Transactions of the SDPS:
Journal of Integrated Design and Process Science
16 (3), 2012, 29-63
DOI 10.3233/jid-2012-0005
http://www.sdpsnet.org

TRIZ-based Anticipatory Design of Future Products and Processes

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Abstract The capability of anticipating the main features of future products and related manufacturing processes is more and more a critical asset in industry, due to the innovation-based competition of markets and to the extremely reduced lead time of modern product development cycles. The paper presents a survey of TRIZ, the Theory of Inventive Problem Solving, as a reference methodology to support design activities driven by the forecasted evolution of technical systems. TRIZ postulates, models and tools are described in the scope of technology forecasting and discussed within a more general design science perspective. The discussion highlights strengths and weaknesses of the theory and suggests relevant directions for further research in the field.

Keywords: technology forecasting, inventive design, innovation

1. Introduction

The development of competitive products is largely based on the capability to bring in the market innovative solutions, i.e. characterized by new functionalities, higher performance, reduced resources consumption and costs and with no undesired effects for the product beneficiaries. The rate of innovation has reached a speed so high that despite the diffused efforts to shorten the lead time, companies continuously struggle for renovating their products on a day-by-day perspective, while long-term strategy definition has become a privilege for a reduced number of fortune companies.

In this context, a relevant research goal in the engineering design domain is the definition of reliable practices and supporting tools for anticipating the main features of future products and related manufacturing processes. While nowadays creative concepts scatter from visions and intuitions of talented designers, in the author's viewpoint, successful firms will progressively rely on innovation roadmaps characterized by largely customizable detail implementation, but with clear long-term directions of evolution. In turn, while most of the detail design choices will be postponed as close as possible to the market issue, the evolution of products architecture could be planned with a long-term perspective by integrating technology forecasting methodologies with design science.

The present paper overviews the potential role of TRIZ, the Theory of Inventive Problem Solving, as a reference theoretical framework to build such integration towards the anticipatory design of future technical systems. The paper is structured as follows: the next section summarizes the origins of TRIZ and surveys its recent developments with a specific focus on its application in the domain of technology

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Published by IOS Press

forecasting. Section 3 presents an original hierarchical classification of the main concepts and reference models of Classical TRIZ, represented according to the formalization proposed by Nikholai Khomenko (Cavallucci & Khomenko, 2007). Section 4 overviews the practical tools of TRIZ to generate inventive solutions, with author's comments on their efficiency and applicability. Section 5, eventually, discusses strengths and weaknesses of TRIZ applied to anticipatory design and opportunities of integration with other emerging disciplines and tools.

2. TRIZ Origins and Application to Technology Forecasting

TRIZ is a Russian acronym (Теория Решения Изобретательских Задач, which stands for "Theory of Inventive Problem Solving") developed by Genrich Saulovich Altshuller between 1946 and 1998. It is commonly referenced as a theory, a methodology, a set of instruments, sometimes even a philosophy to guide and support creative technical activities with systematic means.

A historical overview of its development allows understanding the origins of the lack of formalism of several publications dedicated to TRIZ, as well as the source of some incongruent statements about its features and characteristics. Moreover, several not harmonized customizations and further developments have been proposed in the last decade by his collaborators and followers. In this chapter, the focus will be dedicated to Classical TRIZ, i.e., what has been proposed and/or co-signed by Altshuller. Specific references will be added to clarify what should be considered as a contemporary modification or integration.

2.1. Origins of Classical TRIZ

Born in Tashkent (former Soviet Union, currently Uzbekistan), Altshuller grew up in Baku (Azerbaijan) where he became an employee of the patent department of the Caspian Sea Soviet Navy. At that time, the patents (more precisely Inventor's Certificates) in the USSR used to have a simpler and more readable format than western patents. As a consequence it was possible to study a high number of inventions with relatively reduced efforts. Moreover, the role of Altshuller was to assist inventors in filling out patent applications; this gave him the opportunity to deal with a huge amount of problems and solutions from where the TRIZ theory evolved.

After sending to Stalin a naïve letter, where he presented the first results of his studies together with a critique to the Soviet system of education, Altshuller was condemned to 25 years of reclusion and went through several gulags. After Stalin's death, he was released and continued his studies and dissemination activities according to the main steps hereafter summarized (Fig. 1). Altshuller died in Petrozavodsk, Russia, on September 24th, 1998.

2.1.1. TRIZ development: I stage

The initial work of Altshuller was mainly dedicated to the refusal of a Trial & Error approach to problem solving and to the development of a scientific approach to creating inventions.

Since the very beginning, through the analysis of patented solutions, it was revealed that higher-level inventions do not accept compromises between conflicting requirements. Besides, whatever field of application, new paradigms are characterized by the elimination, or at least the mitigation, of these conflicts, or "contradictions" in TRIZ terms (Altshuller & Shapiro, 1956).

In fact, the same innovative principles underlie the development of different industries and all technical systems evolve according to repeatable patterns. As a consequence, these principles can be codified and generalized for universal application.

2.1.2. TRIZ development: II stage

After gaining awareness about the existence of general patterns of technical systems evolution, Altshuller started working on the development of a "method" for inventive problem solving.

The general suggestions and approaches to the generation of inventive ideas were further developed to build a step by step procedure to analyze a problem, reveal the contradictions behind it and apply some universal principles to overcome them. Since 1964-65, such a procedure was called ARIZ (Algorithm for Inventive Problem Solving, Section 4.1) and has been largely modified and improved until 1985 (Altshuller, 1969; 1979).

At this stage, he completed the development of a “contradiction matrix”, a table where the statistically most effective principles to overcome technical contradictions are associated to the conflicting pair of technical parameters.

More than fifty thousand copies of his book “How to learn to invent” were sold (Altshuller, 1961), and a wider dissemination of Altshuller’s discoveries was initiated: from the fifteen thousand copies of "The foundation of invention" (Altshuller, 1964) to the eighty thousand copies of the second edition of "The Innovation Algorithm" (1973).

2.1.3. TRIZ development: III stage

The current name TRIZ was introduced between the end of the 1960s and the beginning of the 1970s, when the transition from a method for inventive problem solving to a scientific theory was first postulated.

The most relevant result behind this stage was the identification and classification of a system of evolutionary laws characterizing the development of engineering systems. At the same time, several further developments of ARIZ were proposed and published, together with a new more effective solving tool, the Inventive Standards which replaced the contradiction matrix considered not efficient enough to produce highly inventive solutions (levels 3-4 according to Altshuller’s classification)[1].

Within this period, the dissemination of TRIZ was extended through regular training courses in many different cities of the former Soviet Union. Among others, it is worth to mention the first regular Public University of TRIZ, Baku 1971.

2.1.4. TRIZ development: IV stage

While the adoption of a theoretical approach allowed the introduction of further improvements of the algorithm for contradiction elimination (ARIZ), a new target was formulated by Altshuller in the second half of the 1970s (Altshuller & Filkovsky, 1975): from a theory for solving inventive problems to a theory of the development of technical systems.

Therefore, during this stage, apart new versions of ARIZ, the Substance-Field modeling technique and the System of Standard Solutions for Inventive Problems were further enriched (Section 4.2), as well as the pointer to the scientific effects (Section 4.3). Moreover, the first applications of TRIZ to non-technical problem solving were successfully performed.

2.1.5. TRIZ development: V stage

The development of Classical TRIZ is considered concluded in 1985, with the last version of ARIZ approved by his author. Since then, several updates have been proposed by several other authors, but none of them has obtained a common acknowledgement.

Besides, Altshuller dedicated the last years of his life to further interests like the Theory of Technical System Evolution (TRTS in Russian) and the Theory of the Development of Creative Personalities (TRTL), and he promoted the initiative to build a General Theory of Powerful Thinking (OTSM), which helps with the development of powerful thinking skills (Altshuller & Filkovsky, 1975).

This fifth stage can thus be considered as a transition from a theory to a set of complementary theories originated by TRIZ. This is also the age of the dissemination of Classical TRIZ tools in Western

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[1] According to the author’s experience, the contradiction matrix is also characterized by limited robustness, since different TRIZ experts describe the same problem with different pairs of conflicting parameters, thus obtaining different directions to generate an inventive solution.

countries. Nowadays, TRIZ associations exist in all continents and regular conferences are held all over the world with books and papers published in many different languages.

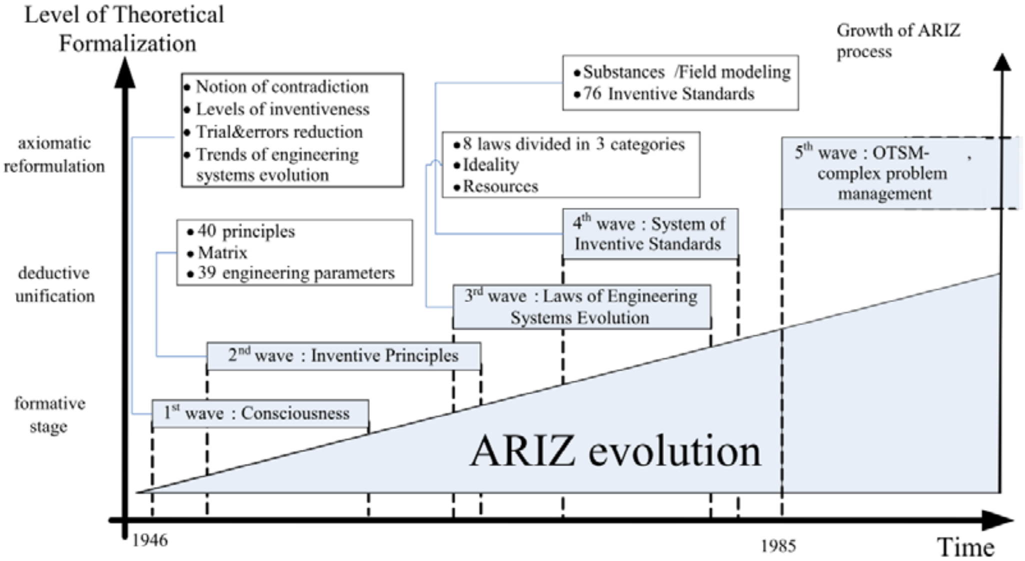


Fig. 1. Evolution of the TRIZ body of knowledge (Khomenko et al., 2007).

2.2. Classical TRIZ and forecasting applications

According to the history briefly summarized earlier, TRIZ has not been conceived for forecasting purposes. Nevertheless, it is actually recognized as a useful support to the prediction of technical systems evolution and several forecasting techniques have been initiated from its fundamentals.

The first reference to forecasting in TRIZ-related literature appeared in the manuscript “About forecasting of technical systems development” prepared by Altshuller for a seminar in 1975. Here, after a short review about technological, economic and social forecasting methodologies, Altshuller blamed their poor repeatability and focused the attention on the most important answers that an inventor is looking for: What is the growth potential of a given engineering system? Which systems will substitute the existing one in future? Which are the most critical problems to be solved in the future? Then, he started presenting some additional concepts in a chapter dedicated to the “strategy” of inventive activities (Altshuller, 1979).

By adopting the concept of S-curve as representative of the way the main characteristics of a system evolve, he proposed a correlation between the corresponding sections of the S-curve and other figures as the number of inventions, the level of inventions and the profitability (Fig. 2).

Altshuller later proposed the concept of the System Operator (Section 3.4) as a multi-screen approach for system thinking to support the vision about the evolution of systems (Altshuller, 1979). Moreover, a system of 8 Laws describing the evolution of technical systems was presented (Section 4.4).

A further implicit contribution to forecasting applications of TRIZ was published later (Althsuller et al., 1985). The integration of TRIZ solving tools with a customized form of Value Engineering for analysis purposes (eight ways to increase the “Ideality” of a technical system were proposed) suggested some general directions to anticipate the characteristics of future systems, later on mostly referred to Boris Zlotin; e.g., the trend toward customization for specific purposes, the trend to increase adaptability to different operating conditions, the reduction of human involvement, etc.

Mostly developed by Zlotin and Zusman, but still co-signed by Altshuller (Altshuller et al., 1989), a procedure was first dedicated to technological forecasting based on TRIZ. Such a four-part procedure was constituted by 26 steps dedicated to situation analysis and the development of an aggregated forecast based on the application of the Laws of Engineering Systems Evolution and a set of more detailed “lines of evolution” characterizing different fields of application.

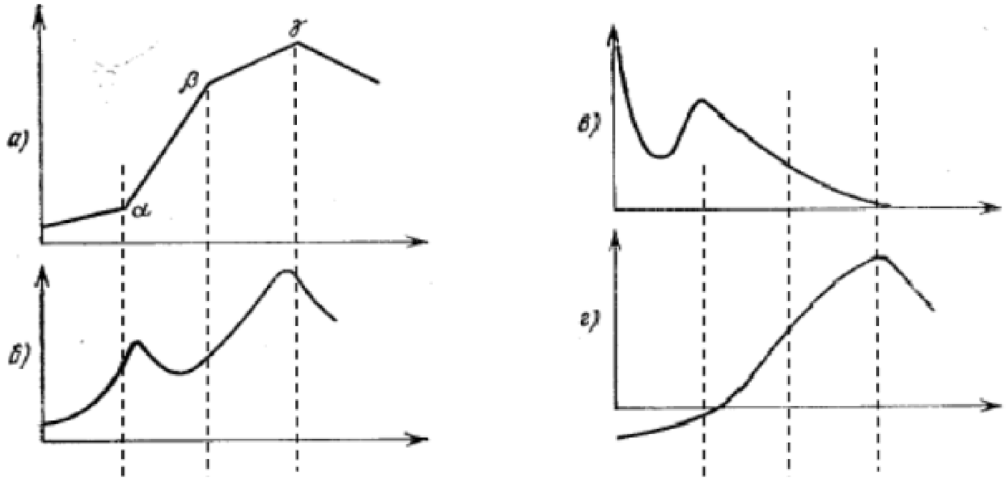


Fig. 2. Correlation between the stages of the “life” S-curve of a technical system (top, left) with the number of inventions (bottom, left), the level of inventiveness (top, right) and the related benefit, i.e., profitability (bottom, right) (Altshuller, 1979; Chapter 7).

Altshuller dedicated part of his life to the study of the personality of creative people with the aim of eliciting the rules to improve individual’s creativity. Being at the same time an active science fiction writer, he performed an extensive analysis of science fiction literature in order to study the rate of fantastic ideas which become real engineering systems as a potential support to long term forecasting (references available on http://www.altshuller.ru/rtv/sf-register.asp).

