

Improving the Skills of Engineers in Systematic Thinking

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Abstract

Thirty-six engineers from mechanical and electrical backgrounds were involved in extensive training in systematic thinking (based on the Russian Theory of Inventive Problem Solving – TRIZ). Training included approximately 60 hours of face to face work, and around four months of individual project work. Engineers studied the following tools: Situation Analysis, Method of the Ideal Result, Substance-Field Analysis, Innovative Principles and the Contradiction Table. Every engineer took on a real company task as a project. Some projects were unresolved company problems; some were related to new product development and failure analysis and prevention. Projects were conducted individually by the engineers, under the author's supervision, who helped the engineers to apply tools of TRIZ systematic thinking properly. Thirty-three projects have been successfully resolved with tangible and intangible outcomes. In their reflections, the participants identified a lack of systematic problem-solving tools in their engineering work prior to the introduction of TRIZ thinking tools. Participants found that TRIZ thinking tools helped them to come to solutions that had been previously unachievable. They also found that their own thinking had been affected by the experience- it had become more systematic.

Introduction

We live in a rapidly changing world. Sony releases over 5,000 new products a year. Drug manufacturers have reduced the development time of new drugs from ten years to four. To innovate continuously and to lead the market, Procter & Gamble employs more scientists than MIT, Harvard and Berkley combined. The pressure on engineers and scientist to innovate and problem solve efficiently is constantly growing. Nonetheless, the educational system does not place enough emphasis on training future engineers and scientists to employ adequate skill of problem-solving and innovation.

The amount of information created in fields of science and engineering annually, already exceeds what an ordinary engineer is able to comprehend. And the rate at which new information is created is rapidly growing. In his profession, an engineer is expected to create new products and to resolve problems related to existing products. Usually, only a limited period of time is given to an individual and/or team to achieve this. A lack of formal education in engineering problem-solving means that trial and error is the most widely used approach in day-to-day engineering work. It is also common for an engineer to use brainstorming and deploy various analogies when faced with a problematic situation¹. These approaches to problem-solving are not systematic. The thoughts and actions of an engineer using trial and error are unstructured, so the result of the problem-solving process is

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unpredictable and is heavily dependant on the personality of a problem solver and her/his experience.

This is not a surprise. Both in high school and in university students are often encouraged to better prepare for the examination, in order to answer questions which are likely to be in the exam paper. This ensures that they will achieve good grades. As a result, students look for ways in which to correctly answer questions that have been presented by their lecturers. They try to learn how to analyse and resolve problems which have the 'right' answers and solutions. Some academics may even request that students use a particular technique to derive the right answer, and deduct marks when different methods are used, even though the correct answer is found. Therefore, it is not surprising that students expect every question to always have the right answer, and that the question must be resolved only by the approved method. This approach to problem solving is often taken by the students from university into their professional work. Contemporary approaches employed in educating engineers have not worked successfully so far – graduates needed many years of practice to be able to adjust their minds to the real engineering world. This approach is currently stunting the development of many engineers and scientists in the 21st Century.

Life expectancy of products and processes in the 20th Century was sufficient to permit a number of redevelopments and 'improvements' to the products and processes over their lifespan. Engineers using trial and error were able to cope with the existing pace of product development and product improvement. The natural life of products today is much shorter. This is understood even by the world's tax offices. Most of them allow businesses to replace laptop computers every two to three years, for example. The engineering profession of the 21st century requires solutions of a different sort. In the words of Charles Handy, "Life seems to be a succession of open-ended problems with no right answers, but problems, nevertheless, which demand an answer."² Therefore, engineering education needs to be adjusted to ensure that engineers of the next decade will be able to deal efficiently with open-ended problems, which often occur under uncertainty and with considerable information overload. To achieve this, engineering graduates need to be more creative- they must become more systematic in their problem-solving work.

Over the years, many authors have investigated the skills of problem-solving and creativity³⁻⁵. They have suggested that in order to be able to approach open-ended problems, a practitioner needs to improve his/her thinking skills. Moreover, they found that those thinking skills can be taught^{4, 5}. Scholars model thinking processes by emphasising various aspects of cognition. They have subdivided thinking into many areas: systematic thinking, systems thinking, critical thinking, lateral thinking, wishful thinking, big-picture thinking etc.⁶⁻⁸ Researchers have also propose various tools to improve human thinking.^{1, 4, 5} Thinking in general is defined as using the mind "to consider something, to form connected ideas, to try to solve problems..."⁹ Therefore, an improvement in thinking may be related to any aspect of cognition.

