TECHNICAL SPECIALISTS MANAGING PROJECTS	TECHNICAL SPECIALISTS MANAGING PROJECTS	HIGHER NUMBER OF SKILLED PROJECT MANAGERS
	WORK PERMITS TAKE TOO LONG TO BE ISSUED	WORK PERMITS TAKE TOO LONG TO BE ISSUED	QUICK WORK PERMITS OR CONTINUOUS WP
RESOURSES/PEOPLE	PROJECT TEAM WITH DIFFERENT SKILL LEVELS IN THE CAPEX PROCEDURES	PROJECT TEAM TRAINED IN THE CAPEX PROCEDURES	PROJECT TEAM FULLY SKILLED IN THE CAPEX PROCEDURES
	REDUCED PROJECT TEAM	BIGGER PROJECT TEAM BUT STILL BASED ON THE TECHNICAL SPECIALISTS	PROJECT TEAM INCLUDING MORE PROJECT MANAGERS
	HIGH NUMBER OF NOT SKILLED CONTRACTOR PROJECT MANAGERS	NOT SKILLED CONTRACTOR PM STILL PRESENT	SKILLED PROJECT MANAGERS TEAM
	HIGH NUMBER OF THIRD PARTY PROFESSIONALS	LOW NUMBER OF OWNER COMPANY PROFESSIONALS	PM TEAM ONLY BY THE OWNER COMPANY

Fig. 5 Context Map - The problem discussed in time and space (9 boxes diagram)

-Problem Resources Map

Fig. 6 shows the typical 9 boxes diagram with the identified available resources in time and space.

	TIME -2 YEARS	TODAY	+2 YEARS
ENVIRONMENT/ CONTEXT	NO ASSEMBLY FRAME CONTRACT	ASSEMBLY FRAME CONTRACT AVAILABLE	2 ASSEMBLY CONTRACTORS AVAILABLE
	NO CIVIL CONSTRUCTION FRAME CONTRACT	CIVIL CONSTRUCTION FRAME CONTRACT AVAILABLE	2 CIVIL CONSTRUCTION CONTRACTORS AVAILABLE
	SCAFFOLDING CONTRACT SUPPORTING MAINTENANCE AND PROJECTS	SCAFFOLDING CONTRACT SUPPORTING MAINTENANCE AND PROJECTS	SCAFFOLDING CONTRACT SPECIFIED FOR PROJECTS
	SMALL PROCUREMENT TEAM	PROCUREMENT TEAM NEAR THE PROJECTS TEAM	PROCUREMENT TEAM INTEGRATED TO THE PROJECTS TEAM
	NO LEGAL CONTRACT SUPPORT	LEGAL SUPPORT NEAR THE PROJECTS TEAM	LEGAL SUPPORT INTEGRATED TO THE PROJECTS TEAM
	REDUCED FIELD SUPERVISING	FIELD SUPERVISING PROVIDED BY THIRD PARTY	FIELD SUPERVISING COORDINATED BY OWNER PROFESSIONAL
	ONLY 1 CONTRACT FOR ENGINEERING EXTERNAL SUPPORT	ONLY 1 CONTRACT FOR ENGINEERING EXTERNAL SUPPORT	ADDITIONAL CONTRACT WITH A LOCAL ENG. CONTRACTOR
PROBLEM		PROJECTS ARE DELIVERED WITH DELAY AGAINST THE PLANNED DATE	
	MANY PROJECTS WITHOUT SCHEDULE	SCHEDULES ON THE MS PROJECT	SCHEDULES ON THE MS PROJECT
	NO PLANNING PROFESSIONAL	SPECIALIZED THIRD PARTY PLANNER	PLANNER INTEGRATED TO THE PROJECT TEAM AND PERFORMING THE RISK ANALYSIS
RESOURCES/ PEOPLE	JUST A FEW PROJECT MANAGERS BY THE OWNER	NEW PROJECTS MANAGERS BY THE OWNER	OWNER PROJECT MANAGERS FULLY SKILLED WITH INTERNAL PROCEDURES
		THIRD PARTY PROJECT MANAGERS	NO THIRD PARTY PROJECT MANAGERS
	ENGINEERING SUPPORT CONTRACTOR FROM ANOTHER STATE	ENGINEERING SUPPORT CONTRACTOR FROM ANOTHER STATE	MAIN ENG. SUPPORT CONTRACTOR AT THE SAME CITY
	TECHNICAL SPECIALISTS AVAILABLE	TECHNICAL SPECIALISTS AVAILABLE	ADDITIONAL SAFETY SPECIALIST INCLUDED IN THE PROJECTS TEAM
	O SW FOR SCHEDULES RISK SIMULATION	SW FOR SCHEDULE RISK SIMULATION AVAILABLE	SW FOR SCHEDULE RISK SIMULATION FULLY USEFUL BY THE PLANNER AND THE PROJECT TEAM
	NO SCHEDULE STANDARD	SCHEDULE STANDARD IN USE	MILESTONE PROPERLY USED IN THE SCHEDULES
	NO CAPEX PROCEDURE INTERNAL AUDIT	SEVERAL AUDIT RECOMMENDATIONS TO IMPROVE	AUDIT RECOMMENDATIONS DONE

Fig. 6 Resources Map - Available resources examined considering time and space. (9 boxes diagram)

As the present situation and the ideal one were already clear, the ideality audit (real x ideal) was not detailed.

4.3 TRIZ Tools Selection

As it comes to managerial situations with easily identifiable contradiction, it was used the Business Matrix Contradictions (Mann, 2009) and the adapted inventive principles to treat them. For more alternative proposals, one should identify the associated physical contradiction (to get the desired result we need a variable that has simultaneous contrary behaviors, for example, the temperature should be high and low, the system must be fast and slow at the same time).

-Identifying the "Technical Contradiction”
Improving feature: speed of projects execution
Adapted TRIZ parameter: Production Time.

Worsening feature: quality, cost and risk of the final system

Adapted TRIZ parameters: specification of production, costs of production, production risk.

In Fig. 7, we can see a section of the business contradiction matrix indicating the suggested inventive principles (arrows intersection = green painted cells).

BUSINESS MATRIX — Improving Parameter → / Worsening Parameter ↓	5 R&D Interfaces	6 Production Spec/ Capability/ Means	7 Production Cost	8 Production Time	9 Production Risk	10 Production Interfaces	11 Supply Spec/ Capability/ Means
Worsening Parameter	5	6	7	8	9	10	11
4 R&D Risk	6; 29; 15; 14; 17; 25	24; 35; 10; 3; 13; 11	5; 35; 40; 23; 1; 12	5; 40; 20; 15	11; 23; 39; 7; 9; 33	7; 3; 17; 23; 24	5; 35; 13; 26; 6
5 R&D Interfaces	5 see physical contrad.	5; 6; 17; 40; 33; 10; 26	15; 23; 29; 5; 13	15; 40; 23; 3; 24; 13	7; 5; 3; 37; 10	28; 40; 6; 29; 13; 31; 30	6; 35; 15; 13; 14
6 Production Spec/ Capability/ Means	5; 6; 17; 40; 33; 10; 26	6 see physical contrad.	15; 25; 3; 10; 5; 8	**1; 35; 21; 15; 4; 10**	6; 27; 35; 22; 12; 37	3; 25; 17; 35; 12	7; 13; 22; 6; 35
7 Production Cost	15; 23; 29; 5; 13	15; 25; 3; 10; 5; 8	7 see physical contrad.	**1; 24; 19; 10; 27; 3; 14**	26; 10; 1; 3; 25; 12	26; 1; 37; 25; 2; 28	5; 2; 30; 35; 17; 8; 25
8 Production Time	15; 40; 23; 3; 24; 13	1; 35; 21; 15; 4; 10	1; 24; 19; 10; 27; 3; 14	8 see physical contrad.	10; 27; 15; 6; 3; 22; 29	10; 15; 38; 20; 27; 6; 3	5; 17; 16; 3; 10
9 Production Risk	7; 5; 3; 37; 10	6; 27; 35; 22; 12; 37	26; 10; 1; 3; 25; 12	**10; 27; 15; 6; 3; 22; 29**	9 see physical contrad.	5; 6; 23; 20; 7; 10; 25	5; 25; 3; 35; 2; 10
10 Production Interfaces	28;40; 6; 29; 13; 31; 30	3; 25; 17; 35; 12; 13	26; 1; 37; 25; 2; 28	10; 15; 38; 20; 27; 6; 3	5; 6; 23; 20; 7; 10; 25	10 see physical contrad.	6; 2; 37;40; 10

Fig. 7 Business Contradiction Matrix –suggested inventive principles (Mann, 2009)

The meaning of the suggested inventive principles can be seen in Fig. 8. *Additional Principles suggested by Darrel Mann (Mann, 2009). The focus on the problem through each of the suggested inventive principles, one at a time, led the solution proposals generation. # 52 (fifty-two) solution proposals were listed based on the Contradictions Matrix, as shown in Fig. 9. (See section 6 for comments on using the selected best proposals).