2.3. TRIZ-based techniques for system evolution analysis after Altshuller

Among the numerous publications presented in the last two decades about TRIZ-based techniques for predicting the evolution of technical systems, the most relevant contributions will be mentioned here as a general reference for further studies.

2.3.1. The wave model (Salamatov, 1991)

The wave model proposed by Salamatov (Fig. 3) is a unified representation of the relationship between the increase of the performance of a technical system and the consumption of resources, in correlation with the laws of evolution. Such a model was still proposed as a support to the analysis of technical system development, within the scopes of inventive problem solving.

2.3.2. Directed Evolution (Zlotin & Zusman, 2001)

The methodological approach called “Directed Evolution” proposed by Zlotin and Zusman is the first structured TRIZ-based approach to forecasting.

As schematically represented in Fig. 4, it is based on a five-step process, in which the first three stages are dedicated to the analysis of the historical evolution of the technical system, aimed at defining a vision of the future, and the second part is a sort of normative approach to control the concretization of the preferred scenario.

The prediction phase is performed through the application of classical TRIZ tools, such as the patterns of evolution to increase systems ideality, with more recent instruments as the hybridization technique (Prushinskiy et al., 2005).

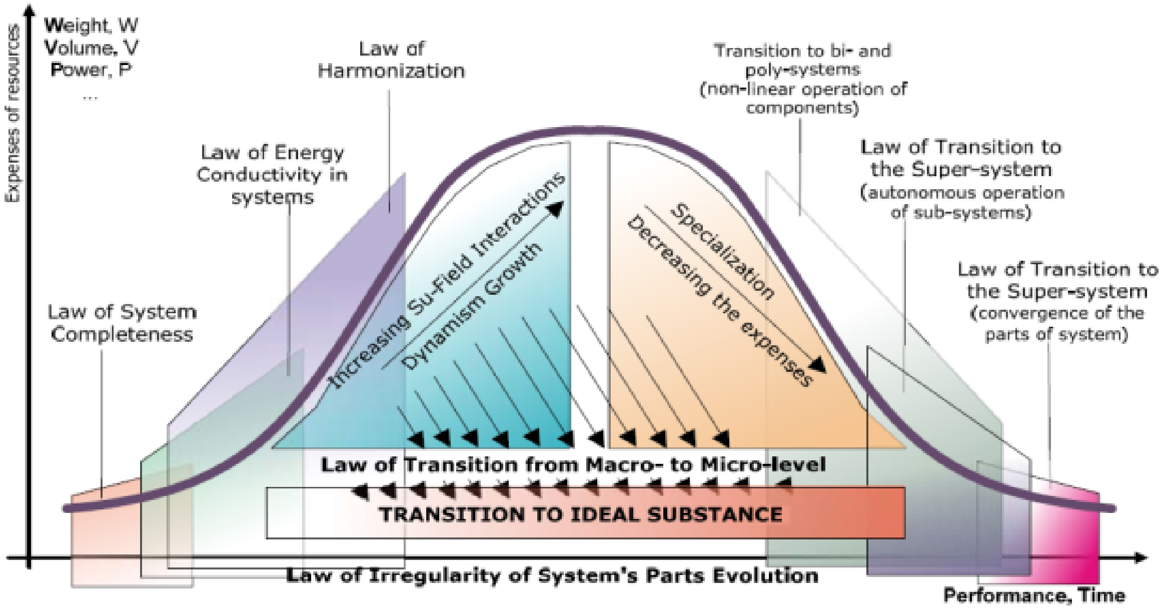


Fig. 3. The wave model (Salamatov, 1991).

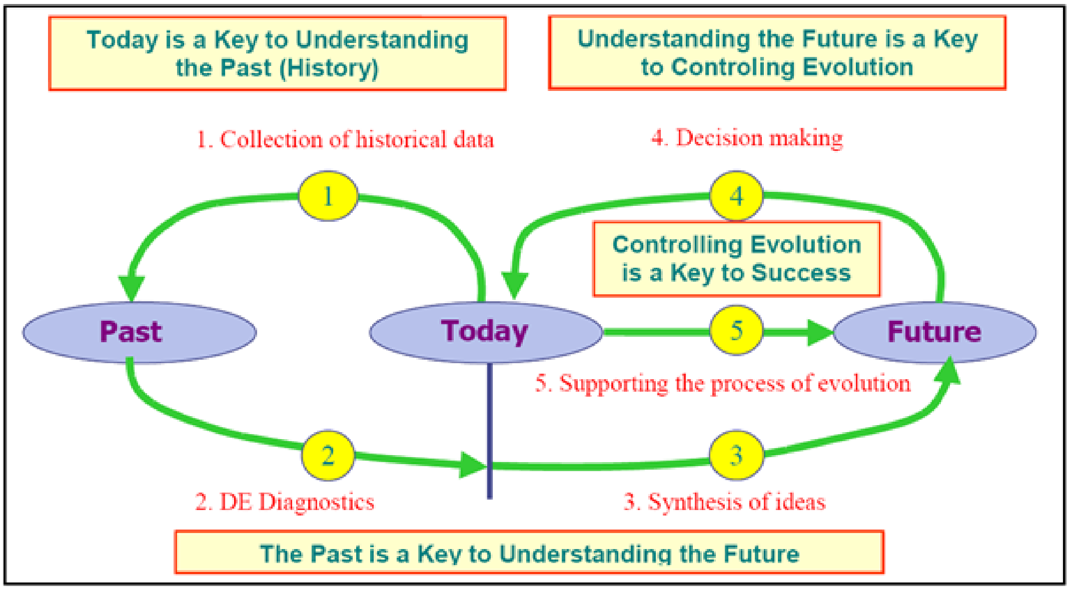


Fig. 4. Directed Evolution general schema (Zlotin & Zusman, 2001).

2.3.3. Evolutionary Potential (Cavallucci, 2001; Mann, 2003)

Cavallucci (2001) proposed to integrate the TRIZ Laws of Engineering Systems Evolution into the product development cycle, as a means to predict the impact of a technical solution, through a comparison of the current state of development of a certain technical system with the potential evolution pointed by the Laws (Fig. 5, left). The same approach was adopted also by Mann (2003) to measure the potential evolution of a technical system through a radar plot.

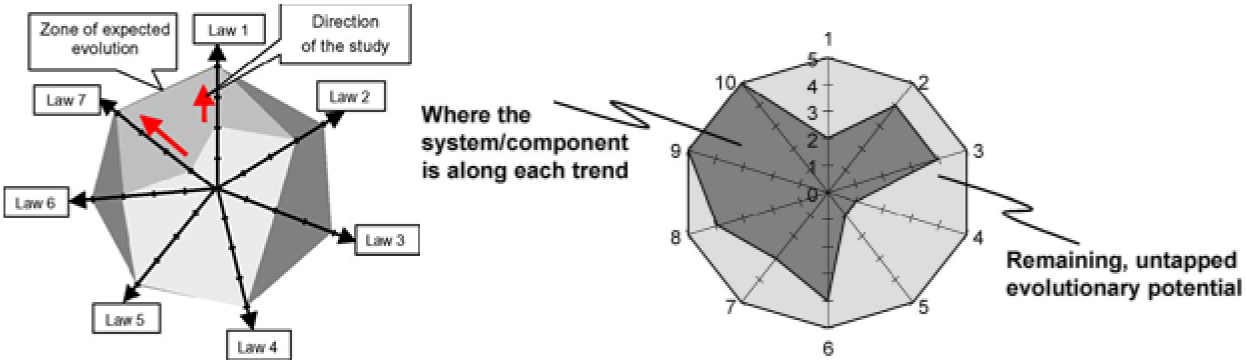


Fig. 5. State of development of a technical system and domain of expected evolution (Cavallucci, 2001, left; Mann, 2003, right).

2.3.4. *Evolution Trees (Shpakovsky, 2006)*

In analogy to Directed Evolution, Shpakovsky (2006) proposed a structured approach based on the TRIZ evolutionary patterns and laws, with detailed guidelines about their application. The output of the process is an evolution tree (Fig. 6) representing possible paths to the future of the technical system under study.

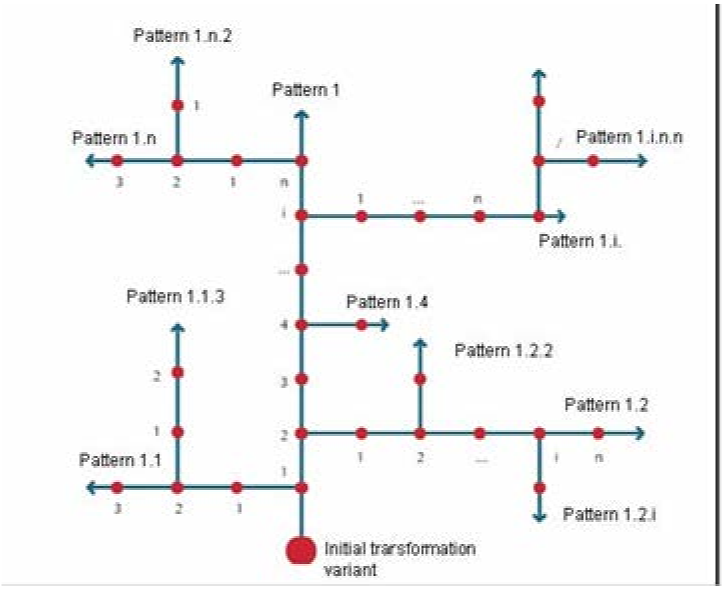


Fig. 6. The evolution tree structure (Shpakovsky, 2006).

2.3.5. *Technology change and forecasting (Kucharavy, 2008)*

The most scientifically sound approach to technology forecasting based on TRIZ fundamentals, as well as on the integration of other acknowledged techniques as the Logistic Substitution Model and the analysis of waves and cycles, has been proposed by Kucharavy (2008) with the aim of producing a reliable forecasting, not limited to qualitative predictions, but with precise directions about timing and rationale of the expected evolution. His six-step process, still under further refinement, compared with other TRIZ-based forecasting approaches, takes into account not just the Laws of Evolution, but also the contradictions (more specifically the Network of Contradictions) which limit the achievement of the expected features and functionalities (Fig. 7). The most recent advancements about how to improve the reliability of the logistic substitution model for anticipating the technological future within a TRIZ-based forecasting study have been published in (Kucharavy & De Guio, 2011).

