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FBS ONTOLOGY TO EXTEND THE EFFICACY OF 40 TRIZ INVENTIVE PRINCIPLES

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1. Introduction

Altshuller screened patents in order to find out what kind of contradictions were resolved or dissolved by the inventors/inventions and the way this had been achieved. From this he developed a set of 40 inventive principles.

Since the first Altshuller's formulation [1997], the inventive principles have been largely used and studied by academic institutions and private companies operating in the product innovation field. Research on inventive principles focused on improving principle definitions by providing a huge list of examples to be used as analogy and customizing definitions for specific domains (i.e. informatics, business, chemical, manufacturing and others). Meanwhile, many authors worked on classifications and comparisons with other design models or problem solving methods.

One of the reasons for this interest can be found in an attempt to reduce the degree of subjectivity in the use of this tool. This problem can be attributed to the high degree of abstraction with which many of the principles are written, inevitably inducing to a certain freedom of interpretation. In some cases, when approaching the problem, this ambiguity may lead not fully capture the inventive essence.

The goal of this work is to analyze all 40 principles from a new design perspective, i.e. the Function Behaviour Structure (FBS) theory [Umeda et al. 1984], [Gero 1990], in order to overcome their ambiguity and improve their efficacy.

This analysis has revealed that in many cases there is already a perfect match between the original Altshuller definitions and the FBS logic. This means that a large part of the principles forces the user to act both on the function, the behaviour and the structure of the system.

Where the match with FBS is not complete, this classification/reformulation can help to enlarge the range of its interpretation/suggestions, conducting to a greater number of solutions.

The paper is structured as follows. Section 2 presents a state of art about TRIZ theory, inventive principles and FBS theory. Section 3 explains our reformulation of the principles. Section 4 presents a test on a set of industrial case studies by mechanical and management engineering students and by a group of TRIZ experts. Section 5 draws the conclusions.

2. State of the art

2.1 TRIZ theory

The TRIZ theory was born thanks to Altshuller in the second half of the forties; He sought to extract and map a common resolutive path, by analyzing a large number of patents. The first official publication about TRIZ dates back to 1956 [Altshuller and Shapiro 1956]; in which the authors outline, albeit in an early form, some of the most well-known tools of the theory, such as technical contradictions, concept of ideality, multiscreen and inventive principles. In 1963 ARIZ was introduced, an algorithm that map TRIZ theory and its tools in a sequential manner.

Over the years, the tools have been refined with the contradiction matrix (1964), the increase in the number of inventive principles (see below) and ARIZ [Altshuller 1963] and the introduction of the standard solutions [Altshuller 1985]. The physical contradictions [Zlotin et al. 1977] represent a turning point in the method and they were preferred by Altshuller compared to the administrative and technical contradictions due to the increased resolutive strength.
TRIZ theory can be generally summarized in three steps:

- General problem formulation: starting from a specific problem, you gather all the information and you reformulate it in an abstract way, using some of the tools of the theory (top model or small model, ENV model [Cavallucci and Khomenko 2007], ideal final result [Altshuller 1984]. The final reformulation is in terms of contradictions or a kind of functional analysis called su-field model [Altshuller 1984].
- Concept/General solution definition: Contradictions and other problem models can be translated into conceptual solutions by means of TRIZ techniques (ARIZ, separation principles, contradiction matrix, 40 inventive principles, 76 standard solutions). In this way the designer works with a finite number of general suggestions.
- Specific solutions definition: the designer must translate the conceptual identikit of a solution into a real and working solution by using resources already present in the product itself or in its environment.

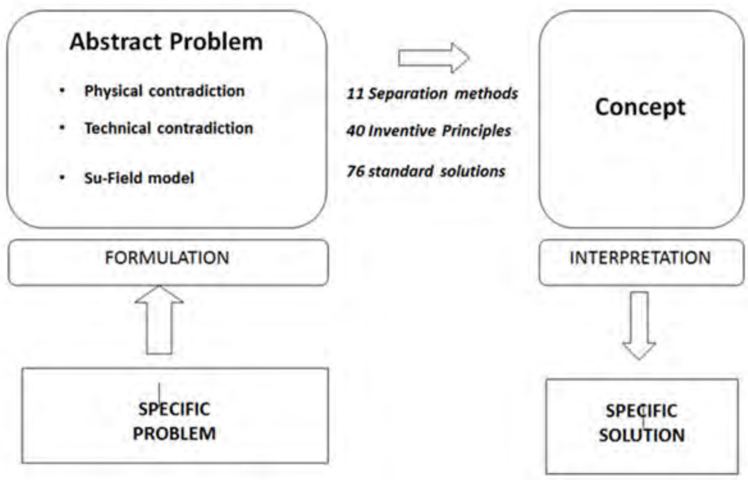

Figure 1. TRIZ working framework

Recent developments of the methodology include various re-updating of the contradiction matrix [Mann 2003] and OTSM-TRIZ [Cavallucci and Khomenko 2007].