IMPROVING	WORSENING	INVENTIVE PRINCIPLES				
PRODUCTION TIME	PRODUCTION SPECIFICATION	1= SEGMENTATION	35= PARAMETERS CHANGE	21= HURRYING	4= ASYMMETRY	10= PRIOR ACTION
PRODUCTION TIME	PRODUCTION COST	24= INTERMEDIARY	19= PERIODIC ACTION	27= CHEAP DISPOSABLE	3= LOCAL QUALITY	14= CURVATURE
PRODUCTION TIME	PRODUCTION RISK	15= DYNAMIZATION	6= UNIVERSALITY	22= BLESSING IN DISGUISE	29= FLUIDITY	
PRODUCTION TIME	ALWAYS USED *	5= MERGING	25= SELF SERVICE			
PRODUCTION TIME	OTHERS TO CHECK *	13= THE OTHER WAY ROUND	2= TAKING OUT / SEPARATION			

Fig. 8 Inventive principles suggested by the Matrix

TECH	ASSEMBLING TEAM PARTICIPATES IN THE PROJECT DEFINITIONS
TECH	CONSTRUCTION COORDINATION WITH AUTONOMY
TECH	CUSTOMERS AND ASSEMBLING CONTRACTORS MUST BE HEARD IN THE PROJECT DEFINITIONS
TECH	USE FLEXIBLE DAILY TIME SCHEDULE FOR ASSEMBLING SERVICE
TECH	USE STANDARD DOCUMENTATION
TECH	USE A CELL BASE STRUCTURE FOR PROCUREMENT AND ASSEMBLING
TECH	PREPLANNING OF THE ASSEMBLING SERVICE
TECH	START ADVANCED QUOTING WITH POSSIBLE SUPPLIERS BEFORE FINAL PROJECT AUTHORIZATION
TECH	CUSTOMER AND HSEQ MUST BE HEARD DURING THE ASSEMBLING
TECH	INCREASE THE SYSTEM FINAL USER PARTICIPATION IN THE INTERFACE WITH ENGINEERING
TECH	CELL BASED EXECUTION (PROCUREMENT, ASSEMBLING, CONSTRUCTION) FOR EACH CUSTOMER AREA
TECH	CREATE A TASK FORCE FOR EXPRESS EXECUTION (PROCUREMENT & ASSEMBLING)
TECH	CREATE TASK FORCES TO QUICK RESPONSES TO SMALL PROBLEMS
TECH	USE THE MORE EXPERIENCE PROFESSIONALS TO SUPPORT ALL PROJECTS CONCEPTS
TECH	USE STANDARD SOLUTIONS FOR TYPICAL PROJECTS
TECH	USE ASSOCIATION OF MATERIALS AND SERVICE SUPPLIERS
TECH	PROJECTS MEETING SCHEDULES MUST BE ADJUSTED TO THE PROJECT COMPLEXITY
TECH	INCLUDE MATERIALS IN THE ASSEMBLING AND CONSTRUCTION CONTRACTS
TECH	PERFORM CRITICAL TASKS IN ADVANCE
TECH	QUICK ANSWER TO ANY CUSTOMER COMPLAINING
TECH	USE ONLY PRE EVALUATED MATERIALS SUPPLIER
TECH	USE REFERENCE PRICES ACCORDING TO MARKET VALUES
TECH	MONTHLY FEEDBACK FOR PROJECT TEAMS AND CONTRACTORS
TECH	USE A ASSEMBLING/CONSTRUCTION SUPPLIERS ASSOCIATION
TECH	ELIMINATE ALL BARRIERS BETWEEN ENG AND THE INTERNAL CUSTOMERS
TECH	COMBINE EXPERIENCED AND NEW PROFESSIONALS IN THE PROJECT TEAMS
TECH	SMALL ASSEMBLIES COORDINATED DIRECTLY BY CUSTOMER TEAM
TECH	ALLOW SUBCONTRACTING TO OTHER ASSEMBLING CONSTRUCTION COMPANIES WITH SAME EXPERIENCE (LOCAL CONSTRUCTION POOL)
TECH	HAVE ALL CONSTRUCTIONS IN ONE SINGLE CONTRACT
TECH	ESTABLISH 30% PAYMENT WITH PO APPROVAL AND THE REST ONLY AGAINST THE FINAL DELIVERY
TECH	REINFORCE THE CONSTRUCTION TEAM WITH THIRD PARTY SUPERVISORS
TECH	PERFORM SEVERAL ASSEMBLING/CONSTRUCTION SIMULTANEOUSLY
TECH	CONTRACT SPECIALIZED COMPANY FOR CONSTRUCTION MANAGEMENT
TECH	INTRODUCE PERIODIC CONTRACT REVIEWS
TECH	INTRODUCE PERIODIC PERFORMANCE REVIEWS IN THE CONTRACTS
TECH	RETURN RETIRED PROFESSIONALS WITH CRITICAL KNOWLEDGE
TECH	USE FLOATING LIMIT DELIVERY DATE AS FUNCTION OF UNEXPECTED FUTURE EVENTS
TECH	SEGREGATE SMALL GROUP FOR DIRECT SMALL ASSEMBLING (ONLY SAFETY REVIEWS AND DOCS AS BUILT)
TECH	BE OPENED TO PROVOCATIONS = NEW IDEAS
TECH	USE WBS WITH MATERIALS/EQUIP AND SERVICES FOR BIGGER PROJECTS
TECH	USE INTRANET FOR PROJECTS COMMUNICATION
TECH	TAKE THE QUICKEST WAY TO THE INTERNAL CUSTOMER AVOIDING TOO MUCH BUROCRACY
TECH	ESTABLISH NEW MEETING ROOMS
TECH	PROJECT TEAM MUST ADJUSTED QUICKLY
TECH	REDIRECT PERSONAL ATTACKS TO THE PROBLEMS
TECH	ACCELERATE FAILURE TO ACCELERATE CORRECTIONS
TECH	USE DISPOSABLE MATERIALS IN THE ASSEMBLING AND CONSTRUCTIONS
TECH	BLAME THE PROCESS NOT THE PROFESSIONALS
TECH	ELIMINATE THE FEAR
TECH	ELIMINATE CHANGES FEAR WITH THE COMPETITION FEAR
TECH	USE MATERIALS SUPPLYING JUST IN TIME
TECH	REDUCE LONG TERM CONTRACT PRICES USING THE PREFERENCE OPTION CLAUSES

Fig. 9 Solution proposals using the Contradiction Matrix

-Identifying the "Physical" Contradiction

To ensure quality is necessary to go deeper in the details, reducing the overall speed. To guarantee the finish date, the speed must be high. We need to be fast and slow, showing a physical contradiction. To address this radical contradiction, the separation principles must be used according to the nature of the situation (in time, in space, condition or in scale).

-Separation type selected

The separation by scale was selected since the separations based on time, in space and on condition were not applicable to this situation. That is, the situation requires high and low speed at the same time, in the same location/space and in any condition. Fig. 10 shows the suggested inventive principles available, excluding the ones already used before. The suggested inventive principles led the search for additional solution proposals.

#14 (fourteen) solution proposals based on the physical contradiction were listed as shown in Fig. 11. (See section 6 for comments on using the selected best proposals).

FAST x SLOW	INVENTIVE PRINCIPLES (SEPARATION BY SCALE)				
SCALE- SUPERSYSTEM	6= UNIVERSALITY	12= EQUIPOTENTIALITY (REMOVE TENSION)	33= HOMOGENEITY	40= COMPOSITE MATERIALS	ALREADY USED
SCALE- SUBSYSTEM	ALREADY USED				
SCALE- INVERSE SYSTEM	ALREADY USED				
SCALE- ALTERNATIVE SYSTEM	8= ANTI WEIGHT	ALREADY USED			

Fig. 10 Inventive Principles suggested – Physical Contradiction

PHY	PROJECT AND PROCUREMENT TEAMS FULLY INTEGRATED
PHY	SELECT AND USE A MORE EXPERIENCED TEAM TO SUPPORT THE PROJECTS
PHY	MAXIMUM INTEGRATION BETWEEN PROJECT TEAM AND INTERNAL CUSTOMER
PHY	USE A STANDARD SCHEDULE AS REFERENCE FOR ALL PROJECTS SCHEDULES
PHY	INCREASE THE NUMBER OF OWNER PROFESSIONALS IN THE PROJECT TEAMS
PHY	PROCUREMENT TEAM PARTICIPATING IN THE PROJECTS PLANNING
PHY	INCLUDE PROCUREMENT AND WAREHOUSE REPRESENTATIVES IN THE PROJECT TEAM
PHY	TRAIN ALL TECHNICAL SPECIALISTS IN PROJECT MANAGEMENT
PHY	PLANNING MUST ISSUE A RISK REPORT FOR EACH PROJECT
PHY	USE EVA TO EVALUATE MONTHLY THE BIGGER PROJECTS
PHY	WAREHOUSE AND ENGINEERING FULLY INTEGRATED
PHY	PROJECTS TEAMS FULLY INTEGRATED
PHY	COMBINE DIFFERENT SPECIALIST IN EACH PROJECT
PHY	USE EXTERNAL EXPERIENCE IN PROJECT MANAGEMENT

Fig. 11 Solution proposals generated based on the Physical Contradiction

At this point, the basic cycle of TRIZ was concluded generating 66 (sixty-six) proposals. One could go directly to the evaluation against the ideality or expand the search for new solution proposals using additional tools. The second option was chosen.

-Trimming and 76 Standard Solutions

By choosing to broaden the search for alternatives using these two additional tools, one must return to the definition phase and perform the function analysis that gives a better view of the characteristics of the specific problem and its relationships.

-Function Analysis

The most problematic relationships were identified in the analysis (Shown in Fig. 12). They will allow the TRIZ tools to be focused on the real issues.

The analysis summary, focusing only on the problematic relationships, can be seen in Fig. 13 (SAO: Subject – Action – Object) and they will be the basis for the additional tools application.

