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TRIZ: Theory of Solving Inventive Problems to support engineering innovation in maritime industry

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Key words: invention, TRIZ, conceptual design, problem solving, technology forecast, innovation

Abstract

The key ingredient, which provides the strongest impact on success of an innovation process, is the stage of generating new inventive solution ideas, which requires creativity and out-of-the-box thinking. Until the beginning of the 2000th, and even still very much today, creative engineering has been random and chaotic as it was not supported by scientifically based methods. As a result, the process has low effectiveness of dealing with situations demanding new inventive solutions. Introduction of TRIZ (Theory of Solving Inventive Problems) has radically changed the situation in many industries. TRIZ provides a structured support to organize engineering creativity based on many years of studies of innovative development of diverse technical systems and technologies. These studies helped to extract and formulate generic patterns of inventive solutions, which can be reused to produce new ideas in a much shorter time period rather than using traditional methods to enhance creative thinking. Although TRIZ has been successfully used in a number of industries, its use in maritime industry has been rather limited, most likely due to the low awareness by maritime engineers. This paper discusses modern TRIZ and presents some of its techniques that can be utilized in maritime engineering.

Demand for inventive solutions

In general, an innovation process focuses on either innovative improvement of an existing product or technology, or creating a pioneering product or technology. This process usually consists of three principal activities:

1) *Creative Phase*: proposing a number of new ideas for future inventions and selecting the most promising one.
2) *Design and Engineering Phase*: designing and engineering a new inventive solution based on a selected idea.
3) *Implementation Phase*: bringing a new solution to the market or implementing it in an industry.

While the second and third phases are relatively well supported by systematic methods, the creative phase is still considered as art instead of science. This occurs due to the lack of knowledge on how to deal with numerous constraints and multiple impact factors, which block the generation of new out-of-the-box solutions. One reason is that these constraints cause a strong psychological inertia, which prevents an inventor from moving in the right direction, which is very difficult to manage.

Since disruptive inventions are supposed to break old engineering paradigms, one can consider a process of obtaining a disruptive innovative solution as a process of solving non-routine problem solving tasks. Meaning, one must first define the boundaries of a space of all possible solutions, then to define a process of navigating within the space, and finally to apply specific principles to identify the most promising solution idea which satisfies all constraints and requirements given. Most difficult situations occur when neither a navigation process nor specific principles are available. Therefore, due to the lack of understanding what search directions should be explored, engineers have to rely on random methods of boosting creativity, such as brainstorming, to expand the solutions search space and to generate as many ideas as possible instead of applying a clearly structured method.

Despite progress in exact sciences, studies of creativity have been primarily focused on exploring psychological aspects of creative behavior of an inventor rather than exploring results of creative processes to attempt to identify psychology-independent regularities and patterns. In other words, most research aims at finding ways how to manage the inventor's behavior regardless of understanding logical mechanisms of producing the outcomes of creative activities (Dhillon, 2006).

As a result, the effectiveness of supporting the inventive process based on random psychological methods appears to be quite low. Solving tough engineering challenges requires generating hundreds or even thousands of ideas without any guarantee that a successful solution will be found.

An approach to structuring and organizing a creative engineering process was proposed by Altshuller and Shapiro (Altshuller & Shapiro, 1956). The founder of the approach, Genrich Altshuller argued that all technical products evolve according to the same patterns irrespectively of the engineering domain. Consequently, in order to understand how to drastically reduce the number of trials and errors during the creative engineering or design phase, the studies should not be limited to understanding psychological aspects of the creative process only but focus on discovering the fundamental principles, regularities and laws which govern innovative development of products and technologies through learning how they were developed since their inception. A well designed theory for organizing support of the creative engineering and design phases should help to make the process of inventing both effective and efficient for any engineer or designer regardless of his/her creative capabilities.

Further studies by Altshuller and his associates based on the assumption of the existence of objective laws of technology evolution resulted in the development of a new discipline of technical creativity: TRIZ, which is a Russian acronym standing for "*Teoria Reshenia Izobretatelskih Zadach*" translated as "*Theory of Inventive Problem Solving*" (Altshuller, 1969).

Modern TRIZ is a large body of both theoretical and applied knowledge, offering a number of practical tools to support a wide range of different tasks related to innovation: from unblocking of a narrow bottleneck in a manufacturing process, to forecasting the future evolution of industrial and consumer products and entire technologies. Today, a number of books have been published with detailed descriptions of modern TRIZ (Altshuller, 1999; Savransky, 2000; Mann, 2002; Gadd, 2011; Bukhman, 2012).

Below we will introduce the main TRIZ discoveries and present the structure and contents of modern TRIZ.