2.2 Inventive principles

In TRIZ theory, inventive principles are considered a basic instrument to generate solutions; they are a finite number of common resolutive directions that Altshuller and his collaborators identified in many thousand analyzed patents. In TRIZ solution path, inventive principles are generally used to determine the general solutions to the problem. Usually, the use of the inventive principles is recommended after having modeled the problem in terms of contradictions and having defined the operative zone and time (the space and time for introducing the solution) are well defined. From the first publication [Altshuller and Shapiro 1956], the inventive principles were enriched several times in line with the following research areas :

- ontology: many authors have reformulated the definition of the inventive principles, Altshuller first, e.g. [1971, 1973, 1984, 1997] and others, e.g. [Rantanen 2002].
- Additions: originally the principles were five [Altshuller 1956], with the different editions were increased up to 40 [Altshuller 1971].
- Sub-principles: original Altshuller's inventive principles were reorganized and divided into sub-principles e.g. [Terninko 1998], [Belski 2003].

- Classifications: Ross [2006] proposes a classification matrix of principles based on physical attributes and mechanisms. De Saeger and Claeys [2008] discriminate against the principles that specify the technology to be used and those that specify the boundary conditions. Cong and Tong [2008] and Glaser [2009] instead deepen the connection with patents and patent research. Mann [2002] discriminates against the principles according to the degree of abstraction, showing correlation with the number of results obtained. Brainstorming Guide (www.gbtrix.com) links the principles to the type of change made to the system or the environment.
- Applications: there are also many applications of inventive principles to a wide variety of areas: from microelectronics [Retseptor 2002] to chemistry [Hipple 2005] and computer science [Rea 2001].

2.3 FBS theory

Function, Behaviour State/Structure theory [Umeda et al. 1984], [Gero 1990] represents one of the more modern and followed design theories. Compared to other methodologies of design, FBS introduces the concepts of "behaviour" that provides an important link between function and structure and serves as a platform for reasoning between the two [Gero et al. 1992].
The theory was later revised over the years by the same authors (e.g. [Umeda et al. 1995], [Rosenman and Gero 1998] and [Gero 2002]) and others (e.g. [Vermaas 2007], [Galle 2009]) and it was applied in several areas like Computer Aided Inventive (e.g. [Russo et al. 2011]) and patent searching [Russo et al. 2011]. FBS was also linked to other theories such as TRIZ (e.g. [Russo et al. 2013]).

Table 1. FBS definition according to Gero [1990]

Function	The design intentions or purposes.
Behaviour	Attributes derivable from structure or expected of structure. The behavior may also be quantified by physical, chemical or geometrical effects describing a transformation of an input-output flow. [Cao and Tan 2007]
Structure	The elements (of an artifact/design) and their relationships.

3. Proposal

Generally, a traditional inventive principle suggests different kinds of solutions to a technical problem, that, according to our opinion, they can be extended thinking the principle in terms of both time and space. This from diverges the resolutive space, but using FBS we compensate contextualizing the principle in terms of function, behaviour and structures. The result leads to an enlargement of the number of the solutions (through the introduction of new sub-principles) but at the same time to a greater understanding of the level of the results (through the review of principles).
This paper proposes new definitions of the IPs based on FBS in order to make the user aware if he is acting on the function, on the behavior or on the structure of the device.
By analysing the IPs with the FBS theory, we can see that most part of IPs can be extended to all three directions (function, behavior or structure), while only few of them suggest two directions simultaneously. Our extension allows also to couple IPs working on the same features.
In the following we propose a list of reformulated and new inventive principles divided into original suggestions reformulated (REVIEW) and new suggestions proposed (NEW).

