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A NEW SET OF GUIDELINES FOR INVENTIVE PROBLEM SOLVING

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Abstract

The rapid changes characterizing the economy in the last decades convinced companies, especially the most advanced, to heavily invest in innovation and in approaches to support it in a systematic way to increase the qualitative level of their products and reduce the time-to-market. Academia answered to this demand with an increasing number of publications on this topic every year; in addition, industry developed its own procedures, often internally. As result, today a lot of strategies, theories, methods and tools are available for systematic innovation. However, an accepted and unified theory and objective criteria able to assist the problem solver in the selection of the most suitable approach according to her/his needs are still missing.

The Ph.D. thesis refers to this context and its main objectives have been: (1) reviewing and classifying the huge multitude of systematic innovation methods (for new concept design, product improvement, robust design, physical investigation, information retrieval, etc.) and (2) developing a methodology to assist the designer in selecting the most suitable method in accordance with the application context.

Among the several possibilities, I choose to develop a set of guidelines that are both comprehensive and practical to apply especially in industrial contexts. However, writing guidelines is a complicated activity, as demonstrated by the numerous examples from literature describing problems and limitations in conceiving and/or applying them.

Based on literature review, involving not only papers but also patents and empirical evidences collected during the collaborations in industrial projects and tests with students, I identified the main key features of the guidelines for inventive problem solving. They are: the structure of single guideline, the organization of multiple guidelines and the suggested methods and tools. In particular, I focused attention to comprehend how the suggestions provided by the guidelines change in relation to the kinds of addressed problems, the different phases in problem solving activity and the user, and how to enrich them through specific methodological contents.

Then, according to the mentioned features, I developed a set of specific guidelines to improve Spark, a methodology for systematic innovation developed at University of Bergamo, reviewing some parts and integrating with some proposed models.

The research activities have been carried out in **five phases** as described in the following.

During the **first activity**, a state of the art about the kinds of addressed problems, and the main problem solving methods, approaches and strategies to support systematic innovation has been carried out.

In the **second activity**, the main features of the guidelines have been identified through a detailed analysis based on literature surveys, of Design models (e.g., FBS), Risk analysis techniques (FMEA), Problem solving tools (TRIZ) and empirical evidences collected in the companies and by involving engineering students.

The results have been organized according to three main aspects: the definition of the most suitable structure of a single guideline (in terms of provided text, graphical representations and examples), the organization of multiple guidelines (hierarchical maps, random lists, matrices, etc.) and the models and tools suggested by the guidelines in accordance to the addressed inventive problems and the phase in problem solving activity.

This results have then been summarized in a set of rules for writing guidelines.

During the **third activity**, the identified features have been applied to improve some parts of Spark methodology, which is structured as an ordered step by step procedure to enhance the different problem

solver skills: function identification, evolutionary overview identification, problem identification, problem reformulation and idea generation. Even if this methodology has been successfully applied in industrial cases studies, it still presents some limitations (e.g., by supporting new product design).

I tried to improve Spark by expanding its domain of application to all the considered inventive problems and by ameliorating its comprehension and applicability, through an increased level of awareness of the designer while maintaining the suggested path. To do this, I improved the parts of function and problem identification through the introduction of two specific models derived from FBS and FMEA, and I reformulated the part of idea generation by providing a more rigorous ontology and a more intuitive organization to the already contained guidelines. Finally, I proposed a comprehensive set of guidelines to guide the user in the use of the improved version of Spark.

The resulting approach maintains a unique path to face all the considered inventive problems and allows specific iterations and ramifications inside the main steps, depending on the problem and the context of application.

In the **fourth activity**, the goal has been to drive the user to model the problem with a functional approach, in order to be able to consult the Information Retrieval tools in the proper way to find out if someone has already solved the problem in another context. More in detail, this means to conceive a guideline able to support the user in defining the right element on which to work, the function and the behaviour of the solution, at least in terms of physical effect. Patent repository is used as technical source for gathering such an information. During the doctorate, I learned techniques and software prototypes developed by the University of Bergamo, for query expansions based on hyponyms, meronyms, hypernyms and lexical variants. I tested them in industrial case studies, to comprehend how to integrate info gathering into the guidelines structure.

During the **fifth activity**, I recombined all the results previously achieved within of a software platform that I developed. It collects flexible guidelines, able to adapt to the different kinds of problems, which are organized through the conceptual scheme studied during the third activity, and integrates the knowledge retrieval techniques of the fourth activity.

The proposed platform and the guidelines have been tested with real industrial case studies proposed by companies with whom I collaborated, such as ABB, Tenacta-Imetec. The tests involved MsD and PhD students, during thesis works, project works and group sessions with more than 10 students each one. The achieved results, compared to traditional Spark and other approaches, have been encouraging in terms of function identification, by facilitating the determination of the required operative zone and operative time, problem identification, with an increased user’s awareness about the dynamic of occurrence, and idea generation, with a great number of qualitatively better achieved solutions.

Keywords: Systematic Innovation, Guidelines for Inventive Problem Solving, Computer Aided Innovation.

Riassunto

I rapidi cambiamenti che caratterizzano l'economia negli ultimi decenni hanno convinto le industrie, specialmente le più avanzate, ad investire ampiamente sugli approcci a supporto dell'innovazione sistematica, con l'obiettivo di migliorare il livello qualitativo dei propri prodotti e ridurre il tempo di sviluppo. L'accademia ha risposto a questa necessità con un numero di pubblicazioni in quest'ambito crescente di anno in anno; in più anche l'industria sviluppa i propri approcci, spesso internamente. Come risultato, sono oggi disponibili una grande quantità di strategie, teorie, metodi e strumenti a supporto dell'innovazione sistematica. Tuttavia una teoria unificata ed accattata è ancora mancante, così come criteri oggettivi di scelta capaci di supportare il problem solver nella scelta dell'approccio più adatto alle sue necessità.

Questa tesi di Dottorato fa riferimento a tale contesto ed i suoi principali obiettivi sono stati: (1) rivedere e classificare i molti metodi di innovazione (progettazione di nuovi prototipi, product improvement, robust design, investigazione della fisica del problema, ricerca di informazioni, ecc.) e (2) sviluppare una metodologia per assistere il problem solver nella scelta dell'approccio più adatto in relazione al contesto applicativo.

Tra le molte possibilità, ho scelto di sviluppare un insieme di linee guida che siano allo stesso tempo comprensibili e pratiche da applicare specialmente in contesti industriali. Tuttavia, scrivere linee guida è un'attività complicata, come testimoniato da numerosi esempi dalla letteratura che descrivono i problemi e le limitazioni derivanti dalla loro creazione e dalla loro applicazione.

Sulla base di una dettagliata revisione della letteratura, contenente non solo articoli ma anche brevetti ed evidenze sperimentali raccolte durante collaborazioni in progetti industriali e test con gli studenti, ho identificato le principali caratteristiche delle linee guida per la risoluzione dei problemi inventivi. Esse sono: la struttura delle singole linee guida, l'organizzazione di più linee guida ed i metodi e gli strumenti suggeriti da esse. In particolare, ho focalizzato l'attenzione per comprendere come i suggerimenti delle linee guida cambiano in relazione alla tipologia di problema affrontato, alle differenti fasi nell'attività di problem solving e all'utente, e ad arricchire le linee guida attraverso contenuti metodologici precisi.

Quindi, sulla base dei tali caratteristiche, ho sviluppato un insieme di linee guida specifiche per migliorare Spark, una metodologia a supporto dell'innovazione sistematica, sviluppata dall'Università degli Studi di Bergamo, rivedendone alcune parti ed integrandola con modelli proposti.

L'**attività di ricerca** è stata portata avanti in **cinque fasi** come descritto nel seguito.

Durante la **prima attività** è stato eseguito uno stato dell'arte relativo alle tipologie di problemi affrontati e ai principali metodi, approcci e strategie di problem solving a supporto dell'innovazione sistematica.

Durante la **seconda attività** sono state identificate le principali caratteristiche delle linee guida, attraverso un'analisi dettagliata della letteratura relativa ai modelli per la progettazione (e.g., FBS), tecniche di analisi dei rischi (e.g., FMEA), strumenti per il problem solving (TRIZ) ed evidenze empiriche raccolte nelle aziende e coinvolgendo studenti di ingegneria.

I risultati sono stati organizzati secondo tre aspetti principali: la definizione della struttura più opportuna per le singole linee guida (in termini di testo proposto, rappresentazioni grafiche ed esempi), l'organizzazione di più linee guida (mappe gerarchiche, liste casuali, matrici, ecc.) ed i modelli e gli strumenti suggeriti dalle linee guida in relazione ai problemi inventivi affrontati e alla fase nell'attività di problem solving.

Questi risultati sono stati quindi riassunti in un insieme di regole per scrivere le linee guida.

Durante la **terza attività**, le caratteristiche identificate delle linee guida sono state applicate per migliorare alcune parti della metodologia Spark, la quale è strutturata come un percorso ordinato e diviso in fasi per accrescere le differenti abilità del problem solver: identificazione della funzione principale, identificazione della panoramica evolutiva, identificazione del problema, riformulazione del problema e generazione di idee. Anche se questa metodologia è stata applicata con successo in casi studio industriali, presenta ancora alcune limitazioni (e.g., nel supportare la progettazione concettuale di nuovi prodotti).

Ho quindi cercato di migliorare Spark, espandendo il suo dominio di applicazione a tutti i problemi inventivi considerati e migliorando la sua comprensione e la sua applicabilità attraverso l'accrescimento del livello di consapevolezza del problem solver e mantenendo il percorso suggerito. Per far ciò, ho migliorato le parti dell'identificazione della funzione principale e del problema, introducendo due modelli specifici derivati da FBS e FMEA, e riformulando la parte della generazione delle idee con una struttura ontologica più rigorosa ed una organizzazione più intuitiva delle linee guida presenti. Infine ho proposto un insieme complessivo di linee guida per supportare l'utente durante l'utilizzo della versione modificata di Spark.

L'approccio risultate mantiene un unico percorso per affrontare tutti i problemi inventivi considerati e permette iterazioni e ramificazioni specifiche all'interno degli step principali a seconda del problema e del contesto di applicazione.

Durante la **quarta attività**, l'obiettivo è stato guidare l'utente a modellare il problema con un approccio funzionale, in modo da poter consultare nella maniera opportuna uno strumento per la ricerca delle informazioni, così da poter apprendere se il problema in questione sia già stato risolto in un altro contesto. Più in dettaglio, ciò significa concepire linee guida capaci di portare l'utente a definire il giusto elemento sul quale lavorare e la funzione ed il comportamento della soluzione almeno in termini di effetto fisico. I database brevettuali sono stati usati come fonte per la raccolta di tali informazioni. Durante il Dottorato, ho appreso tecniche e software prototipali, sviluppati dall'Università degli Studi di Bergamo, per espandere le chiavi di ricerca basati su iponimi, iperonimi, meronimi e varianti lessicali. Li ho quindi testati su casi studio industriali per comprendere come poter integrare il recupero delle informazioni all'interno della struttura delle linee guida.

Durante la **quinta attività**, ho ricombinato tutti i risultati raggiunti all'interno di una piattaforma software che ho sviluppato. Essa raccoglie linee guida flessibili, capaci di adattarsi alle differenti tipologie di problemi, organizzate attraverso lo schema concettuale studiato durante la terza attività e integra le tecniche di recupero della conoscenza della quarta attività.

La piattaforma e le linee guida proposte sono state testate con casi studio industriali reali, proposti dalle aziende con le quali ho collaborato, come ABB e Tenacta-Imetec. I test hanno coinvolto studenti della laura magistrale e del dottorato, durante lavori di tesi, progetti d'anno e sessioni di gruppo con almeno 10 partecipanti ciascuna. I risultati raggiunti, comparati con Spark tradizionale e altri approcci, sono stati incoraggianti in termini di: identificazione della funzione, facilitando l'individuazione di zone e tempi operativi, di identificazione del problema, con l'accrescimento della consapevolezza relativa alla dinamica di accadimento e di generazione delle idee, con un maggior numero di soluzioni qualitativamente migliori identificate.

Parole chiave: Innovazione Sistematica, Linee guida Inventive per la soluzione inventiva dei problemi, Computer Aided Innovation.

Index

1. Introduction

Nowadays, a huge multitude of systematic approaches to support product innovation are available. The list includes: design and reasoning schemes (e.g., Function-Behaviour-Structure, FBS) to guide the designers during the conceptual design, anticipatory failure analyses techniques (e.g., Failure Modes and Effect Analysis, FMEA) to anticipate the possible future faults of the in order to avoid their occurrence, knowledge-based systems for the management of the information, methods for problem solving (e.g., Theory of Inventive Problem Solving, TRIZ) and tools for idea generation (e.g., eco-guidelines and SCAMPER).

During the years, the research activity about these approaches, carried out by academia and industry, focused on two distinct research fields:

- The introduction of new approaches: the authors that work in this field generally consider the already available approaches insufficient for different reasons (e.g., the difficult industrial applicability and the not-intuitive interfaces of presentation) and they propose ontological reformulations, new schematic representation, methodological reviews and integrations with other methods.
- The introduction of tools for suggesting the proper approaches aims instead to assist the problem solver during the choice of the most suitable existing methods that are considered sufficient but generally not understood and not applied in the proposer way.

As result, in addition to the multitude of methods, also a lot of tools of choice and classifications are today available in literature. These tools involve different parameters to classify the methods: features of the addressed problems (e.g., degree of complexity, the number of involved constraints, the mole of available information, the technical domain); provided suggestions (e.g., abstractions, analogy, stimuli and triggers, sub-problems identification, exhaustive search, analysis synthesis and reformulations); suggested tools (e.g., matrix, hierarchical maps, lists of alternatives, databases). However, a unique and accepted framework able to assist the problem solver in the choice of the right method, in accordance to the context of application, is already missing in literature.

In such a context, the V&K research group (University of Bergamo), for which the candidate collaborated during the three years of the doctorate, developed a methodology called Spark, which is based on five years of industrial practice in small, medium and large Italian companies from different fields (mechanics, electronics, energy, home appliances) and includes marketing aspects, patents information and TRIZ tools. This approach is structures through a step by step procedure that support product innovation from the definition of the requirements to the definition of technological solutions. However, this approach presents some limitations due to the difficult comprehension of some parts and the limited support to certain kinds of problems (e.g., new product design).

The goals of this thesis have been (1) the review and the classification of the multitude of the methods for systematic innovation (new design concepts, product improvement, robust design, physical investigation, information retrieval, etc.) and (2) the proposal of a tool for the choice of the method in accordance with the context of application. In particular, the objective of this thesis deals with the development of a comprehensive problem solving approach to support systematic innovation.

The contents of this thesis work are organized as follows.

Chapter 2 analyses different kinds of technical problems and identifies a set of inventive problems, considered as the domain of application of this thesis.

Chapter 3 presents the state of the art about the main strategies and methods for supporting problem solving, with a focus on TRIZ.

Chapter 4 investigates the rules to write guidelines for problem solving, by presenting the features of the structure of a single guideline (text, examples and graphical representation), the organisation of multiple guidelines and the most popular strategies and tools suggested by the guidelines depending on the different problems and the phases of problem solving. Then, the main advantages of software implementation for the guidelines are discussed and, finally, a set of rules for writing guidelines, summarizing the identified features, are proposed.

Chapter 5 introduces Spark methodology and its main advantages and limitations.

Chapter 6 proposes some integrations and revisions of Spark: A new Conceptual Design Scheme to support the first steps of the methodology, the improvement of a FMEA-TRIZ model to support problem investigation and a new set of inventive principles based on FBS and a new set of guidelines for measurement problems to support idea generation.

Chapter 7 proposes a comprehensive approach, based on Spark and including the introduced models, and the derived guidelines. The last part of the chapter presents an integration of the guidelines with patent databases and a software implementation.

Chapter 8 summarizes the results of some applications of the guidelines in real industrial problem, through case studies and tests. The first application deals with new concept design, the second one deals with product improvement, the third one deals with anticipatory failure investigation, the fourth one application deals with idea generation of problems with contradictions and the last one regards measurement problems. Finally, the results are discussed.

Chapter 9 draws the conclusions and the future developments.

2. Problems classification

In this chapter, different kinds of technical problems and their classifications are investigated and a limited number of inventive problems has been identified as the domain of application for this thesis. This activity has been carried out because the analysis of the problems plays a crucial point in the choice of the most suitable problem solving approach as explained by some authors (e.g., Jonassen and Hung, 2008 [1]). In the following a short summary of the various problem classifications is firstly introduced and then the selected problems are presented.

During the years, several authors worked on this topic by proposing a multitude of different classifications. Ivanov and Barkan, (2006)[2] divided the problems on the basis of their initial state (the problematic situation), the goal state and the affected elements by identifying the following kinds: manufacturing process problems, design problems, creating a new technical system to satisfy new requirements, emergency problems, science and research problems. The institute for learning TRIZ in Irkoutsk proposed a similar classification were the identified problems were: commercial problems, production/manufacturing problems, design problems, maintenance problems and research problems. Some multinational companies proposed their own classifications based on more specific requirements: Intel (Roggel, 2008 [3]) considered the required actions (correct, improve and prevent) for solving the problems, Samsung (Krasnoslobodtsev and Langevin, 2006 [4]) divided the problems in "Standard" engineering problems, "Non-standard" engineering problems that contain contradictions, and research and development problems that are not already faced and solved. Another classification proposed by Samsung classified instead the problems as follow: existing product improvement, new product improvement, manufacturing technology improvement, patent overcoming and patent development, short and long term forecasting, scientific research engineering. Some authors consider instead functional models as base of their classifications: Hirtz et al. (2002)[5] analysed the actions required for solving the problems, by describing them through verbs, while Pinyayev (2007)[6] and Mann (2002)[7] related the problems to the presence of insufficient, excessive or missing functions. Other classifications focused only on problems from specific areas, such as design. Among them, Evbuomwan et al. (1996)[8] identified three kinds of sub-problems: routine design, redesign (in turn divided into adaptive, configurational or transitional and variant, extensional or parametric) and non-routine design (in turn divided into innovative and creative).

In addition to the various definitions, three parameters have been often considered during the years in some classifications: structuredness, complexity and inventiveness. In the following, they are explained in detail.

Structuredness

Structuredness explains the degree of knowledge contained in a certain problem and it was used by some authors to discriminate well-structured and ill-structured problems on the basis of some features reported in the table 1.

TABLE 1: WELL-STRUCTURED PROBLEMS VS ILL-STRUCTURED PROBLEMS DEFINITIONS.

Features	Well-structured problem	Ill-structured problem
Goal declaration (Coyne et al., 2005 [9])	Defined and precisely descripted	Absent or two contradictory goals are required

Definition of a well-defined set of requirements and constraints for problem solving activity (Mayer and Wittrock, 2006 [10])	Yes	No
Definition of the effects on the external environment caused by the problem (Coyne et al., 2005 [9])	Yes	No
Presence of strict step-by-step procedure for problem solving (Jonassen, 2000 [11])	Yes	No
Solutions provided (Jonassen, 2000 [11])	One definite solution	More solutions, no solutions
Testing the solutions: precise criteria are available to test the achieved solutions (Coyne et al., 2005 [9])	Yes	No

Complexity and difficulty

According to Jonassen (2000)[11] and (2015)[12], the degree of complexity of a problem is strictly related to its level of difficulty, since it depends by the following aspects: number of variables of the problem, degree of connectivity among the variables, functional relations of the variables, stability of laws and properties and knowledge required to solve it. According to Frensch and Funke (2014)[13] a "Difficult problem" is characterized by at least one the following features:

- Intransparency: if some elements required to achieve the solution are not known;
- Complexity: if the problem is constituted by a great number of parameters mutually connected;
- Dynamics: if the nature of the problem and their features are time-dependent and not stable;
- Politely: if multiple goals have to be achieved and some of them are non-compatible.

Inventiveness

During the years, several definitions of "Inventiveness" have been provided. According to Patent Law (Patent Cooperation Treaty) an inventive solution satisfies a need by solving a problem that is novel and not obvious to a person "skilled in the art". Becattini et al. (2012)[14] explains instead that inventive problems are characterized by at least two conflicting requirements that cannot be satisfied by choosing the optimized values for system parameters and the request of an inventive solution necessary for facing the contradiction in order to produce a useful, novel and unobvious solution. In addition, the same authors specify that non-inventive problems do not require any inventive step but only an optimal adjustment of the system parameters.

In particular, by analysing problems with contradictions, Altshuller (1984)[15] identifies three kinds of problems: (1) administrative contradictions, if something has to be done, but how to do it is unknown, (2) technical contradictions, if one part or one parameter of a technical system is improved by any known method, some other part or some other parameter will be inadmissibly impaired and (3) physical contradiction, if mutually opposing demands are placed upon one and the same system.