TRIZ discoveries

One of the key assumptions in TRIZ is that an invention which creates value for further development of technology and society is a solution to a standing problem related either to a particular technical product or specific technology to bring them to the next stage of innovative development. Inventions usually emerge from two starting points:

1. A need for a new solution arises when a certain problem cannot be solved with solutions available in an industry. Such situations are usually known as "market pull". In TRIZ, such problems are called "inventive problems". For example, the first catamaran-based vessels were invented in Polynesia about 1500 BC to solve a long-standing problem of stability of a vessel during the ride (Kirch, 2001).
2. A new disruptive idea is developed irrespectively of the scope of known problems. It is usually based on the use of newly emerged technologies or copying principles from other industries or nature (such situations are also known as "technology push"). For example, the invention of a diesel engine for powering heavy oil-mining machinery in the 1890s was quickly adopted for marine propulsion by building the first diesel-powered river tank *Vandal* in 1903 (Thomas, 2004).

Despite the different starting points of new inventions, all successful inventions within a specific engineering domain follows a certain logic of the development of technical products. TRIZ research uncovered the following:

1. Evolution of products and technologies is not random. Long-term TRIZ studies revealed that technical systems evolve according to certain domain-independent objective regularities and trends. Understanding these regularities and trends helps to identify what are the driving forces of development of a specific product or technology and to effectively solve inventive problems as well as forecast future developments regarding design and engineering.
2. To solve a problem innovatively means to find a new engineering or design solution, which either overcomes a current physical barrier or eliminates a contradiction created by conflict of demands. Contradiction is one of the key concepts of TRIZ and will be explained in more detail below.
3. An inventive solution always resides outside an area where a problem belongs. It is difficult to find due to a thinking barrier for an inventor who is usually a narrow specialist in a certain engineering field. To enable solutions search across different domains, the problem solving approach should be knowledge-based and well-structured to organize systematic access to knowledge of various disciplines.
4. To select and solve an ill-defined inventive problem, one needs to properly manage the complexity of the so-called inventive situation: to clarify the situation, to decompose a general problem to a set of manageable sub-problems, to extract the right sub-problem so as to solve and formulate it correctly. Innovators often fail since they invest their efforts to solving the wrong problem.
5. A new inventive problem must be explored not only at the place where it arose but also within the entire technical system where it belongs and even in a higher system if necessary. Any technical product is modeled as a technical system in TRIZ, which consists of interacting material and energy components and produces both internal and external functions within a certain context to fulfill a particular purpose. For example, a boat, a motor, and a pump, can be modeled as technical systems each of which is built to fulfill a specific purpose.
6. In order to effectively and efficiently solve inventive problems, TRIZ proposes a model-based problem solving approach through abstracting critical components of a problem and then applying abstract patterns of solution models which are relevant with the type of problem model. Such abstract patterns are heuristics were gathered during many years of study. They represent the knowledge bank of TRIZ.
7. We often may not see an obvious solution due to psychological inertia inherent to every person or team. To fight psychological inertia, one needs to develop abstract thinking skills, or to use readily available TRIZ generic patterns of inventive solutions, as well as specific techniques developed to reduce the influence of psychological inertia.

Solving inventive problems

As mentioned above, the vast majority of inventive solutions are a result of overcoming a situation when a problem faces conflict of demands, in which the conflict is eliminated rather than compromised. A contradiction emerges when there is a need to implement a certain change but such implementation would cause harmful-side effects that are not acceptable. For example, an attempt to increase a positive parameter – the speed of a boat in water automatically increases the undesirable friction and resistance of water. When a problem solver faces a contradiction which cannot be solved in a way known in his industry, it means that he faces an inventive problem, and its solution usually requires decoupling connection between the parameter or feature we want to improve and the parameter or feature which gets worse. But how and where to search for a solution?

A comprehensive study of patents undertaken by TRIZ researchers based on exploration of around 400,000 inventions in all engineering domains resulted in the following discovery: seemingly a huge number of specific inventive solutions in different industries comply with a relatively small number of industry-independent generic principles which could be used to generate almost all the solutions. In addition, it appeared that the number of typical contradictions is also limited and they were presented and associated with relevant inventive principles. This means that if a new problem is presented in terms of a typical contradiction, a relevant TRIZ principle identified with this contradiction can be used to propose a method to eliminate the contradiction regardless of the technical domain.

The process of abstracting a problem to contradiction and then matching it with a typical contradiction predefined in the TRIZ database helps to considerably narrow the solution search space. Rather than trying to jump to a specific solution and explore all search directions, a problem solver selects those inventive principles which are relevant to his/her problem and directly apply them.