Table 2. List of most representative FBS inventive principles

Altshuller's IP [Altshuller 1974]	Structure	Behaviour	Function
3. Local quality a. Instead of uniform structure of your project, use non-uniform structure of the object. b. Instead of uniform	REVIEW: Instead of uniform/symmetrical structure of your object, use non-uniform/asymmetrical structure of the object	NEW: Instead of a uniform/constant physical behaviour on the entire system, increase or decrease the magnitude of the physical effects only in	REVIEW: Limit the goal (main function) only where/when needed

structure of environment, use non-uniform structure of the environment. c. If two functions are to be performed by the same object but this causes problems, divide the object into two parts. d. Redesign your object and environment so that each part of the object must be conditions proper for operation. **4. Asymmetry** a. If your object has symmetrized shape, make it asymmetrical. b. If your object is already asymmetrical, increase the degree of asymmetry.		a specific part/time according to the local characteristics of the structure	
5. Combining a. Consolidate in space homogeneous objects destined for contiguous operations. b. Consolidate in time homogeneous or contiguous operations.	REVIEW: Merge identical structures or components (in space or in time)		NEW: Merge identical systems that achieve the same goal (in parallel or in series)
6. Universality If you have two objects which deliver different functions, design a new single object that would be capable of delivering both functions.	NEW: If you have two objects which deliver different functions, use only one structure to perform both functions (using two different parts).	NEW: If you have two objects which deliver different functions by using different Physical effects, combine the object in only one system able to provide both physical effects.	REVIEW: Make a system performing multiple functions (in different zones and times).
7. Nesting a. Place one object inside another. b. Increase a number of nested objects. c. Make one object dynamically pass through a cavity of another object when necessary.	REVIEW: Place a structure or a component inside another		NEW: Add a functionality to the device by placing a new structure inside it.
10. Prior Action a. If your object is subjected to harmful factors of environment, create conditions that will prevent the object from harmful factors beforehand. b. If your object has to be changed and this is hard to achieve, perform the required change of the object (fully or partially) beforehand. **11. Early cushion** If your object is unreliable, create conditions in advance that will prevent the object.	REVIEW: If your object is unreliable, prevent critical situations or compensate their harmful effects by modifying its structure or adding a new one.	REVIEW: If your object is unreliable, prevent critical situation changing the way to achieve the goal.	NEW: If your function/goal has to be changed and this is hard to achieve, perform the required function (fully or partially) beforehand.
14. Spheroidality a. Instead of linear parts of the object, use curve parts. b. Use rollers, balls, spirals.	REVIEW: Change flat parts of the structure with a cavity or spherical curvature. Enter inside or	REVIEW: Use centrifugal forces	

c. Use rotary motion. d. Use centrifugal forces.	outside of the device rollers, balls, spirals		
15. Dynamicity a. If your object is immobile, make it movable. b. Divide your objects into parts capable of moving relatively each other. c. Increase the degree of free motion. d. Make your object or environment dynamically change in accord with the required conditions at each stage of operation.	NEW: If your object is static/immobile, make its structure flexible for better adapting to the external environment	REVIEW: Change continuously the way the system achieves the function according to the external environment	NEW: Adjust the function or goal according to the external conditions
17. Another dimension a. If your object moves along a line, consider movement within two-dimensional space. b. If your object moves in plane, consider movement within three-dimensional space. c. Rearrange objects so that instead of one-storied arrangement a multi-storied arrangement can be achieved. d. Tilt the object. e. Use other side of the given area.	REVIEW: Arrange the structure and / or the object in space rather than in a plane	REVIEW: If the structure and / or the object moves along a linear path, move them in a plane. If it moves in a plane, move them in a space	
24. Intermediary a. Use an intermediate carrier to provide necessary actions if it is not possible to use existing objects or parts. b. Temporarily merge your object with another one that will provide the required action and then decompose them.	REVIEW: if it is not possible to use existing objects or parts, add an intermediate structure/component.	NEW: Introduce a mechanical, acoustic, thermal, chemical, electrical or magnetic field, temporarily or permanently, to serve as an intermediary for the transmission of energy, material or information	
26. Use of copies a. If you need to undertake some actions with respect to unavailable, fragile, complicated, or dangerous object, use its simpler and cheaper copy. b. Instead of real objects, use their optical images (pictures, holograms). c. Use infrared or ultraviolet copies.	REVIEW: If you need to use unavailable, fragile, complicated, or dangerous object, substitute it with a physical or optical cheaper structure	REVIEW: If you need to use an unavailable, complicated or dangerous physical effect reproduce or simulate it in order to achieve the goal	
34. Rejected and regeneration of parts a. If a part of an object that has delivered its function had become unnecessary or undesired, eliminate it by dissolving, evaporating, etc. or modify so that the interfering property will cease to exist. b. Restore consumable parts	REVIEW: Restore consumable parts of the object during operation. Remove unnecessary components from the device after they have accomplished their goal and restore them in case of future need	NEW: Remove the annoying physical effects after they have accomplished their goal and eventually restore them in case of future need	REVIEW: Remove a functionality when it becomes useless and eventually restore it later

