Functional Modeling For TRIZ-based evolutionary analyses

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

FUNCTIONAL MODELING FOR TRIZ-BASED EVOLUTIONARY ANALYSES

ABSTRACT

TRIZ literature presents several papers and even books claiming the efficiency of Altshuller's Laws of Engineering System Evolution as a means for produce technology forecasts. Nevertheless, all the instruments and the procedures proposed so far suffer from poor repeatability, while the increasing adoption of innovation as the key factor for being competitive requires reliable and repeatable methods and tools for the analysis of emerging technologies and their potential impact. The present paper proposes an original algorithm to perform a functional analysis aimed at building a Network of Evolutionary Trends for a given Technical System with repeatable steps. Such a goal has been achieved by integrating well known models and instruments for system description and function representation. The overall procedure has been already validated in a number of industrial case studies and it's here clarified by means of an example from the production of tablets in pharmaceutical manufacturing sector.

Keywords: FBS model, EMS model, Functional Basis, Technology Forecasting, Laws of Engineering Systems Evolution

1 INTRODUCTION

Nowadays the analysis of emerging technologies and their potential impact on markets, economies and societies requires reliable and repeatable methods and tools since the related information plays a critical role for strategic decisions of private and public organizations.
Therefore it is not surprising that more than fifty methodologies with different characteristics and specific purposes have been proposed so far in this field [1]. Nevertheless all these techniques reveal several weaknesses [2] as: limited accuracy on middle and long-term forecast; poor repeatability; poor adaptability, i.e. no universal methods are known, besides complementary instruments must be integrated according to the specific goal and data availability.
Within this context TRIZ is emerging as a systematic forecasting methodology [1, 3] and the TRIZ community widely claims the benefits arising from the application of Altshuller's Laws of Engineering System Evolution (LESE) [4, 5] and the corollary trends identified so far.
Besides, as already discussed in [2, 6], also TRIZ instruments suffer from limited repeatability (different teams work independently produce different scenarios) and lack of accredited procedures for their application.
In facts, several TRIZ tools have been proposed to support technology forecasting activities: S-curve, system operator, laws of technical systems evolution, lines of evolution (trends), Ideality increase, morphological analysis, wave model of systems evolution and ARIZ (the Algorithm for Inventive Problem Solving [7, 8]). These tools reveal relevant potentialities in several specific situations and their integrated use for approaching inventive problem solving tasks is exhaustively detailed by the latest version of the ARIZ algorithm [8]. Besides, no accredited integrated procedures are available for forecasting applications.
The present paper proposes a step-by-step algorithm for analyzing a Technical System (TS) and the way its Main useful Function (MUF) is delivered at different detail levels. The working principle is then compared with previous generations of the system in order to build a structured classification of the information, suitable for evolutionary comparisons. These comparisons allow to build a network of scenarios with different involvement of resources, which constitutes a map of the TS evolution, where already commercialized products are visualized together with emerging patented inventions and free spaces for investments. The choice of the favorite strategical direction is still assigned to the beneficiaries of the forecast according to their attitude to the world, their mission and values, as already suggested by Altshuller [4]. Nevertheless, the proposed procedure carefully limits the evolution space by means of a detailed resources analysis.

Such a network of trends proved to be an effective tool for exploratory analysis of potential evolutions of a TS in four extended industrial applications and several minor applications to literature examples.
In this paper, in order to illustrate and clarify the proposed algorithm we report some details from an experience in the field of production of tablets in pharmaceutical manufacturing.
The next section summarizes potentialities and actual limits of TRIZ based technological forecasting methods; then, in section 3, we present an original integration of functional modeling techniques suitable for improving the repeatability of an evolutionary analysis according to TRIZ. The fourth section describes the main parts of authors' algorithm and provides details about the functional modeling step and the process of information gathering and classification. The discussion in the last section is based on the industrial applications performed so far, with specific references to the examples proposed in the previous chapters.

2 TRIZ INSTRUMENTS AND FORECASTING

Fey and Rivin in [9] first positioned TRIZ as a "powerful structured methodology for a directed development of new products/processes" alternative to more classical Technology Forecasting approaches like trend extrapolation, morphological analyses and Delphi methods. Besides, the methodological description was limited to the LESE with a number of examples, without providing proper details about the way the TRIZ laws should be applied.
Then Cavallucci in [10] started integrating TRIZ LESE into the product development cycle as a means to predict the impact of a technical solution.
The abovementioned approaches, indeed adopted by several TRIZ professionals and implemented in some software applications, are helpful to explore variants of the analyzed TS, but no directions are provided to identify elements and functions to be evaluated and further developed according to the LESE. In facts, even authors like Mann [3] who claim the incorporation of TRIZ trends of evolution into a "design method that allows individuals and businesses to first establish the relative maturity of their current systems, and then, more importantly, to identify areas where evolutionary potential exists" limit their attention to list of examples without any instruction about the object of the comparison according to the proposed evolutionary metrics.
As a result, the repeatability of the process is poor and strongly dependent on the skill and the experience of the analyst.
It must be mentioned that a few TRIZ professionals have proposed integrated procedures for technology forecasting purposes [11, 12]; nevertheless, the authors believe that both Directed Evolution by Zlotin, Zusman and Evolution Trees by Shpakovsky are still mostly focused on the interpretation of the LESE than on the analysis of the system the forecast is about.
Such a lack of preliminary classification, especially in case of complex systems, is the main reason for poor repeatability of TRIZ forecasts, since different researchers apply TRIZ LESE to different details/characteristics of the same technical system and/or limit their study to superficial features of the system itself.
The authors are working on the definition of an algorithm for building evolutionary scenarios of a technical systems by applying the LESE. The original contribution of this work is the definition of a systematic procedure to analyze a technical system and build its functional model aimed at accomplishing an evolutionary comparison according to the TRIZ patterns of evolution. Such a comparison and classification is the first step to synthesize new opportunities of development as well as to assess the limitations of the resulting forecast.

3 AN INTEGRATED MODEL FOR FUNCTIONAL ANALYSIS

As stated in the previous section, a crucial issue is the identification of the proper function(s) delivered by the analyzed system, the influence on its evolution of auxiliary functions and undesired side effects, the competing alternative technologies. In order to provide systematic directions to function classification and to adopt a terminology well known by the scientific community, the algorithm has been based on well known models of Design Theory.