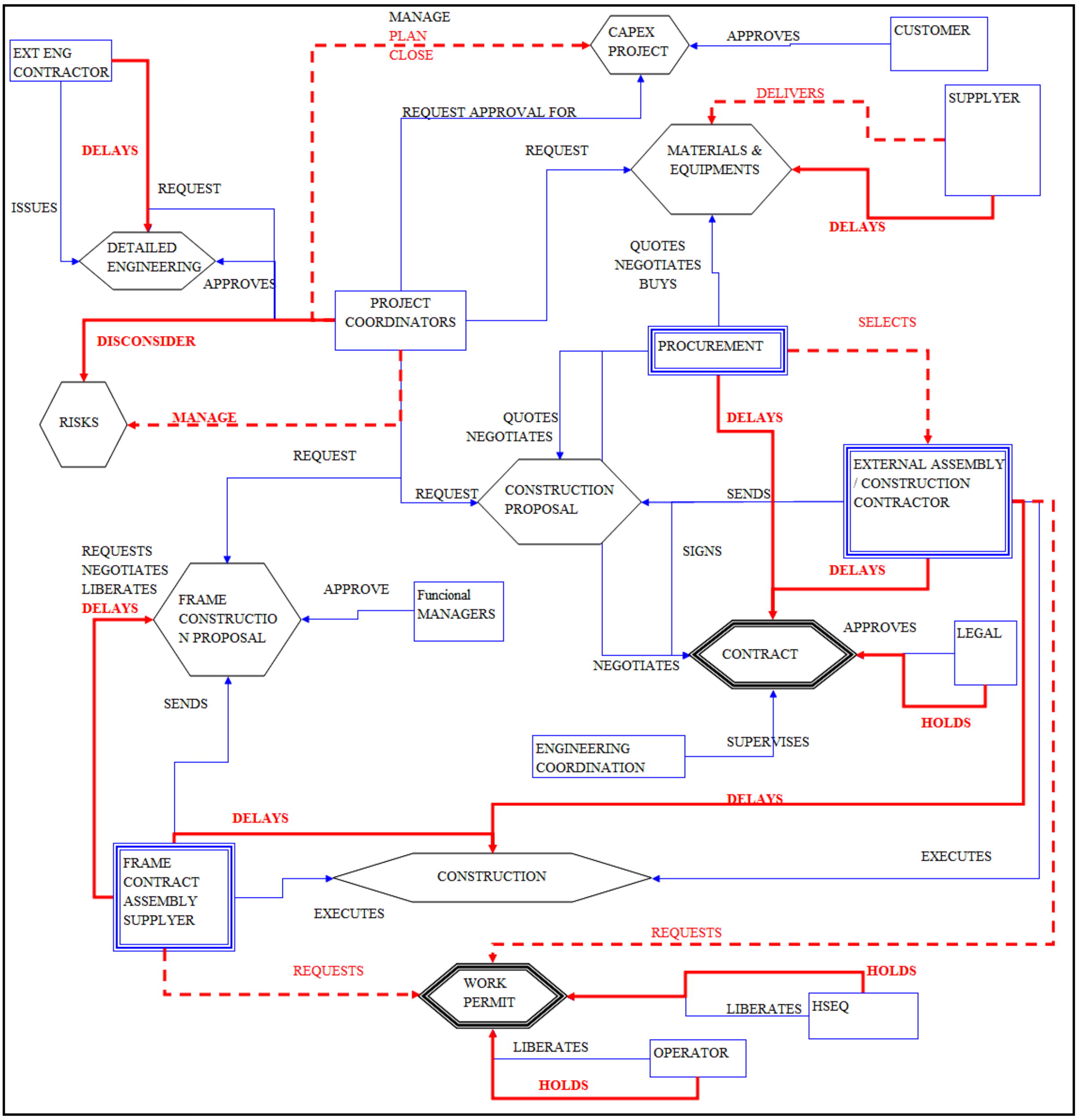

Fig. 12 Function Analysis (threats or insufficiencies in red dotted or thick lines)
Note: Red dotted lines = insufficiencies; Red thick lines = harms/threats; Blue thin lines = satisfactory

CAT	SUBJECT	ACTION	OBJECT	FUNCTION	TYPE
I	PROJ COORDINATORS	PLAN	CAPEX PROJECT	PLANNING	INSUFFICIENT
I	PROJ COORDINATORS	CLOSE	CAPEX PROJECT	CLOSING	INSUFFICIENT
TH	PROJ COORDINATORS	DISCONSIDER	RISKS	RISK MANGT	THREAT
TH	MAT&EQT SUPPLIER	DELAYS	MAT & EQUIP	DELIVERY	THREAT
I	PROCUREMENT	SELECTS	EXT ASSEMBLY CONTRACTOR	SELECTION	INSUFFICIENT
TH	PROCUREMENT	DELAYS	CONTRACT	BUYING	THREAT
TH	LEGAL	HOLDS	CONTRACT	APPROVAL	THREAT
TH	EXT ASSEMBLY CONSTRUCTION CONTRACTOR	DELAYS	CONTRACT	SIGNING	THREAT
TH	EXT ASSEMBLY CONSTRUCTION CONTRACTOR	DELAYS	CONSTRUCTION	EXECUTION	THREAT
I	EXT ASSEMBLY CONSTRUCTION CONTRACTOR	REQUESTS	WORK PERMIT	WORK PERMIT REQUISITION	INSUFFICIENT
TH	FRAME CONTRACT ASSEMBLY SUPPLIER	DELAYS	FRAME CONTRACT PROPOSAL	PROPOSING	THREAT
TH	FRAME CONTRACT ASSEMBLY SUPPLIER	DELAYS	CONSTRUCTION	EXECUTION	THREAT
I	FRAME CONTRACT ASSEMBLY SUPPLIER	REQUEST	WORK PERMIT	WORK PERMIT REQUISITION	INSUFFICIENT
TH	HSEQ	HOLDS	WORK PERMIT	WORK PERMIT LIBERATION	THREAT
TH	OPERATOR	HOLDS	WORK PERMIT	WORK PERMIT LIBERATION	THREAT
I	EXT ENG CONTRACTOR	ISSUES	DETAILED ENG	ENG DETAILING	INSUFFICIENT
TH	EXT ENG CONTRACTOR	DELAYS	DETAILED ENG	ENG DETAILING	THREAT
I	PROJ COORDINATORS	CLOSE	CAPEX PROJECT	CLOSING	INSUFICIENT

Fig. 13 SAO: Identified Problematic Relationships

-Trimming

This tool operates questioning each of the problematic relationship as follows.

-Can we eliminate the function?

-Could the object perform the function itself?

-Is it possible to remove the subject / the agent or the object?

-Is it possible to get rid of the agent / the subject after the function performed?

-Is it possible to remove any system parts?

-Can any other agent or other object perform that function?

-Any available resource could perform the function?

The answers to the questionnaire generated 6 (six) solution proposals as shown in Fig. 14. (See section 6 for comments on using the selected best proposals)

TRIM	PREFERENCE FOR THE FRAME CONTRACTS SUPPLIERS
TRIM	USE PRE EVALUATED SUPPLIERS ONLY
TRIM	ALLOW THIRD PARTY TRAINED PROFESSIONALS TO LIBERATE WORK PERMITS
TRIM	CONTINUOUSLY EVALUATE THE FRAME CONTRACT SUPPLIER
TRIM	WORK PERMIT RESPONSIBLE MUST BE INFORMED ABOUT THE PROJECT SINCE THE PLANNING
TRIM	USE CLEAR KIP'S FOR EACH SERVICE SUPPLIER

Fig. 14 Solution proposals generated based on the Trimming tool and SAO

-76 Standard Solutions

From the same list of problematic relationships, one can test the standard suggested principles for each of the categories identified in the problem. It was used the Oxford Standard Solutions adapted from the traditional 76 Standard Solutions re-arranged into three categories: harm, insufficiency and measurement (Gadd, 2011).

The tool guided us in treating both identified categories, as the follows.

a) Threat (Harm)

Four basic strategies for dealing with harms.

a1. Eliminate – trim out the harm (already tested in Trimming)

a2. Stop – block the harm.

a3. Transform the harm – turn harm into good.

a4. Correct – put right the harm.

b) Insufficiency

Two basic strategies to improve, change or enhance functions by changing:

b1. The components (subject / object or their surroundings)

-Add something to the subject and/or object or to the environment.

-Change/evolve the subject or/and object.

b2. The action or field that acts between components.

This tool returned 26 (twenty-six) solution proposals as shown in Fig. 15. (See section 6 for comments on using the selected best proposals).

STD	PRE APPROVED STANDARD CONTRACT
STD	ENGINEERING PARTICIPATES IN THE SUPPLIERS SELECTION CRITERIA
STD	CONTINUOUS WORK PERMITS
STD	USING PRE APPROVED SUPPLIERS ONLY
STD	CONSTRUCTION CONTRACTOR MUST INFORM 1 DAY EARLY ALL TASKS PLANNED
STD	IMPROVE SUPPLIERS SELECTION CRITERIA
STD	USE SUPPLIERS THAT ARE AWARE OF THE OWNER INTERNAL PROCEDURES AND STANDARDS
STD	ACCELERATE THE PROPOSALS FROM SERVICE SUPPLIERS
STD	SUPPLIERS RANKED CONSIDERING HIGH WEIGHT ON DELIVERY DATE HISTORY
STD	HAVE A CHAMPION SUPPORTING ALL RISK MANAGEMENT SINCE TH EARLY PLANNING
STD	USE INTEGRATED CONTRACTS FOR THE MOST COMMON MATERIALS
STD	INCLUDE DETAILED SCHEDULE IN THE ASSEMBLING PROPOSALS
STD	EXECUTE SCHEDULE RISK SIMULATION BEFORE FINAL PROJECT AUTHORIZATION
STD	INCLUDE A SAFETY TECHNICIAN IN THE ENGINEERING TEAM
STD	USE PROJECT RISK KIP'S
STD	ENGINEERING COORDINATOR MUST MANAGE THE PORTFOLIO RISKS
STD	PROCEDURES FOR WORK PERMIT MUST BE INFORMED TO ALL
STD	TRAIN THE PROJECTS COORDINATORS IN RISK MANAGEMENT
STD	UPDATE WORK PERMIT PROCEDURES
STD	HAVE 2 FRAME CONTRACTORS AVAILABLE
STD	CONTRACTORS MUST KEEP SAFETY TECHNICIAN GUIDING ITS OWN TEAM
STD	KEEP LIST OF ALTERNATIVE HIGHLY QUALIFIED SUPPLIERS FOR EMERGENCIES
STD	CONTRACT THIRD PARTY PLANNER WITH RISK MANAGEMENT EXPERIENCE
STD	APPLY DELAYS PENALTIES IN THE CONSTRUCTION CONTRACTS
STD	INCLUDE DELIVERY CONDITIONS IN THE INDIVIDUAL EVALUATION FOR EACH PROJECT COORDINATOR
STD	CONSIDER ALL DELAYS POSSIBILITY IN THE PRELIMINARY SCHEDULE

Fig. 15 Solution proposals generated based on the Std. Solutions tool

4.4 Other Tools

In order to exhaust the alternatives, the Inventive Triggers were used (X-Factor; Life and Death analogies; Smart Little People; Time-Size-Cost; Subversion). The most effective one was the "size / time / cost" - minimum & maximum in which each of these three critical dimensions is radically overstated (zero to infinite) for the alternatives generation.