of the object during operation.			
35. Change of physical and chemical parameters a. Change the object's aggregate state. b. Change concentration or composition of the object. c. Change the degree of flexibility of the object. d. Change the temperature of the object or environment.	NEW: Modify the physical and chemical parameters of the structure	REVIEW: Change magnitude of the physical effect	

4. Test

In order to test the inventive principles reformulated, we have provided students two technical problem to be solved. These problems have been deliberately supplied in a sufficiently abstract to allow multiple directions of intervention on different levels of depth (function, behavior, physical effects and structure). As a result, problems have been formulated at the functional level, focusing on a description of how to meet the requirements of the customer, such as efficiency, fuel consumption and lifetime.

4.1 Test participants

The authors have introduced the problem during a course at the University of Bergamo and to professionals from academia and industrial sector.

The university course is named "Methods and tools for product lifecycle" (i.e. PLM-Product Lifecycle Management) and is an elective course for the master degree in Mechanical Engineering and Management Engineering. The course is followed by two kinds of students: one group of students with previous knowledge of TRIZ theory (course "Product and Process Innovation") and the other which has never worked with TRIZ.

The professionals come from different areas:

- University researcher involved in TRIZ: researchers and PhD students dealing with product and process innovation through engineering design, problem solving and CAE methods;
- University researcher not involved in TRIZ: researchers and PhD students belonging to the branch of mechanical engineering and biomechanics dealing with CAD and FEM analysis;
- Industrial researchers: engineers working for mechanical and software industry.

4.2 Case study

Two case studies have been proposed:

1. **Hair dryer:** the functions of a modern hair dryer is not only to ensures a good drying, but also the ability to fold, the possibility of adjustment, the aesthetics, the compatibility with accessories and in particular the energy consumption. In commerce they are less energy-intensive models which do not guarantee the same quality of the more energy-consumptive competitors. The objective in this case is to provide a model equally efficient and performant. To achieve these goals are not precluded the more radical changes concerning the structure of the hair dryer, the physical effects used, or the same mode of drying.
2. **Joint for high voltage cables:** in this problem we have to satisfy two functions: "ensure the physical continuity of the cables" and "ensure the electrical continuity cables". The material of the joint also ensures the continuity of the electric arc.

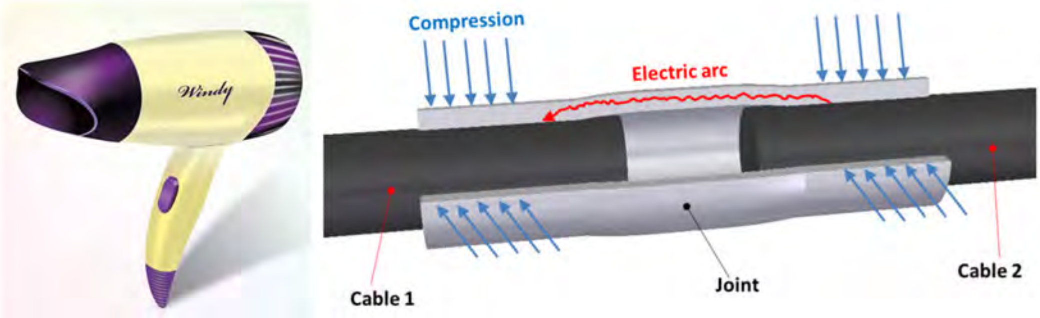

Figure 2. Hair dryer and joint scheme

The actual connection of the cables is realized on the ground because of the difficulty of welding in suspension.

5. Test Execution

Students and researcher were divided into four groups. The aforementioned problems have been assigned to users in 3 different sessions (see Table 3). In all sessions users could use only a set of inventive principles but in different versions:

- "Classical session" used the original definition of Altshuller's inventive principles;
- "FBS session" used a new definition of the inventive principles based on FBS, without any training;
- "FBS advanced session" used the same definitions of FBS sessions, but after a theoretical explanation (1h).