The collection of TRIZ *40 Inventive Principles* (Altshuller et al., 2005) still remains the most known and widely used TRIZ problem solving technique to date. Each Inventive Principle in the collection is a guideline, which recommends a number of directions for solving a particular type of inventive problem. There are 40 inventive principles in the current collection, which are available in a systematic way according to the type of contradiction that arises during attempts to solve the problem. Each principle is accompanied with a number of examples to illustrate its application in different fields. Example of the inventive principle is the so-called "*Principle of Segmentation*" (Figure 1).

In maritime industry, we can observe numerous inventive applications of this principle:

- The contradiction "increasing the area of a sail to capture more wind leads to decreasing controllability over the sail" was solved by splitting one large sail into a number of smaller sails.
- The first propeller for marine propulsion, patented by Francis Pettit Smith, was a screw made by a single blade rotating along a cylindrical axis. Increasing the length of the screw did not help to increase speed but created high turbulence. An accident split the blade into two and as a result the boat's speed doubled (Bourne, 1852).

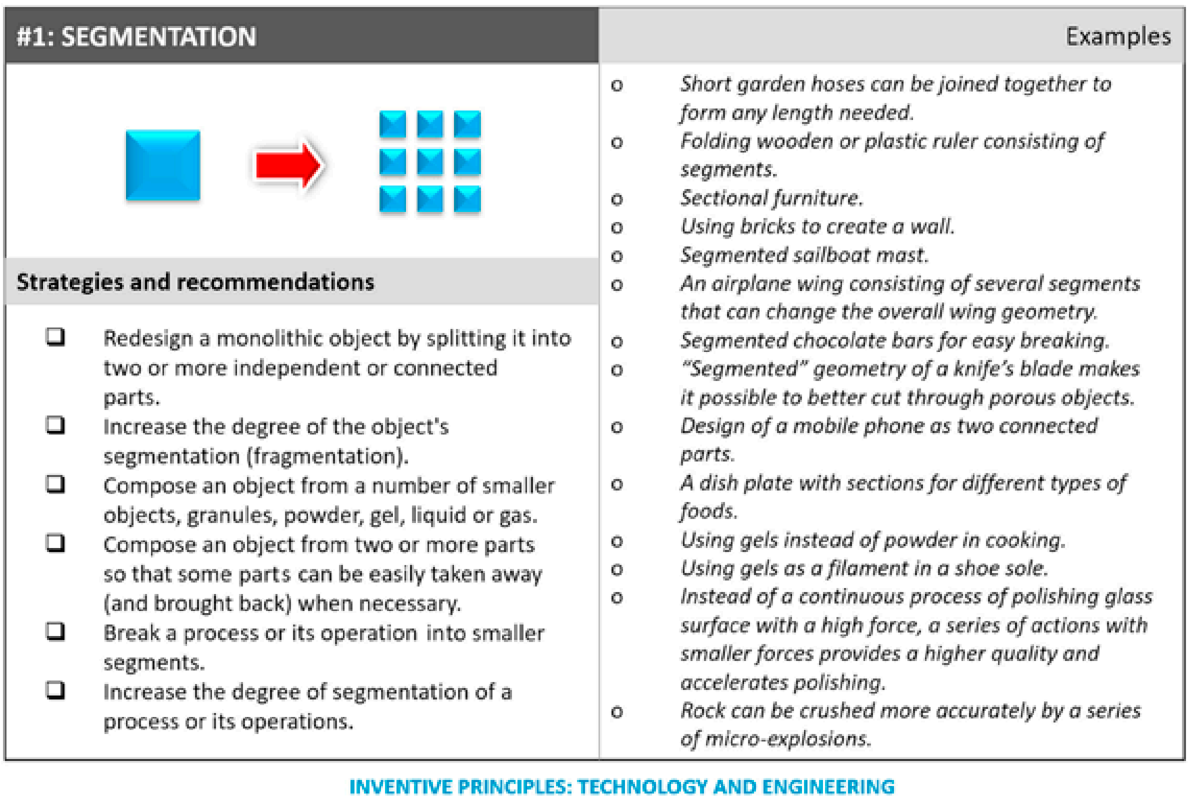


Figure 1. Inventive "*Principle of Segmentation*" in TRIZ. The examples in the right part demonstrate how the same principle is used in different industries (Souchkov, 2017b; Mann, 2002)

- The stability of a boat can be increased by increasing the area of its surface loaded to water. But a large area in the water increases water friction and wettability. Designing the boat as a catamaran or trimaran eliminates this contradiction (Harris, 1965).
- An anchor chain consists of metal segments which provide the required length when the anchor is in the water but at the same time requires much less space when stored onboard.
- Composing a body of ship compartments which can be hermetically sealed to prevent water from moving throughout the entire ship's interior during the accident.
- The mast on a sailboat should be tall to allow the large sail to be connected. But the taller the mast, the fewer bridges the sailboat can go under. The solution is to make a foldable mast, allowing it to split into several segments.