The tool generated more 7 (seven) solution proposals as shown in Fig. 16. (See section 6 for comments on using the selected best proposals).

As a last tool, the Trends of Evolution were quickly tested (increasing ideality; S-curve; non–uniform evolution of parts; matching and mismatching; less human involvement; increasing complexity followed by simplicity; increasing dynamism & controllability) returning more 4 (four) solution proposals shown in Fig. 17 (See section 6 for comments on using the selected best proposals).

However, many redundant solutions were generated, if compared to the alternatives already identified, indicating some degree of exhaustion.

TRI	LONG TERM FRAME ASSEMBLY/CONSTRUCTION CONTRACT
TRI	CONTROL ALL SERVICES THROUGH SERVICE ORDERS TO APPROVE BEFORE ANY COMMITMENT
TRI	ALL PURCHASE ORDERS MUST INCLUDE ALL CONDITIONS TO BE FOLLOWED FOR THE SERVICE EXECUTION
TRI	PARTNER SUPPLIERS SIGN ONE SINGLE RESPONSABILITY MOU TO COVERS ALL SERVICES TO EXECIUTE
TRI	USE ALWAYS THE SAME EXECUTION TEAM FOR ALL PROJECTS
TRI	EVALUATE TO AUTHORIZE PROJECTS BASED ON THE DEFINED SCOPE
TRI	CONTRACT EXTERNAL ENGINEERING AND CONSTRUCTION COMBINED

Fig. 16 Solution proposals generated based on the inventive triggers

TRENDS	PROCUREMENT & LEGAL FOLLOWING THE PROJECT SCHEDULES
TRENDS	CUSTOMER ENGINEERING LEADS ITS OWN SMALL PROJECTS
TRENDS	PROJECT TASKS PERFORMED 24 X 7 AROUND THE WORLD
TRENDS	ASSEMBLING RESOURCES DEFINED ACCORDING THE APPROVED PROJECT PORTFOLIO

Fig. 17 Solution proposals generated based on the Trends of Evolution tool

5. Assessment against the ideality

Until now, the proposals were generated without any formal evaluation. At this step, it is necessary to rank the proposals in order to identify the best ones and those easier to implement. As a reference for decision-making, the assessment was done using multiple criteria selection based on the concepts of ideality (Rantanen& Domb, 2008):

-Were threats eliminated?

-Are useful features retained and new benefits added?

-Have new threats arisen?

-Did the system become more complex?

-Was the main physical contradiction eliminated?

-Were free or ignored resources used?

By adding a criterion related to the ease of implementation, one can prioritize proposals according to the ideality ranking starting by the easiest one to put in practice (Fig. 18). Depending on the environment in which the projects are executed, other criteria and individual weights may be used.

As an exhaustive process, many repeated proposals came through different tools. Eliminating redundancies/repetitions, there were 109 additional proposals over the 10 preliminary ones. Of the total 119 proposals, 61 ones reached ideality rating

SOURCE	IDEALITY CHECK	HARMS DISAPPEAR?	USEFUL FEATURES KEPT? NEW BENEFITS APPEAR?	NEW HARMS APPEAR?	SYSTEM BECOMEs MORE COMPLEX?	PRIMARY PHYSICAL CONTRADICTION SOLVED?	IDLE, EASILY AVAILABLE, IGNORED RESOURCES USED?	OTHER: EASE TO IMPLEMENT?	TOTAL
	WEIGHT	3	1	2	1	5	1	1	
	Ideal	10	10	0	0	10	10	10	TOTAL
TRI	LONG TERM FRAME ASSEMBLY/CONSTRUCTION CONTRACT	10	10	0	0	9	7	9	91,8%
STD	PRE APPROVED STANDARD CONTRACT	10	8	0	0	9	5	8	87,3%
STD	ENGINEERING PARTICIPATES IN THE SUPPLIERS SELECTION CRITERIA	8	8	0	0	9	3	7	79,1%
TECH	ASSEMBLING TEAM PARTICIPATES IN THE PROJECT DEFINITIONS	7	8	0	0	9	5	8	79,1%
STD	CONTINUOUS WORK PERMITS	7	10	1	0	9	5	7	78,2%
PHY	PROJECT AND PROCUREMENT TEAMS FULLY INTEGRATED	7	10	0	0	9	3	5	76,4%
TRENDS	PROCUREMENT & LEGAL FOLLOWING THE PROJECT SCHEDULES	7	8	1	1	8	6	6	70,9%
STD	USING PRE APPROVED SUPPLIERS ONLY	6	7	0	0	8	5	7	70,0%
TRENDS	CUSTOMER ENGINEERING LEADS ITS OWN SMALL PROJECTS	8	6	5	1	8	10	7	69,1%
TECH	CONSTRUCTION COORDINATION WITH AUTONOMY	6	7	1	0	8	5	5	66,4%
STD	CONSTRUCTION CONTRACTOR MUST INFORM 1 DAY EARLY ALL TASKS PLANNED	7	9	0	3	8	0	6	66,4%
TECH	CUSTOMERS AND ASSEMBLING CONTRACTORS MUST BE HEARD IN THE PROJECT DEFINITIONS	6	8	0	0	7	5	7	66,4%
STD	IMPROVE SUPPLIERS SELECTION CRITERIA	5	8	0	0	8	3	7	66,4%
PHY	SELECT AND USE A MORE EXPERIENCED TEAM TO SUPPORT THE PROJECTS	6	7	0	0	7	5	7	65,5%
TECH	USE FLEXIBLE DAILY TIME SCHEDULE FOR ASSEMBLING SERVICE	2	10	0	1	8	8	9	65,5%
TECH	USE STANDARD DOCUMENTATION	2	10	0	0	8	7	9	65,5%
STD	USE SUPPLIERS THAT ARE AWARE OF THE OWNER INTERNAL PROCEDURES AND STANDARDS	5	9	3	0	9	3	5	64,5%
TRIM	PREFERENCE FOR THE FRAME CONTRACTS SUPPLIERS	10	8	5	0	6	5	7	63,6%
TRI	CONTROL ALL SERVICES THROUGH SERVICE ORDERS TO APPROVE BEFORE ANY COMMITMENT	0	9	0	0	9	7	9	63,6%
TECH	USE A CELL BASE STRUCTURE FOR PROCUREMENT AND ASSEMBLING	4	10	3	0	9	5	3	62,7%
STD	ACCELERATE THE PROPOSALS FROM SERVICE SUPPLIERS	7	8	0	0	7	0	5	62,7%
STD	SUPPLIERS RANKED CONSIDERING HIGH WEIGHT ON DELIVERY DATE HISTORY	5	7	0	0	7	5	7	62,7%
TRIM	USE PRE EVALUATED SUPPLIERS ONLY	6	9	1	3	8	0	7	62,7%
PHY	MAXIMUM INTEGRATION BETWEEN PROJECT TEAM AND INTERNAL CUSTOMER	5	10	0	0	7	3	5	61,8%
TECH	PREPLANNING OF THE ASSEMBLING SERVICE	6	10	2	1	8	0	5	61,8%
PRE	PROCUREMENT TEAM DEDICATED TO PROJECTS	4	10	3	1	9	7	0	60,9%
TRI	ALL PURCHASE ORDERS MUST INCLUDE ALL CONDITIONS TO BE FOLLOWED FOR THE SERVICE EXECUTION	8	7	3	0	6	7	5	60,9%
PHY	USE A STANDARD SCHEDULE AS REFERENCE FOR ALL PROJECTS SCHEDULES	5	5	0	0	6	7	10	60,9%
TECH	START ADVANCED QUOTING WITH POSSIBLE SUPPLIERS BEFORE FINAL PROJECT AUTHORIZATION	6	10	1	0	7	0	5	60,0%
PHY	INCREASE THE NUMBER OF OWNER PROFESSIONALS IN THE PROJECT TEAMS	5	7	2	0	7	5	8	60,0%
STD	HAVE A CHAMPION SUPPORTING ALL RISK MANAGEMENT SINCE TH EARLY PLANNING	3	8	0	0	7	5	9	60,0%

Fig. 18 Evaluated Solution Proposals Summary (>/=60% ideality ranking)

above 50% as a first filter. The proposals show corrective and preventive approaches that could be used as a specific filter, if needed. The rest of the proposals should also be examined because it contains ideas whose immediate execution may be difficult but with significant positive impact if implemented in the future.

A summary containing the higher-ranking 31 solution proposals (complying >/=60% to ideality and ease to implement) is shown in the Fig. 18. (See section 6 for comments on using the selected best proposals).

Note: The identified sources are TRI (triggers), STD (standard solutions), TECH (technical contradictions), PHY (physical contradictions), TRENDS (trends of evolution), TRIM (trimming), PRE (preliminary solutions). Confirming the TRIZ contribution to reveal new possibilities one can see only one proposal coming from the preliminary proposal list (PRE) in this higher-ranking group.

As a preliminary guidance on similar situations and based on the number of solutions generated (Fig. 19), the most effective tools to treat such problems were the elimination of the technical contradictions (48%) and the 76 standards solutions (24%) followed by the elimination of the physical contradictions (13%). It shows that the basic cycle of the workflow was capable of generating half of the potential solutions (51%). Being quicker and effective, the basic cycle becomes the best option for similar cases in which the speed is critical and the time may be short to develop the whole workflow.