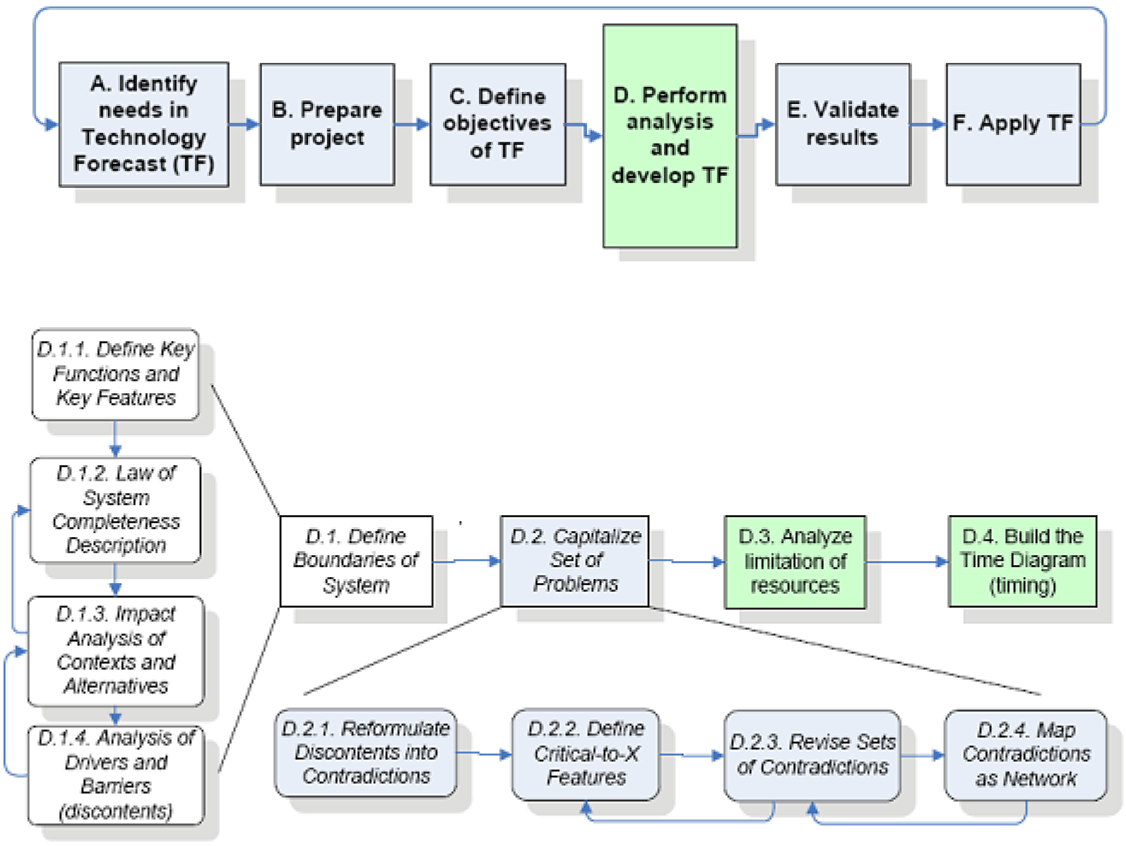


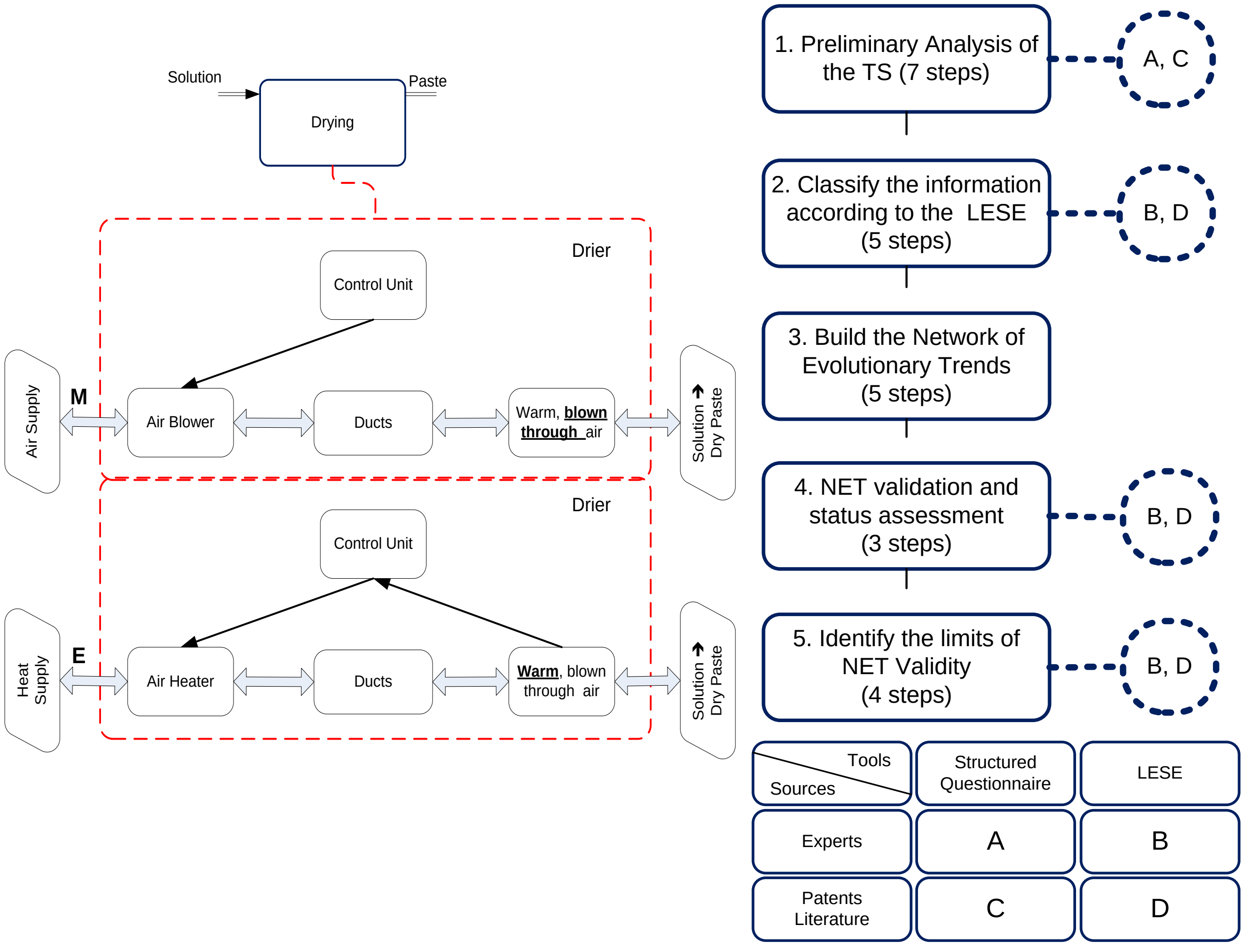
Fig. 7. Six-step project for Technology Forecast (top) and detailed steps for Technology Forecasting development (bottom) (Kucharavy, 2008).

2.3.6. NET: Network of Evolutionary Trends (Cascini et al., 2009, 2011)

The NET approach proposed by the authors (Cascini et al., 2009, 2011) aims at overcoming the poor formalism of TRIZ-based forecasting approaches with consequent limited repeatability. In fact, even the most structured techniques described above are also mostly focused on the application of the Laws of Evolution, rather than on the analysis of the forecast system.

Such a lack of preliminary classification, especially in the case of complex systems, is the main reason for the poor repeatability of TRIZ forecasts, since different researchers apply TRIZ Laws to different details or characteristics of the same technical system and/or limit their study to superficial features of the system itself. Thus, it is proposed to start with the construction of a Network of Evolutionary Trends after the completion of a comprehensive functional model which integrates well known concepts, like the Function-Behavior-Structure model by Gero, the NIST Functional Basis for Engineering Design for harmonizing the level of detail of the representation, or further classical TRIZ models (System Operator, Minimal Technical System, etc.) (Fig. 8, left).

The five-part algorithm makes use of custom text mining tools for information gathering and classification (Fig. 8, right).



Tools / Sources	Structured Questionnaire	LESE
Experts	A	B
Patents Literature	C	D

Fig. 8. Example Behavior represented through the model of the Minimal Technical System associated to an elementary function described through the EMS model (left). Main parts of the NET algorithm and relationships with information sources and gathering tools (right) (Cascini et al., 2009, 2011).

3. TRIZ Postulates and Reference Models

As summarized in the previous section, even though TRIZ has been originally developed with an inductive process, by extracting heuristics from the analysis of multitude of inventive solutions, its body of knowledge can be presented with a more structured approach. TRIZ aims now at being a science which studies processes on the boundary of two elements: persons and technology. The sphere of its study includes both the thinking of a person and the laws of the evolution of technical systems.

Astronomy became a science when the laws of planet movement were discovered; alchemy became chemistry when the laws of the interaction and transformation of substances were described. TRIZ is the first effective attempt to build a science of invention.

Any theory has a fundamental character, but it also develops its applied tools. TRIZ develops tools for the solution of creative problems: ways of narrowing a search field, methods of conscious management of unconscious processes.

Still within the limits of the short description of TRIZ fundamentals, this section introduces the three main postulates on which the whole theory relies and a number of reference models formalizing its problem solving process, the way problems and solutions are represented, the characteristics of powerful creative thinking. In the next section, a survey of its main instruments will clarify how these models are adopted in practice.

3.1. TRIZ postulates

The whole TRIZ theory is based on the following three postulates which constitute its founding bricks.

- Postulate 1: Existence of Objective Laws of Engineering Systems Evolution (LESE)

The observation of the history of technical systems has demonstrated that any human artifact evolves by following repeatable patterns, despite the specific goal of such transformations. In other terms: Technical Systems evolve according to objective laws which are not dependent on the field of application or the function that the technical system is supposed to deliver. These laws (hereafter LESE) govern the development of technical systems just like natural laws regulate the development of biological systems. The knowledge of genetics allows to predict the characteristics of a living organism; similarly, the LESE allow to anticipate future developments of technical systems.

- Postulate 2: Contradictions

In conformity with the first of Engels' Laws of Dialectics, i.e. the law of the unity and conflict of opposites (Engels, 1883), system evolution implies the resolution of contradictions, i.e., conflicts between a system and its environment or between the constituting elements of the system itself. The inventive solutions bringing a major contribution to the development of a technical system do not compromise between opposite requirements. Overcoming contradictions is thus a driving force behind technology evolution and their identification is the first step of any invention process[2].

- Postulate 3: Specific Situation and Resources

Each stage of evolution of a system takes place in a specific environment (context, situation), which influences the transformation of the system and provides specific resources. The concept is very similar to the Theorem "Source of Product Requirements" presented in (Zeng, 2004).

As the environment impacts the growth of a living organism, whatever its genetic code is, similarly the resources surrounding a technical system constitute a primary engine to its development.

3.2. Main reference models of the TRIZ problem solving process

TRIZ aims at improving the efficiency of a problem solving process by eliminating trial & error and providing a structured approach to idea generation. The following models should not be considered as alternative paths for transforming a problematic situation into a solution, but as complementary descriptions of the characteristics of any TRIZ process. The formalization of these models to describe the Classical TRIZ problem solving process has been originally proposed by Nikholai Khomenko; details available on (Cascini et al., 2009).

3.2.1. Hill model (abstraction-synthesis)

In order to avoid a trial and error approach to idea generation and psychological inertia biases, the problem solving process (Fig. 9) should start with an abstraction phase aimed at transforming a specific inventive situation into a general typical situation (left part of the hill). Then, once an inventive problem is transformed into a typical one, i.e., it is described in terms of unsatisfactory functional interactions or in terms of contradictions, it is possible to apply some general solving instruments and identify the most appropriate model of the solution. Such an ideal solution must then be embodied into a concrete one through a convergence process, which must be focused on the most fruitful exploitation of the available resources (right slope of the hill). The Hill model acquires a more comprehensive meaning through the integration with the Tongs model (see below) which represents the approach to be used during the

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[2] It is worth to highlight that successful (i.e. profitable) innovations are not necessarily related to inventions, therefore a market success is sometimes obtained also by compromise solutions.

problem generalization phase: at the beginning of the problem-solving process the problem is reformulated several times according to the rules of the Tongs model, but each time the level of generalization increases. This abstraction process leads to a more general description of the problem itself and, as a result of this generalization, it is easier to find a direct analogy between problems that look very different from each other.

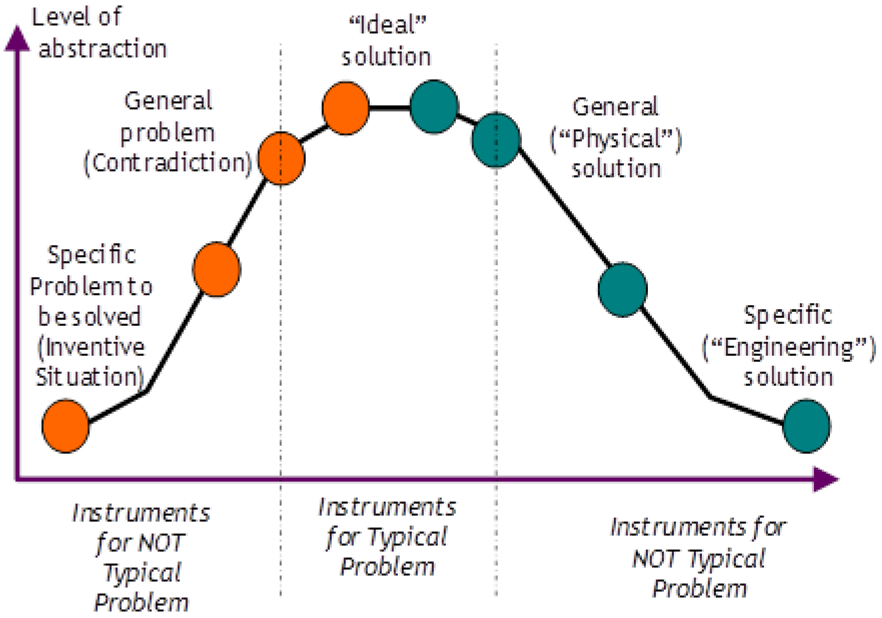


Fig. 9. Hill model of the TRIZ problem solving process (Cascini et al., 2009).

3.2.2. *Tongs model (from current situation to ideality, barriers identification)*

The Tongs model (Fig. 10) provides further details about the analysis stage of a TRIZ problem solving process (Fig. 9, left slope). Once again, it is important to avoid the generation of ideas starting from the current technical system. Besides, it is suggested to depict the characteristics of the Most Desirable Result; then a comparison between the Most Desirable Result and the current situation is the key to identify the barriers which impede the achievement of the expected results. Such a barrier hides one or more contradictions to be elicited and overcome through the TRIZ instruments.

Moreover, the identification of contradictions and the application of the solving principles highlight the possible lacks of knowledge and consequently determine a direction to integrate new competences and technologies systematically.

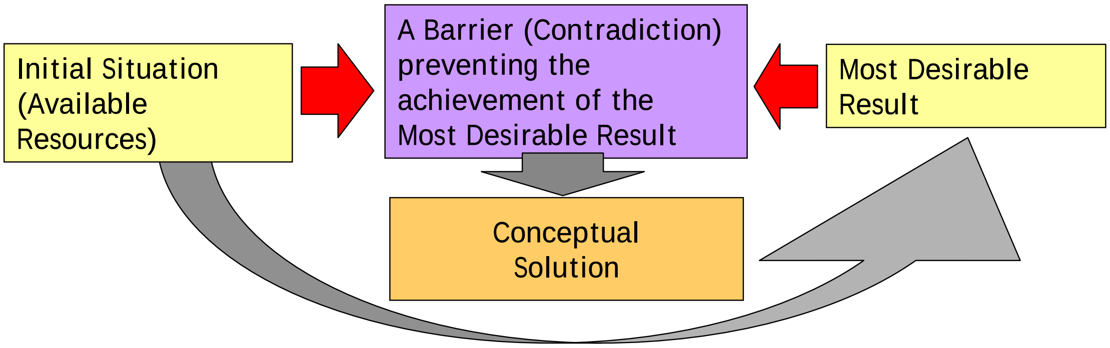


Fig. 10. Tongs model of the TRIZ problem solving process (N. Khomenko, available in Cascini et al., 2009).

3.2.3. Funnel model (convergent process)

Most of the traditional techniques supporting creativity suggest the adoption of a divergent approach, according to the assumption that among multiple ideas there is a higher probability to get a successful solution. Besides, TRIZ starts from a firm refusal of trial and errors and recommends following a convergent approach in order to increase the efficiency of the overall process, i.e., the ratio between effective solutions and the resources involved for their development.

The Funnel model (Fig. 11) depicts a convergent process by taking into account natural laws and personal needs with consequent steps aimed at the definition of the profile of the final solution, i.e., a set of characteristics until its description is unique. There is a large input at the beginning of the problem-solving process in order to observe and analyze the initial situation and narrow output at the end of the problem-solving process that shows a single satisfactory solution. The problem-solving process should be located inside this Funnel and prevent a problem solver from useless trials and errors.

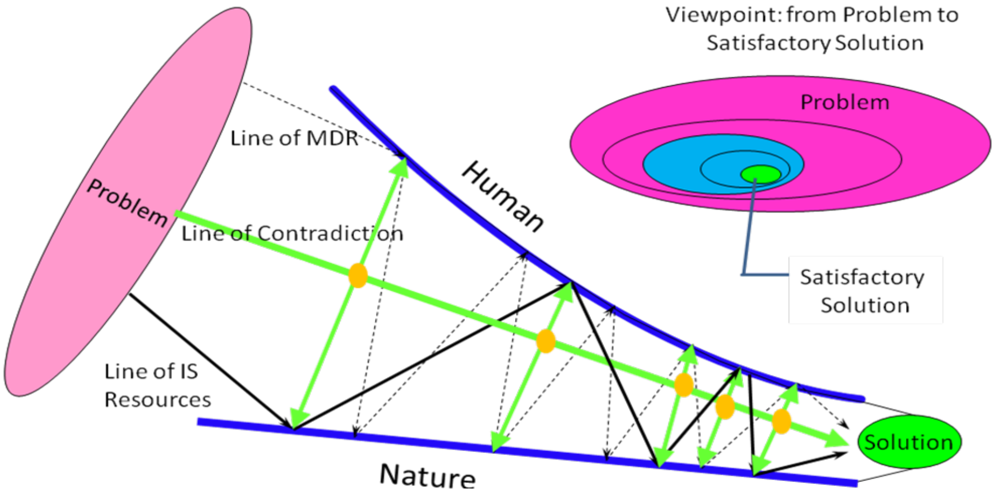


Fig. 11. Funnel model of the TRIZ problem solving process (N. Khomenko, available in Cascini et al., 2009).