As seen, the same principle of segmentation can be applied to resolve contradictions at all levels of the same technical system: both at the components delivering main functionality as well as components delivering auxiliary functions. Its use can produce both incremental and disruptive inventions.

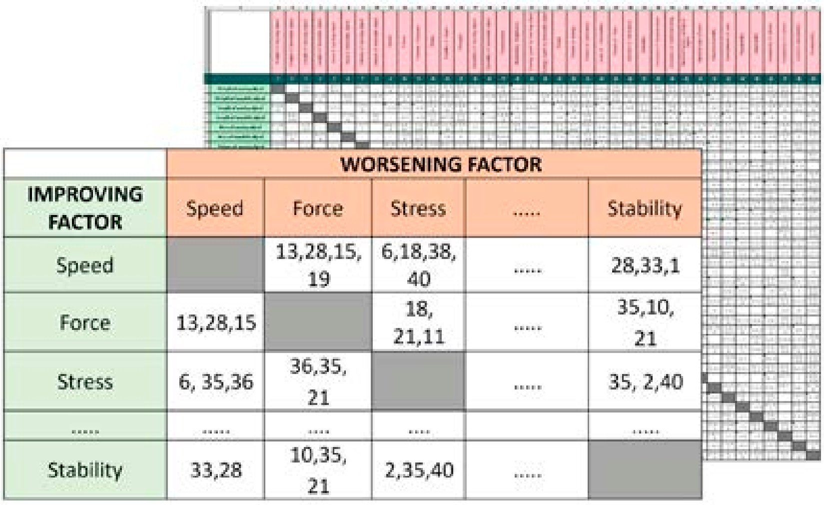
However, often a problem solver might not see a connection between a TRIZ inventive principle and his contradiction. It happens due to the presence of psychological inertia since often an inventive principle recommends a very different direction of searching for a solution, which was previously used in the problem solver's industry. Talking into account that TRIZ contains 40 principles and about 180 sub-principles covering all possible types of contradictions, it would be difficult to figure out which principles should be explored in depth to solve a problem.

To reduce the number of trials, Altshuller and his associates created the so-called *Contradiction Matrix*, which consists of 39 rows and columns (Figure 2). Factors (parameters, features) that have to be improved are listed along the vertical axis while factors that get worse when attempting to achieve the positive effects, are listed along the horizontal axis. By selecting a couple of improving and worsening factors, one can identify which principles should be used to solve the problem. The original Contradiction Matrix included 39 typical parameters, later updates (Mann, 2002) extended the list to 49 typical parameters.

An example on how Contradiction Matrix was used in solving problems for ship building (Nocerino et al., 2011) and protecting ships from corrosion (Weitzenbök & Marion, 2006) can be found in these references.

System and problem analysis

However, it is often the case when it is impossible to formulate a specific contradiction or even to clearly state a problem that can be solved. In such cases, before jumping to Inventive Principles and Contradiction Matrix, analysis of the initial situation should be performed to discover and structure problems, select the relevant problem and perform an in-depth analysis to extract underlying contradictions of a selected problem. To conduct such analysis, two techniques are commonly employed: Function Analysis and Cause and Effect Chain Analysis.



	WORSENING FACTOR				
IMPROVING FACTOR	Speed	Force	Stress	.....	Stability
Speed		13,28,15, 19	6,18,38, 40	.....	28,33,1
Force	13,28,15		18, 21,11	.....	35,10, 21
Stress	6, 35,36	36,35, 21		.....	35, 2,40
.....	.....	.....	.....		.....
Stability	33,28	10,35, 21	2,35,40	.....	

Figure 2. Fragment of the original Contradiction Matrix for eliminating technical contradictions. Typical parameters are located along vertical and horizontal axes. Numbers in the cells indicate what principles have to be used for each couple of conflicting parameters: 1 - Segmentation; 2 – Taking out; etc.