	TOTAL	WITHOUT TRIZ	With TRIZ	TECH. CONTR.	STD. SOL.	PHYS. CONTR.	TRIGGERS	TRIMM.	TRENDS EVOL.
Nr. Ideas	119	10	109	52	26	14	7	6	4
				48%	24%	13%	6%	6%	4%

Fig. 19 Number of Ideas x TRIZ tools

6. The best proposals and their expected effect

Consolidating the figures 4, 9, 12, 14, 15, 16 and 17, the figure 18 summarizes the best proposals already ranked using the proposed multi-criteria. This section presents additional comments and explanation about the context, how to implement and the expected effects derived from each of the best proposals highlighted in Fig. 18. Note that those solutions have derived from the typical contradiction (speed x quality in project management) and specific threats, insufficiencies and opportunities identified in the function analysis (Fig. 12). The projects used as reference are the ones found in a typical industrial environment. That is, most of the proposals could have direct use in other project management environments but some of them will only be useful in the mentioned context. The ranking criteria themselves, as reference for decision-making, may change according to each situation and type of project. As a quick option to use the best proposals list (>50% ideality compliance), consider taking it as a checklist. Such checklist must be evaluated against your real project and environment during the project planning phase aiming the project acceleration. The multi-criteria and weights may be adjusted to your own situation, generating a different ranking, your own one. Another option would be to expose your PM procedure and environment to the TRIZ workflow. It would generate your own set of best proposals to apply to future projects, reinforcing the risk management process.

See the below comments about each of the best proposal in Fig. 18.

Long term assembly/construction contract: when dealing with several small and medium size projects at the same time, this type of frame contract will speed up the contracting phase of execution, usually keeping the same construction partner for most of the jobs.

Pre-approved standard contracts: where is not possible to use the frame contract, the availability of a standard contract form already evaluated and approved by legal department and all other internal stakeholders will speed the contracting process and the project execution.

Engineering participating in the suppliers' selection criteria: the engineering team directly in charge of the projects management must participate in defining which criteria should be used to select suppliers for the vendor list updating by the procurement team. It would avoid contracting a supplier without the skills and means necessary to execute the job in that specific environment. Problematic contractors may stop or delay the job execution delaying the project delivery.

Assembling team participates in the projects definitions: where there is a team directly responsible by the assembling and construction execution, this team must be involved since the definition phases to identify opportunities to speed up the construction and to avoid future problems and restrictions. It would avoid having to deal with problems during the construction when is much more difficult to solve them without spending additional time.

Continuous work permit: when executing projects in an industrial environment with the presence of flammable products, dangerous substances or any other aggressive fluids, the standard safety procedure requests a formal work permit for every job to be done day by day. Usually this permit must be issued by operational team overloaded with the production routines and the maintenance daily demands. In this scenario, it is easy having a delay in the assembling or construction work permit. If the problem keeps repeating day after day, the whole project schedule will certainly delay. One of the solutions would be having a continuous work permit valid for a week if the safety conditions were under control. This would avoid the daily work permit eliminating the time needed to start the tasks daily.

Project and procurement team fully integrated: considering the importance of preliminary cost estimates and all other procurement tasks executed according to the project schedule it becomes clear that the two teams must work together since the planning phases to avoid unreal budgets and schedule. Since the planning phase, the procurement team must be aware of the impact of every package to be bought or contracted in the whole project. The procurement team must also be allowed to contribute with its experience in the project planning. The integration is critical for generating the best budget and schedule and for having the commitment of both teams with the final schedule.

Procurement & legal following the project schedules: when dealing with contracts there will be an interface with the legal team. The integration of the procurement team in the planning can bring together the legal team to the commitment with the projects schedule.

Using preapproved suppliers only: using suppliers and contractors not fully prepared to work in the specific environment can delay all the project execution. In that sense, using only a pre-approved suppliers list is critical for the schedule.

Customer's engineering leads its own small projects: when dealing with small and low complexity projects, if the customer' s engineering structure has enough skill in PM, these small projects can be managed by that structure with some support from the engineering team. This option would allow solving specific customer's problems in a faster way with an accelerated project delivery.

Construction coordination with autonomy: it is usual to have an engineering structure in which the construction/assembling team has its own coordination. The autonomy to participate and interfere in the project-planning phase is critical to have a construction phase running as quick as possible with minimum unexpected problems and the project delivered in time.

Construction contractor must inform 1 day early all tasks planned: this item is related to the daily work permit. If the construction contractor has a schedule to followed and it updates the future tasks one day before it turns the work permit issue and control much easier for all stakeholders, avoiding delays.

Customers and assembling contractors must be heard in the project definitions: if the customers' and assembling contractors' representative are both heard during definitions phase, they not only can contribute avoiding unreal assumptions but also bringing options to accelerate the schedule.

Improve suppliers' selection criteria: the selection criteria must always be improved including factors that can identify the suppliers with the better conditions and historical in delivering the tasks safely and in the time contracted to avoid projects delays.

Select and use a more experienced team to support the projects: if the team has a number of more experienced professionals, the idea is having part of the time of this group available to the less experienced group in order to identify and correct potential problems early in the planning phase as a type of internal coaching and support.

Use flexible daily time schedule for assembling service: sometimes it is impossible to have the assembling tasks starting in the beginning of the workday with the rest of daily routines, meaning projects delays. In those situations, a special daily schedule would be used for the assembling, starting 2 hours later and adding 2 hours at the end of the day, for example.

Use standard documentation: all projects need a huge amount of formal documentation. The use of the same standard forms in all projects accelerates the team skill and helps avoiding mistakes and misunderstandings. Fewer mistakes mean lower probabilities of delays.

Use suppliers that are aware of the owner internal procedures and standards: In complex industrial environments, it is usual that companies have their own procedures about every critical aspect for their operational routines. The potential suppliers must be aware of these procedures and critical requests before issuing their work proposals once the compliance may affect the costs. A financial unbalance during the execution may generate potential delays in the job.

Preference for the frame contracts suppliers: it is usual to develop partners for specific kinds of jobs negotiating and signing frame contracts with them. These contracts establish the commercial and general conditions. At each job to be done, a specific proposal is issued covering the specific scope and schedule but referring the general conditions already negotiated. The frame contracts accelerate the contracting phase and so the execution in each project.

Control all services through service orders to approve before any commitment: considering an environment with valid frame contracts, it is critical that each job has its own service order based on a proposal covering scope, cost and schedule. It avoids misunderstandings during execution and so delays for the whole project.

Use a cell base structure for procurement and assembling: this option considers having a small procurement group ("cell") dedicated to small projects. The same concept applies to the assembling cell. The idea is that these cells would have autonomy to develop the tasks related to small projects contributing to higher delivery speed.

Accelerate the proposals from service suppliers: the time to obtain the formal proposals for services and goods is critical for the schedules. The time requested to return the proposal must be planned in the schedule and must be considered by the procurement teams.

Suppliers ranked considering high weight on delivery date history: the delivery time history must be a critical factor when selecting the potential suppliers to avoid the ones not capable of following the schedule.

Use pre evaluated suppliers only: having a suppliers list with updated evaluation related to the schedule commitment is critical to avoid general delays.

Maximum integration between project team and internal customer: this integration is critical for the definition and planning phases. Without this integration, the probability of having an incomplete or wrong solution defined is higher, increasing the possibility to spend more time during the execution trying to fix the problems.

Pre planning the assembling service: the assembling must be planned to avoid potential problems during the execution, leading to delays.

Procurement team dedicated to projects: the ideal situation is having a procurement group dedicated to the projects not executing tasks for other areas to avoid waste of time in this interface.

All purchase orders must include all conditions to be followed for service execution: the suppliers must be informed before the proposal of all the requests and risks in the environment in which the job will be executed. It avoids surprises that are time consuming to solve during the execution.

Use a standard schedule as reference for all projects schedules: as all other standard forms, using a standard schedule structure for all projects turns easier to prepare it and to understand it avoiding time-consuming misunderstandings.

Start advanced quoting with possible suppliers before final project authorization: the advance quoting is critical to generate better budgets for the projects. An understated budget will make a project short of funds leading to interruptions in execution and delays.

Increase the number of owner professional in the project teams: the higher number of owner project professionals in the team compared to third part ones may increase the commitment with projects problem solutions. In that sense, keeping an owner project professional's core group is critical for the commitment with cost and schedule.

Have a champion supporting all risk management since the early planning: having an experienced risk professional available to support all the project team when dealing with potential threats and opportunities in the schedule management is critical for good results. This professional could also support the TRIZ tools application.

7. Conclusions

If the solutions derived from the current project management procedure are satisfactory, just apply them, you don't need TRIZ. In more complex cases, when results are not reaching the desirable level and the current PM procedure is limited to compromising options, the TRIZ tools support the search for inventive solutions, identifying the hidden contradiction and developing the specific situation analysis.

In the evaluated case, one can see clearly that the preliminary ideas had not the same coverage as those ones generated through TRIZ. That is, the contribution of TRIZ to accelerate projects while maintaining the quality was significant in quantity and focus. As a general conclusion and based on 109 solutions generate using the TRIZ tools, we might say that the project management practice, like any other group of processes, can also benefit from the exposure to the TRIZ concepts, mainly for problems in which the usual solutions may lead to a compromise.

TRIZ can take the standard PM procedure beyond the usual limits to deal with real problems in executing any project. It does it by turning clear the harms and insufficiencies and focusing on solving the main contradiction without compromises.

Based on the number of solutions obtained through each tool, the most effective ones for similar cases were the elimination of the technical and physical contradictions. Being part of the proposed workflow's basic cycle, they were quicker and generated 51% of the entire contribution. They can be considered the best option for similar cases in which the schedule is critical and the time to develop the whole workflow is short.