3.3. Main reference TRIZ models for the description of systems, problems, solutions

The following models constitute the elementary bricks which allow the description of any inventive situation, both to analyze a problem with its key characteristics and to describe the profile of a solution according to the convergent process described above.

Due to its improved formalization and consequent repeatability, the OTSM-TRIZ formulation of these models is here adopted (Cavallucci & Khomenko, 2007).

3.3.1. ENV model (Element, Name of the property, Value of the property)

The ENV model is a universal model adopted in OTSM-TRIZ both to represent any kind of problematic situation and to describe step by step the characteristics of an inventive solution. From this point of view, the ENV model must be capable to represent real and imaginary technical systems. The structure has been derived from a well known model in Artificial Intelligence Object-Attribute-Value (OAV) (Minsky, 1975; Sowa, 1984). Element (E) is any kind of item in the system under analysis (both material and immaterial). The Name (N) of the property indicates any characteristic, feature, variable which can be associated to the element E. Finally, whatever is the Property, it must have at least two possible values (V), i.e., the element E can assume at least two possible states distinguished by different values V1 and V2 for the property P.

The ENV model can be adopted to describe a system or to describe a problem (e.g., the rotating speed of a shaft should be higher than 12,000 rpm, but its actual value is 10,500 rpm: Element = Shaft; Name of the property = rotating speed; Current Value = 10,500 rpm; Desired Value = 12,000 rpm). Table 1 exemplifies an arbitrary description of an orange fruit through the ENV model.

Table 1. Example description of an item (an orange) according to the ENV model

Element = Orange	
NAME of the Property	**VALUE of the Property**
Shape	Spherical
Colour	Orange
Edibility	True
…	…

3.3.2. Model of function

The function of a Technical System is the motivation for its existence. A function is completely defined by means of the following elements: a function carrier (in TRIZ terms a “tool”), an action and an object receiving the function. The action is properly formulated if it can be expressed as a combination of one among four verbs (increase, decrease, change, stabilize) and the name of a property of the object, in agreement with the ENV model (Fig. 12, top). The property of the object (e.g., the size, color, electrical conductivity, shape) is thus set to a certain value (e.g., one meter, red, five siemens per meter, spherical) due to the impact of the function.

If the modification of the object property is desired, the function is considered useful, while if the modification of the object property is undesired, the function is considered harmful (Fig. 12, bottom). Among the useful functions, if the property of the object assumes precisely the expected value, then the function is sufficiently useful; besides, if the value of the property is inadequate, then the function is considered useful but insufficient. The properties adopted to characterize the function are therefore considered Evaluation Parameters of the function itself.

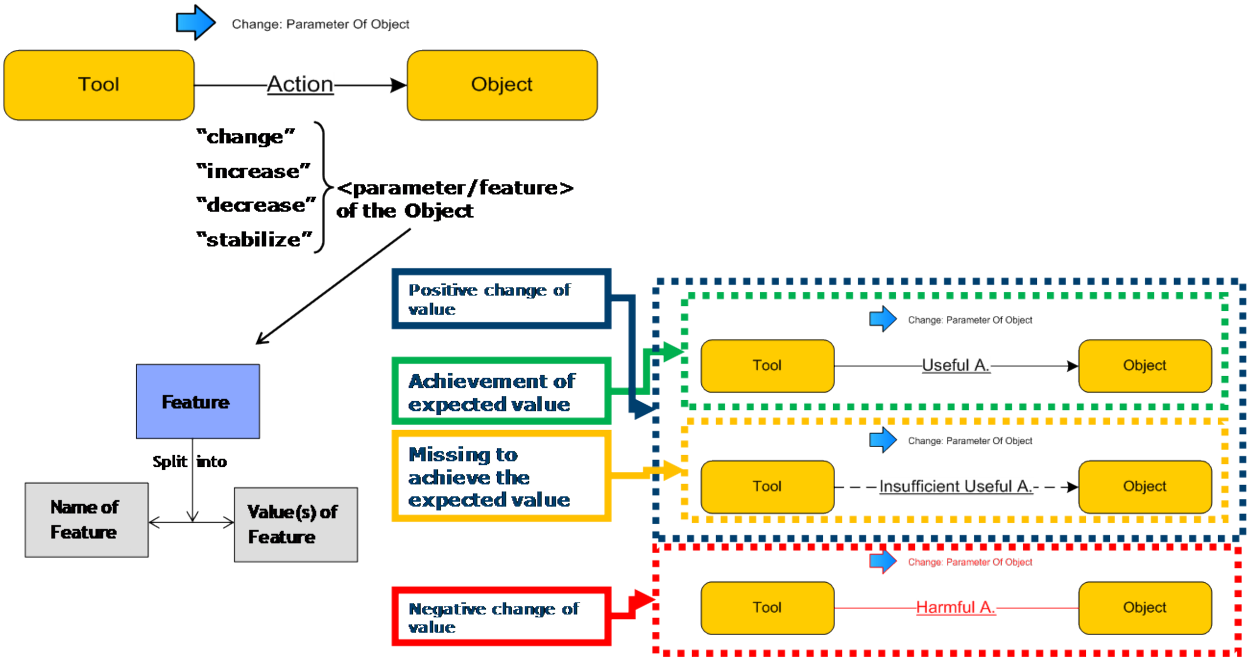


Fig. 12. Model of function (top) and related characterization according to its impact on the object (bottom).

3.3.3. *Model of the Minimal Technical System*

According to the first Law of Engineering Systems Evolution (Altshuller, 1979), i.e., the Law of Completeness (Section 4.4.1), a system capable to deliver any function must be characterized by four elements (Fig. 13):

- a Tool, which is the working element delivering the function of the TS, i.e., exerting a certain effect on its object
- an Engine, i.e., the element providing the energy necessary to produce the expected effect of the function
- a Transmission, i.e., the element transmitting energy from the Engine to the Tool
- a Control, i.e., an element governing at least one of the previous elements

According to the classical TRIZ definition of the Minimal Technical System, energy flows should only be taken into account and typically the Engine is identified going back from the Tool upward the energy flow, until a transformation in the type of energy is found (e.g., from electrical to thermal energy due to the Joule effect). Besides, according to the author's experience, the concept of the Law of Completeness of System Parts can also be extended to different types of flows, namely Material and Signals (Cascini et al., 2009). The adoption of a four-block decomposition of a TS provides at least the following benefits: it keeps a manageable number of elements to be contemporarily taken into account, whatever is the complexity of the system to be analyzed, and it invites the analyst to focus the attention just on the elements relevant to a specific function/sub-function at a time.

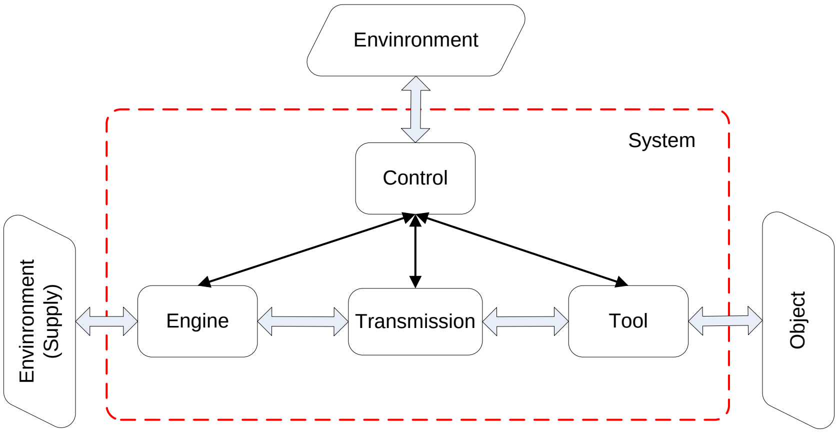


Fig. 13. Model of the Minimal Technical System (1st Law of Technical Systems Evolution).

3.3.4. *Substance-Field model*

In order to deliver a certain function, a certain interaction must exist between the Tool and the Object. Such an interaction is modeled in classical TRIZ by means of a Field, while the interacting elements are called Substances. A Field is an interaction characterized by a flow of energy (of any type), information or mechanical force, etc., generated by a substance, potentially impacting other substances.

The type of field is defined by the nature of the interaction between two substances (Table 2). It is worth mentioning that the definitions of the field types sometimes overlap: a biological field can also be considered chemical at a deeper detail level; heat transferred by radiation can be considered as a thermal and an electro-magnetic field. Nevertheless, such ambiguity does not impact the usability and effectiveness of the modeling technique as long as a coherent definition is followed within the entire analysis of a certain technical system. Fig. 14 (left) shows an example Su-Field (Substance-Field) model, i.e., a complete triad involving two Substances and a Field. Su-field models can also represent both useful and harmful interactions, according to the same criteria described for the functional model (Fig. 14, right).

Table 2. Field types and related symbols

Field type	Description	Symbol
Gravitational	The natural force of attraction between any two massive bodies, which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them	FGr
Mechanical	Interaction relating to, or governed by, mechanics, i.e., forces on matter or material systems (friction, inertia, elasticity, lifting, buoyancy, pressure of fluids)	FMec
Acoustic	Interaction arising from, actuated by, containing, producing or related to sound waves, even outside the audible frequency range	FAc
Thermal	Interaction related to heat transfer of any type (conduction, convection, radiation)	FTh
Chemical	Interaction related to the composition, structure, properties and reactions of a substance	FCh
Electrical	Physical phenomena arising from the behaviour of electrons and protons that is caused by the attraction of particles with opposite charges and the repulsion of particles with the same charge	FEl
Magnetic	Force exerted between magnetic poles, producing magnetization	FM
Electromagnetic	Interactions related to the generation, propagation, and detection of electromagnetic radiation having wavelengths greater than x-rays, e.g., light and vision	FEM
Biological	Interactions related to, caused by or affecting, life or living organisms, e.g., fermentation, decay	FB
Nuclear	Interactions related to forces, reactions and internal structures of atomic nuclei, e.g., fusion, fission, rays	FN

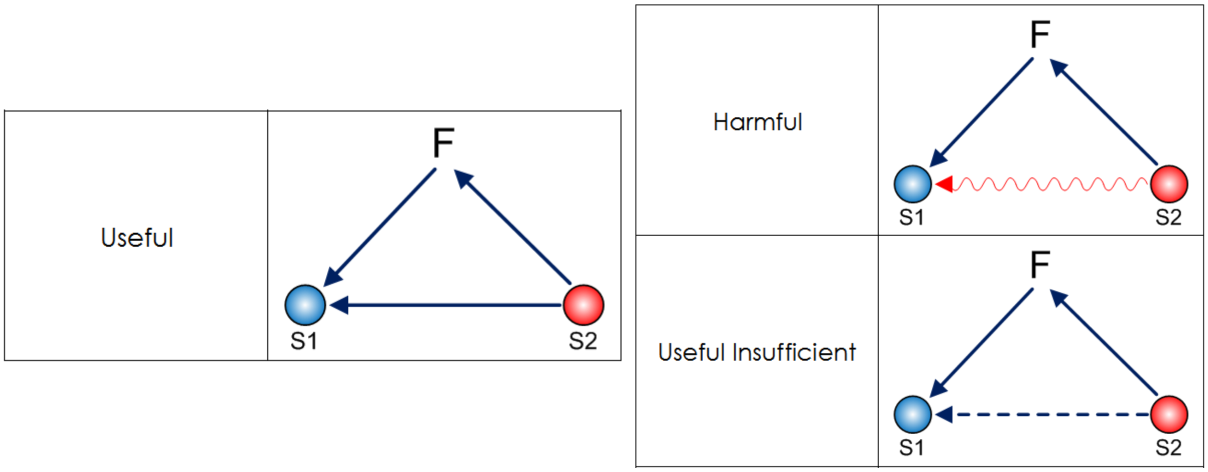


Fig. 14. Substance-Field (Su-Field) Models.

3.3.5. *Model of contradiction*

As mentioned earlier, the recognition of the refusal of compromises between conflicting requirements as a major mechanism for system evolution is among the TRIZ key findings. As a direct consequence, any problem solving process should start with the identification of the contradictions limiting the ideality of a technical system. The complete model of a contradiction comprehends three parameters (Khomenko et al., 2007) similarly to the concept of atomic conflict in (Yan & Zeng, 2011):

- Two (2) Evaluation Parameters (EP) constituting a measure of system requirements satisfaction;
- One (1) Control Parameter (CP) whose value impacts, with opposite results, both the Evaluation Parameters.

More specifically, a contradiction occurs when two Evaluation Parameters are coupled in such a way that the attempt of improving any of them determines the worsening of the other (Fig. 15). The Control Parameter constitutes a design variable governing both the EPs, such that the following statements apply:

- <Control Parameter> of Element X should assume Value 1 in order to improve Evaluation Parameter 1 of Element Y, but then Evaluation Parameter 2 of Element Z worsens;
- <Control Parameter> of Element X should assume Value 2 (such that Value 2 ≠ Value 1) in order to improve Evaluation Parameter 2 of Element Z, but then Evaluation Parameter 1 of Element Y worsens.

It is worth noting that the contradiction is formalized in accordance with the ENV model. A graphical representation of a contradiction is shown in Fig. 16, where EP(+) should be interpreted as "EP improves" and EP(-) should be interpreted as "EP worsens".

Classical TRIZ literature often distinguishes between Technical/Engineering contradictions and Physical contradictions, the former expressed just taking into account the Evaluation Parameters (right part of the model in Fig. 16), and the latter focused only on the opposite requirements for a same Control Parameter (left part of the model in Fig. 16).

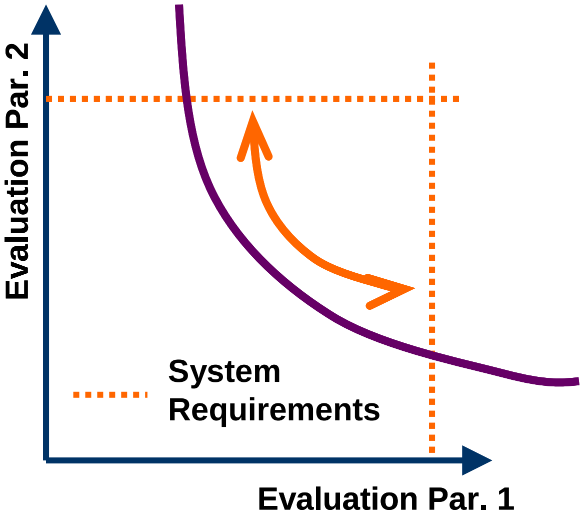


Fig. 15. A contradiction appears when two Evaluation Parameters are coupled.