It is well known that when students study regularly and systematically, they achieve more than whilst working without a good plan. This suggests that using thinking tools systematically may help to improve the outcomes of problem-solving and idea generation. The subject of this investigation was to find out whether systematic application of TRIZ thinking tools could enhance the thinking skills of engineers, and therefore change the outcomes of their engineering work. There was a further interest in whether engineers valued their thinking skills, and whether it was worthwhile for these skills to be taught separately.

Method

Thirty-six engineers from mechanical and electrical backgrounds were involved in extensive TRIZ training. All engineers worked for the research and development centre of a large engineering company. Training consisted of 60 hours of face-to-face learning workshops, and four to five months of individual project work, where the participants applied the tools learnt in a systematic way to real company tasks under the author's coaching. Face-to-face workshops were conducted over two weeks in a mode similar to a short course. During the 60 hours of workshops, engineers studied the following tools of TRIZ: Situation Analysis, Method of the Ideal Result, Substance-Field Analysis, 40 Innovative Principles and the Contradiction Table, Laws of Development of Technical Systems, and Analysis of Conflict Zones (CZ).

Workshops were followed by a practical component, whereby engineers were involved in individual projects closely related to their work. Engineers involved in the trial continued to work full time and were able to use up to 5 hours a week for their TRIZ project work. Most of the individual projects were unresolved company problems. Some projects were devoted to new product development, cost reduction and failure analysis and prevention. In their project work, engineers were requested to follow the Seven Steps of Systematic Thinking.¹⁰ Most practical projects took 4 to 5 months to finish. Project coaching was conducted via e-mail, fax and telephone conversations. The main aim of project coaching was to help participants apply the thinking tools learnt during the face-to-face workshops properly. Sometimes, suggestions on which tool was to be used next were also given.

Thinking Tools of TRIZ

TRIZ is the Russian acronym for Theory of Inventive Problem Solving. It is a well-established system of tools for problem-solving, idea generation, failure analysis and prevention. TRIZ originated in Russia more than 50 years ago.⁵ TRIZ thinking tools branch from the evolution of products and processes, which have been revealed through the analysis of thousands of patents. Developed behind the iron curtain, TRIZ was used by Russian engineers and contributed to many inventions. TRIZ entered the Western world in the early 1990s, and has already helped many western companies to achieve enormous improvements. The following is a short description of the tools which the participants of the training were taught.

Situation Analysis (SA)

Situation Analysis was used by the participants as the first thinking step, on the way to situation improvement. SA is designed to question the assumptions of a user and his/her perception of the problem. To solve a problem, it is imperative to understand what the problem is about. Our perception of the situation and our entire outlook concerning its improvement often changes when various needs of the situation become apparent.

When humans consider real problems (situations) they often mix many issues together. Technical matters are often blended together with human emotions. These issues are indeed

related, but they often correspond to very different aspects of the situation and can therefore be dealt with differently. Usually, the people improving the situation attempt to address all the human and technical issues at once. This is not the most efficient method by which to achieve success. Proposed actions rarely achieve the outcomes expected. An approach such as this often results in time and resources being wasted.

The SA tool deployed in this study required participants to answer a set of questions. This was intended to achieve the following outcomes:

- to clarify the situation under consideration
- to separate human perceptions from the reality of the situation
- to identify different problems embedded in the situation
- to formulate the tasks that were to be undertaken for the situation improvement

Most projects under the SA procedure required two to four weeks to be completed.

Method of The Ideal Result (MIR)

Method of the Ideal Result (MIR) has been developed by the author.¹¹ MIR is based on the TRIZ notion of the Ideal Ultimate Result (IUR). It has been found that when engineers face problematic situations and need to devise some improvements, two main issues are especially challenging. They are:⁴

- to identify the most problematic issue to focus on during the improvement
- to be able to utilise the resources which are available, almost for free.