The solutions derived from this paper can be applied in other similar cases as a checklist to evaluate the situation regarding speed and quality of the projects under planning. However, some of the solutions are specific to the situation and environmental under analysis and may be not relevant to other cases.

Due to the characteristics of the TRIZ workflow, it can be adjusted (using part of the available tools) according to the situation's complexity or the dissatisfaction with the amount and / or quality of the solution proposals obtained so far. The workflow facilitates the use of the tools by beginners.

For better results, a multidisciplinary group, including members with deep knowledge of the problem, should perform the exercise of TRIZ.

One thing that becomes clear along the process is that the structured and progressive TRIZ workflow used in this paper turns quickly available strong means to identify the real critical problems. Around these critical points, all energy and inventiveness are concentrated to generate a huge amount of possible solutions in a very short time period.

It is important to make clear that the TRIZ tools were not meant to replace the project management procedures. Their application only makes sense over an established project management methodology when facing a real problem or limitation in getting the desired projects results. If there is no project management procedure in use, the first step would be to introduce it, otherwise TRIZ would only generate solutions that certainly would already be part of any consolidated project management good practice.

As seen, TRIZ can be a powerful support to improve the PM practices if one considers that PM is about delivering quality results under restrictions of time, cost, and scope, a typical scenario with contradictions and compromises.

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A New Perspective on EFL Teaching: Applying Fuzzy QFD in TRIZ for Teaching Quality Improvement

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Abstract

Teaching quality has been a frequently studied topic in education literature; however, a creative approach for improving teaching quality is rarely discussed. In this paper, a systematic framework based on the TRIZ methodology is suggested to generate creative solutions for improving teaching quality. First, the determinants of teaching quality were investigated based on a comprehensive review of language teaching. Subsequently, a parameter-corresponding table was developed to apply the TRIZ contradiction matrix effectively to solve language-teaching problems. Cochran test was used as a statistical hypothetic test during this phase. The correlation between "the vague opinions from the supplier and receptor of teaching" and "the determinants of teaching quality" was analyzed by using fuzzy QFD to identify the critical determinants related to teaching quality improvement. The corresponding parameters can be effectively applied in the TRIZ contradiction matrix to identify the inventive principles. The appropriate re-explanations of the inventive principles developed for foreign language teaching are discussed. A case study proved the usefulness of the approach in EFL courses, and practical solutions are presented to demonstrate the valuable contribution of the TRIZ methodology to the education field.

Keywords: Teaching quality, Teaching improvement, TRIZ, EFL, Fuzzy QFD

1. Overview

The teaching quality of universities has been increasingly emphasized since Boyer (1990) proposed expanding scholarship beyond teaching, integration, and application. Although educators have begun to realize the importance of improving teaching quality, the processes remain uncertain. Planning a university course is a complex activity (Barone & Lo Franco, 2009); therefore, enhancing teaching quality involves substantial shifts in thought and practice. In this study, a methodology for innovatively resolving teaching problems and improving teaching quality was developed to foster meaningful and long-term learning for students.

TRIZ (*Theoria Resheneyva Isobretatelskehuh Zadach*) is a Russian abbreviation for "theory of inventive problem solving," which is a well-developed system of tools used for idea generation, problem solving, and failure prevention (Akay, Demıray & Kurt, 2008; Belski, 2009). One tool, contradiction analysis, which consists of 39 parameters and 40 inventive principles, is the most frequently used method (Su & Lin, 2008). TRIZ is a popular subject regarding technological innovation (Mann, 2000) and has recently been proven to be an innovative and well-structured method for solving problems in non-technical fields (Mann, 2000; Saliminamin & Nezafati, 2003). However, there is a lack of TRIZ-specific research addressing the teaching quality domain, which is another reason for undertaking this study.

Quality function deployment (QFD) is a method for developing and managing products or services to assist planners in identifying product or service characteristics from the viewpoints of customers (Celik, Cebi, Kahraman & Er, 2009). The practice of QFD has primarily relied on market surveys for acquiring customer requirements, and planners typically employ linguistic variables to set various parameters. However, the outcomes of market surveys and linguistic variables are often imprecise or unclear and may reflect biased results. Scholars have combined the fuzzy set theory with QFD to solve this problem (Liu, 2011). In contrast to traditional QFD, the input data of fuzzy QFD are expressed and represented in fuzzy numbers instead of crisp numbers (Chen, Fung, & Tang, 2006). In the current study, fuzzy QFD was used to identify critical teaching-quality determinants; this is crucial because numerous researchers have proposed that teaching is one of the primary services of a university (Harvey, 2003; Barone & Lo Franco, 2009).

In this study, the "quality" of a university course is defined as the degree to which the course satisfies the teaching expectations of the supplier and the receptor. Tribus (1993) stated that quality is what makes learning a pleasure and involves the way in which the teaching process is performed. In this regard, teachers and students are the primary parties responsible for achieving the goal of improved teaching quality. Accordingly, this paper addresses both teacher and student perspectives.

The study is structured as follows: Section 2 presents a review of the literature; Section 3 provides a description of the proposed approach; Section 4 presents the application of the proposed approach to English as a foreign language (EFL) courses; and Section 5 offers concluding remarks and suggestions for future developments.

2. Literature review

TRIZ offers a comprehensive toolkit for analyzing and solving problems according to various perspectives and is based on the knowledge and experiences of a wide range of inventors (Moehrle, 2005). The foundation study of TRIZ research was one of the largest studies on creativity conducted, involving more than 1,500 person-years of study and an analysis of more than two million patents globally (Mann, 2001; Zhang, Chai, & Tan, 2005). In this foundation study, an exceedingly small number of inventive patterns and strategies were identified and extracted (Mann, 2001). The strengths of TRIZ are described as follows. First, TRIZ encourages planners to break out of the conventional "begin with the present situation" style of thinking, and to start instead by considering ideality (Mann, 2001). Second, it transforms the undesirable elements of a system into useful resources and removes contradictions rather than encourages trade-offs or compromise (Mann, 2001; Zhang, et al., 2005; Su & Lin, 2008). Third, it helps to prevent psychological inertia, which is inherent in human thinking, because it involves devising a comprehensive set of feasible solutions (Zhang et al., 2005). Fourth, by providing a predefined direction, TRIZ complements and adds structure to, rather than replaces, an inventor's natural creativity (Mann, 2001; Moehrle, 2005). TRIZ facilitates developing numerous high-quality ideas effectively and systematically (Zhang et al., 2005).

The most commonly applied TRIZ tool is the contradiction matrix, which consists of 39 rows and 39 columns involving the 1,482 most common contradiction types (Mann, 2001). The rows of the matrix contain the desired factors of a system, whereas the columns comprise the harmful elements of a system. In each cross-field, up to 4 of 40 inventive principles are advised for eliminating the contradiction. Using different inventive principles occasionally generates similar ideas. The inventive principles lead planners in specific directions, but concrete solutions must be formed by combining inventive principles with the knowledge and creativity of the individual problem solver (Moehrle, 2005).

During years of development and application, TRIZ has proven its effectiveness and efficiency in resolving technical problems and in removing all boundaries across a broad range of areas and problem types (Mann, 2001). Several papers have presented discussions on the 40 inventive principles in various fields, such as business (Mann & Domb, 1999), finance (Dourson, 2004), society (Terninko, 2001), software (Rea, 2001), microelectronics (Retseptor, 2002), food (Mann, & Winkless, 2001), quality management (Retsptor, 2003), eco-innovation (Chang & Chen, 2003), construction (Teplitskiy & Kourmaev, 2005), service operations management (Zhang, Chai, & Tan, 2003), education (Marsh, Waters, & Marsh, 2004), and marketing, sales, and advertising (Retsptor, 2005). Several studies have also presented discussions on the parameters in the TRIZ contradiction matrix for non-technical fields, such as business (Mann, 2002), education (Marsh, Waters, & Mann, 2002), service quality (Su, Lin, & Chiang, 2008), and English learning (Sokol et. al., 2008). The literature on applying TRIZ in improving teaching quality has been limited, particularly in the area of foreign language teaching.

To strengthen their strong points (Tan, 2002), integrating TRIZ with other leading methods, such as QFD (Domb, 1998; Terninko, 1998; Schlueter, 2001; Yanashina, Ito, & Kawada, 2002), the theory of constraint (Stratton & Warburton, 2003), and Six Sigma (Verduyn, 2002), is a recent trend (Tan, 2002). Su and Lin (2008) proposed a systematic method for integrating fuzzy QFD and TRIZ to improve e-service quality. Because of their application success, the model of Su and Lin was applied in this study to resolve problems in an EFL teaching context.

3. Proposed approach

Based on the literature review, the systematic problem-solving process used in previous research (Su, Lin, & Chiang, 2008; Su & Lin, 2008) was applied, with slight modifications, to improve teaching quality. The proposed approach comprises five primary phases.

Phase 1: Clarify the scope of the problem and distinguish the segment under which it is classified. Assisting problem solvers in clarifying the depth of the original problem requires identifying the specified area and focusing on resolving issues in the same segment. For instance, problems arising in EFL courses are classified under the segment of foreign language teaching. Consulting teachers and students to collect existing information on the possible problem is an easy and common practice for gathering situational information accurately. Function and attribute analysis (FAA) can also be used to access the root causes of the problem.

Phase 2: Extract the determinants affecting teaching quality from a review of various perspectives. Reference materials related to teaching quality are extensively analyzed to identify the critical characteristics regarding teaching quality improvement.

Phase 3: Develop a parameter-corresponding table for foreign language teaching. Once the resulting table of the identified segment is constructed, the assured TRIZ parameters can be efficiently extracted and applied in the contradiction matrix. This phase comprises five steps:

Step 3-1: Link the implications of the determinants assembled in Phase 2 with the TRIZ 39 engineering parameters according to their analogical interpretations. A survey of a focus group or several semi-structured interviews may be conducted in this step.