3.1 Reference models for system analysis

As stated above, the proposed procedure adopts a few reference models to systematize the analysis and to maximize the repeatability of the overall approach. Hereafter, a brief survey of these founding models is reported.

3.1.1 EMS model

EMS modeling [13] is a classical technique for representing the expected function of a certain technical system: any technical system can be modeled as a black box channeling or converting energy (E), material (M) and or signals (S), i.e. information, to achieve a desired outcome (figure 1). As such, EMS models typically represent only the functions performed by the system under study, while inefficiencies and undesired side effects are neglected.

In [14] the adoption of the EMS model was proposed also for problem formulation and analysis as an alternative means to the typical TRIZ technique Su-Field modeling [4]. Nevertheless, the decomposition of the black-box into its constituting elements, in TRIZ terms sub-systems, lacks precise directions about the level of details to be provided. Moreover, quite often the functional model of a complex system results overwhelmed by a high number of boxes, most of which are just marginal to the core of the study.

Figure 1. EMS model: Energy, Material and or Signals are channeled or converted to deliver a certain function.

3.1.2 Minimal Technical System

In order to deal with a repeatable modeling approach, whatever is the complexity of the system to be analyzed, it is proposed to decompose it into the elements constituting the TRIZ model of a minimal technical system [4]. According to the first Law of Engineering Systems Evolution, i.e. the Law of Completeness, a system capable to deliver any function must be characterized by four elements (figure 2, above):

- 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 Supply to the Tool;
- a Control, i.e. an element governing at least one of the above elements.

According to the classical TRIZ definition of the minimal technical system, just energy flows should be taken into account and typically the Supply 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 due to the Joule effect).

Besides, according to the authors' experience, the concept of the Law of Completeness of System Parts can be extended also to different types of flows, namely Material and Signals. In facts, a TS like a funnel is characterized by no energy flows while delivering its function to channel the stream of a liquid substance into a small-mouthed container. Still, by following the material flow through the system, it is useful to recognize a tool (the small hole at the apex of the funnel), a supply (the large opening), a transmission (the conical part in the middle), a control (in this case not belonging to the funnel itself, but demanded to the user who defines the position, the direction etc. of the flow.

Among the others, the adoption of a four blocks decomposition of a TS provides at least the following benefits: it keeps a manageable number of elements to be contemporarily taken into account; it invites the analyst to focus the attention just on the elements relevant to a specific function/sub-function at a time.

3.1.3 System Operator

The System Operator is another key item of the TRIZ body of knowledge, constituting at the same time an effective tool for avoiding psychological inertia in several steps of the problem solving process, as well as the essence of the way of reasoning of a creative person [15].

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 and a "Time" dimension constituting its horizontal axis. A talented problem solver, whatever is the TS he is dealing with, always recognizes

and takes into account the environment and the external object the system interacts with (i.e. the super-system); its constituting elements (i.e. the sub-systems); the past, the present and the 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), as a life cycle of an element of a system from its creation to the disposal stage and as speed or acceleration of an action, if these variables are relevant for the specific situation. It is worth to notice that super-system/sub-system relationships, as well as past/future 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 (figure 3).
According to the scopes of the present study, any analysis must be conducted at different detail levels with a proper hierarchical classification of system elements, by taking into account their behavior and modifications in time. As a consequence, each of the four elements of the minimal technical system can be further decomposed into four subsystems with the same structure, thus resembling a sort of fractal decomposition (figure 2, below).

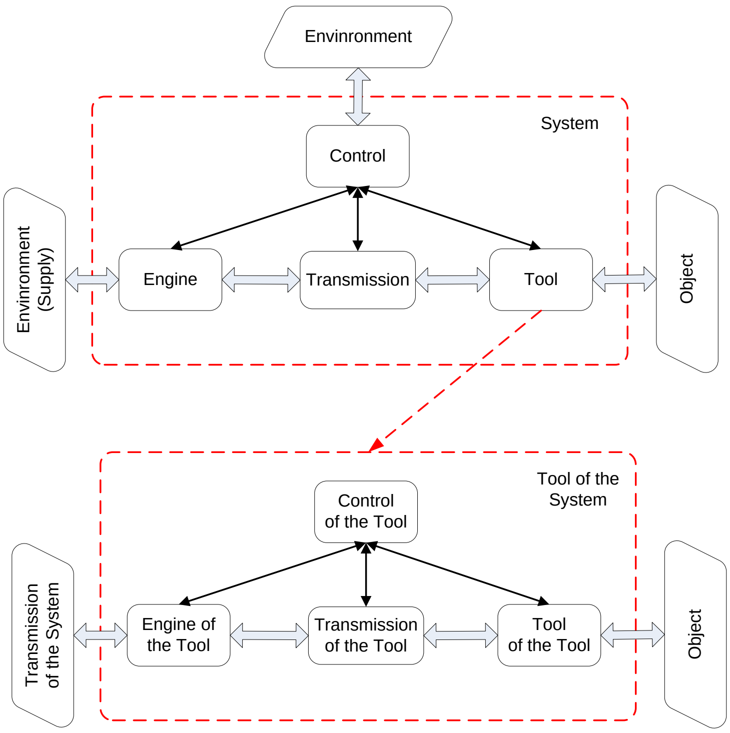

Figure 2. Minimal Technical System (above) and hierarchical decomposition of its elements (below).

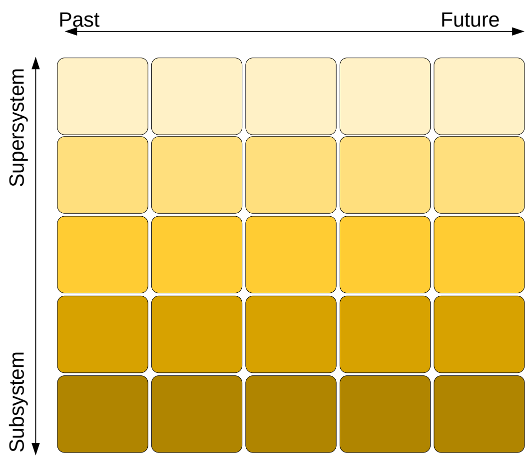

Figure 3. TRIZ System Operator.

3.1.4 Function-Behavior-Structure (FBS)
The well known classification proposed by Gero [16] distinguishes between the Function of a system, its Behavior and its Structure.
The Function of a TS is the motivation for its existence; at the Structure level, a TS is constituted by entities, attributes of these entities and relations among them; the Behavior, defined as sequential changes of objects state governed by the Laws of Nature [17], is the link between Function and Structure. Different Behaviors can produce the same Function, as well as different Structures can be characterized by the same Behavior.
Here such a classification is assumed as a means to classify alternative embodiments, as well as alternative competing technologies, to perform a systematic comparison according to the LESE.