On the basis of these definitions and by considering also the definitions of well-structured problems and the complexity of the problems, the non-inventive problems can be divided into the following categories:

- ***Technical common problems*** are known for a long time, specific methods and tools are available for solve them and their solutions are known. The simple application of the reference theory is generally sufficient for solving them and no particularly knowledge is required to the problem solver. The balancing of a wheel carried by the tire repairer with the proper machine can be considered an example of this kind of problems.

- ***Technical complex problems*** require the application of specific algorithms (i.e., FE analysis) and theories. The solutions are generally not noted and they are iteratively achieved through optimisation.
- ***Industrial design problems*** are characterized by low complexity (only few constraints are generally required and contradictions between the requirements are not present), are not previously solved and are not without supporting by structured methods. Designer's creativity and experience are required to solve them.
- **Inventive problems** share some similarities with technical complex problems (the complexity of the problem, the number of requirements) and with industrial design problems (the lack of supporting approaches). Among the identified problems, the inventive ones have been considered as the reference domain of this thesis and they have further been divided into the following categories according to Jonassen (2000)[11]:
  - ***Improving an existing product*** requires the determination of a series of possible alternative solutions that are better (e.g., less expensive, with lower energy consumption, etc.) compared to the current device in realising its functionalities. The improvement can be made by acting at different level of detail:
    - *Change the function by* modifying the modality of usage for achieving the same goal or, more radically, when we want to use the same product for achieving other purposes.
    - *Change the behaviour:* when the existing physical effects of the device are modified or new effects are introduced for realizing the same functions.
    - *Change the structure:* when the structure of the device is modified without changing the functions and the physical effects.

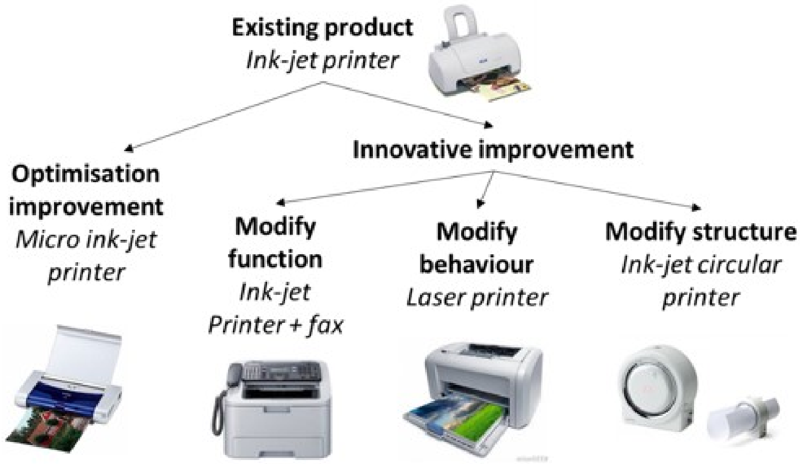


FIGURE 1: EXAMPLES OF DEVICE IMPROVEMENTS (OPTIMISATION VS INNOVATION).

  - ***New concept design*** requires the identification of a new product able to:
    - Satisfy a need yet unsatisfied;
    - Satisfy in an inedited way an already satisfied need, e.g., through the introduction of a physical effect or a new technology.
  - ***Forecasting*** requires predictions about the future developments of the current products and the determination of the next-generation products on the basis of the analysis of technological trends. The problem can be further divided into the following categories:
    - Predicting the evolution of a system: when the possible features of a future device have to be determined in order to determine in what way it can evolve (e.g., Which technology will be used for cutting pipes in the in 50 years?).

- Finding possible future applications for a system: when the problem regards the research of possible future applications of a current product (duly improved), generally not achievable at the present situation, i.e. could laser be used for cooling food?
- Predicting new needs: differently to new product design, in this case we want to predict the future needs of the next generation products (e.g., Glasses for augmented reality).

- ***Anticipatory failure investigation*** requires the prediction of possible undesired unknown effects and unknown causes that can occur in a device and its improvement to avoid them.
- ***Eliminate undesired effect*** requires the elimination of a manifested undesired effect, e.g., the overheating of an electrical component, which is considered dangerous for the user, the environment or the device itself.

3. State of the art about methods for problem solving

In literature, several definitions about problem solving have been provided during the years, and more in particular about technical and inventive problem solving. The definitions involve several key factors, such as the addressed problems, the context of application, the problem solvers' backgrounds, etc. According to Mayer and Wittrock (2006)[10], problem solving is "A cognitive processing directed at achieving a goal when no solution method is obvious to the problem solver", Lynch (2000)[16] defines instead problem solving as "The practical application of reasoning and other types of skills in a process that involves the identification and use of relevant information". Others authors specifically link problem solving to design: e.g., Hatchuel (2003)[17] explains that problem solving theory is a special and restricted case of Design theory.

Other authors identified a general step by step procedure for problem solving. One of the most accepted definition, proposed by D'Zurilla and Goldfried (1971)[18] and reviewed by Chang et al. (2004)[19], is constituted by 4 main steps that require different problem solver skills:

- ***Problem definition and formulation.*** During these phases, the problem solver analyses and comprehends the problem by gathering specific information about it, by identifying demands and obstacles and by setting realistic problem-solving goals (e.g., by changing the situation for the better, accepting the situation and minimizing emotional distress).
- ***Generation of alternative solutions.*** During this phase, the problem solver focuses on the problem-solving goals and she/he identifies all the potential solutions, including both conventional and non-conventional ones.
- ***Decision making.*** During this phase, the problem solver evaluates the potential solutions by hypothesizing the possible negative effects of each one and by choosing the "best" or potentially most effective solution.
- ***Solution.*** During this phase, the problem solver implements the chosen solution by considering all the arising issues.

Although this approach is very general and related to generic problem solving (e.g., social problem solving), it can be taken as reference also for technical problem solving (e.g., optimisation) and in particular for inventive problem solving to support systematic innovation (e.g., designing new products, introducing new functionalities and physical effects, using the existing products in an unusual way, etc.), since constitutes the basis for the supporting methods. In the rest of the chapter some problem solving approaches and methods are presented with a focus on those supporting inventive problem solving such as TRIZ, which is one of the most diffused especially in industrial contexts.

During the years, several definitions about problem solving methods have been provided in literature. According to Clancey (1985)[20], a problem solving method describes the reasoning to reach a goal in terms of a series of actions that required knowledge, which can be divided into two categories: domain knowledge and generic knowledge. The first one is directly linked to the domain of application of the problem, while the second one provides the methodological knowledge for supporting the application of the methods in different context of applications and it typically works with a higher level of detail. According to Benjamins et al. (1996)[21], a problem solving methods is instead a series of abstract actions related to domain knowledge and to the goals of the problem by a series of assumptions, which are made by the problem solver. Clancey (1985)[20] defines a problem solving method as the sequence of four steps (called knowledge roles) and three inference actions that lead to one role to another. In each step, different kinds of knowledge are required: for “Observables” and “Solutions” steps, the knowledge is linked to the domain of application while for “Abstract observables” and “Solution abstractions” steps the knowledge is abstract and not related to the specific domain of the problem. Abstract observables and solution abstraction work at different level of abstraction and dependences with the domain knowledge of the problem to solve. TRIZ (Altshuller, 1984 [15]), Design-by-Analogy (Moreno et al., 2014 [22]) and Bio Inspired Design (Fu et al., 2014 [23]).

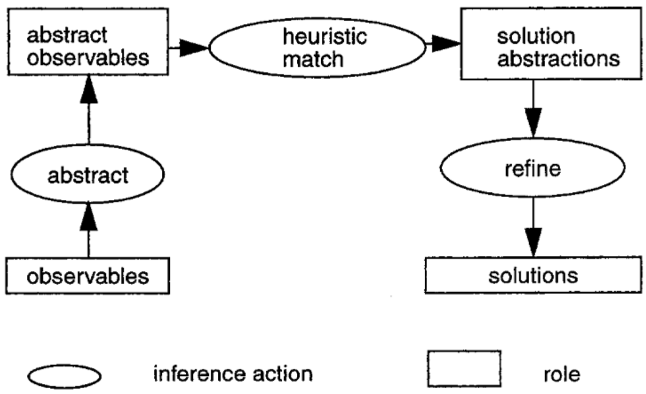


FIGURE 2: A PROBLEM SOLVING METHOD ACCORDING TO CLANCEY, 1985 [20].

Classification of the methods

The classifications of the problem solving methods proposed in literature and in industry are based on different comparison parameters, such as the problem constraints, the involved knowledge, the context of application, etc. Some of them e.g., that proposed by Wang and Chiew (2010)[24] compared the methods with the problem solving strategies, by identifying the following categories:

- ***Abstraction*** is a problem solving strategy based on the solution of a model of the problem rather than of the problem itself and on the adapting of the achieved results to the real problem. This strategy is heavily used in engineering and physics, where models are quite often used for simplifying complex problems (e.g., mathematical models, finite element analysis, simulations). Several reasoning schema for design, such as function-behaviour-state (Umeda et al., 1990 [25]), Synectics and the TRIZ tools of TOP model, Energy-Material-Signal model and Su-field model are involve to this strategy.
- ***Analogy*** is a problem solving strategy based on the adoption of existing solutions already exploited for solving analogous problems. In design problems, this strategy is called Design-by-Analogy, while Tomiyama et al. (2009)[26] and Shah et al. (2000)[27] linked TRIZ method to this strategy, respectively by defining it as modification based design and history based design. Other methods that work in this way are Kritik, IDEAL, McAdams and Wood method and Word three.
- ***Root cause analysis*** is one of the most diffused strategies for identifying the root causes of a problem. Several methods including Failure Modes and Effects Analysis - FMEA, the Theory of Constraints, Ishikawa diagrams, Kepner-Tregoe method, Fault Tree Analysis, Why-Why are based on this strategy.
- ***Stimuli and triggers*** are problem solving strategies that propose different kinds of stimuli (textual, visual and audio) for enhancing idea generation. Differently to heuristic strategies, stimuli and triggers are based on random or weakly associations with the problem to be solved. Focal object (Orloff, 2006 [28]) and SCAMPER (Eberle, 1996 [29]) work in this way.
- ***Sub-problems identification*** is a problem solving strategy that decompose a large and complex problem into smaller simpler problems. Generally used in engineering and in management, this

strategy is also particularly common in design strategies based on functional decomposition, e.g., SAPB (Pahl and Beitz (1977)[30]).

- ***Lateral thinking*** is a problem solving strategy based on the research of new points of views of the problems for raising new questions and new possibilities. STC (size-time-cost) (Fey and Rivin, 2005 [31]) is a TRIZ tool based on this strategy, which suggest to exaggerate or minimize the resources of the technical system.
- ***Exhaustive search*** is a problem solving strategy based on the systematic search of all the possible solutions. It can be supported by brainstorming and techniques for information retrieval, such as Functional Behaviour Oriented Search (FBOS) (Montecchi and Russo, 2015 [32]) and Knowledge Organizing Module (KOM) (Russo et al., 2012 [33]).
- ***Analysis, synthesis and reformulations*** are problem solving strategies that reduce a given problem to a known category and they suggest how to find a particular solution for it. ARIZ (Altshuller, 1985 [34]) is one of the most TRIZ tools, which works in this way for solving technical problems.

Other classifications (e.g., Porter (2010)[35]) of the methods can be more extensive and they classify the methods into families on the basis of the implemented specific approaches and tools (e.g. statistical analyses, matrices, road- mapping, trend analysis, expert opinions, scenarios analysis, etc.).

3.1. TRIZ

Among the multitude of methods to support technical problem solving, TRIZ (Theory of Inventive Problem Solving) is one of the most known, used and appreciated, especially in the companies. The theory has been developed by Altshuller since the second half of the forties, through the determination of a common resolutive path for supporting problem solving, identified in a large number of patents. The first official publication about TRIZ dates back to 1956 (Altshuller and Shapiro, 1956), in which the authors outlined some of the most well-known tools (technical contradictions, ideality, multiscreen and inventive principles) that constitute the theory. Over the years, the existing tools have been reviewed and new tools have been introduced. Among them, the introduction of the formalisation for physical contradictions (Zlotin et al., 1977) represented a turning point in the method, by considerably improving its usefulness. Recent developments of the methodology include various re-updating of the contradiction matrix (Mann, 2003 [36]) and OTSM-TRIZ (Cavallucci and Khomenko, 2006 [37]).

In extreme synthesis, TRIZ can be summarized through following steps:

- ***General problem formulation:*** starting from a specific problem, the theory suggests to gather all the information and to reformulate them in an abstract way (e.g., physical contradiction), by using some of the TRIZ tools (e.g., Top model, ENV model (Cavallucci and Khomenko, 2006 [37]), Ideal Final Result (Altshuller, 1984 [15]).
- ***Concept/General solution definition:*** the abstract problem is translated into a concept by means of TRIZ techniques (ARIZ, Separation principles, Contradiction matrix, 40 inventive principles, 76 standard solutions).
- ***Specific solutions definition:*** the concept is finally translated into a specific solution through the use of the resources available in the system and in the environment.

The typical TRIZ path is presented in the following scheme (Figure 3):

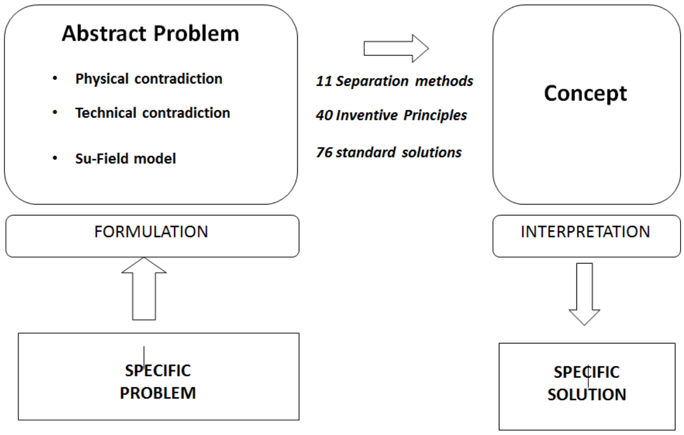


FIGURE 3: TRIZ SCHEME.

Among the TRIZ tools, some of them, e.g., the contradictions (Altshuller, 1984 [15]) and the 40 inventive principles (Altshuller, 1997 [38]), are more popular than others, typically used in few specific applications. Some studies presented a frequency ranking of the tools by highlighting how the preferences are affected by several aspects including the problem field of application. In particular, through an analysis of the TRIZ case studies in literature in the last 15 years (Spreafico and Russo, 2016 [39]), I analysed the frequency of utilization of TRIZ tools. The achieved results confirm what found in previous surveys (see Figure 4), so the situation seems not changed during the years.

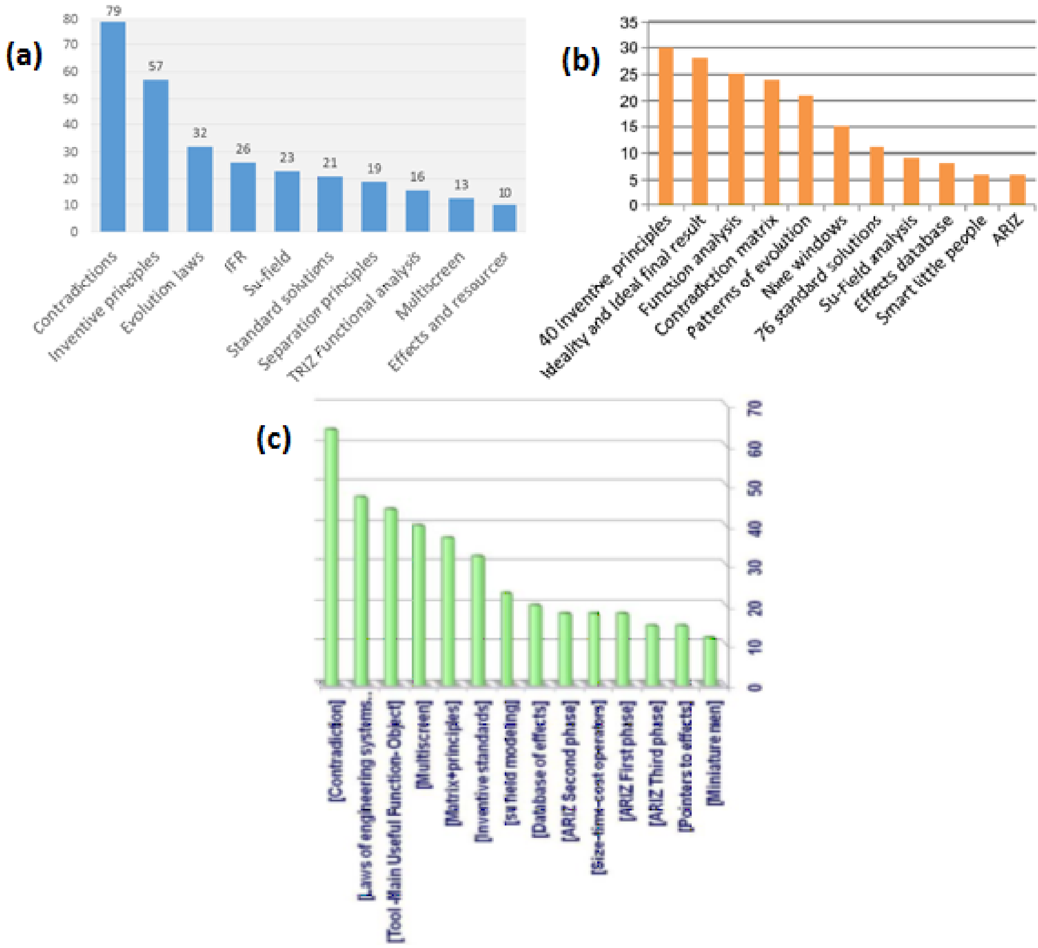


FIGURE 4: FREQUENCY OF UTILISATION OF TRIZ TOOLS IN PRACTICAL APPLICATIONS IN THREE DIFFERENT SURVEYS. (A) SPREAFICO AND RUSSO (2016)[39], (B) ILEVBARE ET AL. (2013)[40] AND (C) CAVALLUCCI (2009)[41].

Among the different TRIZ contexts of application, the following categories have been identified in Spreafico and Russo, (2016)[39]:

- ***Early design:*** TRIZ is used for conceptual design, in order to identify alternative physical effects or define the behaviour of a potential solution. Several examples show TRIZ integrated with Pahl and Beitz approach and FBS Function Behaviour Structure theory.
- ***Optimization and Robust design:*** TRIZ is used to support optimization stage during design, FEM analysis, and robust design.
- ***Decision making and Forecasting:*** TRIZ can lead a different prospective highlighting new business opportunities and forecasting.
- ***Eco-design:*** TRIZ is used in an eco-design approach, especially to solve contradictions that emerged from the application of a partial solution.
- ***Design for X:*** TRIZ is used for improving product manufacturing, assembly and maintenance or for improving risk management models.

Figure 5 shows the absolute frequency of utilization of TRIZ in the different identified problem solving activities.

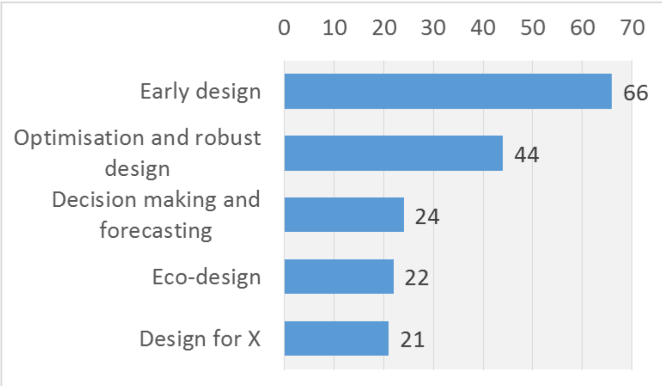


FIGURE 5: NUMBER OF CASE STUDIES DESCRIBING IDEAS, CONCEPTS OR FINAL PRODUCTS DESIGNED BY USING TRIZ (SPREAFICO AND RUSSO, 2016 [39]).