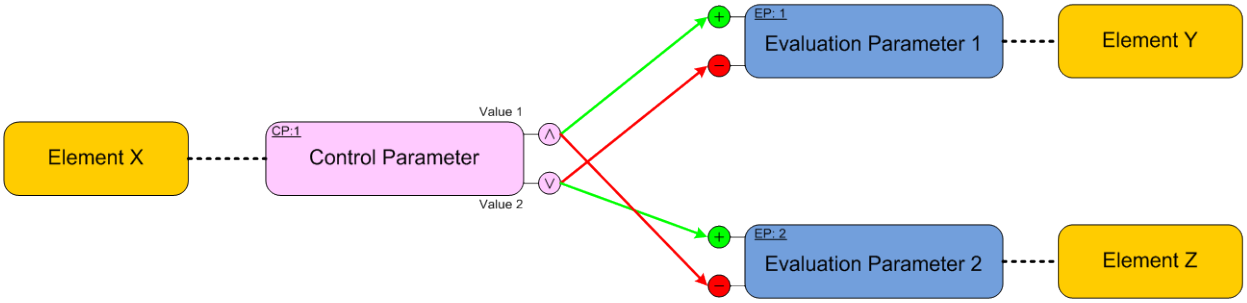


Fig. 16. OTSM model of TRIZ contradiction.

3.4. Reference TRIZ model of system thinking (System Operator)

Often referred as Multi-screen Schema, the System Operator is another key model of the TRIZ body of knowledge, aimed at providing system thinking capabilities to any problem solver. In facts, it constitutes an effective means for avoiding psychological inertia in several steps of the problem solving process, and the essence of reasoning of a creative person (Althsuller & Vertkin, 1994).

In a few words, the System Operator (typically depicted as a 3x3 matrix of “screens”) is characterized by a vertical axis representing the level of detail of the analysis (to be intended as the subsystem level of the analysis focus) and a “Time” dimension constituting its horizontal axis. A talented problem solver, whatever the Technical System dealing with, always recognizes and takes into account the environment and the external object that the system interacts with (i.e., the super-system), its constituting elements (i.e., the sub-systems), and the past, present and future of each detail level. Depending on the specific situation, the Time dimension can be considered as a historical time (the evolution of certain systems), as a process time (while analyzing a chain of events, even with their cause-effect relationships), or as a life cycle of an element of a system (from its creation to the disposal/recycling stage and as speed or acceleration of an action), if these variables are relevant for the specific situation. It is important to observe that super-system/sub-system relationships and the past/future relationships are just relative concepts; in other terms, the representation of the System Operator as a nine-screen schema is just conventional, but its dimension should be considered arbitrarily extendible in any direction (Fig. 17).

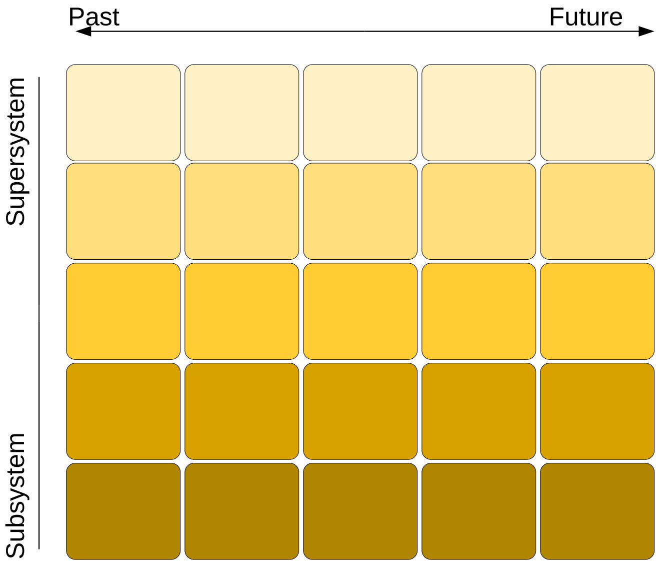


Fig. 17. System Operator.

4. TRIZ Methods and Instruments

Even though most of the literature in English refers to TRIZ instruments just mentioning the Contradiction Matrix, the Classical TRIZ toolkit is characterized by further, more powerful, instruments. Hereafter, the aims and scopes of the last problem solving methods and tools proposed by Altshuller are presented together with essential comments on their strengths and weaknesses based on the author’s experience.

4.1. Algorithm of Inventive Problem Solving (ARIZ)

As mentioned in the previous section, ARIZ is the algorithm developed by Altshuller until 1985 to solve non-typical problems. Indeed, ARIZ is also a means to improve the thinking capabilities of a problem solver, since its logic is eventually assimilated and the whole process is performed at a subconscious level. In the course of ARIZ evolution, the analysis and contradiction resolution steps were continually improved, by adding the capability to solve more and more complicated problems. Currently, Altshuller's last ARIZ version (ARIZ 85-C) is a highly detailed method and may seem complicated. Nevertheless, TRIZ newcomers should also try to learn it since the very beginning due to its powerful inherent logic.

In facts, ARIZ constitutes the methodological framework to guide the thinking process of a problem solver, according to the models described in Section 3. Some phases of this process are supported by specific tools as the System of Inventive Standard Solutions and the Pointer to Effects described below. Hereafter, its main constituting parts are overviewed since a detailed explanation of each step of ARIZ would require a much longer presentation. Interested readers are kindly invited to visit the following suggested web sites with exhaustive explanations and examples: http://www.tetris-project.org and http://www.triz.co.kr/TRIZ/intro.html.

Once again, it is necessary to mention that ARIZ has been originally developed for problem solving purposes and not for supporting technology forecasting activities. The logic of ARIZ reflects all the models of the TRIZ problem solving process described in the previous section (Hill model, Tongs model, Funnel model), as well as the mental approach of system thinking (System Operator).

Thus, for example, in accordance with the Hill model, the initial problematic situation must be processed in order to build a model of the problem according to a canonical formulation, wherefrom a solution can be built with codified techniques.

The preliminary exploratory analysis of a problem situation is approached according to the nine steps proposed in the "A" version of ARIZ 85 (Altshuller, 1985):

0.1. Determine the final goal of the solution
(note by the author: The Laws of Engineering Systems Evolution, and particularly the concept of Ideal System (Section 4.4.4), provide a systematic support to the accomplishment of such a task, where an exploratory analysis is performed and there are no precise directions to follow due to external inputs)

0.2. Investigate a "bypass approach"
(note by the author: such a step can be valuably supported by the systematic application of the multi-screen perspective of the System Operator, by changing the level of detail of the analysis and moving from preventive to compensative approaches)

0.3. Choose the best problem to solve among those identified at step 0.2
(note by the author: the choice should also take into account the maturity level of the Technical System under study and the availability of resources for its further development; in any case, "wrong" choices are efficiently highlighted by the following analysis driven by the ARIZ algorithm, and in particular by the steps of part 6)

0.4. Determine the required quantitative characteristics

0.5. Increase the quantitative characteristics by considering the time of invention implementation

0.6. Define the requirements for the specific conditions in which the invention is going to function

0.7. Examine if it is possible to solve the problem by direct application of the Inventive Standards

0.8. Enrich the information base about the problem through patent analysis

0.9. Use the STC (Size, Time, Cost) Operator
(note by the author: the STC Operator is a tool for overcoming psychological inertia by searching for analogies with radical modifications of the operational space and/or operational time of the main function of the system under study and/or its cost).

The following analysis can be performed according to the last official version of the algorithm published by Altshuller, i.e., ARIZ 85C. The general process is divided in nine parts, as summarized by the flow diagram shown in Fig. 18:

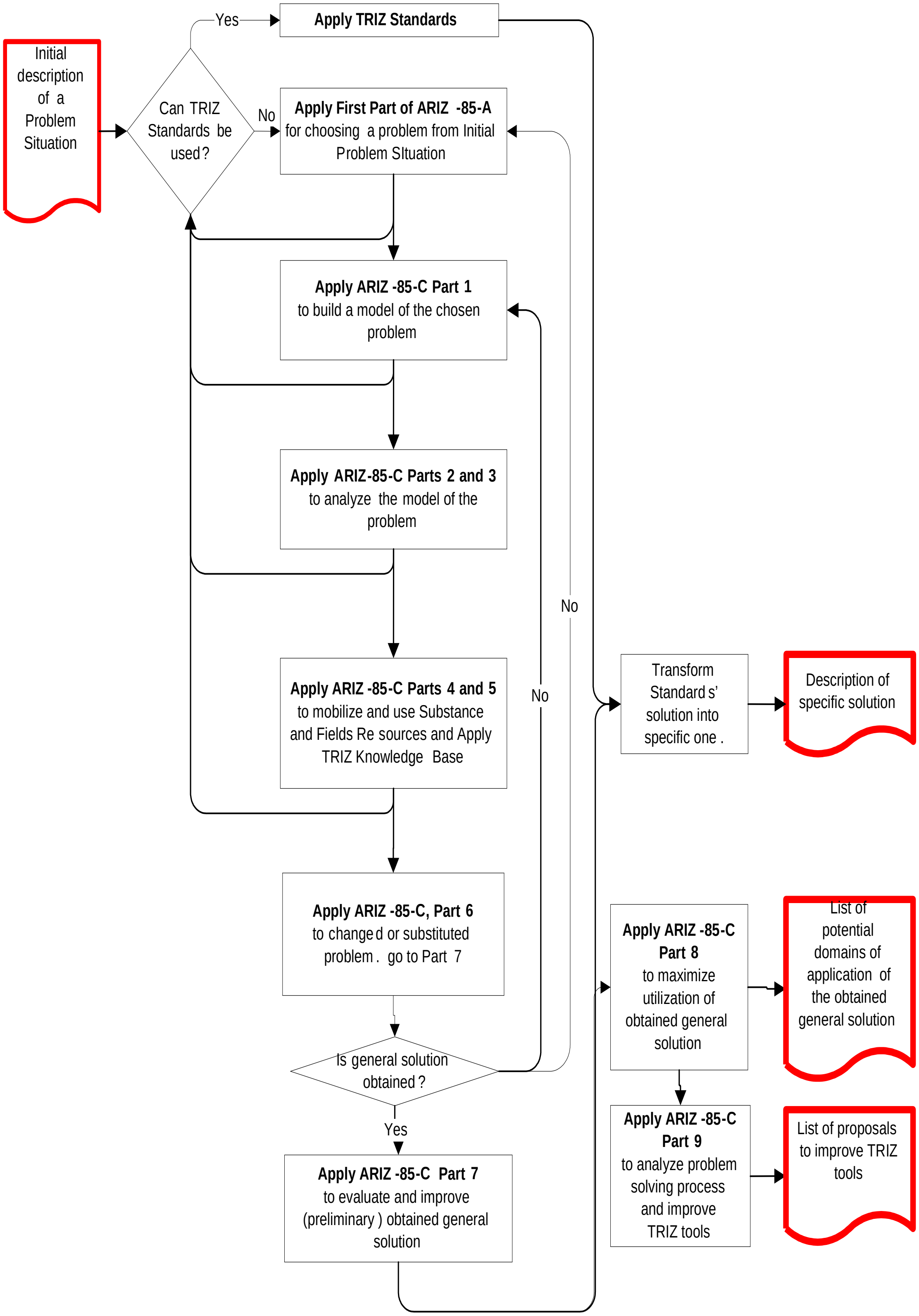


Fig. 18. General process of ARIZ 85C (Khomenko et al., 2007).

1) Construction of a model of the problem and application of the Standard Solutions.
   The aim of the first part of ARIZ is to create a model of the problem to be solved. At the end of the first part, the problem selected from the initial situation is formulated as a technical contradiction – a contradiction that describes a conflict between two parameters used for evaluating the quality of a given system (Evaluation Parameters, Section 3.3.5). The Tongs model provides a general direction for the identification of the key technical contradiction to overcome. The first part of the algorithm ends with a tentative application of the Inventive Standards to the model of the problem.
2) Analysis of the available resources.
   The second part of ARIZ is conceived for analyzing the problem model built at the previous stage and for preparing the recognition of in-depth physical contradictions underlying the problem. This is done by identifying available resources (space, time, substances, fields).
3) Identification of the physical contradictions and definition of the ideal solution.
   The resources identified at the previous stage are then analyzed to check their potential impact on the Evaluation Parameters of the contradiction characterizing the model of the problem. Consequently, a number of alternative physical contradictions is elicited and further analyzed through complementary formulations at macro and micro levels. Here the Ideal Final Result corresponding to each physical contradiction contributes to the definition of the profile of the final solutions to be obtained by their convergence (Funnel model of the problem solving process). It is worth noting that the higher is the number of physical contradictions identified, the more precise is the picture of the final solution (just like adding more features and values to the description of a system according to the ENV model). In many cases, valuable solutions are already depicted at the end of the third stage of the algorithm.
4) Mobilization of resources.
   The fourth part of ARIZ is designed to help understanding how the available resources can be used to solve the problem as defined in the third part of the algorithm, and to increase the effectiveness of the solutions already found. If one of the obtained solutions fits the expected results defined at stage 0, then the algorithm suggests moving to the seventh part for preliminary evaluation of the solutions in accordance with the ARIZ rules. If, on the contrary, no satisfactory solution has been found, the analysis continues according to the fifth part of the algorithm.
5) Application of the TRIZ Knowledge Base.
   The model of contradiction built in the previous steps, and reformulated according to the directions provided by parts 3 and 4, can be effectively approached by applying the TRIZ Knowledge Base, i.e., the Standard Solutions, the principles for solving physical contradictions, the pointer to physical, chemical and geometrical effects.
6) Changing and/or substituting the initial problem description.
   The sixth part of the algorithm offers recommendations regarding the change or substitution of the problem definition or the problem model. If no satisfactory solutions have been identified, then the reformulated problem is analyzed starting again from the first part of ARIZ. It is worth to mention that in a small percentage of situations, the resources available both at system level and at super-system level are exhausted (Fig. 19, blue line); in such cases it is not possible to determine a solution to a mini-problem, i.e., a solution preserving the current technology through the maximum exploitation of the available resources. As a consequence, major changes must be introduced (e.g., a transition to micro-level, see the laws of evolution below) as represented by the red line in Fig. 19.