3.1.5 Functional Basis for Engineering Design
The need for formalized representations in function-based design is often overlooked in the literature; however, it is an issue of critical importance to reduce ambiguity at the modeling level (when multiple terms are used to mean the same things, or when the same term is used with multiple meanings) and to improve repeatability of the models (the larger the number of terms there are in a vocabulary, the more different ways there are to model or describe a given design concept).
The distillation of a large body of terms into a concise basis as proposed in [18] does not eliminate these problems entirely, but it significantly lessens their occurrence. A further advantage of the functional basis approach is that it fits with the previously mentioned models, since the taxonomy of functions is expressed by a number of functional verbs applied to EMS flows. The formers are hierarchically subdivided into 8 classes, 21 secondary and 24 tertiary actions on flows; these are classified in three levels including 6 secondary and 11 tertiary material flows, 12 secondary and 4 tertiary energy flows, 2 secondary and 7 tertiary signal flows. Nevertheless, it is worth to notice that although the efforts for a standard taxonomy for engineering functions by the NIST Design Repository Project are well established, they still lack operational relationship with FBS behaviors [19].

3.2 Integrated model for function-behavior analysis
The reference models presented in the previous section can be integrated in order to provide systematic and repeatable means to perform the analysis of a TS before to perform comparisons and extrapolations based on the LESE.
TRIZ practitioners usually express functions in terms of triads Subject-Verb-Object such that the Subject modifies a parameter of the Object according to the action described by the Verb. In other terms, a function is characterized by a function carrier, an action and an object receiving the function. The action is properly defined 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. The property of the object, e.g. a size, the color, the electrical conductivity, the shape, is thus set to a certain value e.g. one meter, red, five siemens per metre, 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. Among the useful functions, if the property of the object assumes precisely the expected value, we have a sufficient useful function; besides, if the value of the property is inadequate the function is considered useful but insufficient.
Nevertheless, in order to adopt a formulation compatible with the Functional Basis for Engineering Design mentioned above, it is suggested to use the EMS flow approach, still keeping the TRIZ classification of functions.
Generally speaking, the EMS model of a TS hides several elementary functions, since the TS may impact several parameters of the same object. As an example, a nozzle for sterilization devices heats (increases temperature) and directs (changes direction) a sterilant.
Thus the EMS model must be split into elementary black boxes each delivering one of the basic actions constituting the Functional Basis. Energy, Material and Signal flows can be detailed according to the secondary and tertiary classes proposed in [18].
Such a detailed functional model still doesn't represent the specific solution adopted to deliver each function, i.e. the model must be integrated with the behavior of the TS, or in TRIZ terms the physical, chemical, geometrical effect adopted.
In this paper it is proposed to represent the Behavior of each elementary function by means of the Minimal Technical System model. Besides, different sets of elementary functions can produce the

same result, thus constituting alternative Behaviors to deliver a certain goal function. In turns, the first step of the analysis consists in the identification of these alternative sets of elementary functions to be expressed by means of the functional basis; then the Behaviors capable to accomplish each elementary function are modeled.

Figure 4 clarifies the above statement by means of an example from the pharmaceutical tablets manufacturing sector: the production of tablets consists in combining active principle, excipients and possibly further additives in order to form the tablets through a compression of granules (typical processes) or a direct compression of fine particles (recent developments due to the adoption of a novel type of excipients). The system is modeled through EMS boxes and decomposed into elementary functions until each functional unit can be described in terms of flows and actions belonging to the reference list proposed in [18] (figure 5).

It is worth to notice that the functional models report only the necessary flows (e.g. the particles and the solvent to be mixed), while auxiliary flows, which depend on the specific design choices performed to deliver the expected function, are omitted: besides, they appear in the Behavior models.

Then the Behavior of each elementary function is modeled by means of the TRIZ minimal model of a technical system. Figure 6 shows the outcome of this step for Solution and Drying, i.e. the first two elementary functions of the diagram in figure 4. As stated above, the authors have extended the use of such a modeling technique also to Material and Signal flows.