Following the application of the principles of technical problems, have been proposed to the students two questionnaires with the aim of self-critically assess the quality of the solutions found and the proposed methodology. The first questionnaire compare the results obtained with the traditional principles and the principles FBS, while the latter considers only the application of seconds but after a thorough theoretical session on the theory FBS.

Table 3. Test execution

Round	Group A - Students	Group B - University researcher involved in TRIZ	Group C - University researcher not involved in TRIZ	Group D - Industrial researcher
1st Classical session	Hair dryer	Joint for high voltage cables	Hair dryer	Joint for high voltage cables
2nd FBS session	Joint for high voltage cables	Hair dryer	Joint for high voltage cables	Hair dryer
	Questionnaire			
	FBS Advanced Session			
3rd	Hair dryer	Hair dryer	Joint for high voltage cables	Joint for high voltage cables
	Questionnaire			

5.1 Questionnaire evaluation

Generally the FBS principles allow generating new solutions or resolutive directions: they arise in integrative perspective compared to traditional principles, broadening the spectrum of useful tips. The tests thus confirm the validity of the integration of such a tool, for both students and professionals. The difference between the two broad groups, however, lies in the personal background. Most of the students are foreign about TRIZ and FBS theory; we cannot say the same thing to the professionals. Looking at the total number of received solutions, through the use of the FBS principles accompanied

by an appropriate reference theory, it certainly appeared that an introduction to the FBS theory is useful, if not necessary in the FBS principles.
Students and professionals also confirm these considerations with an exploratory questionnaire about the use of the traditional inventive principles and the FBS principles. We propose the quantitative results to the question proposed, in the following table:

Table 4. Questionnaire results

		Students evaluations (Number: 24)		**Researcher involved in TRIZ (Number: 7)**		**Researcher not involved in TRIZ (Number: 11)**	
Questionnaire	**Questions**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**
1st questionnaire	Are FBS IPs more comprehensible than traditional IP?	19	5			8	3
	Do FBS IPs propose a great number of solutions than traditional IPs?	13	11			8	3
	Are the solutions of the FBS IPs qualitative better than those of the traditional IP?	13	11			6	5
2nd questionnaire (after theoretical explanation "t.e.")	After t.e. are FBS IPs more understandable?	23	1	7	0	11	0
	After t.e. the solutions of the FBS IPs are qualitatively better?	16	8	4	3	7	4
	Overall, do you prefer FBS IPs or IPs?	16	8	4	3	8	3

By students and researcher's other observations and by the review of the results, we have observed that, unlike the traditional inventive principles, the FBS principles lead to consider elements of the FBS theory. For example, the principle #1 Segmentation prescribes to change the structure to solve the problem while the principle #1 in FBS form suggests modifying the function and the behavior. Moreover the FBS principles, urging to work on the function and the behavior of a device, require you to explore in greater depth the concepts of operative zone and operative time. Infact FBS principles are generally viewed more accurate and timely suggestions. This judgment is both positively than negatively: if on the one hand they require preparation and training to be fully understood, on the other hand they lead to solutions complex and concrete.
The students and the professionals have qualitatively evaluated the solutions of the FBS principles as the best; they are considered easier to implement and more effective than the others (emerged with the traditional inventive principles).
As regard the theoretical background available is certainly useful for a clear understanding and a fruitful application in principle of the traditional inventive principles, but also (to a lesser extent) to the principles FBS.
In conclusion, the traditional inventive principles are generally seen as more general suggestions and transverse meter FBS principles as more precise directives to (sometimes) specific problem areas. In this regard, some have suggested an integration of the two possibilities, first approaching the problem with the traditional inventive principles in order to generate solutions and directions for action, more general and then explore them through the application of the FBS principles, from which will come to while generating new solutions.
With regard to the comparison between the solutions found, you can see that the results do not differ greatly between students and professionals basic facts and the FBS principles introduce new solutions compared to the traditional principles.

6. Conclusion

This paper presents a revision of the inventive principles trough FBS theory. In regard to the latter, in our opinion, the principles can be divided into two categories, despite their heterogeneity. Among them the principles which define clearly on which entity FBS intervene and those who leave more freedom. Our review is concerned with the second category. In particular we propose a re-write for every principle that specifies how they can act on function, behavior and structure.

This work has also highlighted the particular similarities between the reformulated principles favoring the fusion of a few.

Finally, the advantage of this work is to reduce the ambiguity inherent in the principles specifying the element to be considered and at the same time to expand the resolutive power of the inventive principles in a conscious and focused manner.

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