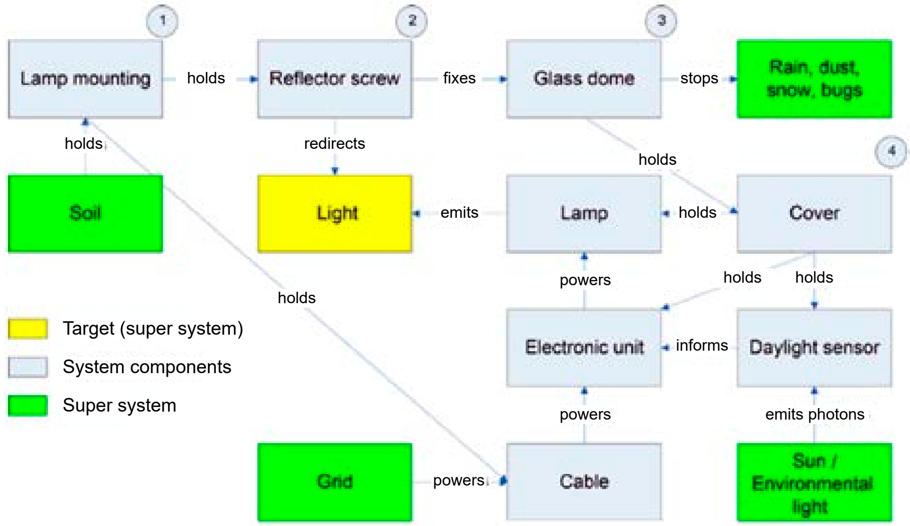


Figure 3. The TRIZ-based Function Analysis helps to identify functional interactions between the systems components, which helps to identify and rank functionality-related problems in the system (Mayer, 2017)

Examples of the application of *Function Analysis* (Figure 3) are presented in (Mayer, 2017) and the application of *Root Conflict Analysis* (a technique which belongs to the Cause and Effect Chain Analysis methods) is shown in (Souchkov, 2017a).

TRIZ innovation roadmapping and forecast

As mentioned above, one of the TRIZ discoveries was that technology evolution is not a random process but is governed by objective laws and trends. In 1979, Altshuller formulated a number of such laws and trends, and proposed to establish a separate discipline of study, which he titled "*Theory of Technical Systems Evolution*" (Altshuller, 1979). Further studies expanded the first set of Altshuller's trends and revealed a number of new trends (Zlotin & Zusman, 2001; Lyubomirsky & Litvin, 2003; Petrov, 2013).

The practical use of the TRIZ Trends of Technical Systems Evolution is possible through the so-called *Lines of Technical Systems Evolution*. Each trend presents one or more lines of evolution which depict a sequence of patterns and generic solutions which specify how a technical system moves to the next step of innovative evolution. For example, one of the TRIZ trends of technical systems evolution is the so-called "Transition to Supersystem". One of the lines of evolution in this trend is known as "mono-bi-poly transition". It states that any technical system can improve its effectiveness by using two or more components instead of a single component: for example, spectacles evolved from a single lens – monocle to two lenses providing stereoscopic vision and later to bi-focal lenses thus in total the number of lens reached four) or by merging with identical or similar systems. The same trend can be easily observed in maritime industry (Figure 4). Another line of evolution is that any system can eventually become a part of another system. For instance, the photo camera became a part of the smartphone. A detailed description of this trend can be found in (Salamatov, 1999).

The importance of knowing the TRIZ trends and the lines of technology and technical system evolution is that they can be used to assess the current state of the art of a technical system or of its part and identify what phases of evolution the technical system or its part has passed. Knowing which of the steps reside on the line, it is possible to forecast what disruptive changes the system might experience in the future with a high degree of probability.

One of the key concepts of TRIZ is the so-called "ideality" which serves as a major guideline when comparing alternative solutions to the same problem. The degree of ideality is a non-dimensional parameter which is identified as a qualitative ratio between the overall value of the main parameters of the solution (parameters that feature functionality, useful effects, design, societal values) and harms and costs needed to provide the value (material, energy, labor, etc). A better solution always provides a higher degree of ideality than alternative solutions. Solutions close to the ideal ones always tend to produce as little harm as possible and have the costs needed to provide their value as low as possible. TRIZ introduces a hypothesis that every technical system – either a consumer product, industrial machine, or manufacturing equipment tends to evolve towards a higher degree of ideality.