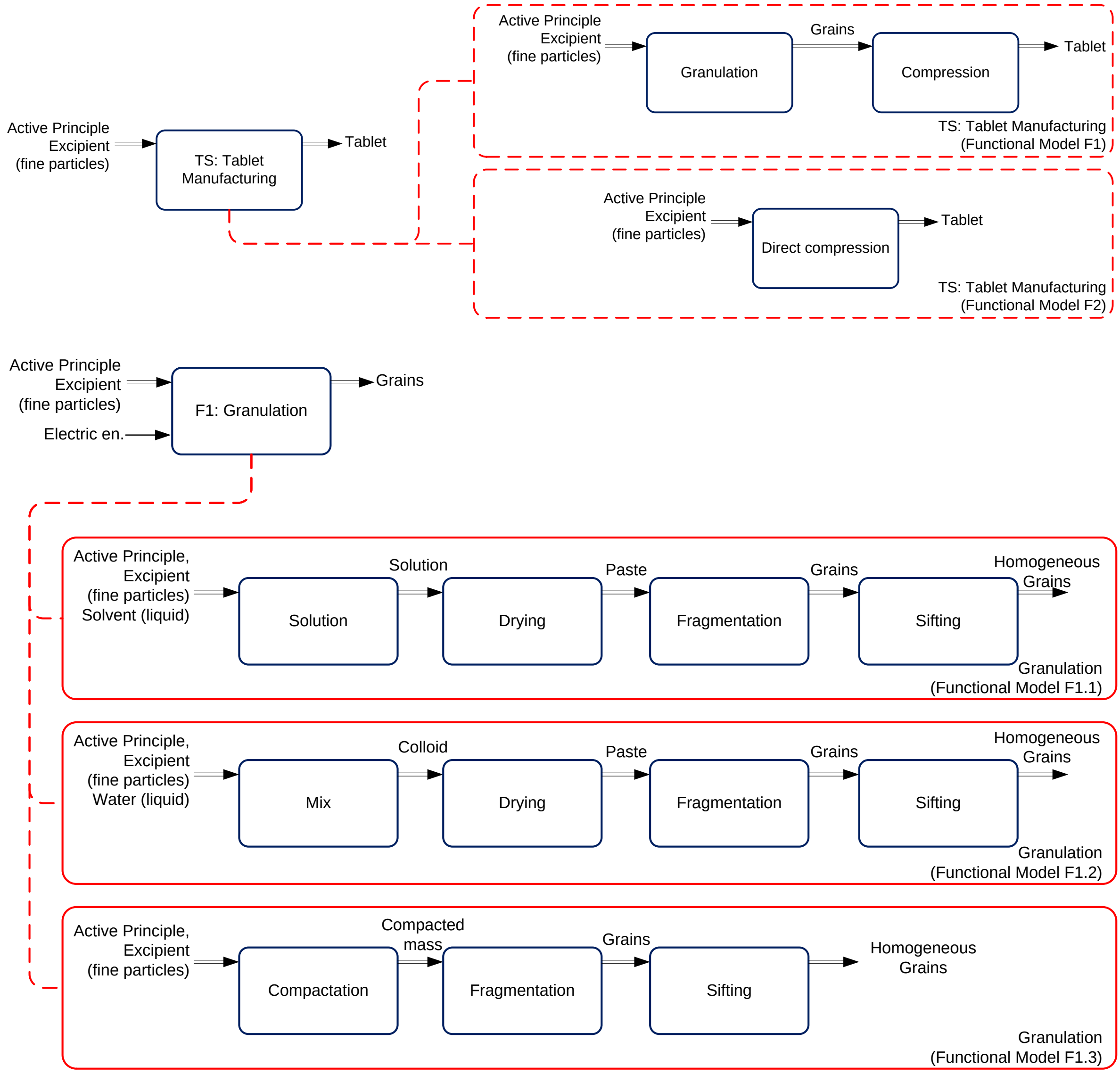

Figure 4. Functional model of a pharmaceutical tablet manufacturing process. EMS model of the overall TS and preliminary identification of the alternative technologies (above). Detailed functional decomposition of the granulation phase (below).

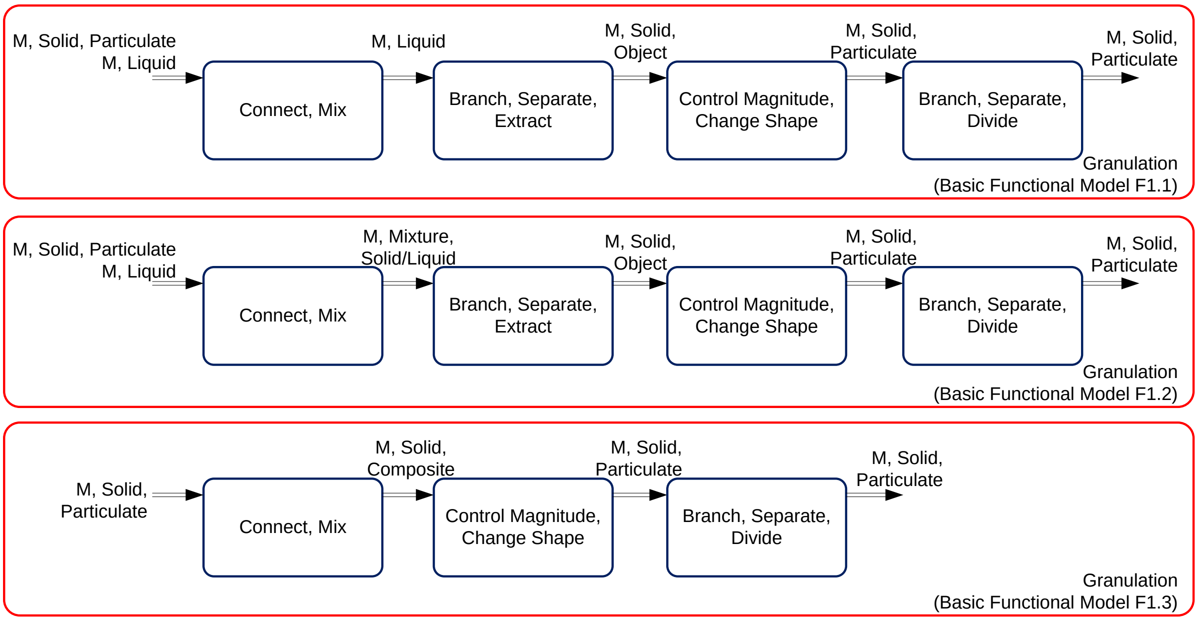

Figure 5. Elementary functions of the granulation phase according to the functional basis [18].

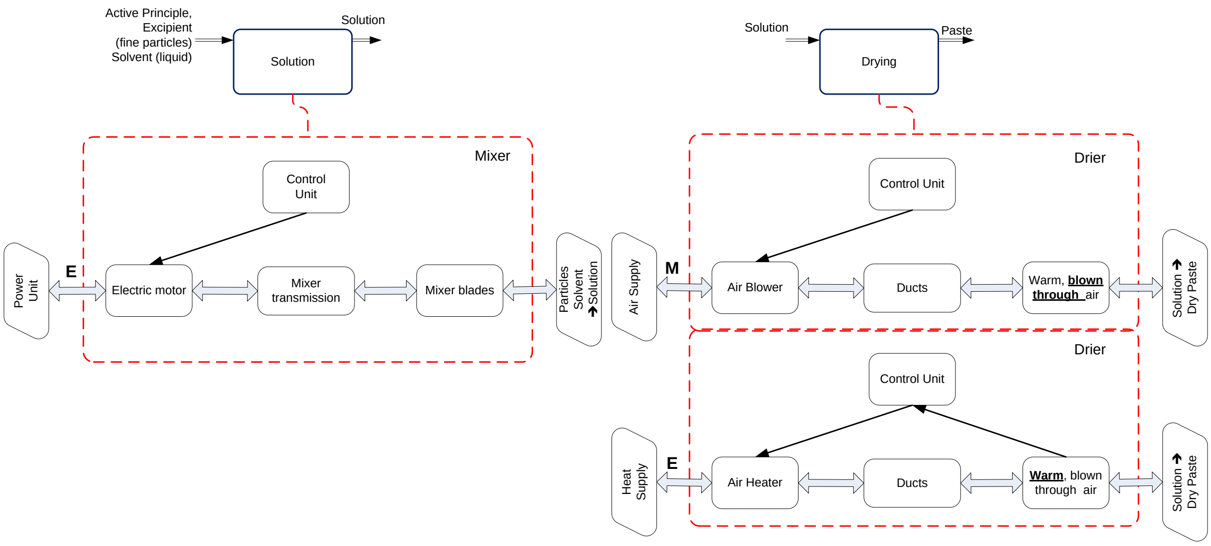

Figure 6. Exemplary Behaviors of the first two elementary functions of figure 4 represented through the TRIZ minimal model of a technical system.