TRIZ improvements

Despite the multitude of successful applications of TRIZ in industrial and academic applications, some limits and shortcoming have been identified and several improvements have been proposed. Among them, some authors and companies directly modified the methodology, while others integrated TRIZ with other methods and tools. In the following, the most popular improvements are summarized:

- ***Unified Structured Inventive Thinking (USIT):*** Developed on the basis of SIT (Systematic Inventive Thinking), an extreme simplification of TRIZ that drastically reduced the number of the inventive principles, USIT (Sickafus, 1997)[42] was developed in Ford Motor Company starting from 1995, with the aim to simplify TRIZ theory and facilitate its industrial application. Nakagawa (2000)[43] summarized USIT as follow:
    - The theory aims to be applied to real practical problems for rapidly generating multiple conceptual solutions. Differently to TRIZ that does not put emphasis on amazing inventions.
    - USIT provides a clearly defined simple procedure for applying the methodology, divided into three steps: Problem Definition, Problem Analysis, and Solution Generation.
    - Elements of techniques in USIT are simple and well explained in guidelines.
    - No outside knowledge bases and software tools are used in USIT.
    - Engineering details, such as specifications, figures, numbers, costs, deadlines, etc., are put aside the consideration during the USIT procedure.

- ***OTSM-TRIZ:*** Developed by Cavallucci and Khomenko (2006)[37], OTSM-TRIZ aims to improve the TRIZ ability in solving complex problems through the introduction and the modification of some TRIZ tools, such as the Contradiction Network, a tool for solving a system of multiple contradictions where the parameters are mutually interdepended.
- ***Advanced Systematic Inventive Thinking (ASIT):*** Introduced by Horowitz (2001)[44], ASIT simplifies TRIZ by improving the concept of ideality the solution of the contradictions and the inventive principles, while it eliminated other TRIZ tools.
- **TRIZ integrations:** A lot of authors combined TRIZ with other methods and tools for better supporting some specific tasks, especially those less supported by traditional TRIZ tools, such as the management of the requirements with the integration of the Quality Function Deployment, the function analysis with Energy Material Signal model and the decision making through the integration with Fuzzy logic and the principles of the Value engineering.

4. Investigating the rules to write guidelines for problem solving

During the years, a lot of guidelines for problem solving have been proposed in literature and several studies to investigate their efficacy have been presented. On the basis of this material and through empirical evidences collected during industrial collaborations and tests with students, I identified the main features of the guidelines or the most suitable structures, organisations, suggested strategies and tools and software interfaces in relation to the application context. The results have then been summarized in a concise framework. In the following they are presented in detail.

4.1. How to structure a guideline

In this chapter, the main elements constituting a guideline (structure of the content, texts, examples, images) are analysed in relation to the methodological content provided, the addressed problem, the context of application and the user.

Structure of the content

Among the several possibilities for organising the content of a guideline (e.g., Jonassen, 2000 [11] and Anderson, 2009 [45]), the approach proposed by Russo and Duci (2014)[46] has been taken as a reference for its simplicity and concision in describing the main parts in relation to the main aspects of problem solving activities. According to the authors, (well-written) guidelines are constituted by the following 5 parts:

- **Description of problem type (Main goal):** The first part of the guidelines suggests the problem to be faced by providing the information about the initial state of the problem (e.g., “Presence of a harmful action”), or the description of the present situation that the guideline wants to change, and the goal of the guideline (e.g., “Reduce the harmful action”), or in what manner the guideline can change the initial situation.
- **Description of the sub-goal:** This description clarifies the declared main goal, by explaining, the conceptual solutions that the guideline can lead to. If the guidelines are a lot, the selection of the proper one can be based on the information provided by the declared goal and sub-goal.
- **Generic suggestion:** This is the part of the guideline that explains how to manipulate the current state for achieving the declared goal and sub-goal. Differently to the sub-goal, the suggestion works with a more practical and operative point of view and they provide strategies and suggestions for achieving the considered goal and sub-goal.
- **Specific suggestion:** provide more detailed information about the modalities to exploit the generic suggestions, by suggesting a list of materials, the physical effects or the operative zone. For instance, if the generic suggestion is “Modify a substance”, the specific suggestions can be “Make the substance flexible” or “Change the shape of the substance”. Russo and Duci (2015)[47] proposes a set of guidelines were generic and specific suggestions are clearly defined and for each generic suggestion, more specific suggestions can be considered. Often, some guidelines merge the two, without providing a clear distinction: e.g., see the guidelines proposed by Russo et al., 2011 [48].

- **Examples:** present the possible solution for the considered guideline, derived from its application in other problems.

Text

Several authors analysed the textual information provided by the guidelines by focusing attention on some features such as the used lexicon, the length of the text, the choice of the functional verbs. On the basis of them, two opposites kinds of guidelines have been identified:

- ***Textual stimuli and triggers****:* are characterized by a synthetic textual form, often limited to one word, and they consist in random associations of suggestions, generally weakly related or not related to the context of application of the problem and they aim to be used as source of inspiration. Some authors (e.g., Goldschmidt and Sever, 2011 [49]) highlighted their positive effects in supporting idea generation, especially in design problems, others (e.g., Chiu and Shu (2012)[50]) explained the influence of suitable verbs to increment the user's creativity.
- ***Structured textual guidelines:*** are instead characterized by a wider descriptive content and they are more precise in explaining the strategies, the involved elements, the examples and their role during problem solving activity.

Graphical representation

In addition or in substitution to the text, some guidelines also provide graphical representations, such as images, photos, icons, which can be, as the text, dependent or independent from the domain of application of the problem. In the following the main advantages of the most diffused representations are presented.

- ***Random images:*** are generally used as stimuli to enhance idea generation, with good results in some cases from literature. Goldschmidt and Sever (2011)[49] empirically demonstrated their positive effects on problem solves' creativity during design problems. Van der Lugt (2005)[51] experimented instead positive influences during brainstorming. Sarkar and Chakrabarti (2008)[52] tested instead the goodness of images for common problem solving activities, especially during the first stages of conceptual design and in well-defined problems.
- ***Methodological schemes:*** improve the comprehension of the guidelines, by adding methodological knowledge through graphical specific notations (abstract symbols) without providing specific domain knowledge to the guidelines. The guidelines supported by them are used for problem identification (e.g., TRIZ MTS model), for problem description (e.g., TRIZ Su-Field analysis and TRIZ functional analysis) and for idea generation (e.g., Russo and Duci, 2014 [46]).

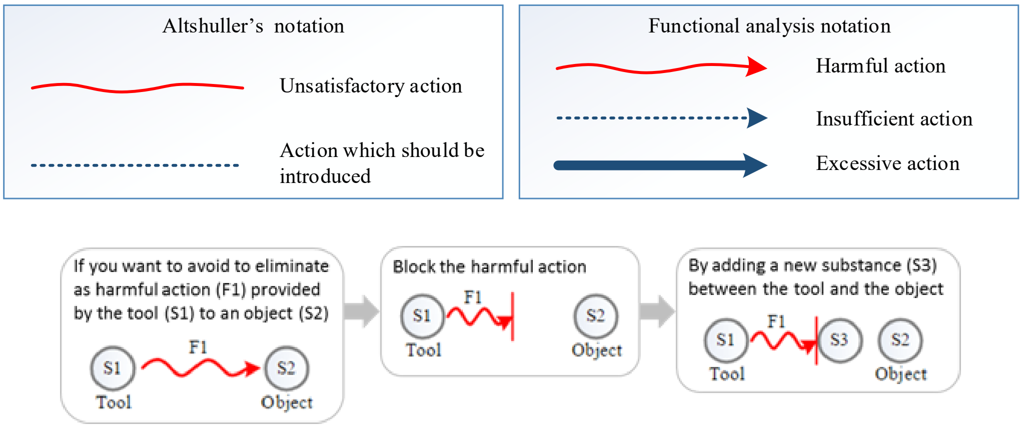


FIGURE 6: GRAPHICAL REPRESENTATIONS TO SUPPORT (A) GUIDELINES FOR PROBLEM DESCRIPTION (SU-FIELD MODEL) AND (B) GUIDELINES FOR PROBLEM SOLVING (TRIZ STANDARD SOLUTIONS: RUSSO AND DUCI, 2014 [46])

- ***Specific images related to the domain of application:*** are used to better contextualize the guidelines to the problem, by providing domain knowledge in addition or in substitution to the text. This approach is particularly useful especially when the addressed problem is too specific and well-defined, and if the space of the solutions is reduced.

Provided examples

On the basis of what found in literature, two kinds of examples have been identified, which aim to achieve two specific objectives:

- ***Improving the comprehension of the guidelines:*** and in particular of their methodological content, also for novice users, by showing how the guidelines have been previously applied in different domains of application.
- ***Improving the application of the guidelines to solve specific domain problems:*** the examples provided in these cases are generally more specific and they come from the same domain of application of the faced problem. The numerous examples provided to TRIZ 40 inventive principles (available on TRIZ journal, www.triz-journal.com) help the problem solver in apply them in specific cases such as architecture, economics, chemistry, etc. In table 2 some examples are summarized.

TABLE 2: EXAMPLES FOR TRIZ INVENTIVE PRINCIPLES.

Application fields	Principle	Provided examples
Architecture (Mann, 2001 [53])	Principle #1 Segmentation, Part A: Divide an object into independent parts (unchanged)	- Multi-room/multi-storey housing - Dual circuit wiring to provide back-up when failure occurs in one circuit - Provide separate receptacles for recycling materials (glass, paper, cans, etc.) in office buildings - In factory design separate the office accommodation and manufacturing facility - In hotel design separate the bedroom block from public areas - Design against progressive structural collapse.
Quality management (Retseptor, 2003 [54])	Principle #3 Local quality, Part C: Make each part of an object or system function in conditions most suitable for its operation.	- Locate distribution near to customers. - Match personality types to the task to be performed. - Educational modules - different in content and duration for different organizational levels.

4.2. How to organize multiple guidelines

A set of guidelines can be arranged in different ways depending on their content and the problem that aim to support. Four main kinds of organisation of the guidelines have been identified:

- ***Random lists of guidelines:*** provide a series of alternative suggestions to identify, describe and solve a problem, without prescribing a preferential order of their application. For this reason, this approach is generally recommended when the guidelines are few, in order to facilitate their comprehension. SCAMPER (Eberle, 1996 [29]), random stimuli and some TRIZ such as MATCEMIB and MATCEMIB+ (Belski, 2007 [55]) work in this way to support idea generation.

- ***Ordered list of guidelines*** is instead generally used to present a strict procedure sequentially applied, where each guideline can be applied after the previous ones, on the basis of their suggestions. The guidelines contained in ARIZ methodology (Altshuller, 1985 [34]) are organized in this way.
- ***Hierarchical maps of guidelines*** are schematic representations where the relations between the guidelines are constituted by one father with two or more sons. This organisation can be considered as the combination of random list and ordered list of guidelines. In this case a guideline can suggest other sub-guideline, typically more specific, and so on. The guidelines for eco-design (e.g., ECODESIGN online PILOT (www.ecodesign.at), Life-Cycle Design Strategy Wheel (LiDS) (Brezet and Van Hemel, 1997 [56]), Eco-map (Russo et al, 2011 [48]) are generally organised in this way, by providing various alternative suggestions (e.g., Reducing the raw material, reducing the packaging) to refine more abstract guidelines (e.g., Reducing the product impact during manufacturing). In order to be organized in this way, the guidelines have to be ascribable to precise categories.
- ***Matrices*** are generally used to organize the guidelines that depend on a combination of two or more categories. TRIZ matrix (Altshuller, 1985 [34]) is an example of this kind of organization: in this case, the problem solver selects two parameters in contradictions to improve among a list of 39 and the matrix provides one or more guidelines (among the set of TRIZ 40 Inventive principles) for solving the contradiction.

No one of the 4 organisational models of the guidelines is better than others, their choice depends by multiple factors such as the kinds of problem, the context of application, the phase in problem solving activity, etc. In the following chapter, different organisational models have been compared in relation to the suggested strategies and tools by the guidelines and the faced problems.

4.3. Strategies and tools suggested by the guidelines

With the aim to investigate the most suitable strategies and tools suggested by the guidelines according to the addressed problem, the context of application and the phase in problem solving activity, a literature survey based on industrial case studies about inventive problem solving has been carried out as first screening.

During the analysis, for each case study, the used approaches have been compared to the problem addressed by the case study and to the phase during the problem solving activity. E.g., a certain author used brainstorming (approach) to identify the limits (phase) of an already existing product that has to be improved (problem). The considered problems are those selected in chapter 2, while the considered phases are "Problem investigation" (i.e. Problem definition and formulation) and "Idea generation" (i.e., Generation of alternative solutions) according to Chang et al. (2004)[19], which explain that the first one is responsible of the identification of the problem and its reformulation in a more suitable way to be solved, while the second one regards the research of the possible solutions to the problem.

In the following, the poll of paper is firstly introduced and then the identified approaches are presented in relation to the considered phases. The most popular ones, based on the frequency of use, have then been further investigated through dedicated surveys in order to highlight their main advantages and limitations.

<u>Selected documents</u>

During the analysis, 218 papers from TRIZ journal, ETRIA TRIZ Future Conference and other journals of engineering design (Research in Engineering Design, International Journal of Product Design) have been analysed. The criteria of selection have been: (1) The relevance of the considered journal and conference, based on the impact factor and the number of published proceedings according to Scopus clustering functions. (2) The presence of well explained case studies about inventive problem solving, which declare the considered requirements and constraints, the used approaches, methods and tools and the achieved outputs. The considered keywords were: innovative problem solving, innovations, technical problem solving, etc.

Figure 7 shows the time distribution of the considered documents during the years and the industrial fields of application.

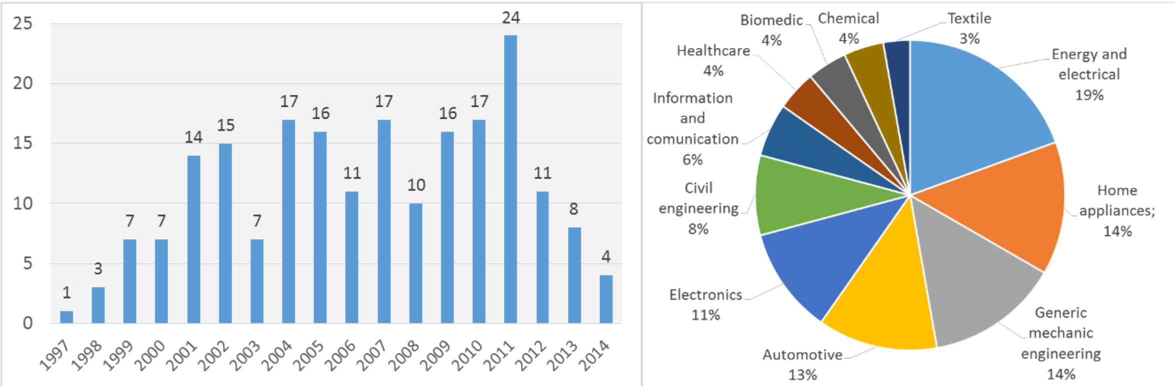


FIGURE 7: (A) TIME DISTRIBUTION AND (B) INDUSTRIAL SECTORS DISTRIBUTION OF THE CONSIDERED PAPERS.

4.3.1. Approaches to support problem investigation

The most common methods and approaches used in the case studies to support problem investigation have been classified according to the following two categories:

- ***Models:*** they support the description of the initial situation of the problem in a qualitative way by summarizing only the main elements involved (the object, the user, the environment, and other main elements) and their relations. The most popular identified models are: Substance-Field (Su-Field) model, MTS model, Function Behaviour Structure (FBS) model of design, Energy Material Signal (EMS) model.
- ***Analytical methods:*** they describe the problem in a more structured way through quantitative parameters and they support the analysis of the problem through strict procedure. The most common identified analytical methods are: Qualitative Function Deployment (QFD), Fault Tree Analysis (FTA), Failure Modes and Effects Analysis (FMEA).

In some case studies, the models and the analytical methods are used both during problem investigation: the first ones are used to identify the key factors and the second ones to analyse them.

Table 3 summarizes the frequencies of use of models and analytical methods to support problem investigation in the considered documents.

TABLE 3: MODELS AND ANALYTICAL METHODS USED TO SUPPORT THE CONSIDERED INVENTIVE PROBLEMS.

Kinds of problems	Only models		Only analytical methods		Models and analytical methods	
Product improvement	51	59%	32	37%	4	5%
New product design	30	75%	6	15%	4	10%
Eliminate undesired effect	15	79%	2	11%	2	11%
Anticipatory failure analysis	0	0%	16	76%	5	24%
Total	**96**		**40**		**15**	

Figure 8 summarizes the distribution of the approaches.

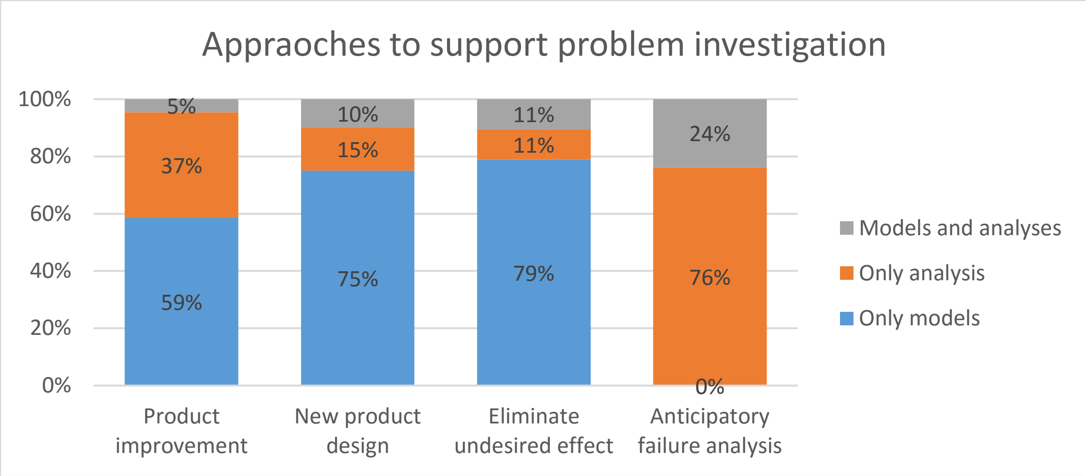


FIGURE 8: DISTRIBUTION OF THE MOST POPULAR APPROACHES TO SUPPORT PROBLEM INVESTIGATION PHASE IN THE CONSIDERED INVENTIVE PROBLEMS (PRODUCT IMPROVEMENT, NEW PRODUCT DESIGN, ELIMINATE UNDESIRED EFFECT, ANTICIPATORY FAILURE INVESTIGATION).

On the basis of the achieved results emerged that models are generally used in New Product Design and in the Elimination of undesired effects, while Anticipatory failure analysis is supported by analytical methods. In product improvement, models and analytical methods are instead more uniformly distributed.

For this reason, product improvement has been divided into two more specific categories:

- Re-design: in case product improvement involved to reconsideration about product functionalities and the physical effects.
- Quality improvement: in case product improvement involved minimal modifications related to technological aspects (i.e. the structure).

In this way, as we can see by the graphic below, a clearer stratification of the results has been highlighted: models seem more popular to support re-design, while analytical methods are used for quality improvement.

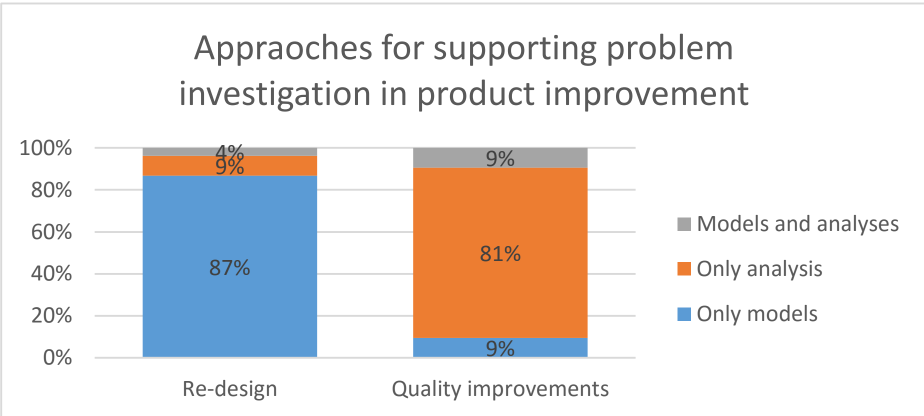


FIGURE 9: DETAIL OF THE DISTRIBUTION OF THE APPROACHES TO SUPPORT PROBLEM INVESTIGATION PHASE IN PRODUCT IMPROVEMENT (DIVIDED INTO PRODUCT RE-DESIGN AND QUALITY IMPROVEMENT).