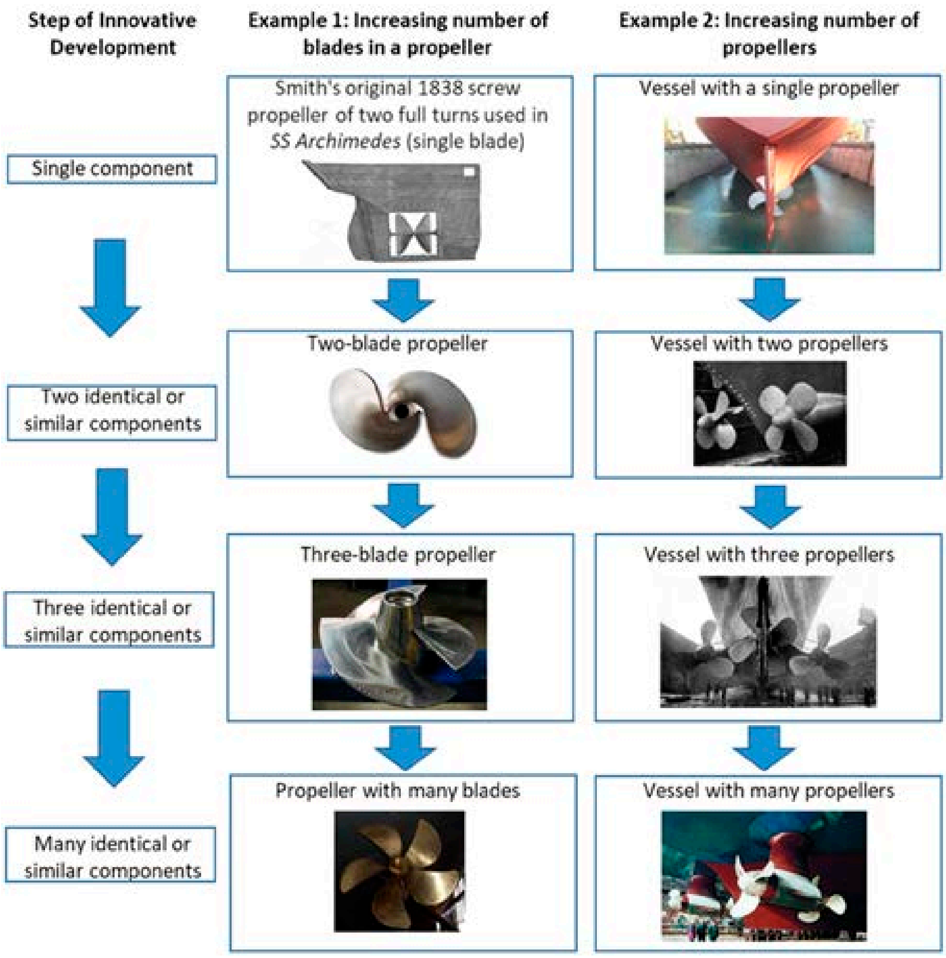


Figure 4. Steps of the TRIZ Line of Evolution "Mono-bi-poly" for a ship's propeller. Example 1 shows an increase in the number of blades of the propeller (Wikipedia, 2018a; Pro Drive Motors, 2018; Nevsky Shipyard, 2018). Example 2 shows an increase in the number of propellers on a ship (Marine Insight, 2017; Wikipedia, 2018a, 2018b, 2018c)

Inventive problem solving process

Due to the limits of this article it is not possible to present all techniques, thus we will only show how the problem solving process is organized (Figure 5). It represents a stage-gate process in which each stage includes relevant techniques according to the desired outcome.

Modern TRIZ: structure and key techniques

The collection of TRIZ tools developed at the beginning of the 1990s is known as "Classical TRIZ" (Zlotin et al., 1999) and includes mainly tools for solving specific inventive problems. Later, researchers and practitioners worldwide extended "Classical TRIZ" with a number of new methods, techniques,

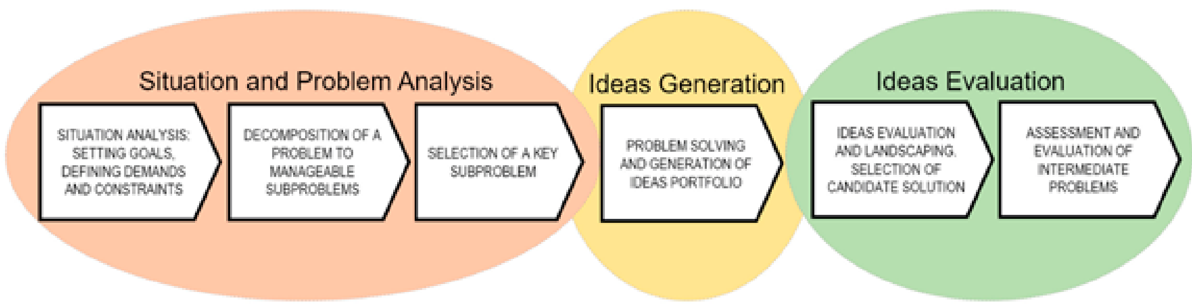


Figure 5. Problem solving process with TRIZ. At the stages of analysis and ideas generation of TRIZ tools are most relevant to a type of a problem given