More precisely, the following steps must be followed to build the minimal model representing the candidate Behaviors for a given elementary function:

1. identify the Product, i.e. the object of the function which determine a transformation of the input flow into the output;
2. identify the Tool, i.e. the element which acts directly on the Product;
3. determine which property(-ies) characterize the Tool's capability to deliver the function to the Product;
4. for each of the properties defined at step 3, identify the "Engine" from where the properties derives;
5. complete the model of the minimal technical system, by adding the transmission from the Engine to the Tool, the control and its interactions with the other subsystems and the external supply of the engine.

Let's consider the above sequence of steps for the Solution and Drying elementary functions mentioned above:

- (Solution - figure 6, left) The product is constituted by particles and solvent which are transformed into a solution; the element directly acting on particles and solvent is the blade of the mixer, thanks to its motion which increases the kinetics of the chemical reaction. The rotation of the mixer blade is introduced by an electric motor which constitutes the engine of the model; the transmission is represented by the blade shaft while the supply (Energy flow) is a power unit connected to the electric motor. Finally the control acts by regulating the rotational speed of the motor itself.

- (Drying - figure 6, right) In this case the product is the paste derived by the solvent removal from the input solution; a typical Behavior of a drier is constituted by a worm air flow blown through the solution until the required residual moisture content is reached; thus the air is the tool capable to dry the solution thanks to two complementary properties: high temperature and motion through the product. In this case, two minimal models must be built, each describing how those properties are provided. In facts, an air blower is the engine to move the air through the solution, while an air heater is the engine to have warm air. The other elements are identified consequently. The presence of a temperature feedback is represented by means of an arrow from the warm air to the control unit.

Once that the available Behaviors have been modeled for each elementary function, a Su-Field model related to the interaction of each pair of interacting elements of the Minimal Technical System model is added, i.e. Tool-Product, Transmission-Tool etc. Figure 7 reports three exemplary Su-Field models related to the Tool-Product interactions of Figure 6. It is worth to notice, that thanks to the classical TRIZ classification in terms of useful/harmful, sufficient/insufficient interactions, these Su-Field models allow to represent also the actual Behavior of a TS, and not just the expected one which derives from the functional model; in other terms, the proposed approach allows to represent into a unified model the comparison between the desired behavior (Be) and the behavior extracted from the structure (Bs) [16].
Moreover, the Su-Field models highlight the nature of the interaction, which is a relevant information for evolutionary analyses according to the Standard Solutions (mostly Class 2 and 3) and for the Laws of Evolution 7 and 8 [4].

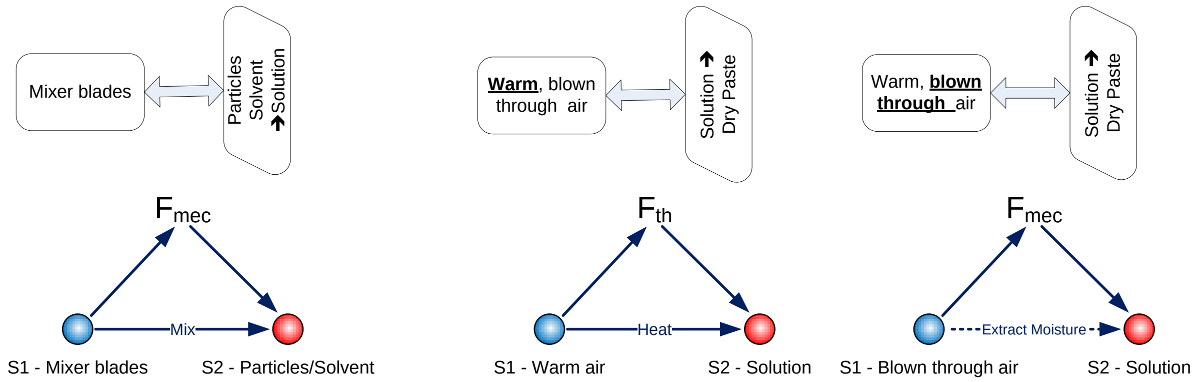

Figure 7. Exemplary Su-Field interactions between pairs of elements of the minimal models of technical system representing the Behaviors of the TS functional units.

4 TOWARD AN ALGORITHM FOR BUILDING A NETWORK OF EVOLUTIONARY TRENDS (NET)

The above described modeling technique is embedded into a step-by-step algorithm aimed at the construction of a Network of Evolutionary Scenarios (NET). The main steps of the proposed algorithm are represented in figure 8. Here a major attention is dedicated to the first part of the algorithm, while the following parts will be just mentioned and further detailed in a next publication.
The preliminary analysis of the TS aims at the identification of the MUF, the Structure and the Behavior of the system at different detail levels, both of its current version and its historical evolutionary steps. Then the resulting functional and behavioral models are compared according to TRIZ trends of evolution. The third step consists of assembling the relevant trend recognized for each element into a map representing also: links between different generations of the TS characterized by a different behavior, usually due to a Transition to Microlevel; links between the four elements of each minimal technical system associated to each function and links between an element and its subsystems. Browsing the NET is then possible to identify missing implementations of the TS through

trends interpolation/extrapolation: within this fourth step, unexpected patent activities of the competitors are likely to appear, as well as virgin scenarios where to focus R&D activities. Finally the limits of the NET validity must be checked by analyzing what happens if an assumption fails or a certain functional parameter has sudden variations out of the expected range.