More in detail, for the inventive problems supported by models during problem investigation (re-design, new concept design and eliminate undesired effects), the distributions of the kinds of models has been analysed. The results are shown in the following graphs (Figure 10):

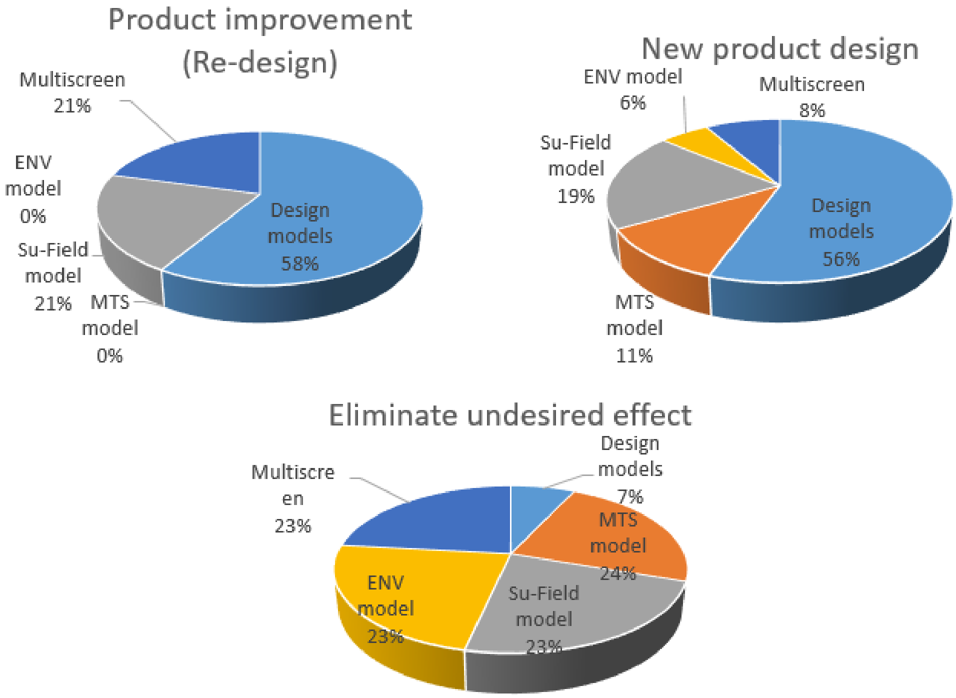


FIGURE 10: MAIN UTILIZED MODELS IN PRODUCT IMPROVEMENT (RE-DESIGN), NEW PRODUCT DESIGN AND ELIMINATION OF UNDESIRED EFFECTS.

Re-design and new product design result supported by design models (Function-Behaviour-Structure models), while the problems of the elimination of the undesired effects are supported by various TRIZ models: MTS, Su-Field, ENV and Multiscreen. These facts can be due to the different nature of the considered problems: re-design and new product design are generally more related to conceptual design activities and consequently are better supported by models able to identify and describe the different key features of design, such as product's function, behaviour, physical effects and user's interactions. The elimination of undesired effects seems instead to require more immediate and focused modelling of the problem provided by the TRIZ tools.

The most common analytical methods to support quality improvement and anticipatory failure investigation are reported in the following graphs (Figure 11):

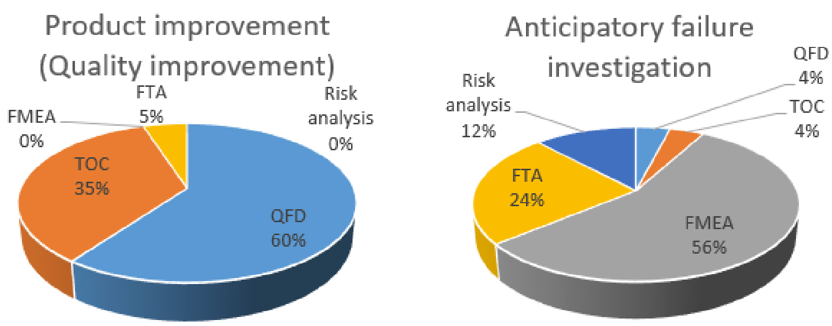


FIGURE 11: MAIN COMMON ANALYTICAL METHODS FOR PRODUCT IMPROVEMENT (QUALITY IMPROVEMENT) AND ANTICIPATORY FAILURE ANALYSIS.

On the basis of the achieved results, quality improvement has been mainly supported by Quality Function Deployment (QFD) and Theory of Constraints (TOC) while anticipatory failure investigation has been supported by Failure Modes and Effect Analysis (FMEA) and Fault Tree Analysis (FTA).

The achieved results provided an indicative framework about them methods and the approaches for problem investigation. From it, specific analyses, presented in the following, have been carried out with the aim to better investigate their specific use, their limitations and the integrations.

Design models to support re-design and new product design

Among the reasoning schema that support new concept design and product re-design, Function-Behaviour-Structure (FBS) model, proposed by Gero (1990)[57], and its numerous evolutions, is one of the most popular.

In synthesis, the following table (Table 4) summarizes the design entities and relations used by the original Gero's approach to schematize the design process.

TABLE 4: DESIGN ENTITIES AND RELATIONS IN GERO'S SCHEME (1990)[57].

Design entities	Design relations
- Function (F): The design intentions or purposes. - Behaviour (B): How the structure of an artefact achieves its functions. Divided into Expected behaviour (Be) and Actual behaviour (Bs). - Structure (S): The components which make up an artefact and their relationships. - Design description (D): is graphically, numerically, and/or textually representation to transfer sufficient information about the designed artefact so that it can be manufactured, fabricated or constructed.	- Formulation: is the process of transformation of the function into expected behaviour. (STEP 1) - Synthesis: transformation of the expected behaviour into a structure that is intended to exhibit this behaviour. (STEP 2) - Analysis: derivation of the actual behaviour of the structure. (STEP 3) - Evaluation: comparison of the actual and expected behaviour (STEP 4). If positive, the design process is ended, if negative - Documentation: production of the design description (STEP 5) - Reformulation of the structure: choice of new structure. (STEP 6) - Reformulation of the behaviour: choice of new expected behaviour. (STEP 7) - Reformulation of the structure: choice of new functions. (STEP 8)

The following scheme (Figure 12), proposed by Gero's (1990)[57] ressumes the entities and the relations through a unique graphical representation.

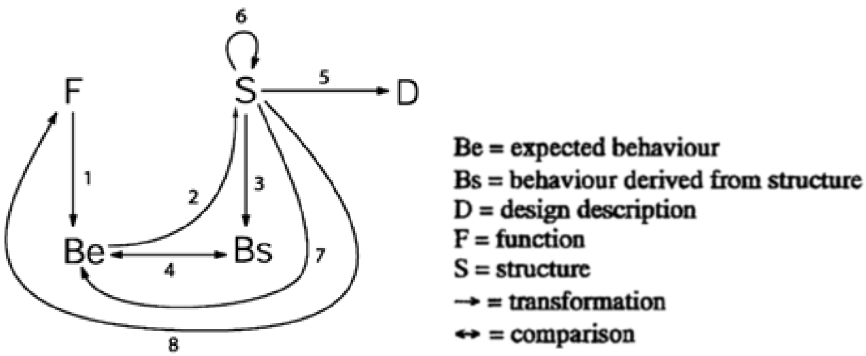


FIGURE 12: GERO'S SCHEME (1990)[57].

During the years, several modifications have been proposed to the methodology in order to improve its application through the introduction and the reformulation of the involved entities and the relations. These improvements can be summarized by the following trends:

- Redefinition of the FBS ontology: (Rosenmann and Gero 1998 [58], Vermaas and Doorst 2007 [59], Galle 2009 [60]).
- Redefinition and integrations of the behaviour of the device: Cao and Tan (2007)[61] explicitly dealt with Physical effects, and Del Frate et al. (2010)[62] that introduced the possible faults of the device.
- Investigating about the relation with user and device: Brown and Blessing (2005)[63] discusses the affordances, focused on the possible user's actions on the device, Cascini et al. (2010)[64] reformulated the interactions between the user and the FBS model.
- Investigating about the role of the requirements: Cascini et al. (2013)[65] reconciled the FBS introducing needs and better describing their links with product requirements.
- Reformulation of the entities of the design process as functions and flows: Hirtz et al. (2002)[5], Ahmed et al. (2003)[66], Bonaccorsi et al. (2007)[67], Borgo et al. (2009)[68] described them with hierarchical taxonomies. Pailhès et al. (2011)[69] approached the problem by using a minimalistic taxonomy to describe both functions and flows in terms of material, signal and energy. The flows of the design process have also been formalized in mathematical terms by Komoto (2011)[70], while Sasajima (1995)[71] modelled Functions and flows by using models belonging to Artificial Intelligence, like Sapphire (Chakrabarti et al., 2009)[72] that proposed structured methodology to better decompose abstract functions in more detailed sub-functions.

All the proposed models, tools, methods, theories and new ontologies are very interesting because they introduce new concepts and clarifications of the original Gero's model and the design process. However, each of them focuses only on certain aspects of the methodology and no one proposes a unique and practical comprehensive framework to support conceptual design.

In the following, the main features and the improvements for each element of the design process are presented in detail.

- ***Designer's actions.*** Gero (1990)[73] describe the phases of a conceptual design project that followed by the designer without specifying his intentions regarding the features that she/he implements on the product. In fact, the designer is not always able to put on the product all she/he wants: sometimes forgets something, sometimes makes mistakes, other times introduces on the product what should not. Gabelloni and Fantoni (2013)[74] identified three results of the designer activity regard the implementation of a feature on the product:
  - o Designed (d): when the feature is if the designer deliberately implemented on the product by the designer.
  - o Designed not to be ($\bar{d}$): if the designer deliberately avoids to implement a certain feature on the device. For instance, a designer chooses to not design features "safety for children" in an industrial power outlet: the children can insert objects into the holes because the cover is not present;
  - o Not designed ($\not{d}$): when the designer not deliberately implemented a feature on the product but the features will also be present. For instance, when a designer insert an airtight cover on an outlet, she/he does not want to implement the features "safety for children" but the features "impermeability", however, also the first feature is present on the device.

- ***Goals and functions.*** During the years, several authors have providing definitions about the concept of goal and function in design theory. According to Umeda et al. (1990)[25], and referring to Sasajima's formulation, the function is the objective that a user sees in a behaviour (B) while the goal derives from the final state of a structure that evolves through a finite number of states $S(t_1)$, …, $S(t_f)$.

$$F = F(B, G)$$

$$G = S(t_f)$$

Gero and Kannengiesser (2004)[75] describe instead the goal as the simulation (Sim) of the product expected behaviour made by a user (U) by observing the structure of product (and in particular its affordances) and the environment around the product in certain instance of time (t_1).

$$G = Sim(U, S(t_1), E(t_1), t_1)$$

- ***Affordances.*** Brown and Blessing (2005)[63] define the affordances of a product as the set of all potential operations that the product communicate the user that is be able to make. For instance, a car with a spoiler suggest to the user a better road grip. Mayer and Fadel (2009)[76] and Gaver (1991)[77] address the problem with other definitions. Cascini et al. (2010)[78] divide the affordances into designer's affordances (A_d), user's affordances (A_u), true intended affordances and false intended affordances. In this way the authors explain how the user can misunderstand certain affordances or do not consider them.

- ***Expected behaviour.*** Gero (1990)[73] introduces the concepts of the expected behaviour as the theoretical behaviour of the product postulated by the designer to accomplish the function, before to design and realize the structure of the product, without specifying the different perspectives of user and designer. As done by Cascini et al. (2010)[78] for the decomposition of the actual behaviour (Bs) into user actual behaviour (Bs_u) and designer actual behaviour (Bs_d), in the proposed scheme also the expected behaviour (Be) has been divided into user expected behaviour (Be_u) and designer expected behaviour (Be_d). The difference between the two kinds of expected behaviour depends by the different point of view about the product of the user and the designer, in turn caused by different level of knowledge of the product and by different background and level of experience and by the different capability of the user in understanding the affordances putted on the product by the designer. In fact, the user imagines the expected behaviour of the product on the basis of the comprehension of the affordances. The designer knows also better the product and in particular the internal components.

- ***Manipulation.*** Differently to the expected behaviour, that is strictly related to the functioning of the product, the manipulation involves directly the user by summarizing his sequence of interactions with the product. According to Cascini (2010)[79] the term manipulation includes both direct physical manipulation and indirect actions of the user.

  For the proposed scheme, the manipulation has been divided into user manipulation (M_u) and designer manipulation (M_d), in order to describe the two possible ways of interaction of the user and the designer with the product that depend of the user and designer's ideas about the structure and its behaviour. In particular, the user manipulation can be seen as a process of simulation provided on the user on the basis of its idea of the goal of the structure, the user affordances derived by the structure and the user expected behaviour in turn derived by the user affordance).

$$Sim(G, S \rightarrow A \rightarrow Be_u) \rightarrow M_u$$

  For instance, if a user wants to sit (G) and do not has a chair, she/he can search an alternative structure to sit (e.g., a bin paint (S)). By observing the geometry of the bin paint the user sees the superior flat cover (A_u) and interpret as a possible seat. Then, the user thinks how to sit on the bin and if the bin can withstand her/his weight (Be_u) and she/he sits on the bin (M_u).

  Despite the simplicity of the problem we can see that the user's affordances are different compared to the designer's affordances (the designer does not the designed the cover as seat), the user expected behaviour is different respect the designer expected behaviour and the user manipulation is different respect the designer manipulation.

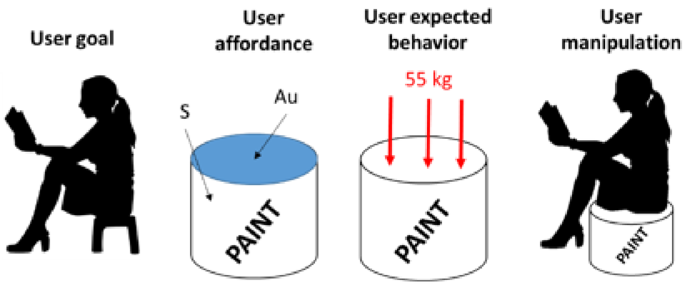


FIGURE 13: REPRESENTATIONS OF USER'S GOAL, AFFORDANCES, EXPECTED BEHAVIOUR AND MANIPULATION.

- ***Structure and Actual behaviour.*** In order to consider the user and the designer's perspective about, the structure of the product has been divided into tree subsets:
    - the designed interface (Sint): the part of the structure with which the user has to interact according to the designer's intentions.
    - the user's interface (Sui): the part of the structure with which the user really interacts.
    - the inner interface (Sinner): the part of the structure with which the user has not to interact according to the designer's intentions.

  The three sets are not completely divided, because the user cannot interact with all the available Sint if she/he does not exploit all the available interface, or she/he can also interact whit the inner interface if she/he does not use the product in the proper way.

  Since the user and the designer can interact in different ways with the structure, they can also experiment different actual behaviours from the structure, respectively called User's Actual Behaviour (Bs_u) and Designer's Actual Behaviour (Bs_d).

- ***Perceived behaviour.*** According to Gero (1990)[73], once the user and the designer experiments the actual behaviour of the product, they compare the perceived it with the expected behaviour in order to evaluate if the product exploit the functions. However, the theory does not consider in what way the user and the designer perceive the actual behaviour. In order to provide clear definitions about perception the concept of the signal has been introduced. According to Hirtz et al. (2002)[5], signals represent the perceptible evidences of behaviours. According to Gero and Fujii (2000)[80] and Shea (2010)[81], the user and the designer perceive an external signal ($Sign_e$) through perception (P) by generating a perceived signal ($Sign_p$). Perception is correct if the perceived signal coincides with the external signal.

$$Sign_p = P(Sign_e) = \begin{cases} = Sign_e \rightarrow \; Correct\ perception \\ \neq Sign_e \rightarrow Wrong\ perception \end{cases}$$

  The perception depends by the observer and its subjectivity and experience. For this reason, user and designer may perceive the same external signal in different manners. For this reason, in the proposed scheme, the perceived behaviour has been divided into user perceived behaviour and designer perceived behaviour.

- ***Comparison and interpretation.*** Once the user and the designer have perceived the behaviour, they compare the perceived behaviour with the expected behaviour (Gero, 1990 [73]). However, this approach is limitative because the comparison can also be made in other way, for instance by comparing the perceived behaviour to behaviour of another similar product.

  In the proposed scheme, in order to extend the concept of comparison, the concept of the interpretation has been introduced. The user and the designer have in fact to interpret the perceived before to comparing it with the expected behaviour and in particular they have to interpret the perceived signals ($Sign_p$) by obtaining the interpreted signals ($Sign_i$).

In the proposed scheme, the comparison is seen as the interpretation of the perceived signal in relation to a comparison signal ($\overline{Sign}$). The interpretation produces the interpreted signal.

$$Sign_i = I\left(Sign_p - \overline{Sign}\right)$$

- The comparison signal can be found in different ways:
  - The comparison signal may represent an ideal signal that the device should produce: if we consider the example of a lawn mower, the external signal may be the length of the grass obtained while the comparison signal is the desired length. This case represent the comparison according to Gero (1990)[73].
  - The comparison signal can be a previous external signal that has been recorded before the action of the device. In this case, the comparison signal is the length of the uncut grass.
  - The comparison signal may represent the signal obtained from an alternative device that carry out the same function. For instance, we compare the length of the grass obtained with a lawn mower, with the length of the grass obtained with a brush cutter.
  - The comparison signal may also be obtained from another device and it can also interest another feature. In fact, if we experiment an innovative product that realizes a new function, we do not have a comparison, so our external signal external derives from another product. For instance, if an innovative product for the gardening bends the grass instead of cutting it, we could compare it with the performances of a traditional lawnmower that cut the grass.

The outcome of the interpretation can be described by a positive signal (logic state = 1) if the evaluator judges it favourably, on the basis of a comparison signal $\overline{Sign}$, or a negative signal (logic state = 0).

$$Sign_i = I\left(Sign_p - \overline{Sign}\right) = \begin{cases} 1 \rightarrow Positive\ interpretation \\ 0 \rightarrow Negative\ interpretation \end{cases}$$

If the designer provides a positive interpretation means that in its opinion, the device carries out the functions, if the interpretation is negative means that the device does not carry out the function or it carries out partially. Anyway, the interpretation is a subjective task, since it depends on the evaluator and his yardstick and for this reason can be affected by some error. Moreover, the yardstick can change during time and by different evaluators (two users or the user and the designer). In the following, the relation among interpretation, perception and goals are explained in detail.

- ***Interpretation and perception.*** Depending on the interpretation is positive or negative, the perception is positive or negative and the comparison signal is correct, some combinations should be considered. Referring to previous work of Gabelloni and Fantoni (2013)[82], the following table (Table 5) describes the possible combinations. At the moment, Interpretation is evaluated only by two logical level (0 and 1), the model can be complicated by including the range of the intermediate levels. In the cells, the repercussion on design evaluation are reported.

TABLE 5: COMBINATIONS BETWEEN PERCEPTIONS AND INTERPRETATIONS.

	Negative external signal ($Sign_e \neq \overline{Sign}$)		**Positive external signal ($Sign_e = \overline{Sign}$)**	
	Negative interpretation ($Sign_i = 0$)	**Positive interpretation ($Sign_i = 1$)**	**Negative interpretation ($Sign_i = 0$)**	**Positive interpretation ($Sign_i = 1$)**
Wrong perception ($Sign_p \neq Sign_e$)	No	Ok	Ok	Ok
Correct perception	Ok	No	No	Ok

(Sign$_p$ = Sign$_e$)

- ***Interpretation and goals.*** The user's evaluation of the product can be investigated by crossing the interpretation of the signals and the expected goals. Some simple remarks can be made. if the user interprets positively a signal and his goals coincide with those of the designer, the user is satisfied with the device, while if user's goal and the designer's goal do not coincide, the user is unsatisfied. On the other side, if the user perceives a negative signal and his goal coincides with the designer's goal, the user is dissatisfied with the device. Finally, if the user interprets negatively a signal but his goals do not coincide designer's goal, the situation is uncertain. Table 6 summarizes these combinations.

TABLE 6: USER SATISFACTION BASED ON GOAL AND INTERPRETATION.

	Coincidence of the goals ($G_u = G_d$)	**Non-coincidence of the goals ($G_u \neq G_d$)**
Positive interpretation (Sign$_i$ = 1)	Satisfaction	Dissatisfaction
Negative interpretation (Sign$_i$ = 0)	Dissatisfaction	Uncertainty

Models to support problem identification for the reduction of harmful effects

The guidelines to support the problem investigation phase in problems requiring the reduction of harmful effects should suggest how to identify and describe the harmful effect to eliminate/reduce. To do this, the guidelines can suggest the most popular specific schemas and models (e.g., the TRIZ tools of MTS model, Su-field model (Altshuller 1986 [83]) and ENV model (proposed by Khomenko in OTSM-TRIZ in 1997) as shown by literature analysis.