Step 3-2: Design a questionnaire based on the parameter-matching results in Step 3-1.

Step 3-3: Administer the questionnaire to a group of professionals to ensure their approval of the matching results. Determine that more than half of the specialists accept remarks as “accepted” or “rejected.” Reform the rejected items according to specialists’ suggestions until all of them are accepted.

Step 3-4 Confirm the relative effectiveness of the expert opinions on the parameter-matching results by using the Cochran test, a statistical test.

Step 3-5: According to the results of Step 3-4, construct a verified parameter-corresponding table for the segment of foreign language teaching. The specified contradiction matrix is now ready for use.

Phase 4: Originate the practicable solutions by using the TRIZ contradiction matrix. Following the indicated TRIZ inventive principles, all probable solutions may be generated through various discussions. This process is divided into the following steps:

Step 4-1: Describe the existing problems specifically and identify the elements of the existing problems based on the interviews conducted in Phase 1.

Step 4-2: Define the ideal situation to be achieved when the existing problems are solved.

Step 4-3: Apply fuzzy QFD with the entries of determinants from Phase 3 to indicate the critical determinants relevant to the existing problems. This step consists of five procedures.

(1) The importance of the relationship between teaching quality determinants from Phase 3 and the elements of the existing problems is described in linguistic terms with five distinct levels, namely, EI (extremely important), VI (very important), I (important), SI (slightly important), and NI (not important). The data can be collected from the opinions of selected teachers and students.

(2) The triangular fuzzy number is employed in this research, and all membership functions for the linguistic input data are standardized in the interval [0, 1]. The triangular fuzzy numbers {(0.75, 1, 1), (0.5, 0.75, 1), (0.25, 0.5, 0.75), (0, 0.25, 0.5), (0, 0, 0.25)} correspond to linguistic variables {“EI”, “VI”, “I”, “SI”, “NI”}, individually.

(3) Assume $T_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk})$ is the triangular fuzzy number of the k^{th} team member assessing the correlative importance between the j^{th} element of the existing problems and the i^{th} entry of teaching quality determinants. Thus, T_{ij} is the average fuzzy number of the i^{th} entry of teaching quality determinants for the j^{th} element of the existing problems. When $T_{ij} = (a_{ij}, b_{ij}, c_{ij})$ and n = the number of team members, T_{ij} can be calculated using the following equations:

$$T_{ij} = \frac{1}{n}\sum_{k=1}^{n} T_{ijk}$$

$$a_{ij} = \frac{1}{n}\sum_{k=1}^{n} a_{ijk}$$

$$b_{ij} = \frac{1}{n}\sum_{k=1}^{n} b_{ijk}$$

$$c_{ij} = \frac{1}{n}\sum_{k=1}^{n} c_{ijk}$$

Assume there is no weighting difference considered among the determinants of teaching quality, and, consequently, the integrated fuzzy number of each teaching quality determinant for m team members (A_i, B_i, C_i) can be calculated using the following equations:

$$A_i = \frac{1}{m}\sum_{j=1}^{m} a_{ij}$$

$$B_i = \frac{1}{m}\sum_{j=1}^{m} b_{ij}$$

$$C_i = \frac{1}{m}\sum_{j=1}^{m} c_{ij}$$

(4) Assume X is the defuzzified value of the integrated fuzzy number for each teaching quality determinant (A_i, B_i, C_i), and can be calculated using the following equation (Su & Lin, 2008):

$$X = \frac{A_i + B_i + B_i + C_i}{4}$$

(5) Based on the computed data, the prioritized significance of each relevant determinant can be ranked successively.

Step 4-4: Discuss the determinants that prevent the desirable situation from being achieved in the top region of the ranking list. The improving and worsening determinants can then be identified from the parameter-corresponding table developed in Phase 3.

Step 4-5: Based on the TRIZ contradiction matrix, indicate the intersection of the improving and worsening parameters and denote the numbers of the TRIZ 40 inventive principles.

Step 4-6: Identify the TRIZ 40 inventive principles that appear at least twice according to the outcome of Step 4-5.

Step 4-7: Based on relevant references, re-explain the inventive principles to suit the identified segment. Link the suggested principles to the existing problems and generate all viable solutions to eliminate the conflict points by discussion meetings.

Step 4-8: Examine the possible solutions and invite experts to rank them according to a set of decision-making criteria.

Phase 5: Implement the attainable solutions. If the existing problems are ineffectively solved, repeat the fourth stage until the conflicts are resolved.

4. Case study

The studied school is a privately funded university in central Taiwan. To aid in a later career, all students are required to master at least one foreign language, specifically, English. The university language center proposed and implemented an English enhancement scheme in 2009. The goal of the scheme is to enhance the English ability of students in a short time. However, since the implementation of the new policy, several students have encountered various problems. In addition to the proficiency and achievement tests (in-class quizzes, mid-terms, and final exams), students are graded according to online learning tests, online learning practices, weekly vocabulary tests, a certificate of English proficiency test, and the English learning passport, which involves participating in English activities. Students are expected to acquire an abundance of knowledge in class and after school.

The case study focused on providing an efficient approach for generating ideas to resolve the problems regarding general English teaching in the university to improve EFL teaching quality. The author first interviewed three teachers and three freshmen who participated in the English enhancement scheme for 1 year. The results showed various contradictions within the scheme, and that TRIZ could be used to resolve the teaching problems.

Phase 1: In the studied case, the university language center is in charge of the general English courses for all students. The problems arising in EFL courses were classified under the segment of foreign language teaching. The FAA diagram in Fig. 1 was developed based on the aforementioned interviews.

Phase 2: In this phase, the author concentrated on various perspectives from the literature review to extract the main determinants of teaching quality in the specified segment. By categorizing the related academic studies within the scope of the case problem, the author concluded that teaching quality improvement is related to educational quality, teaching effectiveness, student achievement, student satisfaction, and potential teaching difficulties. The teaching quality determinants mentioned in this study may suit both EFL teaching and other undergraduate subjects.

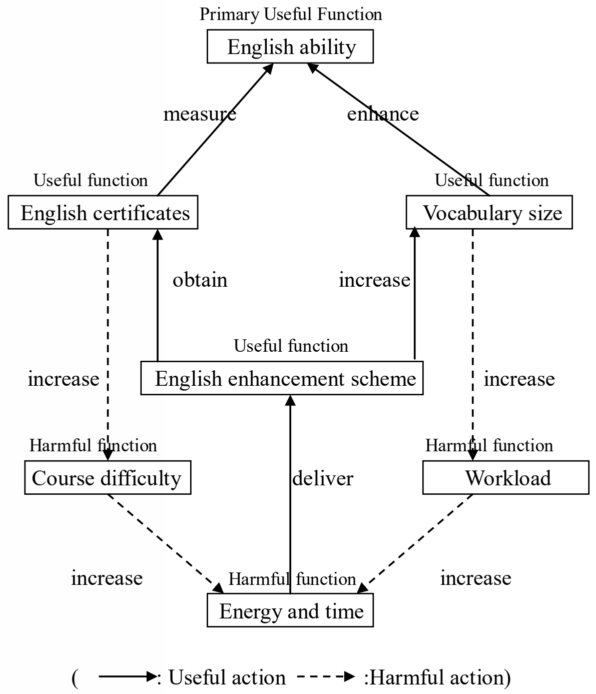

Fig. 1. The FAA diagram for the case study

Phase 3: The determinants of teaching quality developed in Phase 2 were analyzed and explained, and were subsequently correlated with the TRIZ 39 parameters. Semi-structured interviews with five experts in the fields of TRIZ, education, and EFL teaching were conducted to ensure a matching result.

The parameter-corresponding table is presented in Table 1. A TRIZ parameter may match more than one determinant of teaching quality. Furthermore, the determinants of teaching quality are not limited to those shown in Table 1. Each row of Table 1 represents the most similar analogical explanation between a determinant of teaching quality and a specific TRIZ parameter.

Subsequently, the author designed a questionnaire explaining each parameter, and five EFL teachers from the university were invited to answer the questionnaires with their professional opinions. Each item gained the approval of at least three specialists.

The Cochran test was used to confirm the consistency of the specialists' opinions on the parameter-corresponding results, which led to the development of the following null hypotheses:

H_0: No meaningful difference exists among the opinions.

H_1: A meaningful difference exists among the opinions.

"1" was used to express agreement with the matching result, and "0" was used to express rejection. The results were tabulated using c columns (c specialists) and r rows (r determinants). Each entry in the table was either "1" or "0." Ri was the row totals (i = 1, 2, ..., r), Cj was the column totals (j = 1, 2, ..., c), and N was the total number of "1" values in the table. The test statistic was calculated using the following equation:

$$T = c(c-1)\frac{\sum_{j=1}^{c}(C_j - \frac{N}{c})^2}{\sum_{i=1}^{r} R_i(c-R_i)} = 5 \times 4 \times \frac{14}{34} = 8.235$$

The computed statistic value of T was smaller than the critical value 9.488. The null hypothesis H_0 was accepted. Therefore, the 29 pairs of matching parameters were valid.