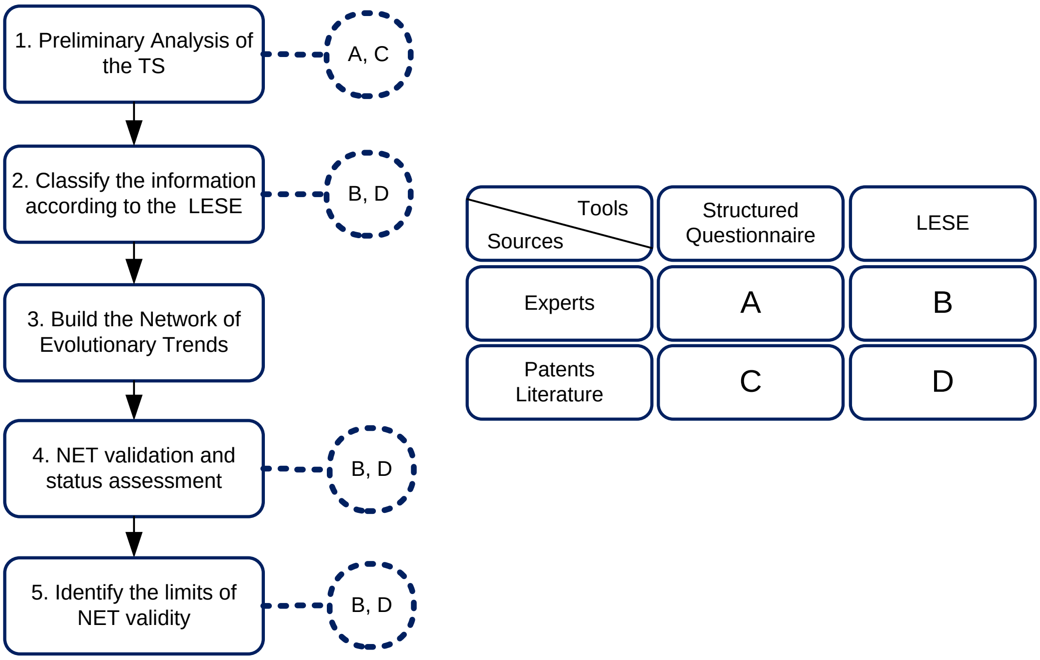

Figure 8: Main parts of the algorithm (left) and relationships with Information sources and gathering tools (right).

4.1 Step-by-step algorithm for function-behavior analysis

1. Preliminary analysis of the TS
   1.1 Identify the MUF of the TS, its characterizing parameters and expected values
   - Identify the Evaluation Parameters defining the performance of the MUF
   - Decompose the MUF, according to the Functional Basis [18], into elementary functions needed to impact those Evaluation Parameters
   - Identify constraints and minimum performance values (e.g. due to standards, certification systems etc.)

   1.2 Analyze the goal of the TS and the role of its MUF at a super-system level; identify all the functions acting on the same object of the MUF
   - E.g.: Let’s consider a sterilization module in a machinery for aseptic filling of beverage containers; its function is reducing the amount of pathogenic organisms (Evaluation Parameter) in the container, e.g. a bottle, before to fill it, until a sealed cap will be applied; in this case it is important to identify further functions acting on the bottle, e.g. handling, because they can interfere with the TS under study.

   1.3 Identify the alternative Behavioral Models (BM) of the TS capable to produce the expected MUF
   - This task should be performed taking into account also out-of-date configurations of the TS
   - Only different BM of the MUF should be mapped, while other differences between possible embodiments (structures) of the TS can be neglected at this stage
   - E.g.: Let’s consider a machine for rubber pulverization (MUF): alternative BMs are cryogenic milling, high-speed cutting, high compression and shear milling, waterjet cutting etc.

   1.4 Identify the Auxiliary Functions requested by each specific BM of the MUF

- E.g.: in the example of bottle sterilization, if the elimination of bacteria is obtained through a chemical substance like peracetic acid, an auxiliary function to be delivered is bottle rinsing, since even small drops of the sterilizer could negatively impact the taste of the beverage.

1.5 Identify the undesired Harmful Effects generated by each specific BM of the MUF

- This step leads to the identification of Technical Contradictions in the following form: the Structure of the TS should have the behavior represented by BM in order to deliver the MUF, but should not have such a behavior in order to avoid its harmful effects

1.6 Identify the amount of resources required by each BM to deliver the MUF

- In order to allow a comparison between different systems with the same BM, the resources should be normalized to the same performance parameter or vice versa performances can be compared with respect to the same usage of resources
- In order to allow a comparison between different BMs, resources should be grouped into homogeneous classes, the most general classification being resources related to Space, Time, Energy, Material, Information
- The analysis of the resources must take into account also the Auxiliary (necessary) Functions identified at step 1.4

1.7 Build the Minimal Technical System model of each BM of the MUF and of the other functions identified at step 1.2-1.4 according to the procedure described in the section 3.2.

- Complete the model with Su-Field analysis of each pair of interacting elements.

4.2 Information gathering and classification

A critical task of a technology forecast is the collection and analysis of information; therefore, specific guidelines must be provided to gather information both from experts and patent databases.

The construction of a network of evolutionary scenarios for a technical system clearly requires collecting and classifying data and information from several sources. These can be mainly divided in two main categories (figure 8, right): experts somehow involved in the product cycle of the TS, i.e. executives, managers, researchers, designers, sales representatives etc.; scientific and technical literature, i.e. articles, patents, catalogues, etc.. Interviews and searches to elicit information from these sources can be driven by specific tools.

At the beginning of the study general structured questionnaires are useful to follow a systematic approach in order to identify functions, relationships with the environment and causal relationships. An example of a structured questionnaire well known by the TRIZ community is the Innovation Situation Questionnaire (ISQ) [20]. The authors have created a customized questionnaire which allows performing a similar investigation, according to the models mentioned in section 3.1, thus collecting information about EMS flows, identifying the main four elements for each function and mapping hierarchical relations among those elements.

The answers provided by the experts can be integrated by specific literature searches; modern text mining technologies provide valuable means to improve the efficiency of this task [21, 22].

Once the general data about the system have been collected, their classification can be approached according to the LESE. Such a structured view of the gathered information clearly raises new questions both to complete the map under construction and to validate the directions suggested by TRIZ trends of evolution. Again experts and literature are fruitful complementary sources to complete the task.

4.3 NET construction

A detailed description of the following steps of the algorithm for building a Network of evolutionary scenarios is out of the scopes of the present paper. Nevertheless, a brief survey of its main steps allows to have a clearer idea of the benefits of the modeling technique described in section 3.