To better comprehend the role of the knowledge contained in these guidelines, a test has been proposed by to R&D technicians, during a collaboration between the University of Bergamo and a medium Italian company. The collaboration concerned the improvement of an industrial dishwasher by drastically reducing its consumption. The entity of the goal required prevents the use of the current plant optimization techniques, by requiring a radical innovation of the same. In particular, 4 R&D specialists had to find the specific problem to be solved by using two TRIZ tools dedicated to problem identification: the object-product transformation (MTS model) and the ENV model. These tools, better describe in the following, support the problem solver in identify the main useful function of the technical system and in specifying what parameters of the product, of the environment and of the affected objects change and in what way during the product functioning.

Two set of guidelines have been proposed to the R&D specialists, to support the use of the tools.

- ***Generic guidelines (Session 1 8h):*** have been proposed after a general introduction (4h) on TRIZ theory and on the tools, with no specific examples. These guidelines explain the generic goal of the tools and how to use them in a proper way.
- ***Specific guidelines (Session 2 8h):*** have been proposed after an advanced training about the tools (4h), during which specific examples have been provided. The specific guidelines explain how to use the tools in a smarter way, by explaining in detail as not to make typical methodological errors. The

application of these guidelines requires a greater knowledge about the method, especially cause of the more researched terminology used by the guidelines.

During the two sessions, no specific domain knowledge about the field of application has been added in the guidelines.

The results, obtained by using the proposed tools whit the help of the guidelines in the two phases, have been evaluated by providing a ranking from 0 to 2 points for each of the 9 identified key features, divided as follow:

- object-product transformation (4 features): identification of Object, Product, and the two main operative functions of the system (Function 1 and Function 2);
- ENV model: identification and description of 5 strategic features regarding the process, regarding safety, reliability and other industrial parameters.

Table 7 summarizes the obtained results:

TABLE 7: RESULTS OF THE TEST.

		Generic guidelines (+ basic training) *Average results*	**Specific guidelines (+ advanced training)** *Average results*
Object|product transformation	**Object**	1	2
	Product	1	2
	Function 1	0	1
	Function 2	1	2
	Total (max 8 points)	***3***	***7***
ENV model	**Feature 1**	1	2
	Feature 2	2	2
	Feature 3	0	1
	Feature 4	0	2
	Feature 5	1	2
	Total (max 10 points)	***4***	***9***

As we can see by the proposed table, the proposed results significantly improve after the introduction of the specific guidelines, both for the object-product transformation and for the ENV model. On the basis of what emerged from phase 1, the professionals have described the assigned problem in an insufficient manner by using the object-product transformation tool (3/8 points) and the ENV model (4/9).

This test seems to confirm the necessity of proposing guidelines with high methodological content to specialists in the domain of the problem. This fact can be due to the major attention of the specialists on the product structure and components rather than on the on the research of unexploited resources, physical effects and the functionalities. The features identified by the professionals, by using the generic guidelines are in fact the most known by the such as the heat exchange towards the environment and they are described in detail, while the crucial aspects such as the evaporation mechanism of the water drop on the dishes, are just mentioned or not even identified.

For these reasons, the use of guidelines with more structured un-domain methodology, achieved for instance by improving their terminology or by adding more detailed explanations about the followed methodology seems to ameliorate the achieved results and to provide more exhaustive descriptions of the problem.

Anticipatory failure analysis techniques

Among the approaches to support anticipatory failure investigation, FMEA seems the most used. However, FMEA has not a shared and accepted framework and several modifications have been proposed during the years. Through a detailed literature analysis has been performed, the main problems and limitations and the improvements have been studied.

Research methodology

First, the similar surveys of other authors have been considered. Sutrisno and Lee (2011)[84] studied service reliability assessment using FMEA, analysing papers from 1994 to 2010 from literature databases. Liu et al. (2013)[85] concentrated their attention on risk evaluation approaches in FMEA, reviewing 75 FMEA papers published, evaluating the research trends and the popularity of the proposed approaches in term of citations. Tixier et al. (2002)[86] reviewed 62 Risk Analysis techniques, classifying methodologies through input and output data and providing the mechanism for risk evaluation.

Despite FMEA has been accepted successfully in a lot of different fields, nowadays there are again many doubts about the methodology. Kmenta et al. (1998)[87] highlighted the subjectivity of FMEA that it is linked to experience of those who use it. Moreover, the application of the method is too boring and not creative. The software that have automatized FMEA may help, but not when the user is called to contribute with an active role. Moreover, traditional FMEA does not support the conceptual design phase since it is used to improve an existing product and not a prototype, where the problem solving phase can be surely more helpful and effectiveness, having at this time major margins of modification.

Previous surveys considered only scientific bibliography, leaving out the most part of contributions provided by industries. In this analysis both scientific contributions and published applications (granted patents and utility models) from 1978 to 2016 have been considered.

FMEA literature is really huge. The fields of application are various (mechanical, electronic, medical, etc.) and the jargon changes according to the area of application (e.g., DFMEA, FMECA, AFMEA, etc.). Our analysis includes scientific publications, books, conference proceedings, normative and patents; the sources are many and sometimes not available, such as internal standards developed by companies.

To identify the set of scientific papers, Scopus database has been considered. A combination of terms like "FMEA, FMECA, DFMEA, AFMEA, RFMEA, Failure Modes and Effects Analysis, Risk Analysis, Failure Analysis" was used to set the search query. The final list of journals has been identified by applying Scopus clustering function and then manually selecting the most relevant journals according to their impact factor and the number of published proceedings and citation.

Table 8 summarises the most relevant selected international journals.

TABLE 8: SELECTED INTERNATIONAL JOURNALS, IN BRACKETS THE NUMBER OF PAPERS

- Expert Systems with Applications - International Journal of Quality and Reliability Management	- Journal of Loss Prevention in The Process Industries - International Journal of Production Research

- Quality and Reliability Engineering International - Engineering Failure Analysis - Expert Systems with Applications - Fusion Engineering and Design - International Journal of Advanced Manufacturing Technology	- Engineering Failure Analysis - International Journal of Advanced Manufacturing Technology - International Journal of Productivity and Quality Management - Reliability Engineering and System Safety

To collect the pool of papers, a further analysis was conducted by searching inside each journal using the same query. In addition, also the most important conference proceedings have been considered, with the same criteria of research of the journals.

For the patent pool, the most diffused international free patents databases (Espacenet (worldwide.espacenet.com) and Wipo (www.wipo.int)) have been used. The same query has been used to generate the patent collection.

The selected documents (both papers and patents) have been classified according to the authors (academia or industry), the number of citations, the productivity and scientific impact of the journal (only for scientific literature) and the applicant (only for patents). The following scheme (Figure 14) portrays the search strategy above described.

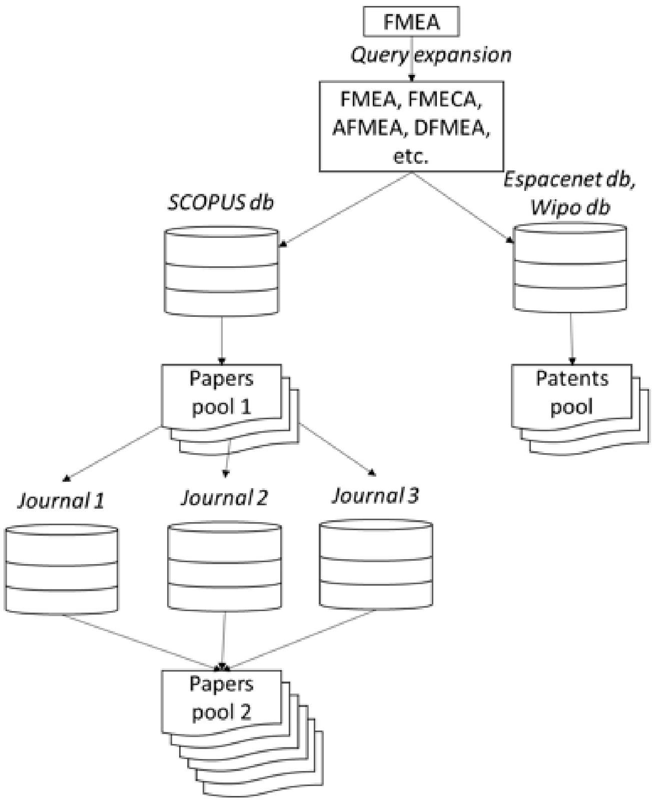


FIGURE 14: SEARCH STRATEGY TO IDENTIFY PAPERS AND PATENTS POOL

The final set counts 262 documents, 153 scientific papers (141 from academia and 12 from industry) and 109 patents (23 from academia and 86 from industry). Figure 15 shows the time distribution for both patents and scientific publications. The number of patents is increasing, except for 2014-2015 that does not include all potential patents since they are not disclosed for the first 18 months.

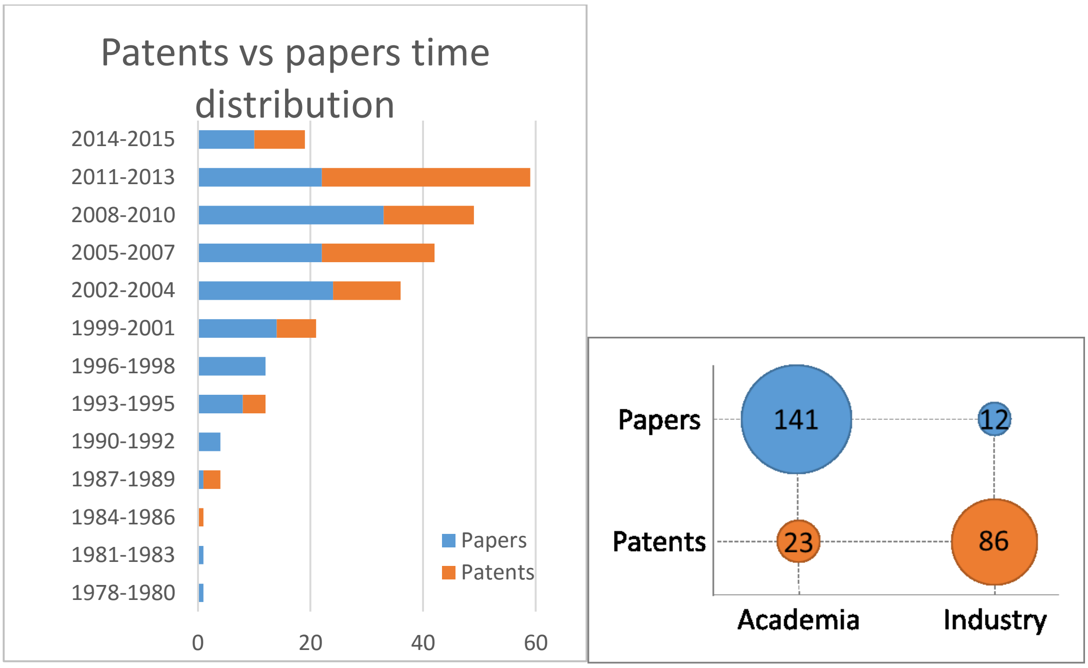


FIGURE 15: (A) TIME DISTRIBUTION (PRIORITY DATE) OF THE COLLECTED DOCUMENTS AND (B) COMPOSITION OF THE FINAL SET OF DOCUMENTS (PAPERS VS PATENTS AND ACADEMIA VS INDUSTRY).

<u>The structure of traditional FMEA</u>

Nowadays, even if there were the multiple efforts in standardization, a unique reference structure for FMEA does not exist, unlike other sectors such as Life Cycle Assessment and quality management. Some efforts of standardization come from Department of Defence (US) that developed and revised the MIL-STD-1629A guidelines during the 1970's and from Daimler Chrysler, Ford and General Motors that jointly developed an international standard named SAE J1739-2006 documentation for FMEA. Others guidelines are: AIAG FMEA -3 from automotive Industry action group, ARP5580 from the SAE for non-automotive applications, EIA JEP 131 from electronic industry, P-302-720 from NASA's GSFC spacecraft and Instruments and Semantec 92020963A-ENG for semiconductor equipment industry.

Briefly, "Traditional FMEA" method (see Table 9) consists in a decomposition of the product/process or system in elementary subsystems in order to identify failure modes, their causes and effects. For each component, the failure modes and their resulting effects on the rest of the system are recorded in a specific worksheet.

Most critical failures are identified by the priority risk number RPN, calculated estimating (P) failure Probability, (S) Severity and Detection. The following actions of improvement of the product, process or system will have to be principally oriented on Failure Modes with the highest values of RPN. The FMEA can be than repeated after the improvement to verify if the values of RPN are decreased.

TABLE 9: TRADITIONAL FMEA STRUCTURE.

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Design Controls		Detect	RPN	Recommended Actions	Response &Target Complete Date	Action Results				
							Prevent	Detect					Action Taken	SEV	OCC	DET	RPN

The method moves from left to right, firstly considering the list of the functions/items, depending on the standard, the potential failure modes, the linked potential failure effects and the potential failure causes until to the multiparametrical fault evaluation (RPN on the right in figure) in term of severity, occurrence and detection.

Problems and limits of traditional FMEA

The goal has been to identify the main problems and limits of the traditional FMEA as well the similarities and differences between academia and industry contributions. The problems have been classified into four categories: applicability, cause and effect chain determination and representation, risk analysis and problem solving. For each of them a further subdivision into sub-problems has been proposed.

- ***Applicability.*** Several authors have expressed their doubts and uncertainties about the application of the methodology, by comparing different fields of application and case studies and finding a series of problems in industrial practice of every day. Among them, Denson et al., (2014)[88] criticized the tediousness and the excessive time-consuming of the method, Kmenta and Ishii (2004)[89] highlighted the absence of stable definitions and Mader et al., (2013)[90] explained that FMEA is not useful when it is applied too late in the product development.

TABLE 10: PROBLEMS RELATED TO FMEA APPLICABILITY

Problems	**Sub-problems *(about FMEA applicability)***	**Number of citations in papers/patents**		
		Academia	**Industry**	**Total**
Applicability in different context	Excessive subjectivity of the method	18	3	21
	Wrong time of application of the methodology	3	3	6
	Complex systems analysis: difficulty to manage the several components that mutually interact	4	1	5
Management of the information	Missing information for BoM selection. For instance, how to choose assemblies and single components.	5	4	9
Integration with other methods	Lack of Integration with database of physical effects and PLM software	7	2	9
	Necessity of continuous improvement of the methodology for a better integration with other tools	5	1	6
Costs and time consuming	Time consumption	11	5	16
	The project can be too expensive in term of involved resources (humans and methods of management)	3	1	4
Difficult relation among team members	Low level of preparation of team members, lack of involvement of team members, lack of staff communication	3	4	7
Total		**59**	**24**	**83**

The most common critical issues are the subjectivity and the time consuming both for academia and for industry.

- ***Cause and Effect:*** Several authors criticize the cause and effect chain representation due to the lack of relations between the Failure Effects and the Failure Causes and the ambiguity of their definitions and the inefficiency of FMEA to represent the combinations among multiple simultaneously effects (e.g., Price and Taylor, 2002 [91]).

TABLE 11: PROBLEMS RELATED TO CAUSE AND EFFECT

Problems *(about cause and effect chain)*	Number of citations in papers/patents		
	Academia	Industry	Total
Lack of secondary effects in cause effect chains, especially for environment and health effects	10	2	12
Lack of guidelines to consider human interactions with the faults	2	2	4
Lack of Multi-physics modelling	8	2	10
Effects description at too high level	3	3	6
Lack of guidelines to distinguish between failure modes and effects	5	1	6
Total	**28**	**10**	**38**

The most common problems for cause and effect chain are the lack of secondary effects and Multi-physics modelling, especially for academia, and high-level description of effects for industry.

- ***Risk analysis:*** The most experienced limit of FMEA in risk analysis is the lack of an accepted definition of risk and the evaluation parameters. Liu et al., 2014 [85] criticized the inconsistencies of RPN to evaluate risks while Rhee and Ishii, 2002 [92] explained the incapacity of RPN to quantify risks in economic terms.

TABLE 12: PROBLEMS RELATED TO RISK ANALYSIS

Problems *(about risk analysis)*	Number of citations in papers/patents		
	Academia	Industry	Total
Subjectivity in risk evaluation	19	3	22
Results inconsistency for decision making and problem solving	8	0	8
Too limited risk evaluation measure	6	0	6
Ambiguous definitions	4	1	5
Lack of economic quantification	4	0	4
Total	**41**	**4**	**45**

In general, most of criticisms comes from academia and the most common issue is represented by the subjectivity of the risk evaluation.

- ***Problem solving:*** Some authors comment about the possibility to effectively use FMEA for decision making and problem solving activities. Xiao et al, (2011)[93] explained that FMEA produces results that do not facilitate decision-making.

TABLE 13: PROBLEMS RELATED TO PROBLEM SOLVING

Problems *(about problem solving)*	Number of citations in papers/patents		
	Academia	Industry	Total
Lack or weak representation of the results (quantitative parameters or tests)	7	3	10
Difficult decision making: poor influence and lack of evaluations about the implementation of the solutions	8	0	8
Final FMEA framework not suitable for problem solving	2	2	4
Total	**17**	**5**	**22**

The most common limits are the difficulty to support decision-making with traditional FMEA (only for academia) and the lack or weak representation of results (both for academia and for industry).

Summary of problem analysis

The following figure (Figure 16) shows the comparison of identified problems between academia and industry.

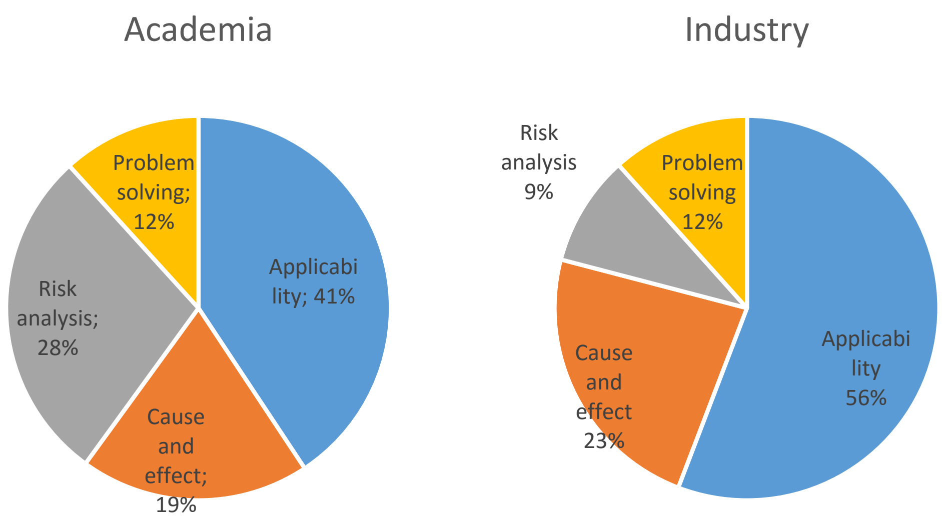


FIGURE 16: DISTRIBUTION OF THE PROBLEMS AND SHORTCOMINGS FOR ACADEMIA AND INDUSTRY.

Academia is more interested in risk analysis (28% of the cases) compared to industry, while there are many similarities for the other categories.

The following chart (Figure 17) shows the time distribution of FMEA problems (identified by papers and patents). The problems are classified according to the four mentioned categories (e.g., Applicability, Cause and Effect, Risk Analysis and Solving) and the authors (Academia or Industry).