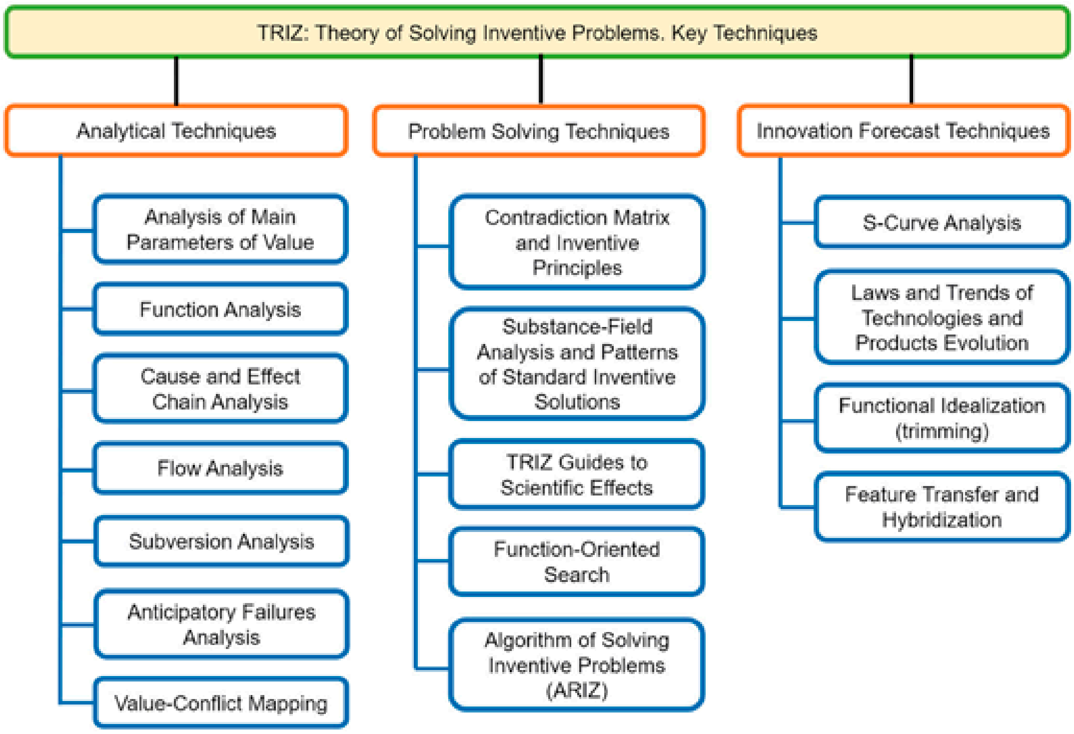


Figure 6. Structure of modern TRIZ and its key techniques

and tools to improve inventive problem solving as well as to perform analysis of systems and processes to identify their innovation potential and define ranges of issues to be addressed.

Modern TRIZ offers a number of practical techniques, which help to analyze existing products and processes, assess inventive situations, extract key problems, reveal potential opportunities for evolution, and generate new solution concepts in a systematic way – either to existing problems or to forecast future generations of products and technologies. In addition, the use of the TRIZ techniques is organized in a number of processes which define and structure the use of relevant techniques and tools according to the desired outcome.

There are many tools proposed by different TRIZ development parties but we limited ourselves by mentioning only the most widely used tools (Figure 6).

In summary, contemporary TRIZ includes the following key techniques which can be grouped in three categories, presented below.

Analytical TRIZ techniques

Analytical techniques in TRIZ serves two goals: a) to discover and rank inventive problems by focusing on the analysis of various aspects of a technical system or process and helping to extract and formulate specific problems in terms of TRIZ problem solving tools; and b) to analyze specific problems, look at them at different angles, formulate right problems, or predict future problems. Among them are:

- *Analysis of Main Parameters of Value*: identification of key technical parameters which most critically impact market value of a specific technical system. This technique helps to focus on the most important directions of innovative improvement rather than wasting efforts on dealing with non-essential incremental improvements.
- *Function Analysis*: building function models of technical systems or processes which enables identification of negative, insufficient and ineffective functions that need to be either eliminated or improved. The technique helps to discover and rank inventive problems.
- *Flow Analysis* helps to identify bottlenecks in the “flows” of material, energy or information throughout a system or process.
- *Cause and Effect Chain Analysis*: exploring a chain of effects and causes resulting in a tree of causes and contradictions by decomposing a general problem to manageable sub-problems.
- *Subversion Analysis*: a technique which is used when causes of a problem cannot be easily identified. Instead of trying to explain why a problem occurs, the technique proposes to explore different ways of creating the problem.

- *Anticipatory Failures Analysis*: a technique for predicting future problems that can be caused by a new invention which has not been implemented and tested yet.
- *Value-Conflict Mapping*: identification of critical contradictions and barriers which block further inventive evolution of a technical system or technology.