2. Classify the information according to the LESE

2.1 Compare the BMs of the MUF according to the Law of Transition to Microlevel

- The transition from macro to micro level, i.e. a transition to a smaller scale of the principle a BM is based on, is a typical trend of technical systems. Since such a transition is typically associated to major changes in the TS, it is suggested to apply this classification of the BMs before proceeding with more detailed comparisons

2.2 Analyze the Structure associated to each BM of the MUF and its level of completeness according to the first Law of evolution

- Check if the supply of the flow characterizing the MUF is integrated in the TS
- Check if the control of the flow characterizing the MUF is integrated in the TS and which is the controlled element
- This step, as well as the following, should be performed iteratively for each BM of the MUF

2.3 Analyze the Structure associated to each Auxiliary Function and its level of completeness according to the first Law of Evolution

2.4 Analyze the interactions between each pair of elements of the Minimal Technical System for each BM of the MUF and perform a comparison according to the LESE and the TRIZ trends of evolution

- The priority should be given to the interaction existing between the Tool and the Object, then to the other pairs of elements, i.e. Transmission-Tool, Supply-Transmission, Control-Tool etc.
- Among the different formulations of TRIZ trends of evolution available in literature, the authors make use of the following to be applied to each pair of elements
  - Increase of controllability: introduce closed-loop feedbacks, move the control closer to the tool
  - Geometric harmonization: geometrical evolution (1D-2D-3D and related modifications), increase of asymmetry, segmentations (voids, surface, volume), dynamization
  - Rhythm harmonization: parts coordination, frequency of action
  - Material harmonization (it is worth to note that this is not a classical TRIZ trend; nevertheless, the authors have encountered several systems evolving towards a harmonization of the materials of interacting elements)
  - Mono-Bi-Poly and Trimming: Mono-Function Homogeneous systems, Mono-Function systems with Shifted Characteristics, Multi-Function Heterogeneous systems, Inverse Function, Partial Trimming, Extended Trimming; the assessment of the evolution-convolution stage should be performed also by taking into account the ratio between the performance of the function under analysis and the resources involved for its implementation
  - Increase of Fields involvement

2.5 Analysis of the contradictions and their relationships with the trends formulated at step 2.4

- Contradictions identified at step 1.5 disappearing due to the application of one or more trends
- Contradictions identified at step 1.5 not solved by the trends
- New contradictions emerging by the application of a specific trend of evolution
- New contradictions emerging by the application of two or more trends generating conflicts between the available resources

3. Build the Network of Evolutionary Trends

3.1 Order the Minimal Technical System models of each BM of the MUF according to the trend Transition to Microlevel analyzed at step 2.1

3.2 Within the same stage of Transition to Microlevel, order the BMs according to their completeness (without recurring to the support of external systems or to humans)

3.3 Add the models of decomposed subsystems (figure 2, below)

3.4 Add the models of the functions identified at step 1.2

3.5 Represent as branches of a network the trends identified at step 2 by links to the corresponding elements of the model built at steps 3.1-3.4

4. NET Validation and status assessment

4.1 Mark the nodes of the network corresponding to an existing configuration of the TS

- The authors usually apply a red circle around these nodes; further differentiations can be applied by highlighting with different colors sub-classifications like competitors, years of development, market sectors etc.

4.2 Mark the nodes of the network corresponding to features found in patents, but still not brought to the market

- The authors usually apply a yellow circle around these nodes (figure 9, above).

4.3 Identify new opportunities of implementation of the TS

- Recognize interpolation opportunities due to missing configurations in a trend of evolution (figure 9, middle).
- Recognize extrapolation opportunities due to not exhausted trends of evolution (figure 9, below).
- The authors usually apply a green circle around these nodes

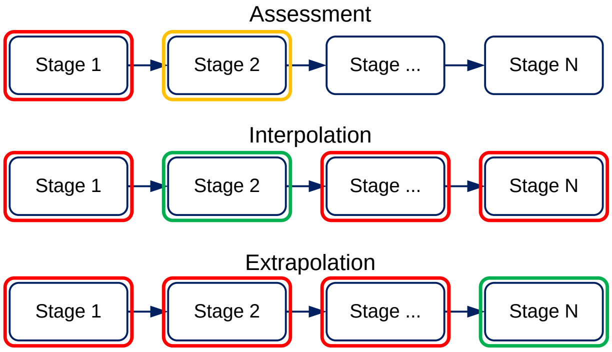

Figure 9: Evolutionary assessment of the NET branches and identification of new opportunities for the TS.

5. Identify the limits of NET validity

5.1 Search for functions alternative to the MUF capable to achieve the same overall goal

- It is suggested to start from the results of the analysis performed at step 1.2 and to apply the System Operator in order to identify alternative functions (in different screens) providing the same benefits of the MUF to the supersystem

5.2 Analyze the parameters of the object of the MUF and check which variation of such parameters makes the TS incapable to provide the expected benefits, thus failing in the achievement of the goal

5.3 Analyze the parameters of the object of the MUF and check which variation of such parameters makes the TS useless

5.4 Investigate the impact of the removal of the constraints identified at step 1.1 or the introduction of new ones

The description of the algorithm (and most of all, steps 2.4 and 2.5) should be further detailed, but due to space limitations the authors have limited the explanation of tasks accomplished according to procedures already well discussed in literature (e.g. [11, 12]).
It is worth to notice that the structured approach of the investigation together with the precise directions of search provided by the trends allows to perform very precise questions to the experts, thus triggering their implicit knowledge, as well as to make use to a maximum extent of the functionalities provided by modern Text-Mining technologies, while analyzing electronic documents like patents and scientific papers.

5 DISCUSSION AND CONCLUSIONS

The authors have tested the proposed algorithm in four extended case studies related to disabled walkers, wood pellets production, aseptic filling of beverage containers and pharmaceutical tablets production
In each of these case studies conducted from September 2007 to December 2008 the role of the authors was the definition of a structured set of scenarios to support company's management in the selection of the most appropriate directions for investment.

The algorithm was carefully applied to collect and classify the implicit knowledge of company's experts as well as to direct the search for further relevant information from patent databases and other scientific sources.
Typically the implementation of the overall algorithm in a specific field requires about 3-4 man-months, from the initial questionnaire to the experts to the construction and assessment of the NET.
An interesting outcome of this activity is that in every implementation it was possible to identify several relevant patents not previously known by the company, even outside the traditional field of application. For example, in the field of aseptic filling of beverage containers, new sterilization technologies were highlighted and the company identified new technologies to be monitored to avoid the appearance of unexpected innovations from the competitors.
In all these applications, the NET has been used to define the strategic development of R&D activities, of course in accordance with the company's vision. The authors consider the positive judgment of the proposed results by the companies a contribution to the validation of the algorithm presented in this paper.
In conclusions, the original algorithm for system analysis presented in this paper has revealed so far an adequate applicability to technical systems belonging to different fields of application and with radically different characteristics (operating machines, end products etc).
As a result it is possible to build with systematic and repeatable steps a Network of Evolutionary Trends to be used for supporting multi-criteria decisions and to highlight opportunities of development.
Compared with TRIZ-based forecasting approaches published in literature, the authors have focused their attention on the definition of a precise procedure to identify the elements and the features to be analyzed and benchmarked according to the TRIZ Laws of Evolution.
The authors are further developing the proposed algorithm with the aim of taking into account the analysis of entire business processes, where the evolution of each technical system involved in the process is impacted also by the development of the engineering systems adopted in the other phases; thus, the process itself as a whole is considered as an evolutionary engineering system.
A further direction for investigation is the definition of criteria to prioritize the analysis of certain branches or details of the network in order to provide means for express analyses when short time resources are available.