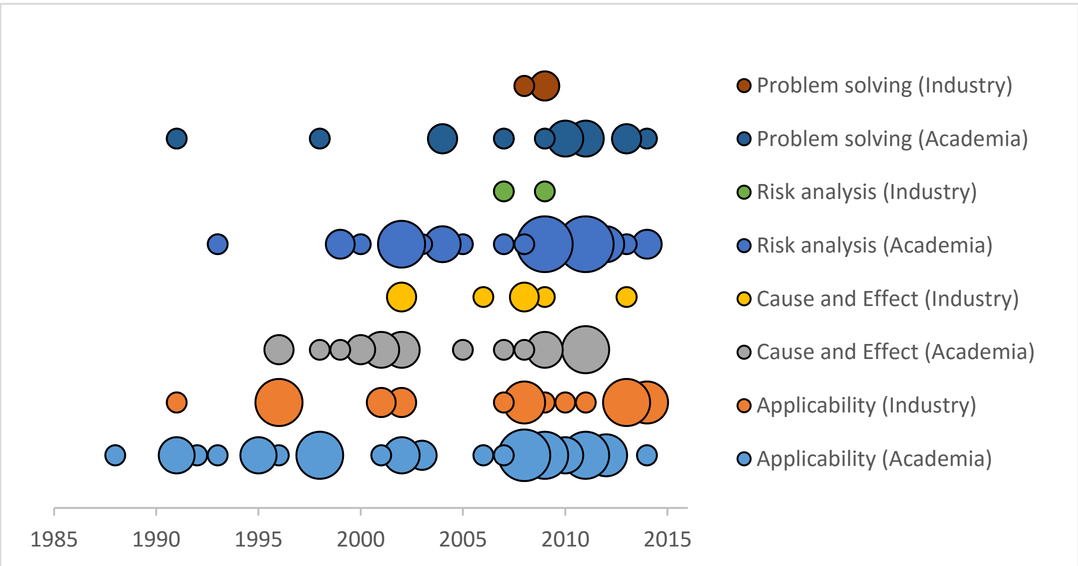


FIGURE 17: TREND EXTRAPOLATION.

By analysing the graph, the following observation can be stated:

- Industry generally follows academia with a delay of five or more years. Probably, this relies on the fact that academia is more used to write scientific publications, while industry generally publishes at the end of a project. This trend is also confirmed by time distribution of patents, generally produced by industry.
- The average of publications per year in the last 5 years increases of more than 200% respect the average in the previous 25 years (1985-2010). The trend is valid for both academia and industry and this is mainly due to the high increase of Chinese publications, especially patents.
- Compared to the absolute distribution of the publications in the considered period, in the last 5 years the distribution of the problems in the four categories is not constant and both academia and industry focused the attention mainly on the application of the method.

<u>Suggestions to improve FMEA</u>

Since its introduction, FMEA has been continuously modified and implemented according to two main fields of research: development of the traditional FMEA and its modification. The first one, with standards and scientific papers, contributes to improve the comprehension of the traditional methodology and its application in several fields maintaining the original structure. The second one includes modified methods and the traditional structure of FMEA is changed as well steps sequence.

Using the same pool of papers and patents, the solutions/improvements proposed to solve problem categories previously described have been identified. Then, for each problem category, the methods and tools to solve them have been identified.

In the following, the solutions identified to solve/improve mentioned problems are proposed.

- ***Applicability:*** The documents that improved the applicability operate in different directions but without modifying directly the order of application of the traditional FMEA steps. The improvements propose to anticipate the analysis in order to improve the efficiency (Rhee and Ishii, 2003 [94], Liu et al. 2011 [95]), to automate the entire methodology, to reduce or exclude the human intervention (Price and Taylor, 2002 [91]).
- ***Cause and effects representation:*** The authors that try to improve Cause and Effect chain representation act in different ways, but always with the objective to increase the efficiency of failures detection. Some of them improved the number of Failure Modes, Failure Effects and Failure Causes. In additions, an interesting field of research has deepened the capability of the method to analyse multiple effects (e.g., Price and Taylor, 2002 [91]) to model simultaneous failures and evaluate the consequences.
- ***Risk analysis:*** In general, the researchers that improved risk analysis modify the RPN calculation introducing new techniques of analysis that can be divided into:
    - Qualitative methodologies based on the evaluation of the judgments of involved people.
    - Statistical evaluation that uses the probability distributions.
    - Cost-based approaches that provide economic quantification of the faults.
    - Requirements-based approaches that compare the customer’s un-satisfaction about the fault.
    - History-based methods that consider historical data about faults.
- ***Problem solving:*** the authors generally work to ameliorate the presentation of the results and integrate problem-solving methods (e.g., Liu et al. 2011 [95]).

Table 6 summarises the solutions identified to solve FMEA problems and the number of citations in papers and patents.

TABLE 6: PROBLEMS AND SOLUTIONS TO IMPROVE FMEA.

Problems	Solutions	Number of citations in papers/patents		
		Academia	Industry	Total
Applicability	Anticipate FMEA analysis	47	18	65
	More automation	29	18	47
	Improve management of the information	38	8	46
	Introduce new guidelines to rapply FMEA	28	12	40
	Apply to very complex systems (extensive number of elements)	15	5	20
	Ameliorate user interface by providing data filing template	10	9	19
	Introduce criteria to reduce the number of ITEMS to be analysed	3	2	5
Cause and effects representation	New methods for Failure Modes identification	32	29	61
	Increase the number of determined Failure Effects	26	12	38
	Combine multiple Failures Effects, studying the result and the possible synergies	16	7	23
	Increase the number of the determined Failure Cause, including root causes	9	4	13
Risk analysis	Quantify statistically and logically the probability of the faults	44	9	53
	New measure to evaluate the risks according to the requirements	25	6	31
	Quantify the potential faults according to economic criteria	13	3	16
	Quantify the potential faults according to historical data	5	3	8
	Analyse qualitatively the risk, using personal judgments and impressions instead of aseptic measurements and numerical ratings	1	4	5
Problem solving	Improve presentation of the results	25	7	32
	New methods to be integrated into FMEA (TRIZ, Maintenance management tools, etc.)	9	10	19
	Use FMEA for other purposes	3	5	8
Total		**375**	**171**	**546**

The following figure (Figure 18) shows the comparison betweeen Academia and Industry with regards to solutions to overcome FMEA problems.

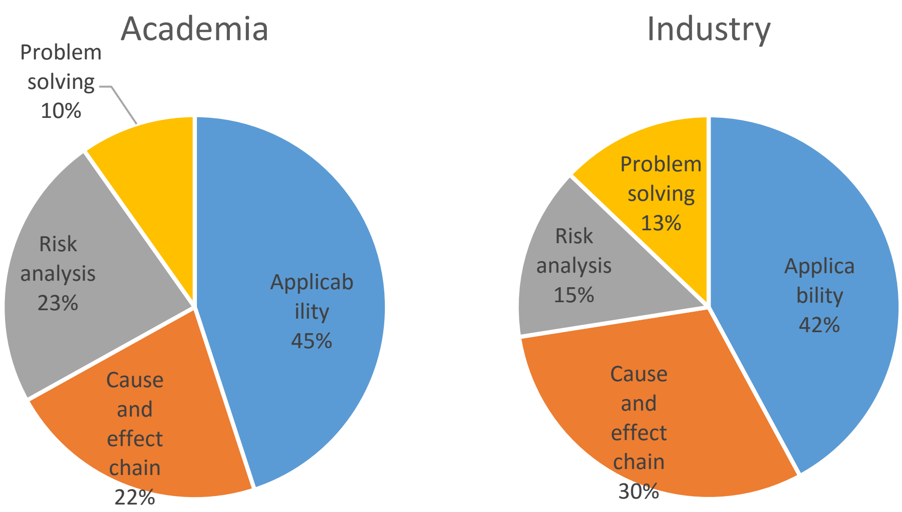


FIGURE 18: MAIN PROBLEMS AND SOLUTIONS PROPOSED BY ACADEMIA AND INDUSTRY.

Figure 19 portrays the time distribution of the four categories of improvements divided into academia and industry.

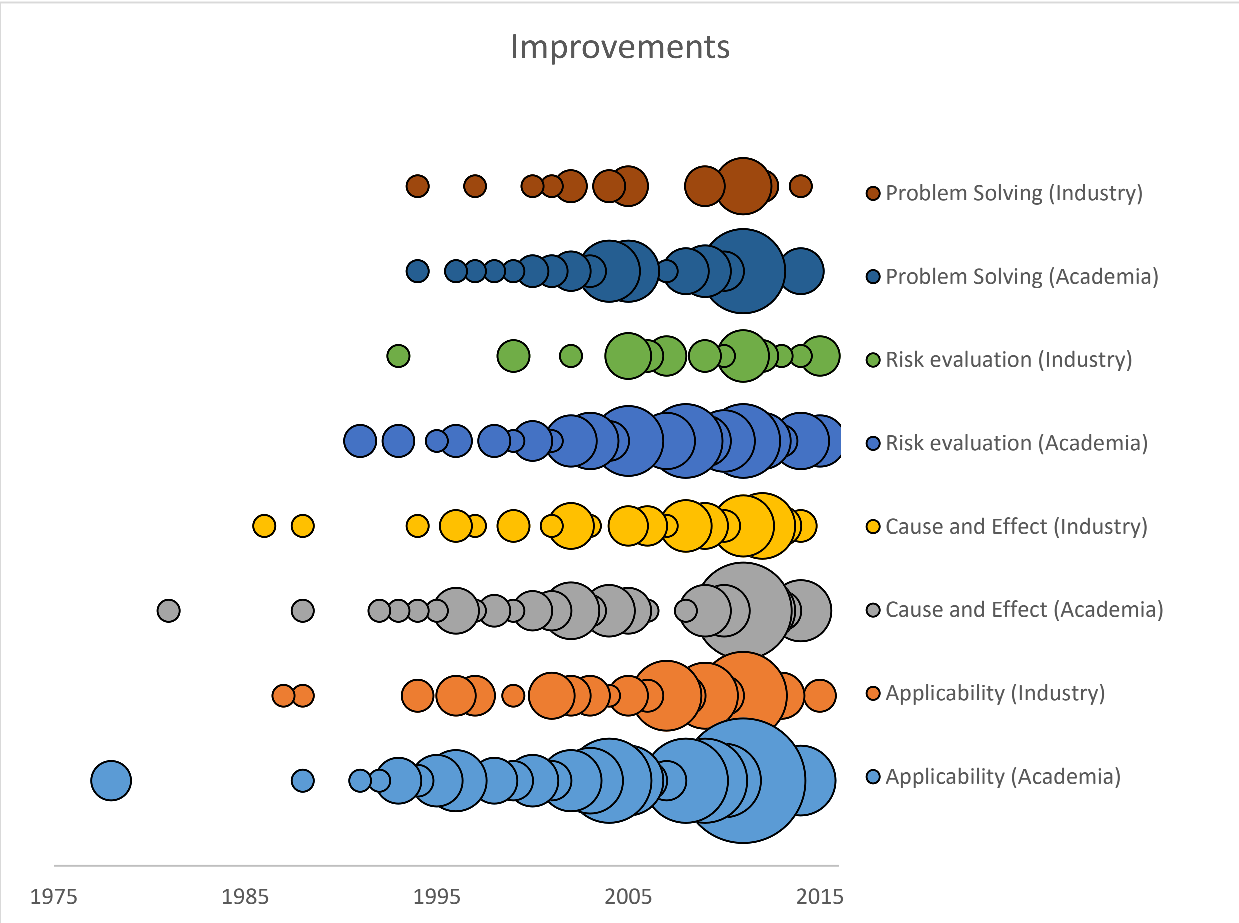


FIGURE 19: TRENDS EXTRAPOLATION OF FMEA IMPROVEMENTS

Analysing the global results, the following observations can be stated:

- The most criticized problems seem to be also the most considered for improvements. In general, many solutions for each declared problem have been identified.
- Academia proposes more methods than industry, among 3 times more. From a statistical point of view, the most numerous suggestions regard "anticipate FMEA analysis" (both for academia and industry) and "quantify statistically and logically the probability of the faults" (only for academy). More in general, a great effort has been spent to automatize the method and to manage the information with the goal to make the method quicker, less subjective, with less error probability, with few choices for the user and with a more limited use of resources.
- Only in few cases, the declared needs remain unsatisfied: solutions for team building management are missing and there is only one solution to adapt FMEA structure for problem solving.
- In general, academia and industry operate in a similar way, even if in some cases, some peculiarities can be identified:
    - To improve applicability, academy focuses on the management of information, especially for complex system, while industry offers fewer solutions. Industry on the contrary worked on the automation and the amelioration of the user's interface.
    - To improve cause effect representation, industry expressed a great interest in new methods for failure modes identification.
    - To improve risk analysis, industry suggests much less solutions than academy.
    - For problem solving, regarding the high request of solutions representation, a very high offer of academic methods against a limited industrial activity has been found. On the contrary, many solutions based on the integration with other methods have been collected, especially from industry with regard to maintenance.

On the basis of the trend analysis, during the last 5 years, both academia and industry tried to find efficient solutions for all the four problem categories; while previously the focus was almost exclusively on the application of the method.

Methods and tools

Several authors suggested integrating FMEA with other methods and tools to improve it. Some of them combined FMEA with Quality Function Deployment or Fault Tree Analysis. Others introduced logical models like Fuzzy or databases about historical data and costs quantification.

Methods and tools identified for each of considered problem categories are as follows:

- ***Applicability:*** For the representation of the methodology, some approaches are proposed such as ontologies (e.g., Ebrahimipour et al., 2010 [96]).
- ***Cause and effect representation:*** Some authors change the way to detect the Failure Modes by suggesting different approaches, such as databases and physical description (Price and Taylor, 2002 [91]). The Scenario representation (e.g., Kmenta and Ishii, 2000 [97]) is used to map the entire cause-effect chain by including also the secondary effects that typically affect the user.
- ***Risk analysis:*** Some authors (e.g., Bowles and Peláez, 1996 [98]) introduced Fuzzy logic to better evaluate the reliability through statistical considerations, while others (e.g., Rhee and Ishii, 2002 [92]) integrated FMEA with cost databases.
- ***Improve solving:*** Sheng et al. (2005)[99] and Regazzoni and Russo (2011)[100] proposed to use TRIZ. In particular, Regazzoni and Russo (2011)[100] modified FMEA structure developing a new method to enhance risk management.

Methods have been grouped in different categories (e.g., database, statistical, mathematic and logic). Table 8 summarises methods and tools proposed for each problem category.

TABLE 8: PROBLEM CATEGORIES VS METHODS AND TOOLS

		Applicability		Cause and effect		Risk Analysis		Solving		Total	
Categories of methods	**Methods/tools**	**Academia**	**Industry**	**Academia**	**Industry**	**Academia**	**Industry**	**Academia**	**Industry**	**Academia**	**Industry**
Databases	Physical effects	0	0	8	5	0	0	0	0	**8**	**5**
	Historical data	1	0	12	11	3	0	0	0	**16**	**11**
	Costs DB	0	0	0	0	1	1	0	0	**1**	**1**
	Others DB	10	6	0	0	0	0	0	0	**10**	**6**
	Subtotal	***11***	***6***	***20***	***16***	***4***	***1***	***0***	***0***	***35***	***23***
Statistical	***Subtotal***	***0***	***0***	***0***	***0***	***1***	***0***	***0***	***0***	***1***	***0***
Mathematical and logic	Fuzzy	0	0	0	0	40	4	0	0	**40**	**4**
	Bayesian network	3	1	3	0	4	0	0	0	**10**	**1**
	Petri net	0	0	1	0	0	0	0	0	**1**	**0**
	Others (Topsis, Izonote, AHP, Graph theory)	0	0	0	0	0	0	0	0	**0**	**0**
	Subtotal	***3***	***1***	***4***	***0***	***44***	***4***	***0***	***0***	***51***	***5***
Problem solving	QFD	0	1	0	0	13	1	0	0	**13**	**2**
	TRIZ	0	0	0	0	0	0	4	0	**4**	**0**
	Maintenance management	0	0	0	0	0	0	3	9	**3**	**9**
	Brainstorming	0	0	0	0	0	1	0	0	**0**	**1**
	Subtotal	***0***	***1***	***0***	***0***	***13***	***2***	***7***	***9***	***20***	***12***
Prototyping	Simulation	0	0	7	5	0	0	0	0	**7**	**5**
	Test	0	0	1	4	0	0	0	0	**1**	**4**
	Subtotal	***0***	***0***	***8***	***9***	***0***	***0***	***0***	***0***	***8***	***9***
Others	Infographics	5	4	0	2	0	0	0	0	**5**	**6**
	Functional Analysis	0	0	8	11	0	0	0	0	**8**	**11**
	Ontologies	7	4	0	0	0	0	0	0	**7**	**4**
	FTA (Fault Tree Analysis)	0	0	2	4	0	0	0	0	**2**	**4**
	Scenario	0	0	3	0	0	0	0	0	**3**	**0**
	Others (Kano, Hazop, Project management, Optimisation models)	0	0	0	0	0	0	3	1	**3**	**1**
	Subtotal	***12***	***8***	***13***	***17***	***0***	***0***	***3***	***1***	***28***	***26***
Total		**26**	**16**	**45**	**42**	**62**	**7**	**10**	**10**	**143**	**75**

On the basis of the analysis of the proposed table, the following observation can be stated:

- With regard to applicability and cause and effect chain, academia and industry have generally adopted the same number of methods and tools;
- Academia proposed many methods for risk analysis; while industry seems to be satisfied by the traditional FMEA tools.
- The most popular method is Fuzzy, even if it is clearly related to academia. Historical data DB and Functional analysis follow and are equally distributed between academia and industry. Quality Function Deployment is generally linked to FMEA almost exclusively in academia.
- To improve cause and effect chain analysis both academia and industry mostly use historical-data DB, Functional Analysis, Physical description and Simulation.

The presented survey of case studies has contributed to confirm the importance of using FMEA and risk analysis to support the problem of the anticipatory failure investigation to improve the products. In addition, the huge multitude of proposed improvements suggest the possibilities to develop a specific set of guidelines able to suggest both the main aspects of the traditional FMEA and the better improvements.

Through the survey, the main suggestions that should be provided by the guidelines have been identified: the involved entities, the relations among them, the steps for describing a design process and the ontologies to describe all the involved elements. In addition, by considering the better identified improvements, the guidelines can suggest, how the subjectivity of the analysis, how to anticipate the analysis during the early stages of the design process, in order to guarantee more freedom to operate to the problem solver, and how to identify new less onerous modalities to determine the failure modes.

4.3.2. Approaches to support idea generation

The analysis of the case studies identified some of the most popular models to support idea generation: guidelines (e.g., 40 inventive principles, TRIZ separation principles, guidelines for eco-design, guidelines for design by analogy and triggers such as MATCEMIB), 76 standard solutions and Databases (effect DB, structural DB, patent DB and biological DB). Figure 20 shows the classification of the approaches in relation to the considered problems.

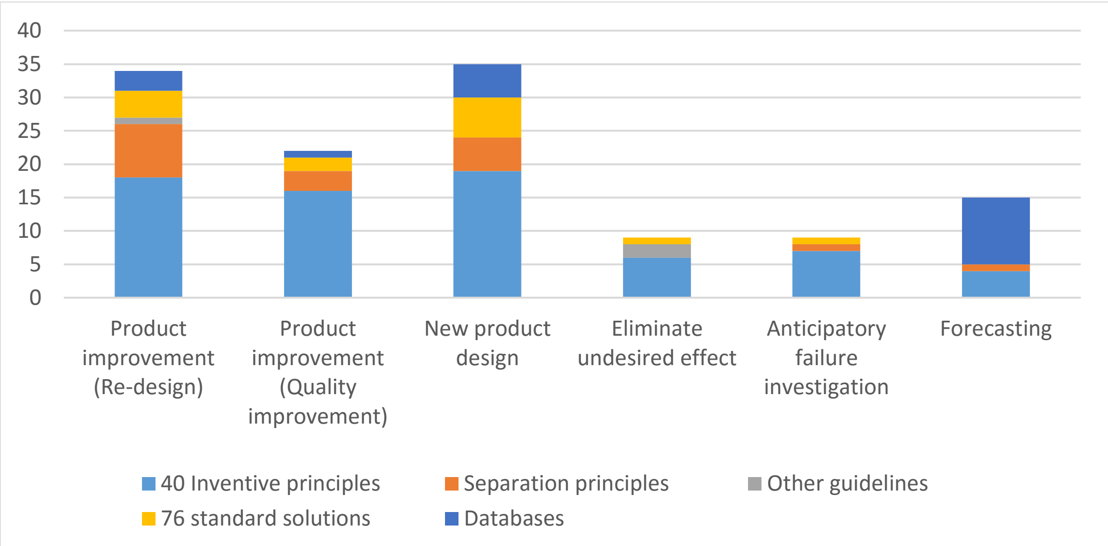


FIGURE 20: MAIN METHODS AND TOOLS USED TO SUPPORT IDEA GENERATION IN DIFFERENT INVENTIVE PROBLEMS.

However, as we can see by the graph, since the approaches seem uniformly distributed between the problems, an alternative classification has been considered on the basis of:

- ***Problems without contradictions:*** require the improvement of the unsatisfactory parameters without compromising the realisation of any others.
- ***Problems with contradictions:*** include two parameters of the problem that are in contradiction, and the improvement of one of them compromises the realisation of the others.

The following graphs (Figure 21) summarize the distribution of the tools according to the two kinds of identified problems. As we can see, through this new classification, a clearer idea about the use of the tools during idea generation is provided.