TRIZ problem solving techniques

- *Inventive Principles and Contradiction Matrix* are based on a list of problem solving strategies (Inventive Principles) which indicate how to eliminate one or more types of technical contradictions. Currently it contains 40 Inventive Principles which are available systematically through the Contradiction Matrix. At the moment it's the most widespread TRIZ technique.
- *Substance-Field Modeling and Standard Inventive Solutions*: a technique based on modeling an inventive problem as a set of substance-field interactions and a list of patterns which indicate how to change a physical structure of a part of a system where a problem resides. Currently the collection includes 76 such solution patterns.
- *TRIZ Guides to Scientific Effects* is a collection of effects and phenomena drawn from physics, chemistry and geometry and structured according to technical functions that can be delivered on the basis of these effects. Such a database is different from databases of effects published in scientific disciplines since in the TRIZ database, each effect has linked multiple technical functions which can be directly or indirectly obtained on the basis of the effect. Currently, it database of HIS Markit Goldfire™, a leading software package which includes support of TRIZ, contains over 8000 physical, chemical and geometrical effects (IHS, 2018).
- *Function-Oriented Search*: a technique for searching analogous solutions which deliver the same function as required but in different areas of technology. It helps to identify already existing solutions to a general problem and adapt them to problems existing in other domains.
- *Algorithm of Solving Inventive Problems* (*ARIZ*): a technique for solving inventive problems which cannot be solved with the above mentioned techniques. It applies to the most difficult problems containing physical barriers or causing strong psychological inertia.

TRIZ innovation forecast techniques

Theory of Technical Systems Evolution is a large area of TRIZ which studies domain-independent patterns and lines of innovative evolution of technical systems. It is presented by the number of techniques:

- *S-curve Analysis* helps to identify positions of different parts of a technical system on S-curve of evolution (showing the relation between the value of a certain parameter or set of parameters and time) and relevant models of evolution of a technical system.
- *Laws and Trends of Technologies and Products Evolution*: A collection of laws, generic patterns and lines for the development of technical systems.
- *Feature Transfer and Hybridization* techniques help to invent new concepts by transferring features of competing or complimentary products.
- *Function Idealization* (*Trimming*): a set of principles to simplify technical systems without losing quality and performance.

TRIZ: applications

Numerous reports and case studies presented in publications demonstrate that TRIZ has been used successfully in the following application areas:

- Innovatively improving an existing technical product, manufacturing process, or technology.
- Inventing a disruptive technical product or technology.
- Radically decreasing costs of a technical product or manufacturing process without sacrificing quality and performance.
- Forecasting potential failures of newly developed products and technologies.
- Strategic roadmapping of innovative development of products and technologies illustrated by future engineering and design concepts obtained with the use of TRIZ Trends and Lines of Technical Systems Evolution.
- Adjacent markets identification.
- Patent circumvention.
- Intellectual Property strategy development.

Conclusions

Compared with traditional random methods of supporting creative engineering design, the use of TRIZ provides the following advantages:

1) A considerable increase in productivity when searching for new ideas and concepts to create new products or to solve existing inventive problems.
2) Increasing effectiveness of the idea generation process by providing immediate access to hundreds of unique innovative principles and thousands of scientific and technological principles stored in TRIZ knowledge bases.
3) Reducing the risk of missing an important solution to a specific problem due to a broad range of generic patterns of inventive solutions offered by TRIZ.
4) Assessing and identifying the evolutionary potential of a technology or product and select the right direction of evolution with the help of TRIZ trends and lines of technical systems evolution.
5) Leveraging intellectual capital of organizations via increasing a number of patented solutions of high quality.
6) Raising the degree of personal creativity by training individuals and groups to approach and solve inventive and innovative problems in a systematic way.
7) Structuring and organizing creative phases of the innovation process.
8) Introducing a common innovation language to improve communication.

Until the beginning of the 2000th, TRIZ was virtually unknown outside the states of the former USSR. Today national TRIZ associations exist in many countries, including China, Germany, France, Italy, Japan, Malaysia, South Korea, Taiwan, and USA. A number of leading multinational corporations consider TRIZ as the best practice of innovation. Among which are General Motors, Hyundai, Intel Corporation, Procter & Gamble, and Samsung Electronics (Shaughnessy, 2013; Goldense, 2016).

Small and medium-sized companies also benefit from using TRIZ. TRIZ helps to define and solve problems much faster and with relatively small efforts thus avoiding large investments to generate new working ideas and concepts.

TRIZ and Systematic Innovation are not easy to master at an advanced level since they form a large body of knowledge, and requires considerable time to reach excellence. However, most of its techniques can be learned and applied independently in a modular way, thus considerably simplifying both learning and implementation processes.

Despite growing distribution of TRIZ among industrial organizations and continued efforts on research and further development, the level of awareness of TRIZ among engineers worldwide still remains relatively low. It also has to do with the complexity of modern TRIZ, which increases the learning curve and a large number of tools that tend to be used in a non-structured way. In order to solve these issues, the international associations of TRIZ developers and users recently started to undertake collaborative actions targeted at creating common standards and sharing the best practices of using TRIZ. For example, the Association of German Engineers (VDI), which is the leading engineering authority in Germany, released the first part of TRIZ Guidelines which structures and defines main TRIZ concepts and process for German industrial and educational organizations (VDI, 2015).

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Ministry of Science and Higher Education
Republic of Poland

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