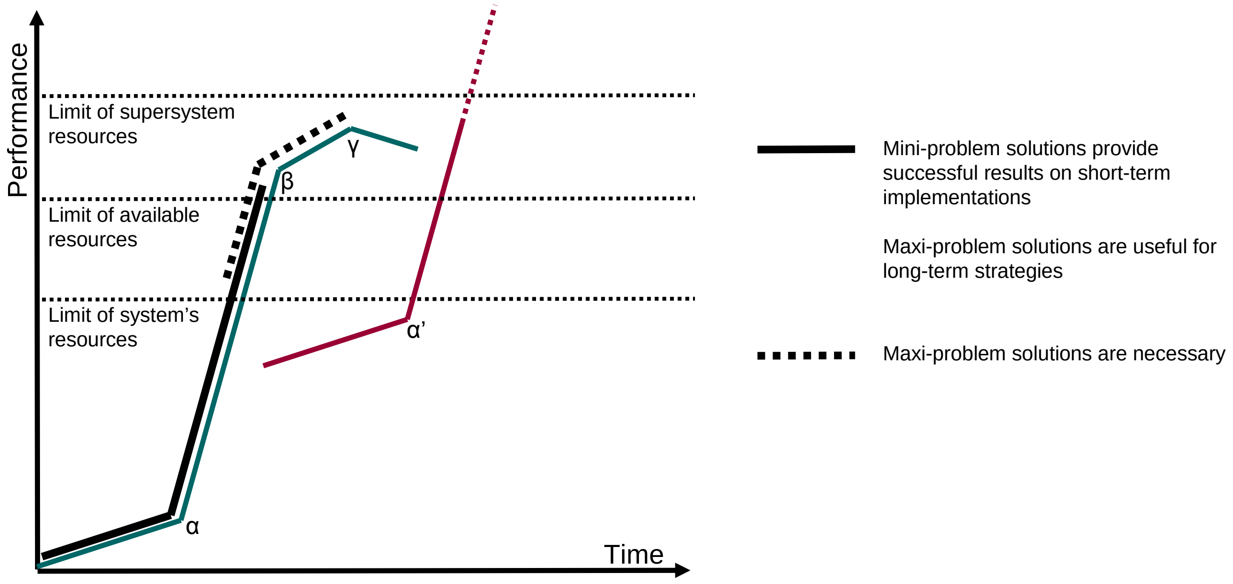


Fig. 19. Impact of Mini-Problem and Maxi-Problem solutions according to the maturity level of a Technical System and the amount of available resources at system and super-system level.

7) Evaluation of the obtained solutions.
The seventh part of ARIZ contains rules for evaluating solutions from the TRIZ viewpoint and for strengthening the obtained solution. In the course of this evaluation, there may appear new ideas specifying or improving the obtained solution, e.g., by eliminating side problems.
8) Expanding the application scope and standardizing a creative solution.
The eighth part is dedicated to prepare the implementation phase, and also to check whether the proposed solution can be applied to solving other problems, including those from different subject areas. This allows the solution to be given a more generalized standard form for further practical application. This part is also necessary for providing better patent protection for the solution (e.g. creating a patent umbrella).
9) Reflection stage.
The main purpose of the ninth part of ARIZ is to increase the creative potential of the person or team involved in the problem solving process, through a careful reflection of the work done. In principle, each ARIZ step should be followed by reflection on how that step was made, what difficulties were faced while performing that step, what difficulties were overcome, how accurately the ARIZ recommendations were performed, whether the work done differs from what is recommended by ARIZ, and why such differences occurred. The answers to these questions develop the reflection skills and facilitate understanding the ARIZ-based problem-solving process at the stage of assimilating the Algorithm on the examples of training problems. At the stage of professional application of ARIZ to real problems, they facilitate further development of ARIZ and the improvement of its effectiveness in solving new, more complex problems.

The use of ARIZ for solving inventive problems is somehow controversial in the TRIZ community. Expert practitioners claim its usability and effectiveness despite the apparently pedantic rigidity of its steps. The author's experience indeed confirms that a large majority of TRIZ beginners finds it too cumbersome and hardly appreciate its benefits. Nevertheless, all the simplifications of TRIZ bring to overlook the analysis phase. As a consequence, the contradictions underlying the problem to be solved are poorly formulated and the emerging solutions often fail to achieve the desired outcomes. Therefore, it is strongly recommended since the first acquaintance with TRIZ to follow at least the inherent logic of ARIZ, i.e. the problem solving process depicted by the models described in Section 3.2. Recently some scholars have demonstrated that a dialogue-based software application can guide users also with very limited TRIZ competences toward the formulation of a TRIZ contradiction (Becattini et al., 2011) and its thorough analysis (Russo & Birolini, 2011).

4.2. System of Inventive Standard Solutions

The Inventive Standard Solutions (sometimes briefly named Standards) are a system of 76 models of synthesis and transformations of technical systems in agreement with the Laws of Evolution of Engineering Systems. Together with ARIZ (Section 4.1), the database of Effects (Section 4.3) and the Laws of Engineering Systems Evolution (Section 4.4), the Standard Solutions constitute the most advanced and effective set of instruments of Classical TRIZ, thus substituting Altshuller's matrix of technical contradictions and the Inventive Principles.

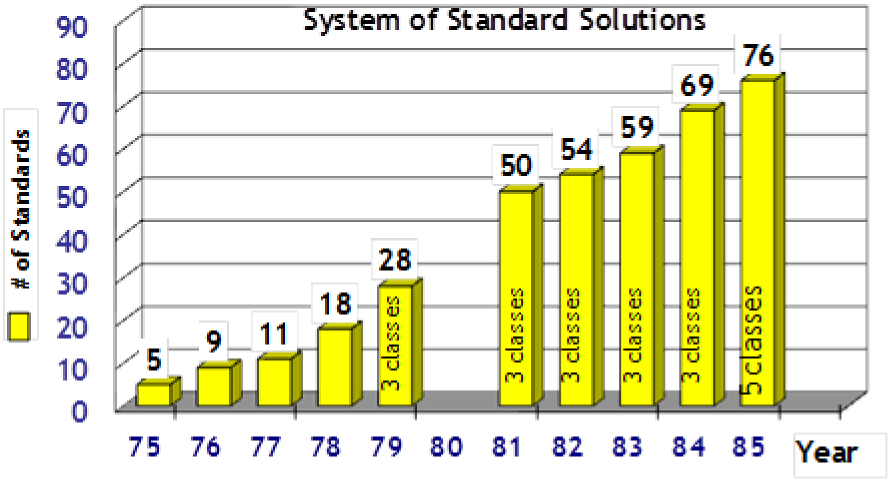


Fig. 20. History of the development of the System of Inventive Standard Solutions.

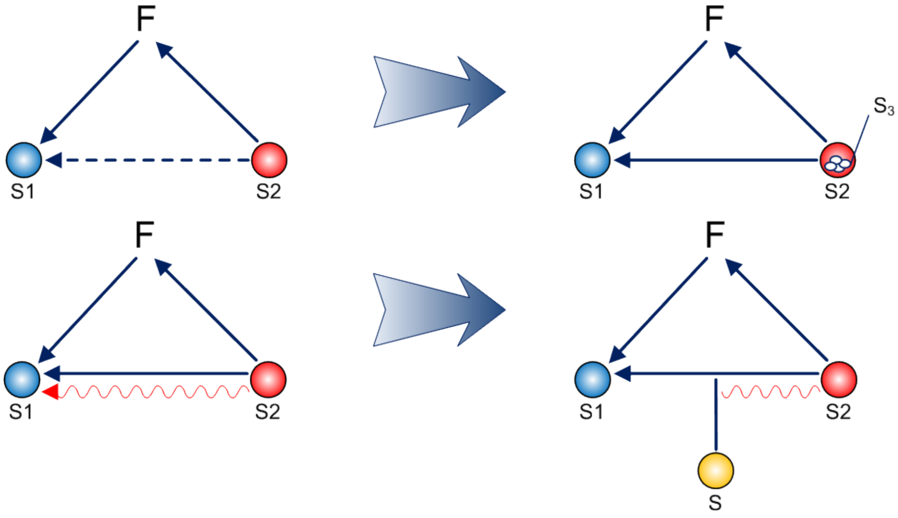


Fig. 21. Two example models of a standard solution: an undesired Su-Field interaction (insufficient interaction above, harmful interaction below) disappears through a transformation of the Su-Field model.

The Standards were developed between 1975 and 1985 with the aim of providing a structured approach to the solution of a technical problem, systematically browsing the knowledge of individuals, as well as of databases of physical, chemical, geometrical effects. Originally, the Standards were listed as separate solution models, numbered according to the order of formalization. A system of 28 integrated Standards classified in three main subsets was presented and published by Altshuller in 1979. In the following years, further standards were added and the final structure of five classes was released (Fig. 20) (Altshuller, 1988).

Inventive Standard Solutions should be used to solve the great majority of “typical” problems to be represented by means of Su-Field models, i.e., when an insufficient or undesired interaction exists between two or more subsystems. Despite the appropriate application of the Inventive Standards requires a preliminary identification of a technical contradiction to solve (i.e. within the ARIZ process), they sometimes allow solving a problem and even to overcome or circumvent contradictions by means of a direct application, with no contradiction identification.

Standards are also useful to browse an individual’s knowledge following a systematic process.

In Classical TRIZ, the Inventive Standard Solutions are grouped into five classes:

1) Improving interactions and eliminating harmful effects
2) Evolution of systems
3) Transition to macro and micro level
4) Detection and measurement problems
5) Meta-solutions, helpers

Each standard solution is typically structured as a transformation of an initial “problematic” Su-Field model into a modified Su-Field model, where the undesired characteristics of the interactions between the subsystems disappear (Fig. 21).

According to the system of standard solutions, the following transformation may be applied to a Su-Field System:

- Introduction of a New Substance: a new element (Fig. 21); an internal additive; an external additive; a resource already available in the environment;
- Introduction of a New Field (Fig. 22, top);
- Modification of a Substance: modification of the Tool (Fig. 22, middle); modification of the Object; modification of the environment surrounding the substances of the Su-Field System; modification of a Field (Fig. 22, bottom);
- Use of Physical, Chemical, Geometrical Effects;
- A combination of any of the previous transformations.

The previous modifications can be applied to a whole element or to a portion in terms of changes/variations of any resource, such as:

- Space: number of dimensions, topology, shape, size;
- Time: timing of action, duration of action, frequency of action;
- Properties: chemical properties, physical (electrical, magnetic, optical, etc.) properties;
- Energy: amount of energy, type of energy (kinetic, thermal, electrical, etc.).

The application of a Standard Solution means following the directions of the selected standard so as to transform the original Su-Field System characterized by poor efficiency and/or undesired effects into another Su-Field system where the problem disappears. The transformation suggested by the selected Standard must be applied taking into account the Substance-Field Resources already available in the system and secondarily new/modified resources to be integrated in the system itself. Such a task can be supported by the navigation of a database of effects in order to complement individual and team knowledge.

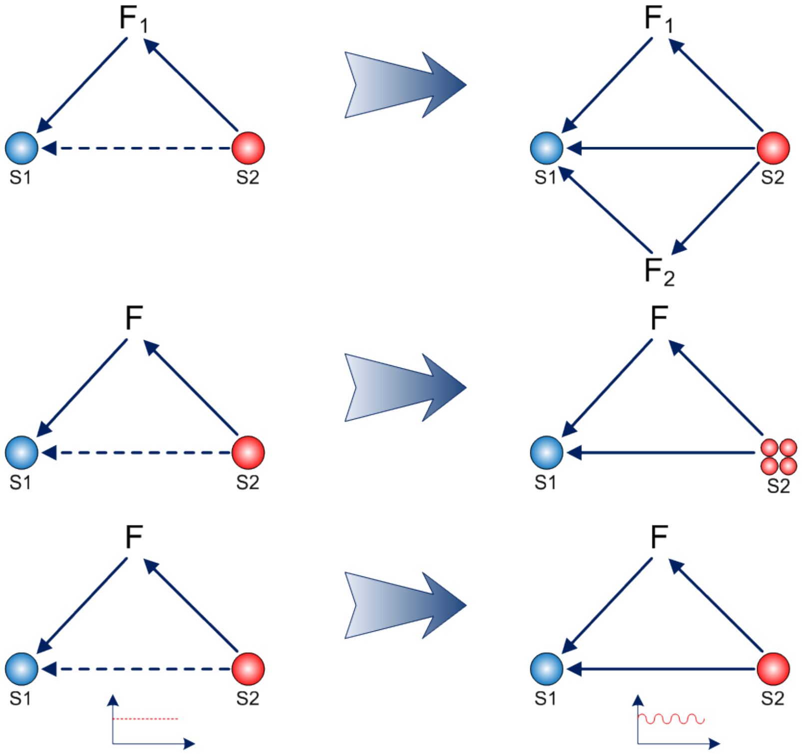


Fig. 22. Further example models of a standard solution: introduction of a new field (top), modification of a substance (middle), modification of a field (bottom).

The classification of the Standard Solutions is a guide to select the correct Standards to apply (Fig. 23):

- If a function is missing or an useful interaction between two elements of a Technical System should be improved, relevant Standards can be found in Class 1.1 (e.g. Fig. 21, above);
- If a problem is characterized by a harmful interaction between two elements of a Technical System, relevant Standards can be found in Class 1.2 (e.g. Fig. 21, below);
- In both cases, the modification of the existing substances/resources can be applied by following the Standards of Class 2 (e.g. those depicted in Fig. 22);
- More critical problems require more radical changes of the Technical System by an integration at Super-System level (Class 3.1, see also Section 4.4.6) or by a transition to a smaller scale of interaction (Class 3.2, see also Section 4.4.7);
- Detection and measurement problems can be approached by eliminating the need for measurement (Class 4.1), building a new interaction for information delivery (Class 4.2), further evolving existing measurement elements (Class 4.3);
- Whatever is the Standard to be applied, some special precautions can be adopted to prevent drawbacks while introducing a new substance (Class 5.1), a field (Class 5.2), a phase transition (Class 5.3), Physical and Chemical Effects (Class 5.4 and 5.5).

As a whole, the Inventive Standards constitute a practical tool to make the generation of conceptual solutions systematic. According to the author’s experience they can be fruitfully used also to support brainstorming sessions, even if the tool reveals to be more efficient if a proper situation analysis is performed before to start triggering ideas with the Inventive Standards. A specific study on the impact of a “Systematized Substance-Field Analysis” on engineering students thinking and problems solving capability has been presented in (Belski, 2009). Inventive Standards are successfully applied in the industrial practice by TRIZ practitioners, as for instance witnessed by (Song et al., 2012).