We often find ourselves in situations where improvement is necessary, but the element that should be focussed upon is not always apparent. Identifying the correct element to focus on is vital. Unless an engineer applies his/her skill and invests money into upgrading the system part which holds up overall performance the most, the outcome of such improvements is likely to be quite unsatisfactory. The first part of MIR is designed to aid users in pinpointing the very element upon which to focus.

Another common mistake made by many engineers is related to the introduction of additional resources (e.g. parts, elements, substances, etc.) to improve the situation, without having a clear picture of what resources are originally available. Any new resource costs money. Most existing resources are either free or inexpensive. Moreover, the existing resources are already available and do not need to be supplied! The second part of the MIR procedure helps a user to identify the resources available, and consider how these resources may be used in improving the situation.

Overall, MIR helps a user to accomplish the following:

- to identify the direction towards an effective and simple solution
- to separate different areas of improvement, and to identify the elements one needs to focus on to deliver the most efficient improvement
- to recognize all the resources at hand
- to sift through all the available resources, with the aim of seeing whether they may help in improvement

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All engineers in the trial used MIR by employing the *TRIZAU MIR Proforma*.¹²

Substance – Field (Su-Field) Analysis

Substance-Field Analysis pictures any natural and man-made system as a set of interacting elements – a set of *substances* interacting with each other by means of *fields*, which are generated by the substances. Substances and fields in Substance-Field Analysis are not equal in representing systems – substances describe real system elements and fields show the interactions between these elements. Nonetheless, both substances and fields are represented in a similar manner – by circles. This ensures that vastly different real systems are modelled in a similar way – by means of *circle-substances* and *circle-fields*. Such generalisations enable a practitioner to represent complex systems by simple structures of circles. This allows a user to consider different systems in a uniform way and to apply similar rules to resolve dissimilar problems. An example of a two-dimensional representation of a system, as a set of fields and substances, is shown in Figure 1.1. The circles with the letter S represent substances, the circles assigned with F symbolise the fields generated by these substances.

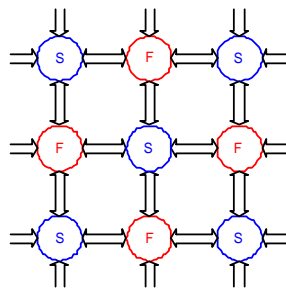


Figure 1.1. A two-dimensional representation of a system in Su-Field

The real picture of a system is often more complicated and has more dimensions than the one shown. Nonetheless, such models and generalisations of circle-substances and circle-fields help to systematise our thinking.

Su-Field Analysis is a general tool for idea generation and failure analysis and prevention. It models a system through a set of interconnecting substances and fields. This converts the real task into its Su-Field model and helps to clearly identify the *conflict zones* of the system. These conflict zones are broken down into *conflict triads*. Five model solutions are considered for every conflict triad. Eight fields of MATCEMIB (Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular, Biological) are deployed to “translate” model solutions into real solutions. Most participants in the trial used contemporary Su-Field Analysis¹³ for idea generation and failure prevention.

The Contradiction Table (CT) and 40 Innovative Principles

The 40 Innovative Principles are “solution recipes”, that have been successfully used in thousands of patents. To derive the 40 Innovative Principles, more than 20,000 patents were analysed.⁵ It was found that dissimilar tasks from distinct areas of engineering and science

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were often solved in a similar manner. The 40 Innovative Principles group these ideas into larger groups, called principles. The 40 Principles can be used separately, but they yield better solutions when used together with the Contradiction Table. The Russian versions of the TRIZ Contradiction Table (CT) and 40 Innovative Principles have remained unmodified for over 25 years.

The Contradiction Table (CT) and 40 Innovative Principles, when used together, represent another idea generation tool which models real systems. Unlike Su-Field, which provides the user with a wide variety of general ideas for implementation, these tools offer solution ideas which are design-ready. The *TRIZ4U CT Proforma* was utilised by the participants to model systems accurately.¹²

Laws of Development (LD) and Patterns of Evolution (PE) of Technical Systems

The Laws of Development of Technical Systems are an efficient tool for product strategy. Laws of Development provide the general directions of systems' evolution. They provide insight into the directions of technology/product/concept evolution, and help in designing tomorrow's products today, and in making the right decisions with regard to disruptive innovations. Patterns of Evolution of Technical Systems (PE) cover the reasons for the evolution of products, reveal patterns of product evolution and provide further insight for designing tomorrow's products today. PE is often studied together with the Laws of Development. Only some participants in the trial used the Laws of Development and Patterns of Evolution of Technical Systems in their project work.