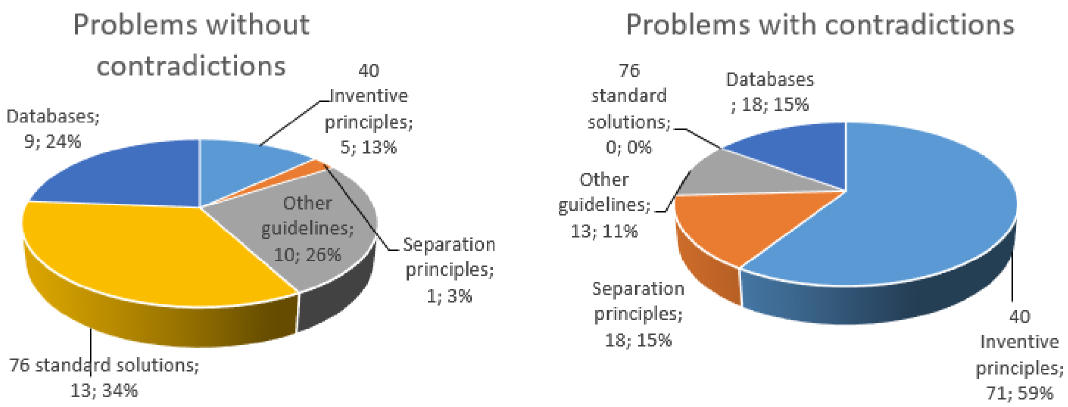


FIGURE 21: MAIN METHODS AND TOOLS USED TO SUPPORT IDEA GENERATION IN PROBLEMS WITH AND WITHOUT CONTRADICTIONS.

In referring to the proposed graphs, 40 inventive principles result the most used tool to support idea generation in problems with contradictions, followed by the separation principles. 76 standard solutions are instead exclusively employed in problems without contradictions, where they are the most diffused tool for the idea generation. This distribution can be attributed to the tools themselves: separation principles are strictly related to the contradictions; 40 inventive principles can be used in both the contexts even if are more effective in solving contradictions while 76 standard solutions are generally used to improve positive features and to reduce/eliminate negative effects not specifically in contractions with other parameters.

In order to provide a more detailed overview about the use of the methods and the tools to enhance idea generation in the two identified problems, literature analyses and tests are proposed in the following.

Approaches to support idea generation in problems without contradictions

As reported in literature, and confirmed by the presented survey, problems without contradictions are generally supported by suggestions (e.g., 76 standard solutions), triggers (e.g., SCAMPER and MATCEMIB) and other more specific guidelines (e.g., eco-design). To discriminate these approaches, two sub-problems have been investigated: un-domain problems and specific domain problems.

Un-domain problems

A test proposed by Belski et al. (2015)[101] to engineering students in different universities around the world, and replicated at the University of Bergamo, investigated the role of guidelines and triggers in supporting idea generation for generic un-domain problems (e.g., “Eliminate the lime from the pipes”), which not require a particular domain knowledge to be solved in an inventive way.

During the tests, the students were divided into 4 groups and they used different approaches to solve the same assigned problems in the same time (16 minutes for each problem). The organisation of the rest is as follow:

- Group A (Control group): no suggestion;
- Group B: 8 random words;
- Group C: the 8 suggestions of the field of MATCEMIB (Mechanical, Acoustic, Thermal, Chemical, Electrical, Magnetic, Intermolecular and Biological);
- Group D: MATCEMIB+: a more extended MATCEMIB classification, called MATCEMIB+ (Belski et al. 2007 [55]) involving more than 50 terms divided into the 8 fields of MATCEMIB classification.

The unique difference between Belski's tests and that replied at the University of Bergamo regards the students involved: in the first case they are from the 1st year of the bachelor's degree, in the second from the master's degree and they have a previous knowledge with 80 hours about TRIZ, thanks to a course offered by the same university.

Figure 22 contains two of the assigned approaches: MACEMIB (first column) and MATCEMIB+ (the second column).

Fields	Interactions Including
Mechanical	Gravitation, collisions, friction, direct contact Vibration, resonance, shocks, waves Gas/Fluid dynamics, wind, compression, vacuum Mechanical treatment and processing Deformation, mixing, additives, explosion
Acoustic	Sound, ultrasound, infrasound, cavitation
Thermal	Heating, cooling, insulation, thermal expansion Phase/state change, endo- exo-thermic reactions Fire, burning, heat radiation, convection
Chemical	Reactions, reactants, elements, compounds Catalysts, inhibitors, indicators (pH) Dissolving, crystallisation, polymerisation Odour, taste, change in colour, pH, etc.
Electric	Electrostatic charges, conductors, insulators Electric field, electric current Superconductivity, electrolysis, piezo-electrics Ionisation, electrical discharge, sparks
Magnetic	Magnetic field, forces and particles, induction Electromagnetic waves (X-ray, Microwaves, etc.) Optics, vision, colour/translucence change, image
Intermolecular	Subatomic (nano) particles, capillary, pores Nuclear reactions, radiation, fusion, emission, laser Intermolecular interaction, surface effects, evaporation
Biological	Microbes, bacteria, living organisms Plants, fungi, cells, enzymes

FIGURE 22: MATCEMIB+ (BELSKI ET AL. 2007 [55]).

The results of Belski's tests achieved by the four groups and in the four considered universities are summarized in the following table (Table 14):

TABLE 14: TEST INDIVIDUAL RESULTS (BELSKI ET AL. 2015 [101]).

Group Information	Australia			Czech Republic			Finland			Russia		
	Stud.	Mean	SD	Stud.	Mean	SD	Stud.	Mean	SD	Stud.	Mean	SD
Control	21	2.02	1.44	18	3.56	1.55	8	5.81	1.89	21	4.32	1.44
Random Word	17	3.25	1.85	16	3.78	1.64	8	5.69	1.03	24	3.29	1.79
MATCEMIB	15	3.65	2.15	17	6.50	1.76	5	9.30	2.59	20	5.65	2.64
MATCEMIB+	18	5.13	2.07	18	6.92	3.19	6	9.67	3.27	23	6.62	2.37

As result, from the test emerged that the students using a structured set of guidelines like MATCEB or MATCEMIB+ propose more creative solutions compared to the others. However, the increasing of the structuredness of the triggers (MATCEMIB+) seems not substantially improve the solving skills in comparison to more simple triggers (MATCEMIB).

Table 15 shows instead the results achieved at the University of Bergamo.

TABLE 15: TEST INDIVIDUAL RESULTS AT THE UNIVERSITY OF BERGAMO.

Group Information	Italy

	Number of participants	Total solutions	Average solutions	St. dev.
Control	9	24	2,7	0,7
Random Words	8	21	2,6	0,9
MATCEMIB	9	44	4,9	0,8
MTECEMIB+	8	42	5,3	0,7

The results of this test confirm the previous ones: also for more expert students, MATCEMIB and MATCEMIB+ are preferable than free creativity approaches and MATCEMIB+ does not seem much more useful than of MATCEMIB.

The tests suggest that simple guidelines (triggers) are useful in supporting idea generation for un-domain problems without contradictions and they can increase the number of the proposed solution, compared to other approaches (e.g., free creativity and random words). However, the increasing of their structuredness seems almost irrelevant, by marginally improving the number of the proposed solutions. In addition, by the analysis of the solutions proposed by students of the University of Bergamo emerged their qualitative level, in terms of novelty and feasibility, achieved with MATCEMIB and MATCEMIB+ is substantially comparable.

Specific domain problems

In specific domain problems without contradictions, more structured guidelines with increased domain knowledge are generally used, in order to make the suggestions provided more comprehensible, especially to technicians. An example are the eco-guidelines developed by Russo et al. (2011)[48]: a set of more than 300 guidelines developed from TRIZ theory, which during the years became more domain specific in order to enhance their applicative efficacy in supporting these problems.

Since their introduction in 2009, the eco-guidelines have been applied and experimented in several industrial contexts and they have been improved several times on the basis of the achieved results. In this way the guidelines gradually acquired a more technical and less theoretical interface of presentation. In the following a summary about the evolution of the guidelines, focused on the main features is presented:

- ***Prologue (before 2009):*** before the creation of the guidelines, the authors used TRIZ for eco-design problems during industrial collaborations. The difficulties in applications experimented by the technicians, generally not involved in TRIZ, suggested the development of the eco-guidelines, in order to explain the theoretical approach.
- ***1st version (2009):*** the first set of eco-guidelines (Russo et. al (2011)[48]) explain how to use some TRIZ tools (e.g., Ideality, Resources and Laws of Technical System Evolution) to reduce the product impact on the environment. These guidelines have been applied in the area of household appliances and tested with engineering students. In comparison to the simple use of TRIZ, the guidelines allow the students a more conscious and focused use of the tools, while the technicians not involved in TRIZ, do not found substantial improvements.
  Consider for instance the following guideline as example of the 1st version of guidelines:

R4.1. Make the actions resonant
Replace continuous actions with periodic or pulsating actions, and then to resonant so that the technical system operation is optimized through mere modification of its component (dimension, mass, and frequency). Nothing is introduced into the system in order to improve the main useful function and efficiency according to the energy conservation. The frequencies of vibration, or the periodicity of parts and movements of the system should be in synchronization with each other, or coordinated (or de-coordinated) with natural frequency of the product.

- ***2^nd^ version (2013):*** the second version of the guidelines was proposed by Russo et al., 2015 [102] after an extensive experimentation with more than 250 small and medium sized enterprises in six countries during an European project (3 years) in the field of eco-design. On the basis of the feedback provided by this activity, the original eco-guidelines were modified, by already including TRIZ tools, even if proposed in a more practical way through specific examples. This time, technicians with good knowledge of the product and basic knowledge of TRIZ, satisfactorily applied the proposed guidelines.

IFR Think about products that don't need packaging (the packaging is already included in the product) **Use packaging mass index** Assessment index: IFR: Zero packaging: 100 ACTUAL: Mass of packaging used **Index**: ((MASS OF PACKED OBJECT - ACTUAL)/ MASS OF PACKED OBJECT)* 100	IFR: absence of packaging, solid inks. The cartridge has been eliminated.  The packaging is already included in the product: Scratch-proof glass 

FIGURE 23: AN EXAMPLE FROM THE 2ND VERSION OF THE ECO-GUIDELINES.

3rd version (2016): the eco-guidelines were further developed in order to be easily applied also by technicians without any knowledge in TRIZ, by providing more practical suggestions and examples, in substitution to TRIZ tools. These new guidelines specify the phase in the product life cycle on what they work (pre-manufacturing, manufacturing, product use, end of life) and the specific goal that they want to achieve (e.g., Reducing packaging, Improving the logistic, Reducing the consumption of raw materials). As result, the guidelines are more immediate and comprehensible; in addition, they can be applied also by technicians not-involved in TRIZ as testified by tests carried out in the companies. In turn, TRIZ experts do not achieved advantages by passing from the second to the third version of the guidelines. The following figure (Figure 24) shows an example of the guidelines from the 3rd version.

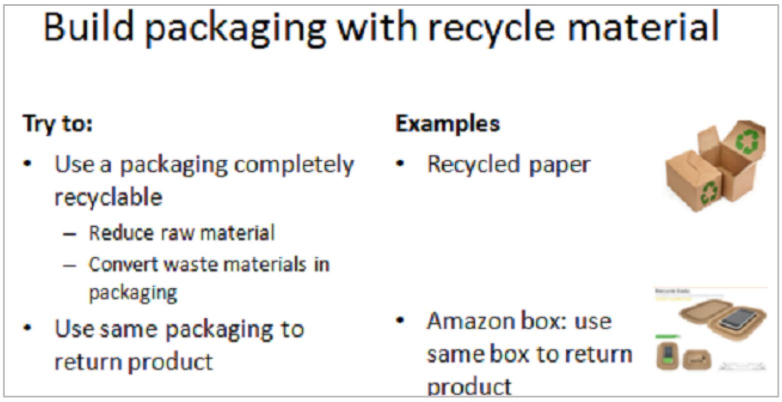


FIGURE 24: AN EXAMPLE FROM THE 3RD VERSION OF THE ECO-GUIDELINES.

The presented synthesis about the development of the eco-guidelines is emblematic as regard the guidelines to support idea generation in specific domain problems without contradictions. In particular, has been tested how the more practical guidelines are necessary to be applied by professionals not involved in TRIZ, while TRIZ experts prefer a more freely interpretation about the method and a more abstract level of detail of the suggestions. The following graph (Figure 25) qualitatively compares the content of the eco-guidelines (in term of methodological and domain knowledge) with the reference users (R&D specialist involved and not involved in TRIZ and TRIZ experts).

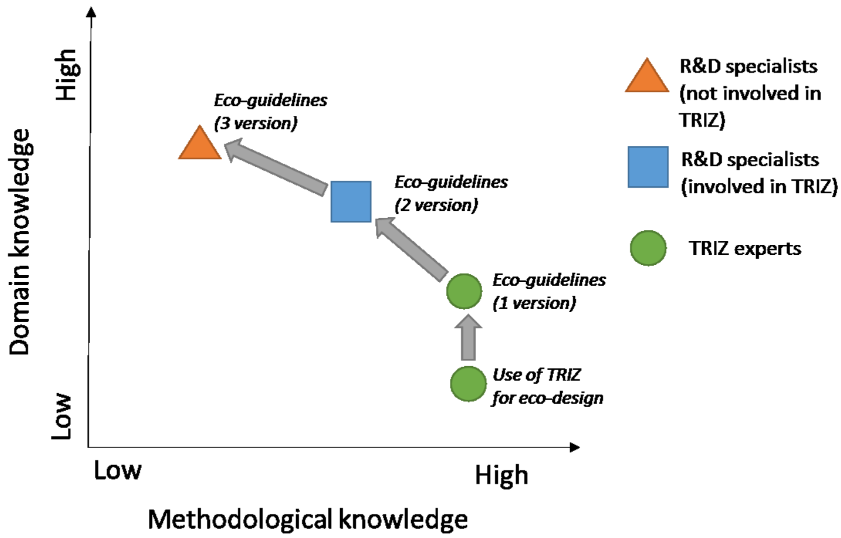


FIGURE 25: THE ROLE OF THE KNOWLEDGE IN THE ECO-GUIDELINES VS KINDS OF PROBLEM SOLVER.

Approaches to support idea generation in problems with contradictions

According to TRIZ, the guidelines to solve contradictions are applied after a strict reformulation of the problem, through the identification of the operative zone and the operative time of the problem. Consequently, this requires to the problem solver a particular attention during the application of the guidelines, so as not to waste the preparation work.

In order to better comprehend how these guidelines work and what are their main advantages and limitations, three tests have been carried out with engineering students: the first one investigates the degree of structuredness of the guidelines, the second one experiments the role of the problem solver's personal experience during the application of the guidelines and the third one analyses the advantages of theoretical explanations in supporting them.

In the following the three experiments and the achieved results are presented in detail:

- ***Test 1: Structured guidelines vs simple guidelines.*** To investigate the role of the structuredness of the guidelines in supporting problem with contradictions, two approaches have been tested by 5 PhD students, with specific TRIZ background: SCAMPER (simple guidelines) and the 40 inventive principles (structured guidelines). The assigned problems are:
  - The improvement of a tank to anodize the aluminium, which must be open on the top side, to allow the rapid entrance and exit of the aluminium plates, and, at the same time, closed to not dispense the content by evaporation.
  - The improvement of a common nutcracker in an innovative way, in order to make it able to crack both walnut and other kinds of fruits such as nuts.

  The PhD students solved the two problems in two different sessions, by using SCAMPER in the first one and the 40 Inventive principles in the second one. The problems have been deliberately delivered in a simplified way, by highlighting the contradictions.

  The provided solutions were evaluated by three researchers on the basis of the following parameters: precision, feasibility, novelty (evaluated through patent analysis) and the provided identification and description about the operative zone and the operative time.

  The test results are summarized in the table 16.

TABLE 16: TEST RESULTS: NUMBER AND QUALITY OF THE PROPOSED SOLUTIONS FOR PROBLEMS WITH CONTRADICTION FACED THROUGH THE SUPPORT OF SCAMPER AND 40 INVENTIVE PRINCIPLES.

	Session 1 (SCAMPER)	Session 2 (40 Inventive principles)
Total number of solutions	13	22
Individual solutions	2,6	4,4
Mean quality (0-6)	3,6	5,3
Standard Deviation "Quality"	0,9	1,0

  As confirmed by the achieved results, 40 inventive principles are more suitable in solving problems with contradictions, compared to triggers such as SCAMPER. Though their help, the PhD students proposed a great number of solutions and qualitatively better, which are more focused regard the operative zone and the operative time of occurrence of the problem. Only two solutions obtained through SCAMPER work exactly in the operative zone and only one solution in the operative time.

- ***Test 2: The role of the personal background in the application of the guidelines.*** In this case, the results, previously achieved by the PhD students by using the 40 inventive principles, have been compared to the those achieved by 12 MsD students with the principles. The students are from a course of Product Lifecycle Management offered for the 5th year students in Management and Mechanical Engineering at the University of Bergamo and they know in TRIZ only at a theoretical level.

  The achieved results have been collected and analysed by the same academic researchers on the basis of the same criteria and they are summarized in the following table (Table 17):

TABLE 17: RESULTS OF THE TEST: NUMBER AND QUALITY OF THE SOLUTIONS PROPOSED BY THE MSD STUDENTS COMPARED TO THOSE PROPOSED BY PHD STUDENTS.

Students	Total solutions	Individual solutions (per person)	Mean quality (0-6)	Quality (St. dev)

MsD students	12	1,2	4,9	1,38
PhD students	22	4,4	5,3	1,00

On the basis of the achieved results, the 5 PhD students proposed a great number of solutions, characterized by an increased qualitative level. In particular, the degree of novelty is better and also the feasibility of the solutions, and they better applied them better in the operative zone and time. These facts seem to confirm that a greater knowledge of the principles and a direct experience in their application are crucial for a more fruitful application.

- ***Test 3: the role of theoretical explanations to support structured guidelines.*** During this test, another set of guidelines, called FBS inventive principles (prototype), based on 40 inventive principles with an improved ontological reformulation derived from FBS theory, has been proposed to other 24 MsD students of the same course to solve the same problems. The FBS inventive principles (prototype) used by the students were a first testing version of the definitive FBS inventive principles proposed in the chapter 6.
  The objective of this test is to investigate if a more rigorous ontology of the guidelines can enhance idea generation of not-expert problem solvers during the resolution of contradiction.
  The same students solved the problems by using both the traditional inventive principles and those improved. The achieved results have been analysed by the same academic researchers and on the basis of the same criteria. The following table (Table 18) quantifies how the introduced principles improved the results proposed by the students in comparison to the use of the traditional inventive principles.

TABLE 18: IMPROVEMENTS IN THE RESULTS ACHIEVED THROUGH THE APPLICATION OF FBS INVENTIVE PRINCIPLES* COMPARED TO THE RESULTS ACHIEVED THROUGH THE TRADITIONAL 40 INVENTIVE PRINCIPLES.

Students that have proposed more solutions	23/24
Students that have increased the average qualitative level of their solutions	16/24

As result, after the application of the FBS inventive principles (prototype), almost all the students found a major number of solutions and more than half of them improved their qualitative level: the proposed solutions are more innovative and feasible and they are more focused in solving the contradiction in the required operative space and in the operative time.

The achieved results confirmed some key features of the guidelines to support idea generation in problems with contradictions. They are generally more complex at theoretical level and they require a greater knowledge and practical experience to the problem solver. For this reason, expert users are advantaged in their application and they can better circumscribe the proposed solutions inside the operative space and the operative time, in order to solve the problem in a more focused way and by better exploiting the involved resources. However, the introduction of more detailed and rigorous ontology and the better specification of the objectives and the suggestions facilitate the comprehension and the application to less expert users.

4.4. Software implementation of methods and guidelines

In this chapter, the main advantages about Computer Aided Innovation (CAI) tools and more in particular software implementation of the guidelines are analysed.

During the years, a huge multitude of CAI tools have been developed by academia and industry. In general, as explained by Husig and Kohn (2009)[103], CAI tools can be classified into three kinds:

- ***Tools to support strategy management*** help to manage the strategic issues of innovation like portfolio or scenario.
- ***Tools to support idea management*** help in manage the front end of the innovation process from the idea generation to the idea collection and evaluation.
- ***Tools to support patent management*** help the problem solving process and idea generation by providing information found in patents.