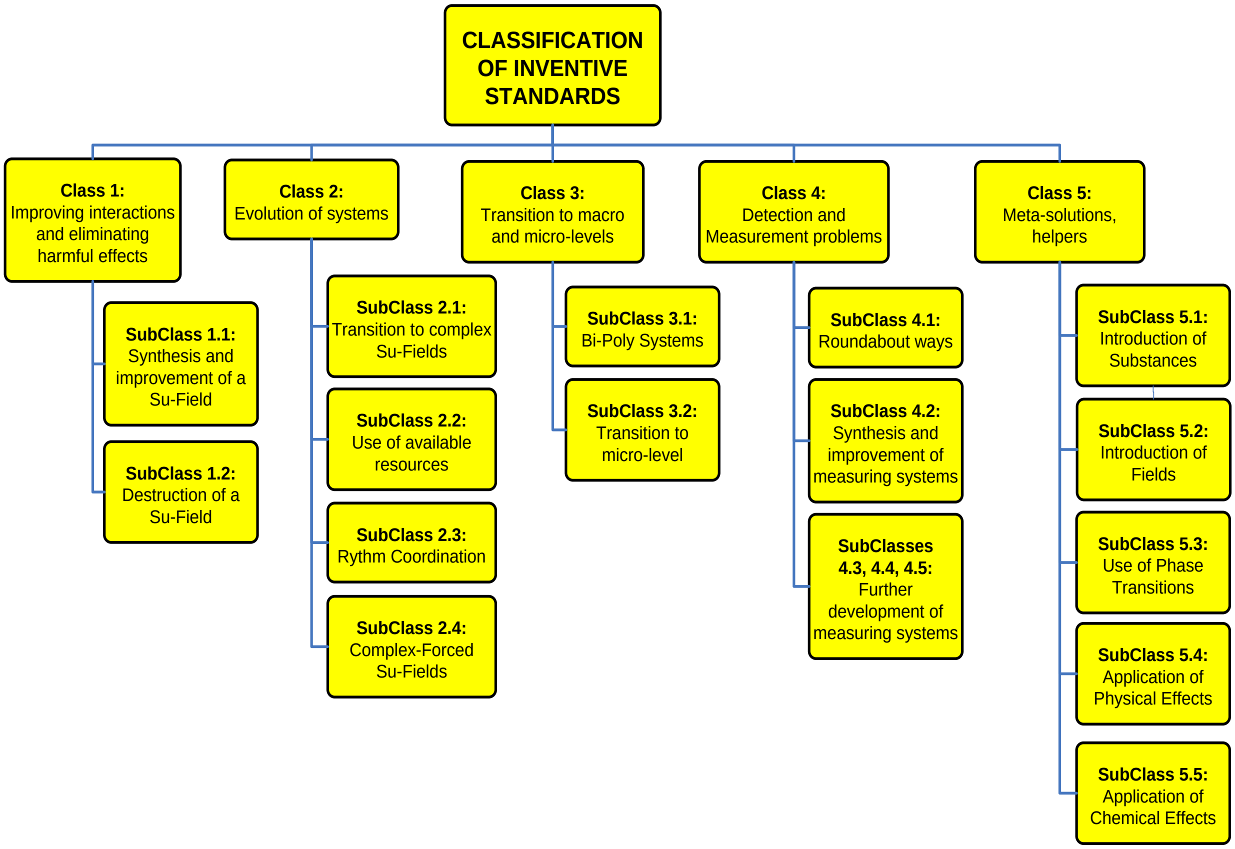


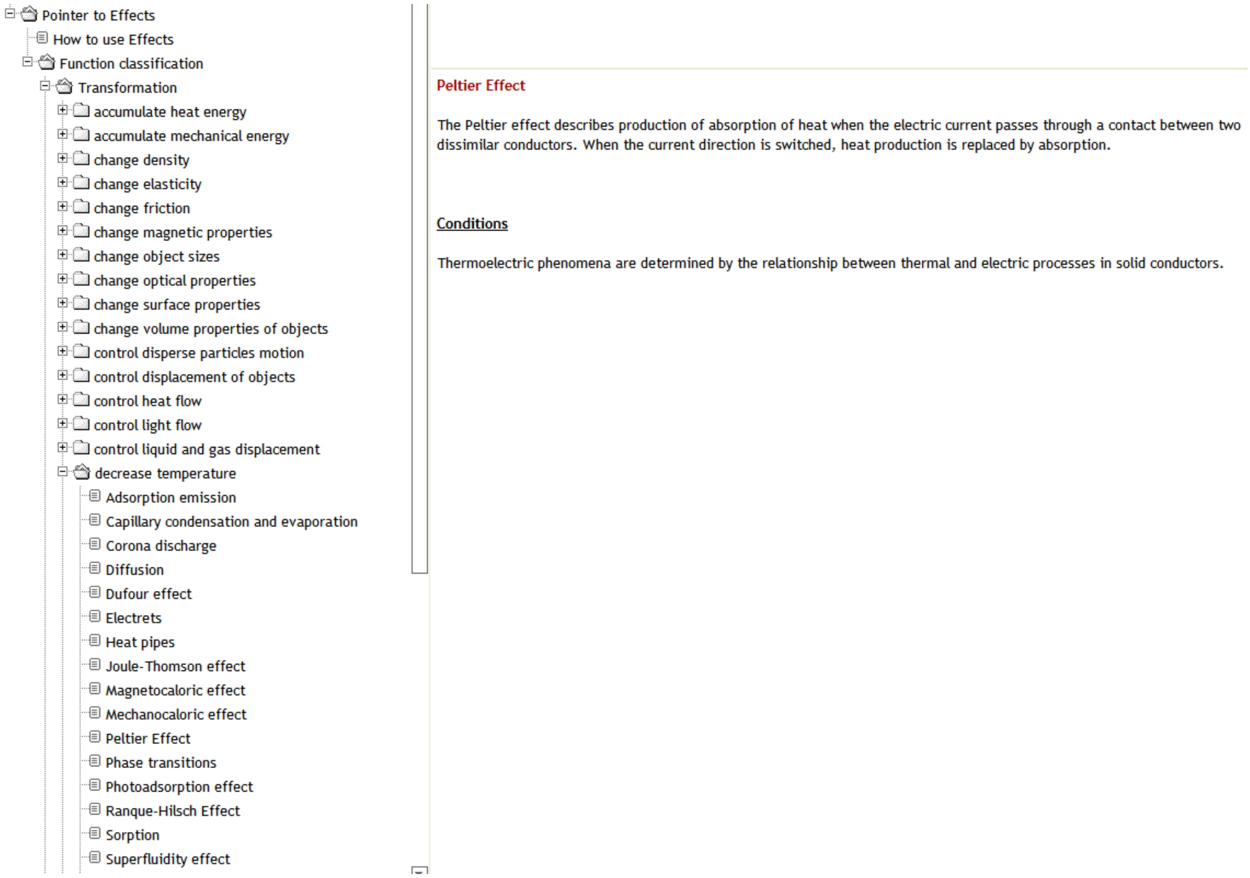
Fig. 23. Classification of the Inventive Standard Solutions.

4.3. Pointers to effects

The analysis of a technical system sometimes brings to the identification of some knowledge lacks which should be covered through systematic means. Generally speaking, many breakthrough inventions introduce in a certain field of application new principles to deliver a function, i.e., novel ways of using natural effects. Since the competence of any engineer, even with adequate background, covers just a small percentage of the available scientific knowledge, Altshuller started the collection of natural effects classified as Physical Effects (mostly related to transformations of energy type) (Altshuller et al., 1987). He also promoted and coordinated the creation of a structured collection of Chemical Effects (transformations of substances) (Salamatov, 1988) and Geometrical Effects (modifications of the distribution of energy and/or substance) (Vikentiev & Yefremov, 1988, 1989).

In order to speed up the usage of such a Knowledge Base and to access to the most appropriate effect, some pointers to effects have been developed according to a functional classification: these databases contain lists of functions and their related effects which can be applied to deliver such functions (Fig. 24).

As further discussed in Section 5.1, the growing performance of current text-mining technologies has largely increased the possibility of automatically feeding a database of physical effects through information retrieval and extraction from scientific journals, patents, web sites etc. Besides, also in this case, the information search should necessarily follow a proper problem analysis: actually, fuzzy queries unavoidably bring to an unmanageable amount of apparently useful physical principles, in fact characterized by a high percentage of irrelevant information.



Peltier Effect

The Peltier effect describes production of absorption of heat when the electric current passes through a contact between two dissimilar conductors. When the current direction is switched, heat production is replaced by absorption.

Conditions

Thermoelectric phenomena are determined by the relationship between thermal and electric processes in solid conductors.

Fig. 24. Example database with pointer to natural effects through a functional basis (freely accessible at http://www.triz.co.kr/TRIZ/frame.html).

4.4. Laws of Engineering Systems Evolution (LESE)

TRIZ has been developed as a theory for solving inventive problems and not specifically dedicated to forecasting applications; indeed, a unanimously accepted TRIZ method for technology forecasting does not exist. Nevertheless it is worth describing with a certain degree of detail the Laws of Evolution, since they have demonstrated powerful capabilities to support the analysis of the evolution of technical systems, and also according to the main goal of the present paper, i.e. postulating the adoption of TRIZ as a reference theoretical framework for the anticipatory design of future technical systems.

As mentioned earlier, Technical Systems evolve by following repeatable patterns which are not dependent on the field of the application or the function that the technical system is supposed to deliver. According to the original formulation published by Altshuller (1979), a harmonized set of eight laws govern the evolution of Technical Systems (TS):

1) Law of completeness of TS parts
2) Law of “energy conductivity”
3) Law of harmonizing the rhythms of TS parts
4) Law of increasing the degree of ideality of the system
5) Law of irregular development of TS parts
6) Law of the transition to a super-system
7) Law of the transition from macro to micro level
8) Law of increasing the involvement of Su-Field interactions

These Laws are typically classified in three groups: the Laws of Statics (1-3), the Laws of Kinematics (4-6), and the Laws of Dynamics (7 and 8). More specifically, the first three LESE prescribe the minimum conditions to be satisfied by a technical system, in order to deliver a certain functionality, with a sort of static description as in a picture. Then the Laws of Kinematics position a technical system into an evolution process, thus taking into account its past, its current status and its expected future. Finally, the third LESE group is related to the laws describing two alternative dynamics of evolution, as detailed below.

These Laws must be considered as a system of coexisting regularities characterizing the evolution of any technical system and its inherent complexity. Nevertheless, for the sake of clarity, they will be described separately and in most cases with distinguished examples from each other. Besides, some interactions between the LESE will be highlighted in order to provide a harmonized and systemic view to the readers.

4.4.1. Law of completeness of TS parts (Statics)

In order to deliver its function, a TS must include, internally or externally (e.g., through the contribution of a human operator), four elements (as described in Section 3.3.3, Fig. 13): Tool, Engine, Transmission and Control. In other words, the first Law claims that a tool by itself is not able to deliver any function (e.g. a screwdriver does not rotate any screw without the energy provided by its user); similarly, it is not sufficient to add energy to the system, if such an input flow is not “controlled” according to the expected intent (e.g. the screwdriver must be properly positioned adjacent to the screw head and rotated according to the desired turning effect).

A corollary of the first law claims that at least one of the previous elements must be controllable to adapt the behavior of the system to the directions provided by the control unit. Even though they are not explicitly mentioned in the original formulation of the LESE, further corollary trends can be associated with the first Law of Evolution: technical systems evolve by integrating all the elements of the Minimal Technical System in order to reduce human involvement. For example, braking systems for reducing vehicle speed were originally constituted just by a clamping mechanism, while both energy and control was demanded to the driver. Then the transmission was integrated through a hydraulic circuit for improved performance and ergonomics. The following step, i.e., the introduction of a servo-device, eliminated the need of energy provided by the user in order to produce high braking forces. Eventually, ABS systems have initiated the integration of the control within the technical system, such that the driver is not supposed to control the braking force on slippery roads. This trend towards the integration of control is still in progress, with current cars integrating radar systems capable to activating the brakes when the vehicle gets dangerously close to another car or to an obstacle.

4.4.2. Law of “energy conductivity” (Statics)

A further minimal condition for the existence of a technical system capable to deliver its function is the unhindered passage of energy through all its parts from the engine to the tool. In analogy with the corollary of the first law, it is necessary to ensure conductivity of energy between the control element and the directly controlled part, so as to control the entire technical system. The second law can also be integrated with logic consequences not explicitly mentioned in the original publication by Altshuller: technical systems evolve towards an increased efficiency of energy circulation, i.e., with reduced energy losses from the supply to the tool. In several circumstances such a trend is obtained through a reduction of the functional distance between the engine and the tool, i.e., after a trimming phase in the convolution process (see the 6th Law below).

If we consider the evolution of the braking system mentioned above, the transition from mechanic to hydraulic transmission is an example of increased efficiency of energy circulation due to the reduction of energy losses related to mechanical friction. The trimming phase might be interpreted as the elimination of any transmission, by applying the braking force as close as possible to the tool (e.g. electromagnetic force acting on the friction element of the brake).

4.4.3. Law of harmonizing the rhythms of TS parts (Statics)

The third essential condition for the functioning of a technical system is a coordination of the rhythm (periodicity, frequency) of all its parts. Any discrepancy between the functioning rhythm of any pair of parts hinders the successful behavior of the entire system. Thus, technical systems evolve towards increased harmony between the parts, when the interaction improves the overall performance and towards purposeful de-coordination when it is preferred to inhibit a certain interaction. Such a matching/mismatching trend can be extended up to the limit of the natural frequencies of a technical system, i.e. when there is a full harmonization of the system with its nearest super-system, the environment. Indeed, it is well known that under resonance conditions a system provides the maximum output for a given input, while anti-resonance determines the maximum impedance, i.e., opposition to energy flow. As an example, it can be mentioned that the cleaning performance of a vacuum cleaner is maximized by tuning the rotating speed of the fan with the acoustic resonance of the ducts.

4.4.4. Law of increasing the degree of ideality of the system (Kinematics)

All systems evolve towards the increase of the degree of ideality (Fig. 25), defined as the ratio between the benefits provided (in TRIZ terms, the useful functions) with the related problems (harmful functions) and costs (resources involved). Such an ideality increase follows a characteristic S-shaped curve along the system development. By combining the growth of system ideality with the consumption of resources described by the wave model mentioned earlier (Salamatov, 1991), two main stages can be recognized: first an increase of performance which exceeds the corresponding growth of resources consumption (evolution); and second, when the performance of the system reaches the maximum expected value, a reduction of the amount of resources needed, still preserving system functionality (convolution). As a consequence, an ideal technical system is a system requiring zero expenditure of resources (economic, social, ecological etc.), while still keeping its working capability (in other words, from the ideality point of view, a system evolves until disappearing, while its function is maintained).

More in details, the S-curve shows three typical stages of development (1 – Childhood; 2 – Maturity; 3 – Old age) characterized by precise mechanisms of Ideality increase, as briefly summarized in Table 3.