Analysis of Conflict Zones (CZ)

Analysis of Conflict Zones is a tool used for the identification and analysis of conflict zones in a system – the parts of the system which limit the system's performance. A TRIZ4U System Model and a TRIZ4U Matching Table are used. Only some participants in the trial used this tool.

Seven Steps of Systematic Thinking

Engineers were asked to conduct their practical work using the Seven Steps of Systematic Thinking¹⁰:

1. Situation analysis.
2. Revealing the system's stage of development.
3. Identifying the ideal solution.
4. Idea generation.
5. Failure prevention.
6. Adjusting the super-system and sub-systems in accordance with the solution found.
7. Reflection on the solution and the process of the solution.

Participants were required to submit project reports regularly to outline their progress.

Results

Two main measures were used to evaluate the effectiveness of the systematic use of TRIZ thinking tools, which included the tangible and intangible. The tangible measures evaluated the success of the projects from a technical perspective – whether the problem had been resolved and how (cost savings and the level of the proposed solution). The intangible measures evaluated the perceptions of an engineer, relating to his or her achievement and level of improvement in thinking ability.

Tangible outcomes

Thirty-three of the 36 project tasks were successfully resolved. Twelve of the proposed solutions ensured significant cost savings, if implemented (only 3 have been implemented so far). Most of the proposed solutions were evaluated by peers as innovative, and even patentable.

Perceptions of engineers

Engineers were asked to reflect on their experience, and on the changes in their problem-solving skills and thinking abilities as a result of the training. The majority of them found that their thinking skills had improved. They also believed that their problem-solving abilities had been enhanced and their idea generation became systematic. Some participants suggested that it would be very favourable to introduce these thinking tools to all engineers, and also into undergraduate engineering degrees. The following are some reflections from the engineers who were involved in the trial

“TRIZ has provided a systematic analytical approach to problem solving and idea generation in design as in the case of this project. It has provided some great ideas which were never thought of while designing the conventional way.”

“The ideas generation phase is an enriching experience while using TRIZ tools. There is always a tendency for designers to focus on an initial idea to solving a problem and overlooking other methods that may be more appropriate. TRIZ encourages the designers to look beyond the fields other than the one he is most familiar. It is very natural for a mechanical engineer to solve a problem using mechanical means, while an electronic engineer would solve the same problem by electronic means.”

“Certain concepts or ideas generated using TRIZ may not be applicable at the current point of time, especially when it is something new and still at the infancy stage of development. The technology may not be available now but that doesn't mean that it will not be in the future. TRIZ helped us to identify and focus on the development of selected core technology and make us ready to implement it on our product when the technology matures.” (This participant was developing a new product).

“On the whole, TRIZ tools offer a systematic thinking process which effectively reduces the traditional thinking process like brain storming, fish bone diagram, etc. It assists the designer by recording the thinking process, which eventually leads to the solution. In this way, the points discussed during the thinking process will not repeat itself.” (Product improvement).

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“One important lesson I learned using TRIZ was: "even if we find a good idea, seemingly the best solution, during any intermediate process of problem solving, we should not stick to it and we should not think it the unique, best solution. We should better treat our thinking process more objectively and apply the problem solving steps of TRIZ properly to our own problem solving; thus we should be able to make our own mind more relaxed to generate a variety of solution concepts.”

“After much practices of using the TRIZ tools, it has slowly set into my thinking habit. For example, when I need to purchase something, I will subconsciously ask myself what is the “super-system” of the “system” I am buying and can I fulfil the “super-system” with something else? I did not notice that I was doing it, until I have done it.”

“TRIZ brought out the structure of ideas and thought in various stages to solve my project. Although the solution was pretty much similar to the current solution, but the time required deriving the solution was shorter (i.e. 2 months instead of 12 months). The cost of trial and error was eliminated therefore reducing the developmental cost. Should this project have started with TRIZ, cost, man-hours and development lead-time could have been significantly reduced.”