ACKNOWLEDGMENTS

The authors would like to thank Alessandro Cardillo from Polytechnic of Milan and Yuri Borgianni and Niccolò Becattini from Università di Firenze for their contribution to the development of the present case study.

LIST OF ACRONYMS

ARIZ: Algorithm for Inventive Problem Solving
BM: Behavioral model
EMS: Energy-Material-Signal
FBS: Function-Behavior-Structure
LESE: Laws of Engineering System Evolution
MUF: Main useful Function
NET: Network of Evolutionary Trends
Su-Field: Substance-Field model
TRIZ: Theory of Inventive Problem Solving
TS: Technical System

REFERENCES

[1] Porter, A.L. et al.: Technology Future Analysis. Toward integration of the field and new methods. *Technological Forecasting & Social Change* 71, 2004, pp. 287–303.
[2] Kucharavy, D. and De Guio, R. Problems of Forecast. *Proceedings of the 5th ETRIA TRIZ Future Conference*, ISBN 3-7011-0057-8, Graz, Austria, November 16-18, 2005.
[3] Mann D. Better technology forecasting using systematic innovation methods. *Technological Forecasting and Social Change* Volume 70, Issue 8, October 2003, pp. 779-795.
[4] Altshuller, G.S. *Creativity as an Exact Science: The Theory of the Solution of Inventive*

Problems. Gordon and Breach Science Publishers, ISBN 0-677-21230-5, 1984 (original publication in Russian - 1979).

[5] Salamatov, Y.P. System of The Laws of Technical Systems Evolution. *Chance to Adventure* (in Russian), ISBN 5-7545-0337-7. Karelia Publishing House, Petrozavodsk, 1991. pp. 7-174.

[6] Kucharavy, D. *TRIZ instruments for forecasting: past, present and future*. Tutorials at the 7th ETRIA TRIZ Future Conference, Frankfurt, Germany, 6-8 November 2007.

[7] Altshuller, G.S. *The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity*. Technical Innovation Center, Inc., 1999, ISBN 0964074044, 312 pp.

[8] Altshuller G.S. *To find an idea: introduction to the Theory of Inventive Problem Solving* (In Russian). Novosibirsk: Nauka, (1st ed.-1986; 2nd ed.-1991). ISBN 5-02-029265-6. Translation available at http://www.triz.co.kr/TRIZ/frame.html.

[9] Fey V. R., Rivin E. I. Guided Technology Evolution (TRIZ Technology Forecasting). *The TRIZ Journal*, January 1999, available at http://www.triz-journal.com/archives/1999/01/c/index.htm.

[10] Cavallucci, D. Integrating Altshuller's development laws for technical systems into the design process. *CIRP Annals - Manufacturing Technology*, vol. 50(1), 2001, pp. 115-120.

[11] Zlotin, B.L. and Zusman, A.V. *Directed Evolution. Philosophy, Theory and Practice*. Ideation International Inc. ISBN 192874706X, 2001.

[12] Shpakovsky N.. *Evolution Trees. Analysis of technical information and generation of new ideas* (in Russian), ISBN 5-9348-6048-8, TRIZ Profi, 2006.

[13] Pahl, G. and Beitz, W. *Engineering Design. A Systematic Approach*, 2nd edition, Springer, ISBN:3540199179, 544 pp., 1996.

[14] Ogot M. EMS Models: adaptation of engineering design black-box models for use in TRIZ. *Proceedings of the 4th TRIZ Future Conference*, Florence, 3-5 November 2004, published by Firenze University Press, ISBN 88-8453-221-3, pp.333-343.

[15] Althsuller G.S., Vertkin I.M. *How to become a genius: the life strategy of a creative person*. Minsk: Belarus, 1994. ISBN 985-01-0075-3.

[16] Gero, J.S. and Rosenman, M.A. A conceptual framework for knowledge based design research at Sydney University’s Design Computing Unit. *Artificial Intelligence in Engineering*, Vol. 5(2), 1990, pp. 65-77.

[17] Takeda, H., Yoshioka, M., Tomiyama, T. and Simomura, Y. Analysis of Design Processes by Functional Evaluation Process, in N. Cross, H. Christiaans and K. Dorst eds., *Analysing Design Activity*, John Wiley & Sons, Chichester 1996, pp. 187–209.

[18] Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S. and Wood, K. L. A *Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts.* NIST (National Institute of Standards and Technology) Technical Note 1447, February 2002.

[19] Kitamura, Y., Kashiwase, M., Fuse, M., Mizoguchi, R. Deployment of an ontological framework of functional design knowledge. *Advanced Engineering Informatics*, Volume 18, Issue 2, April 2004, Special Issue on Ontology and it's Applications to Knowledge-Intensive Engineering, Pages 115-127.

[20] Terninko, J., Zusman, A., Zlotin, B. *Systematic Innovation: An Introduction to TRIZ*. St. Lucie Press, ISBN 1574441116, 208 pages, 1998.

[21] Cascini, G., Fantechi, A., Spinicci, E. Natural Language Processing of Patents and Technical Documentation. *Lecture Notes in Computer Science*, Springer-Verlag Heidelberg, ISBN: 3-540-23060-2, DOI: 10.1007/b100557, December 2004, pp. 508-519.

[22] Cascini G., Russo D., Zini M. Computer-Aided Patent Analysis: finding invention pecularities. Proceedings of the 2nd IFIP Working Conference on Computer Aided Innovation, Brighton (MI), USA, 8-9 October, 2007, published on *Trends in Computer-Aided Innovation*, Springer, ISBN 978-0-387-75455-0, pp. 167-178.