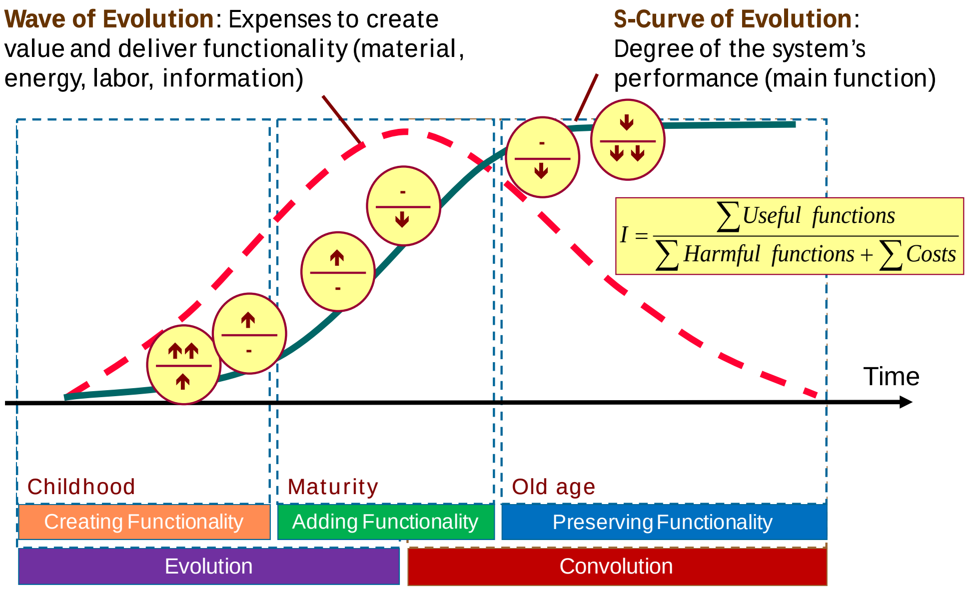


Fig. 25. Trend of Ideality increase (continuous blue line) compared with the consumption of resources (dashed red line) which reflects the wave model by Salamatov (1991) and distinguishes between the evolution and the convolution phases of system development.

4.4.5. Law of irregular development of TS parts (Kinematics)

The evolution of any technical system is characterized by an irregular development of its parts; the more complex the system is, the more unbalanced the developments of its parts are. Due to the different rate of ideality increase of each subsystem, and also due to their conflicting exploitation of system resources, contradictions occur and become the main barrier for system evolution (i.e., generating inventive problems). This law explains why just local optimization can be produced as far as conflicting requirements are compromised, while the elimination of contradictions is the major driving force behind technology evolution.

Looking back at the evolution of wheel braking systems, many contradictions can be observed throughout its development process. For example, the increase of performance of the brake pads determines higher friction forces and consequently more heat to dissipate. Disk with larger and larger diameters have been used to improve the heat exchange surface; nevertheless, this higher consumption of resources (4th Law of Evolution, beginning of the Maturity stage) finally brings to conflicts with the closest super-system, the wheel (the disk must have a smaller diameter!).

4.4.6. Law of the transition to a super-system (Kinematics)

When the resources for further development of a Technical System are exhausted, evolution takes place through the integration of the system itself with other systems, i.e., forming a composed super-system, for mono-bi-poly combination. Further details about such a process of system integration are given by Inventive Standard Solutions 3.1.1-3.1.5 (it is worth noting that the Inventive Standards often describe exemplary trends of evolutions, which detail the more general evolution process depicted by the LESE).

As schematically shown in Fig. 26, during the evolution phase, system efficiency can be improved by combining the original system with one or more systems to form a bi-poly system (e.g. multi-blade razors). A further improvement of system functionality can be achieved by increasing the difference between system components, from mono-function homogeneous systems, to mono-function heterogeneous systems (e.g. red and blue pencils), to multi-function systems (e.g. multi-function portable knives), to systems with inverse function (e.g. pencil and rubber). When the convolution phase takes place, several components are integrated into a single component, while keeping the performance of the overall system, but with reduced consumption of resources. Such a trimming activity can be partial, or even extended, when a more radical transition is likely to happen.

Table 3. Main stages of system evolution and related mechanisms of Ideality increase

Stage	Mechanisms of Ideality increase
Childhood	Improvement of performance parameters of a system through intense usage of resources
	Appearance of new functions through intense usage of resources
Maturity	Improvement of the performance parameters of a system with unchanged costs. System optimization and adoption of resource-saving technologies.
	Appearance of new functions with unchanged costs through the exploitation of the available resources.
	Preservation of system performance under reduced consumption of resources and system simplification.
Old age	Preservation of system performance under reduced consumption of resources and system simplification.
	Significant decrease of resources consumption and appearance of new properties/functionalities of the system.

4.4.7. Law of the transition from macro to micro level (Dynamics)

The seventh Law of Evolution describes the regularities governing the transition to a new technology which necessarily occurs when a Technical System reaches the maximum exploitation of the available resources: these transitions are characterized by a reduced dimension scale of the interaction between the

Tool of the system and the object of the function. In other words, the physical-chemical effect constituting the working principle, which provides the Tool with the capability to accomplish the function, progressively involves phenomena acting at a smaller scale (e.g., solid, dust, crystal lattice, molecules, ions, atoms, subatomic particles, etc.).

4.4.8. Law of increasing the involvement of Su-Field interactions (Dynamics)

The development of Technical Systems proceeds in the direction of increasing the involvement of Su-Field interactions, i.e., towards a transition from incomplete Su-Fields to complete Su-Fields, and from these to more complex Su-Fields structures aimed at increasing adaptability, controllability and the overall performances. Class 2 Standard Solutions provide detailed references to the practical implementation of such a general direction.

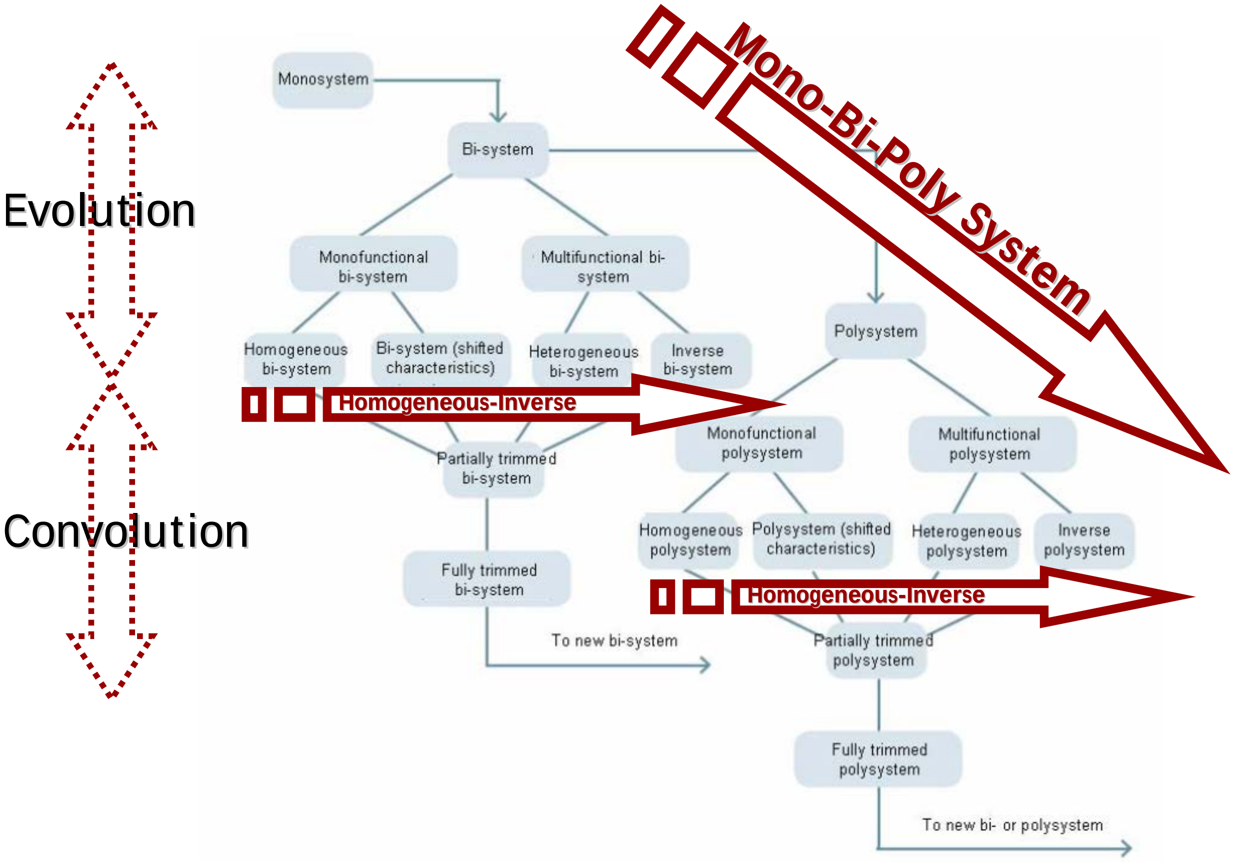


Fig. 26. The Law of Transition to Super-system can be implemented through a Mono-Bi-Poly integration (Standard Solutions Class 3.1.1-3.1.5).

According to the original intent of Altshuller, the Laws of Systems Evolution allow focusing the generation of inventive solutions towards so as to avoid the waste of resources as it typically happens with a purely intuitive and unstructured approach (Cavallucci, 2001). More recent studies have demonstrated the applicability of the LESE for the anticipation of evolutionary scenarios, as for instance in (Zlotin & Zusman, 2001; Shpakovsky, 2006; Cascini et al., 2011).

It is worth noting that the Laws of Evolution have a sufficiently abstract form to be applicable in any field, also when dealing with technologies not existing when Altshuller formulated them. Besides, it is necessary to build an explicit model of the system to be investigated through the LESE, e.g. as proposed in (Cascini et al., 2009), so as to systematically build a comprehensive map of the expected evolutionary scenarios. If the preliminary modeling activity is missing or too simplistic, the application of the LESE is equivalent to a traditional brainstorming session driven by a list of triggers, useful to produce out-of-the-box ideas, but with minor chances to systematically cover the entire solution space of the domain under study.

5. Discussion and Conclusions

Still with several potentialities for further improvements, TRIZ-based forecasting is characterized by an extremely original theoretical foundation and by unique properties which can also be fruitfully exploited in combination with both other Design Methods and Technology Forecasting methodologies.

According to what has been described in the previous sections, TRIZ instruments allow to build a qualitative description of future situations, also anticipating radical modifications of the Technical System under study. These modifications are not predicted by forecasting future customers' priorities, but through a logical application of the evolution regularities identified by Altshuller, namely the Laws of Engineering Systems Evolution, to a generalized representation of the Technical System (Cavallucci & Rousselot, 2011).

Furthermore, the analysis of contradictions highlights which subsystems are the first candidates for improvement, and the analysis of the resources allows to avoid waste of time and efforts for the development of mature sub-systems requiring a more radical transition to super-system or to micro-level.

TRIZ instruments not only help identifying the sub-systems which first deserve partial or essential modifications, but also provide directions about what modifications should be introduced (e.g. through the Inventive Standards, the Principles for overcoming Physical Contradictions etc.). Besides, TRIZ does not provide any information about quantities: none of its instruments is related to quantitative estimations of the expected numerical value of system parameters. Such a lack of quantitative information impacts also timing assessments: indeed, TRIZ does not allow to estimate when a certain modification will occur.

Moreover, as already mentioned in the introduction of the present paper, TRIZ has not been originally developed for supporting forecasting activities, and a unified approach for the application of its tools for the prediction of systems evolution does not exist. A further weakness is related to the limited repeatability of TRIZ-based predictions: different TRIZ experts can approach the study of a complex system focusing the attention in subsystems at different detail levels, thus generating not harmonized anticipations of its future.

A more comprehensive discussion about the limits of TRIZ-based forecasting, also in comparison with other methodologies, is discussed in (Kucharavy & De Guio, 2005).

5.1. Use with other methods and actual frontiers

As with many other techniques for Technology Forecasting, TRIZ also benefits of the integration with other methodologies, even if only preliminary attempts have been published so far. Since established procedures of TRIZ integration with other Futures Research Methodologies still do not exist, a short list of references is provided here, while a more detailed analysis is postponed to a next publication on this journal.

Kucharavy et al. (Kucharavy et al., 2009) explore the TRIZ potential for qualitative anticipation of a system's future combined with Logistic Models to determine the timing of evolution and to integrate quantitative estimations.

Many ongoing research activities are dedicated to the integration of TRIZ-based analyses with data and text-mining techniques. Cascini and Russo (Cascini & Russo, 2007) have proposed text pattern searches for TRIZ concepts identification. (Cascini et al., 2007) presents an algorithm based on semantic processing techniques for performing automatic function analyses of patents and related extraction of relevant components as a means to speed up the analysis of the evolution of technical system with a TRIZ perspective. Statistical text mining techniques with analogous goals are investigated in (Verhaegen et al., 2009). Finally, the problem of improving the speed of gathering knowledge to assist the formulation of key problems for a given domain within the meaning of TRIZ has been discussed in (Cavallucci et al., 2009).

Some preliminary implementations of data mining techniques for speeding up correlation analyses of the number of relevant inventions with the maturity of a technical system (Fig. 2) have been recently proposed by (Li et al., 2012).

The publications mentioned here constitute the frontier of current research activities. Further studies involve method refinements aimed at improving the repeatability of the results and the development of computer support means for complex system modeling and large data set management.

5.2. Conclusions

The present extensive review summarizes into a unified framework the main concepts, models and thinking instruments of TRIZ, the Theory of Inventive Problem Solving, within the specific perspective of anticipatory design of future technical systems, as a means to foster innovation capabilities of companies and R&D organizations.

Thanks to its effective body of knowledge, whose potential is demonstrated by the successful implementation in many worldwide leading companies, TRIZ provides a solid base from where to build a comprehensive methodology suitable to guide strategic decisions for new product development. The paper also refers about the main recent research directions aimed at increasing the robustness of TRIZ-based analyses and at integrating its models with complementary methods and tools.

A more detailed survey of recent research outcomes produced by scholars working in the field will be published in a next paper, together with some relevant examples of application in industry.

Acknowledgment

The author would like to thank all the TRIZ experts who contributed with relevant insights and suggestions to his learning process of such a complex, fascinating, powerful and comprehensive theory. Among them, a special gratitude to Dmitry Kucharavy, whose rigorous materials (www.seecore.org) and comments have largely inspired part of the present paper, and to Nikolai Khomenko for the punctual, patient, extended and valuable replies to any question he received until he passed away.

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