Table 1. Parameter-corresponding Table

No. of TRIZ parameter	Name of TRIZ parameter	Determinants of teaching quality	References
1 3 5 7 15 19	A mobile object	E-learning (web-assisted or web-based courses)	Liaw, Huang, & Chen (2007) Fichten et al. (2009) Liaw et al. (2007) Waschull (2001) Desai, Hart, & Richard (2008) Faul, Frey, and Barber (2004) Uzunboylu (2005)
2 4 6 8 16 20	A stationary object	Traditional classroom instruction	Stephenson, McGuirk, Zeh, & Reeves (2005)
9	Speed	The pace of a lesson	Greenblatt, Cooper, & Muth (1984) Feldman (1989)
10	Force	Group interaction	Phillips, Santoro, & Kuehn (1988) Marsh & Bailey (1993) Chickering & Gamson (1991)
11	Tension/ Pressure	Pressure or stress of students	Hughes (2005) Byrne & Flood (2003) Ginnsa, Prosserb & Barriea (2007)
12	Shape	Overall course impression	Harrison, Douglas, & Burdsal (2004)
13	Stability of composition	Well-designed curriculum	Walker (2003) Holley (2009)
14	Strength	Professionalism of instructors	Glenn (2001) Jumani & Yousuf Zai (2009) Eilam & Poyas (2006)
17	Temperature	Classroom atmosphere	Glenn (2001) Feldman (1989)
18	Brightness	Learning environment	Jumani & Yousuf Zai (2009) Beattie & Collins (2000) Strolin-Goltzman (2010)
21	Power	Enthusiasm and efforts of teachers	Minchella (2007)
22	Loss of energy	Excessive workload	Harrison, Douglas, & Burdsal (2004) Feldman (1989) Byrne & Flood (2003)
23	Loss of a substance	Maintenance of facilities and equipment	Beattie & Collins (2000)
24	Loss of information	Selected course content	Sözbilir (2004)
25	Loss of time	Spending time on classroom management	Van de Grift (2007)
26	Amount of substance	Adequate facilities and equipment	Beattie & Collins (2000)
27	Reliability	Teachers' self-efficacy	Fives & Buehl (2010) Klassen & Chiu (2010)
28	Accuracy of measurement	Accuracy of grading	Harrison, Douglas, & Burdsal (2004) Beattie & Collins (2000) Jumani & Yousuf Zai (2009)
29	Accuracy of manufacturing	Aligning teaching and assessing with course objectives	Biggs (1996)
30	Harmful factors acting on an object from outside	Unnecessary interruptions	Greenblatt, Cooper, & Muth (1984) Kennedy (2006)
31	Harmful factors developed by an object	Disruptive student behavior	Kennedy (2006)
32	Manufacturability	The degree of class difficulty	Harrison, Douglas, & Burdsal (2004)
33	Convenience of use	Convenience of finding support	Klem & Connell (2004)
34	Reparability	Reflective teaching	Farrell (1998)
35	Adaptability	Flexibility in teaching (to respond to external environment or to meet student needs)	Feldman (1989) Zahorik (1990) Knight (1999) Glenn (2001)
36	Complexity of a device	Complexity of a grading policy	Sadler (2005) Linn, Baker, & Dunbar (1991)
37	Complexity of control	Complexity of the issues involved in grading	Guskey (2000) Wood (1994)
38	Level of automation	Self-initiated learning	Feldman (1989) Beattie & Collins (2000) Van de Grift (2007)
39	Capacity/ Productivity	Expectations for student performance	Beattie & Collins (2000) Chickering & Gamson (1991)

Phase 4: According to the results of FAA, the scope of the problem comprised the areas of vocabulary size, English certificates, course difficulty, and workload. These four were the elements of existing problems, and the author defined the ideal situation as the provision of a supportive and motivating environment for students to enhance their English ability without undertaking heavy workloads.

The fuzzy QFD process was initiated to identify the critical teaching quality determinants. The correlative importance between the teaching quality determinants from Phase 3 and elements of the existing problems was determined in linguistic terms based on the opinions of the three teachers and three students who participated in the English enhancement scheme for 1 year. The integrated triangular fuzzy numbers and the rankings of their importance are shown in Table 2.

Table 2. Integrated Triangular Fuzzy Numbers and the Rankings of their Importance

No. of Teaching Quality Determinant	Integrated Triangular Fuzzy Number			Defuzzied Fuzzy Number	Ranking of Importance
	A_i	B_i	C_i		
1	0.250	0.458	0.698	0.466	13
2	0.365	0.615	0.865	0.615	4
3	0.333	0.500	0.698	0.508	8
4	0.094	0.239	0.489	0.265	25
5	0.188	0.365	0.604	0.380	19
6	0.188	0.375	0.625	0.390	18
7	0.313	0.531	0.771	0.536	7
8	0.198	0.396	0.635	0.406	16
9	0.198	0.386	0.604	0.393	17
10	0.032	0.177	0.427	0.203	28
11	0.219	0.417	0.667	0.430	15
12	0.230	0.427	0.646	0.432	14
13	0.073	0.187	0.437	0.221	26
14	0.042	0.115	0.365	0.159	29
15	0.250	0.458	0.698	0.466	12
16	0.084	0.250	0.500	0.271	23
17	0.459	0.698	0.886	0.685	2
18	0.115	0.261	0.511	0.287	22
19	0.313	0.510	0.698	0.508	10
20	0.292	0.500	0.740	0.508	9
21	0.104	0.312	0.562	0.323	21
22	0.375	0.573	0.761	0.570	5
23	0.375	0.625	0.875	0.625	3
24	0.156	0.354	0.594	0.364	20
25	0.323	0.573	0.781	0.562	6
26	0.094	0.240	0.490	0.266	24
27	0.073	0.177	0.427	0.213	27
28	0.615	0.865	0.958	0.826	1
29	0.302	0.500	0.709	0.503	11

The author regarded the first five ranked determinants as the primary characteristics influencing student learning regarding participation in the English enhancement scheme. The selected determinants were self-initiated learning, teachers' self-efficacy, convenience of finding support, traditional classroom instruction, and the degree of class difficulty.

To achieve the ideal situation, the five identified important determinants must be improved. However, this involves several issues. First, encouraging self-regulated learning may require increasing peer interaction and professor interaction. Interaction gives learners the opportunity to model behaviors and to measure their progress, which in turn increases the motivation to learn. Second, improving the self-efficacy of instructors requires extra in-service training. Teachers must spend more time participating in related workshops or seminars. Third, providing more support and offering additional courses increase the workload of teachers. Teachers must increase their efforts to satisfy student needs. Fourth, lowering the coverage rate and the level and amount of material may affect the productivity of students. Teachers may need to lower their expectations for student performance.

Table 3 shows improving TRIZ parameters, the corresponding worsening TRIZ parameters, and the number of TRIZ inventive principles in the intersection of the improving and worsening TRIZ parameters. The principles that occurred at least twice were No. 2, 10, 28, and 35.

Table 3. Improving and Worsening TRIZ Parameters and the Related Inventive Principles

Improving TRIZ Parameters	Worsening TRIZ Parameters	Number of Inventive Principles
38	10	2 35
27	14	11 28
33	21	2 10 34 35
2	21	15 18 19 22
4	21	8 12
6	21	17 32
8	21	6 30
16	21	16
20	21	
32	39	1 10 28 35

The author analyzed each of the inventive principles from the related studies and discussed them with the three teachers and three students who participated in the English enhancement scheme for 1 year to generate ideas for solutions. The study of Marsh et al. (2004), which provides educational examples of the 40 inventive principles, was the primary reference in the discussions.

The first idea was based on Principle 2, extraction. A remedial program can be established, and students with special needs should be separated from the general student population (Marsh et al., 2004). Teachers can arrange meetings with students who require additional assistance. The meetings can be conducted to review course content, emphasize key points, and provide additional practice.

The second idea was developed based on Principle 10, prior action. The accuracy of the placement test must improve. The current type of question is multiple choices, which is too simple for adequately determining the ability of students. Students who enter a class that is not suited to their ability encounter problems. Increasing the number and variety of placement test questions may facilitate determining the actual level of student ability.

The third idea was derived from Principle 2. Students in the studied university were classified according to their placement test performance: superior, intermediate, and average. Students should study materials suited to their English ability. Students should be classified into more than three levels.

The fourth idea was based on Principle 35, transformation of the physical and chemical states of an object. Numerous students do not appropriately equip themselves to study current courses. They must enhance their basic skills, such as phonetic symbols, pronunciation, and grammar. Intensive courses can improve students' skills in a short period of time. These basic courses can be taught during nights, weekends, and summer and winter vacations for a small tuition fee.

The fifth idea was based on Principle 35. Teachers can reduce the volume of vocabulary taught throughout the semester, but assign homework during summer (2 months) and winter (1 month) vacations. Therefore, students can reduce their workload, reducing the probability that they neglect their studies during the semester.

The sixth idea was based on Principle 35. The university offers English classes only for freshmen and sophomores. Instead of teaching a substantial amount of content in the first 2 years, it may be useful to provide courses throughout the 4 years of undergraduate study. Offering English courses to junior and senior students may enhance their learning.

The source of the seventh idea was Principle 35. The general English course is 2 hr per week. Because teachers are unable to teach all the content in 2 hr, it may help to add 1 more hr to the course. Three hours per week gives teachers sufficient time cover all the course content.

The eighth idea was based on Principle 28, replacement of a mechanical system. Teachers can divide students into groups consisting of both high and low achievers. Those who perform highly are responsible for tutoring the others. The study group provides opportunities for students to model desired behaviors.

The ninth idea was based on Principle 35. The university offers courses for preparing English certificates, but only a certain number of students enroll in these classes because of the cost. The school can provide additional classes for all students who want to join the program for a small fee.

These nine ideas were prioritized in the grading from 1 to 10 and were evaluated by five teachers from the university. Cost, time, and manpower were the three criteria considered when making the final decision. The nine ideas were arranged according to priority as follows: Idea 9, 6, 2, 8, 7, 5, 3, 4, and 1.

Phase 5: The school was suggested to implement these nine ideas according to their priority. The results of the implementation are not demonstrated in this case study. Researchers may consider evaluating the results in future studies.

5. Conclusion

The contribution of this study to EFL teaching is the suggestion of a creative approach to improving teaching quality, a contribution that provides a considerable boost toward solving teaching problems. This study also fills gaps in previous research on TRIZ by constructing teaching quality determinants that correlate with the TRIZ 39 parameters. Although the verified parameter-corresponding table may not reflect all the distinct patterns of teaching quality, implementing the proposed approach would produce a considerable effect on the education field.

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