“Through the application of the various TRIZ tools, it has help in generating the various possible solutions which was previously not thought of.”

“TRIZ in a way, helped me to thoroughly search and find the root problem before ideas of possible solutions via the various field available in the world are found.” (Project on failure analysis).

“TRIZ can be a revolutionary tool to incubate innovation among designers. When a designer starts to question himself to explore different methods to solve a same problem, the seed of innovation is planted. TRIZ can be seen as the appropriate ingredient to sprout ideas.”

“After spending six months trying to understand and adopt the TRIZ problem solving methodology, I personally feel that it is an innovative thinking process which effectively reduces the traditional thinking process. Through our educational system, we have been taught/brainwashed on how to solve problems with the correct solution. We are always eager to look for the correct answer, and most often neglecting the minor details which are critically related to the problem. With the help of TRIZ, I began to understand the importance of looking at a task from a wider perspective, recording down the thinking process and generating a more discipline and systematic approach when it comes problem solving, and this is especially beneficial when it involves a complex system. “

“TRIZ has also structured the approach in my thinking process. It has opened a new era of areas in my research to be explored. This structure has allowed to analyse on what have I not covered or duplicated in my research.”(R&D project).

“TRIZ helps me in the project because it is a systematic way of creating new ideas or problem solving. By following the steps it triggers new ideas naturally. Without a system it is much more difficult to develop new idea.”

“The TRIZ methodology has brought about a systematic approach to problem solving. The same set of tools used at different stage leads into a detail and in-depth thinking, which at most times was not given much attention.”

“Basically, I feel that TRIZ on the overall helps me to cover thoroughly the different aspects of the problem in hand. The systematic approach to the problem helps me to focus and understand the problem better. It is a much better tool than the normal brain-storming session that we have.”

“The process of finding the solution in TRIZ is very structured. This helps me a lot. For me, I am always quick to propose a ‘best’ solution and this will actually stifle the generation of other better solutions. TRIZ actually takes away this bad habit. It breaks a complex problem down into many digestible subtasks. This is beneficial especially it is a complex system.”

“My introduction to the TRIZ innovative thinking method has broadened my understanding of product development and technological advancement. Through this program, I arrived at a (*the system’s name*) design quite different from my initial proposal. This is exciting for an engineer who has found a tool that could offer alternative solutions. The SA and MIR is useful in clarifying the circumstances of a problem. I appreciate the emphasis these tools place on time and space resources.

These intangible resources are important engineering considerations but are oft-neglected. Whilst the prior tools try to widen my perspective of the design problem at hand. The subsequent tools of TRIZ, namely MIR (2nd part), Su-Field and Contradiction table draw focus to the critical areas of the problem. The ideas generated then form the basis or guidelines for a design concept. Systematic indeed. Problem solving aside, TRIZ also seems to have predictive tools for technological advancement. I find the study on the stage of development of my system quite interesting. The Line of System Evolution and the Laws of Development put the user in a future-oriented mindset and they cast light on what direction the future may take. This I believe is the key to innovation.”

Overall, the reflections of the engineers can be categorised into four major perspectives:

- They identified that there was a lack of systematic problem-solving tools in their engineering work, prior to the introduction of TRIZ thinking tools.
- Engineers clearly expressed that the TRIZ thinking tools had helped them to come to solutions they were unable to reach before, and often in much less time than was anticipated.
- They found that their own thinking was affected by the experience – it became more systematic.
- The participants were able to utilise their existing knowledge more effectively.

Conclusion

Lester Thurow, writing on the future of capitalism, referred to the importance of education in the 21st Century: “But basically the dominant competitive weapon of the twenty-first century will be the education and skills of the workforce.”¹⁴ The results of this training trial identified the importance of systematic thinking and problem-solving skills in the engineering profession. Training in TRIZ tools of systematic thinking helped engineers to use their existing knowledge more effectively, and to enhance their problem-solving skills.

Consequently, systematic thinking must be incorporated into the engineering curriculum, in order to prepare engineering students for the next frontier of technological development.

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