In literature some advantages of CAI tools can be found: they significantly reduce the time of development of new products and they help the problem solver in redefining "ill structured" problem into "well-structured problem" (Becattini et al., 2012 [14]); they are able to increase user's creativity during idea generation (Gero and Maher, 2013 [104]); they enhance the user's comprehension about the innovation process and the supporting methods (Husig and Kohn, 2009 [103]); finally, they promote teamwork and the collaborations between independent subjects through the information sharing during the innovation process (Flores et al., 2015 [105]).

Part of these advantages are directly related to the guidelines provided by CAI tools. As example, three CAI software are synthetically described in relation to their guidelines.

- ***Creax Innovation Suite*** (www.creax.com), firstly presented in Mann et al. (2005)[106], implements a systematic methodology to support the solutions of problems with and without contradictions in different contexts: new product development, product improvement, creating intellectual property. This software supports the problem solver during the problem identification, the formulation of the contradictions and idea generation.
  In particular, during ide generation, the software suggests the 40 Inventive principles, by providing a lot of examples for each one in order to increase their comprehension. However, only a restricted number of examples are generally provided, which are the most suitable in the application context of the problem. As explained by Low et al. (2006)[107], this aspect constitutes a limitation of the method since it cannot provide an overview about the applications in different operative conditions.
- ***Invention Machine's TechOptimizer*** (2012)[108] supports problem formulation by providing specific modules of Function Analysis and Process Analysis and idea generation by providing Inventive principles and a database with 5000 physical effects with specific examples.
  One of its main peculiarities is the direct involvement of the user, at whom, the problem data (e.g., costs of the components) are required to customize the tools provided during decision making.
- ***BOB-UP*** software (Birolini et al., 2012 [109]) supports the problem solver during the reformulation of the initial problem through a dialogue–based system and an accurate cause-effect chain analysis, in order to converge different users to a unique, correct and more easily solvable reformulation of the initial problem.
  The software is based on a rigid step by step procedure led by textual guidelines that support the user in progressively identifying the damaged element and the critical zone where the undesired effect occurs and the causes of the fault. To do this, BOB-UP stimulates the user in avoiding her/his psychological barriers and it enhances her/his creativity. More in detail, the software is constituted by the following three tools:
  - *The Ill-Balls diagram* is a graphic representation of the undesired effect, proposed to the user to identify though a simple formalism the damaged element in a well-defined zone.
  - *The Fight diagram* is a graphic tool accompanied by a specific ontology to represent the physics of the problem and to identify the time of occurrence of the damage.
  - *A linguistic composer* to automatically collect the information from the previous steps and to compose the reformulation of the problem.

  At the end of the procedure, the software provides to the user the following information about the problem: a reformulation containing a zoom on the product, a physical description in terms of force/energy and time and a set of sketches from different perspectives and with different levels of details. On the basis of these results, the user can apply any creative method in order to eliminate the identified causes of the problem.

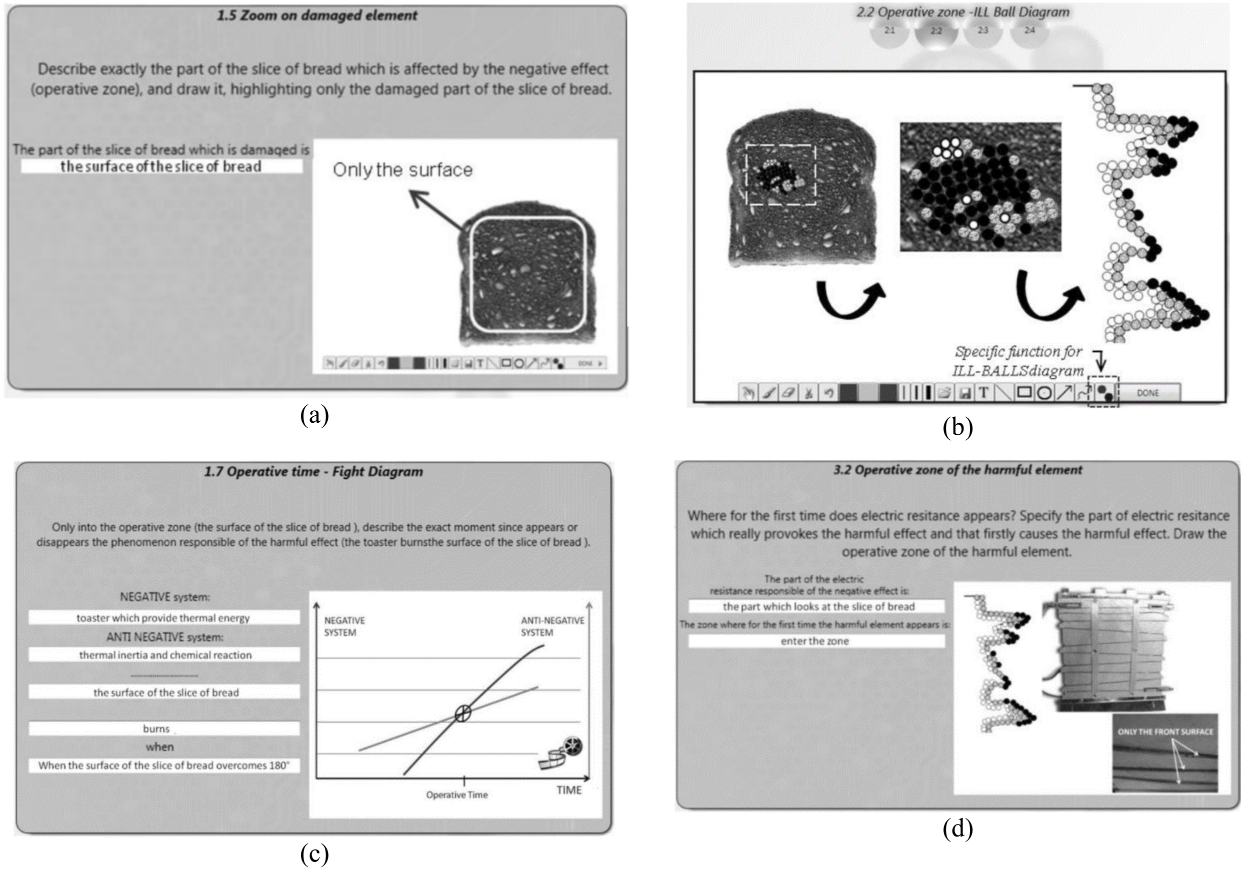


FIGURE 26: DIFFERENT STEPS IN BOB-UP SOFTWARE (BIROLINI ET AL., 2012 [109]): (A) THE INITIAL DESCRIPTION OF THE PROBLEM, (B) THE ILL-BAR DIAGRAM WITH THE DESIGN MODULE, (C) THE FIGHT DIAGRAM WITH THE TEXT AREAS AND THE TIME DIAGRAM, (D) THE OUTPUT OF THE SOFTWARE THAT DESCRIBE THE REFORMULATED PROBLEM.

More in particular, the main advantages deriving from the software implementation of the guidelines and the methods can be summarized as follows:

- ***Contextualisation in the domain of application of the problem.*** Software implementations can customise the guidelines in accordance to the industrial context, by providing part of the domain knowledge through specific examples and by using the knowledge from databases or from the information inserted by the user. Consequently, the comprehension of the guidelines in more immediate especially for technicians and the subjectivity and possible misunderstanding are reduced.

  A web-based software implementation of the 111 Standard Solutions (Russo and Duci, 2015 [47]), carried out at the University of Bergamo, has been specifically developed to achieve these aims. Through the proposed interface, the problem solver inserts the name of the tool that provokes the damage, the name of the problematic action and the name of the object that suffers the effects. On the basis of the collected data, the software selects the most suitable guidelines and it customize them.

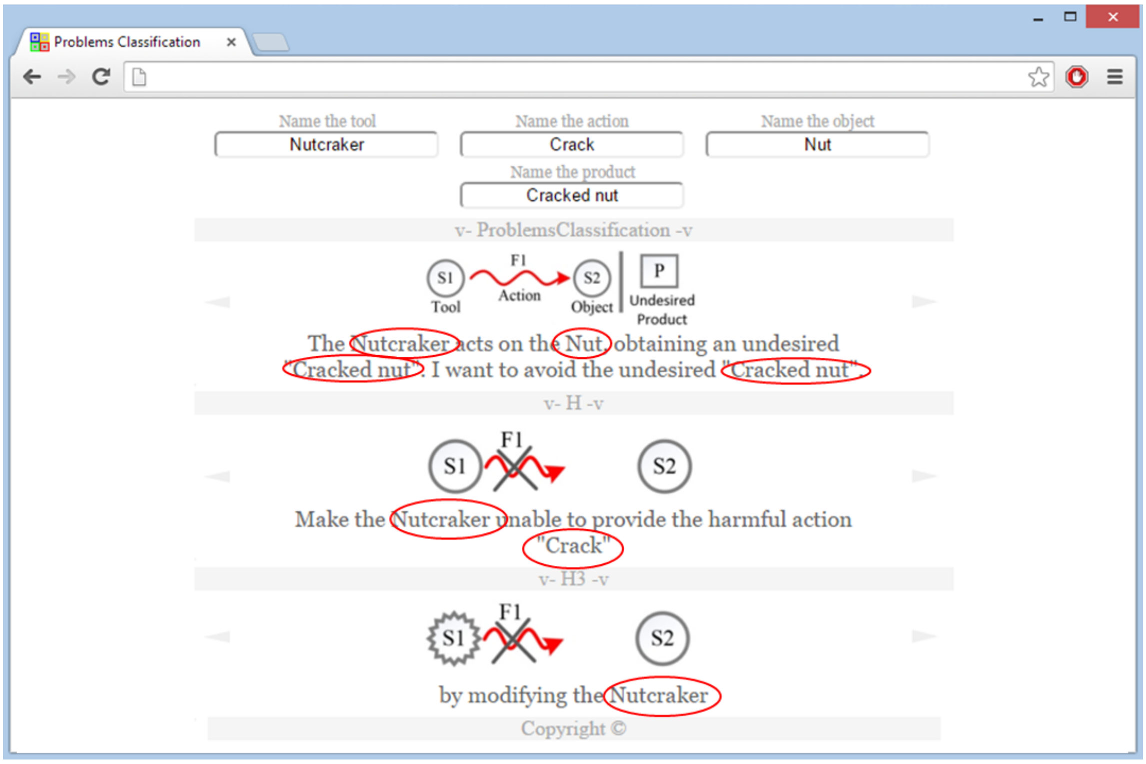


FIGURE 27: WEB-BASED SOFTWARE FOR GUIDELINES (S. DUCI).

- ***Better presentation of the examples.*** Software implementation proposes more intuitive interfaces of presentation to exemplify the proposed guidelines (video, animations, 3d CAD models, etc.). This approach can be particularly advantageous especially when the examples are complex, such as simulations.
- ***Large mole of information addressed.*** Software implementation can manage multiple information about the addressed problem (e.g., the constraints, the bill of material) and the possible solutions such as structural resources and physical effect from databases. In this way the suggestions provided by the guidelines can be more specific and effective.
- ***Filtering of the guidelines.*** Software interfaces can improve the management and the visualisation of the guidelines, especially when they are a lot and they are organised in complex structured (e.g., TRIZ matrix to support technical contradiction).
  An example of filter is provided by an alternative web-based implementation of the 111 standards solutions (Russo and Duci, 2015 [47]) that I personally developed (see Figure 28). This tool organizes the guidelines through a hierarchical map divided into four levels, respectively called: Initial problems, Sub goals, Suggestions and Helpers. In this way the user can initially select one of the guidelines in the first level (1st column) and consequently the tool shows only the related guidelines of the second-level (column 2) which in turn are used to select other guidelines in column 3 and so on. At the end of the path, the lower section summarizes all the guidelines selected by the user.
  Another example is constituted by Eco-map (Russo et. al (2011)[48]), a software developed at University of Bergamo, able to filter more than 300 guidelines about eco-design through an initial questionnaire about the product that has to be improved.

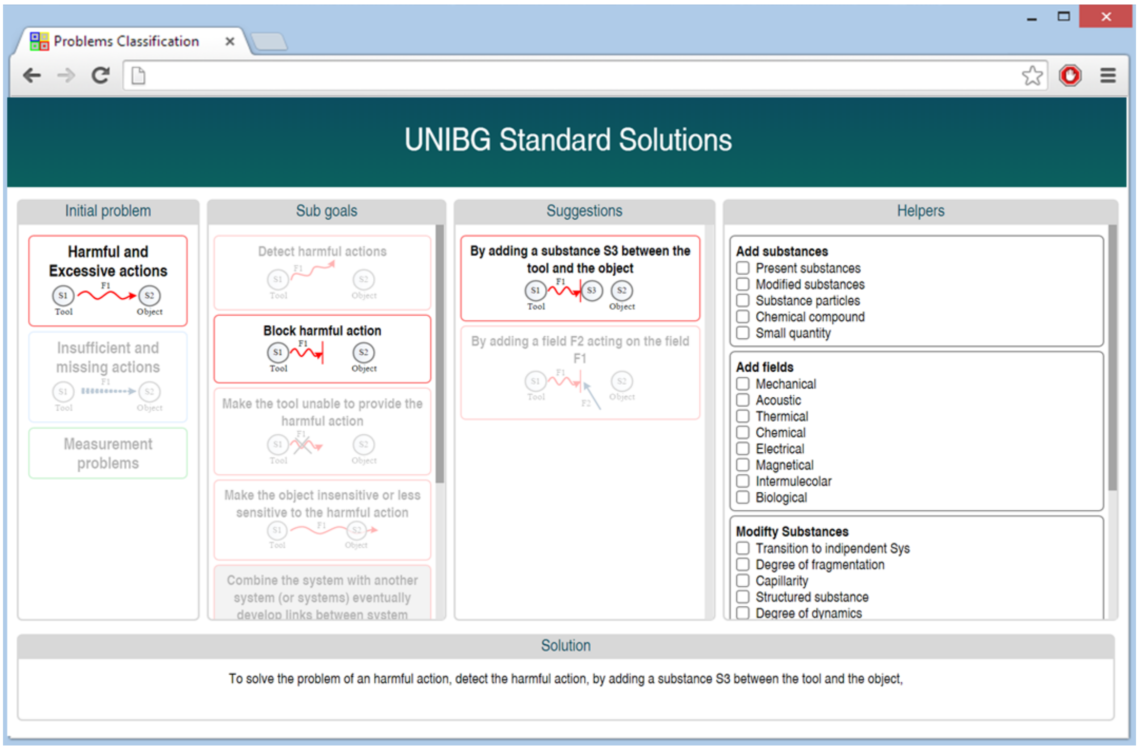


Figure 28: Web-based software for guidelines (Christian Spreafico).

4.5. Summary of rules to write guidelines for problem solving

On the basis of the literature analyses, the collected empirical evidences from industrial collaborations and the tests with students, the identified main features of the guidelines have been summarized and compared to the phases of problem solving activity, the selected inventive problems. The considered features of the guidelines are: text, graphical models, provided examples, organisation of multiple guidelines, suggested strategies, suggested methods and integrations with databases. The problem-solving phases are: function and behaviour identification, problem identification and problem solving/idea generation in problems with and without contradictions.

Table 19 summarizes the results:

Table 19: Main key features of the guidelines to support inventive problem solving.

	Problem solving phases (addressed problems)			
Features of the guidelines	**Function and behaviour identification (New concept design, product re-design)**	**Problem identification (Failure investigation and anticipatory failure investigation)**	**Problem solving and idea generation**	
			Solving problems with contradictions	**Problems without contradiction**
Text of the guideline	High methodological and un-domain content	High methodological and un-domain content. Contextualisation of the domain can be useful for technicians.	High methodological and un-domain content. Contextualisation of the domain can be useful for technicians.	Low methodological and un-domain content (triggers) for common problems or with domain content

				for complex problems
Supporting graphical models	Venn diagrams	Not required	Not required	Analytical models (e.g., Su Field models)
Provided examples	Not required	Not required	Existing solutions from other domains of application	Existing solutions in the same domain for complex problems, not required for common problems
Organisation of multiple guidelines	Ordered lists with possible iterations, design schemes (flowcharts)	Not required	Random lists	Random lists, classes with random lists
Suggested strategies	Abstraction	Analysis	Trial and error, analogy	Trial and error, analogy
Suggested methods	Design models (e.g., FBS), analytical models (e.g., MTS, ENV)	Analysis techniques (e.g., FMEA), analytical models (e.g., Su Field model, Function Analysis, Fault Tree Analysis)	TRIZ 40 Inventive principles, TRIZ Separation principles	TRIZ 76 Standard solutions, SCAMPER, MATCEM, guidelines for eco-design
Integration with databases	Function DB, Effects DB	Effects DB, Costs DB, Historical data DB	Effects DB, Materials DB, Patent DB	Effects DB, Patent DB

5. Introduction to Spark

Among the available approaches, Spark has been considered as starting point to develop the new set of guidelines for problem solving. The reasons of this choice depend by the wide applicability of the methods to the considered problems and to the direct knowledge and experience of its advantages and limitations.

This methodology derives from TRIZ and includes marketing aspects and patent intelligence. It has been developed by the University of Bergamo during some years of experience in industrial projects in small, medium and large enterprises and it has been applied by professionals and students in engineering courses.

The following figure (Figure 29) summarizes the contents of Spark.

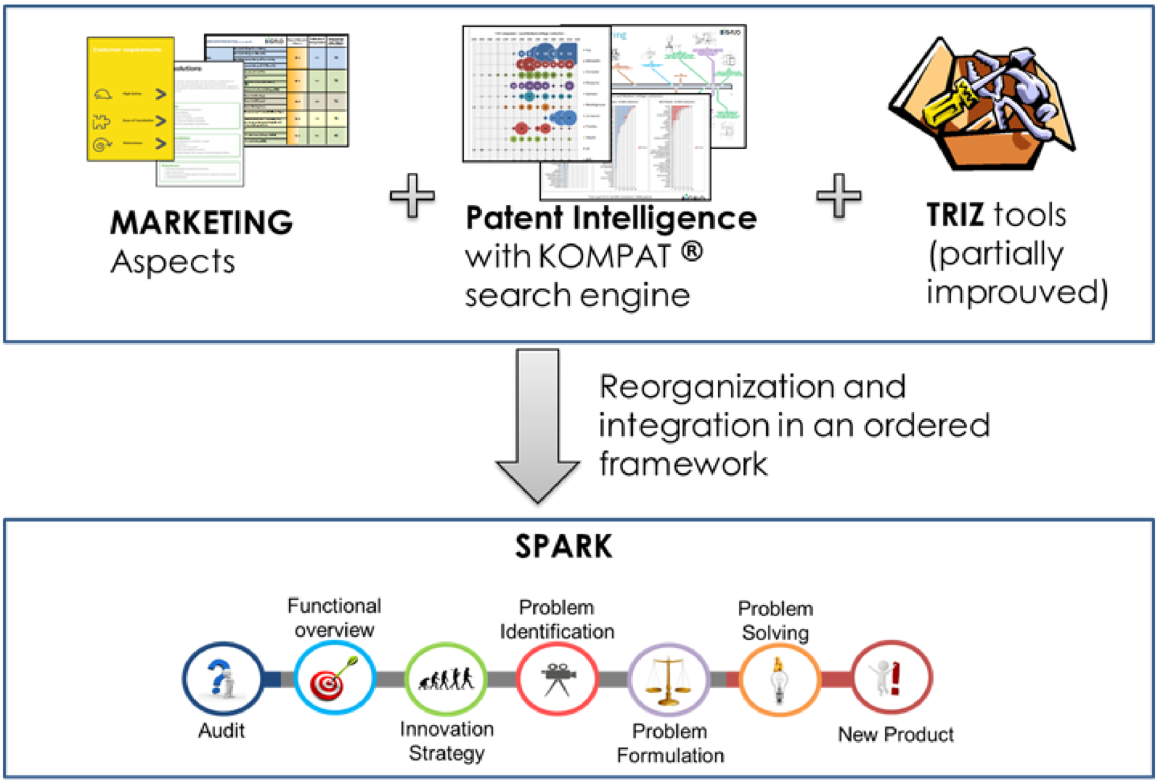


FIGURE 29: THE CONTENT OF SPARK METHODOLOGY.

Spark methodology is divided into the following five steps:

- ***Functional overview*** collects and reorganizes the information about the function that we want to perform with our system/product;
- ***Innovation strategy*** defines the evolutionary overview of the considered product, by evaluating it in accordance to its requirements and in relation to the main competitors;
- ***Problem identification*** identifies the problems and the potential resolutive directions to solve them;
- ***Problem formulation*** support the user in reformulating the problems in a more suitable form to be solved;
- ***Problem solving*** support the idea generation.

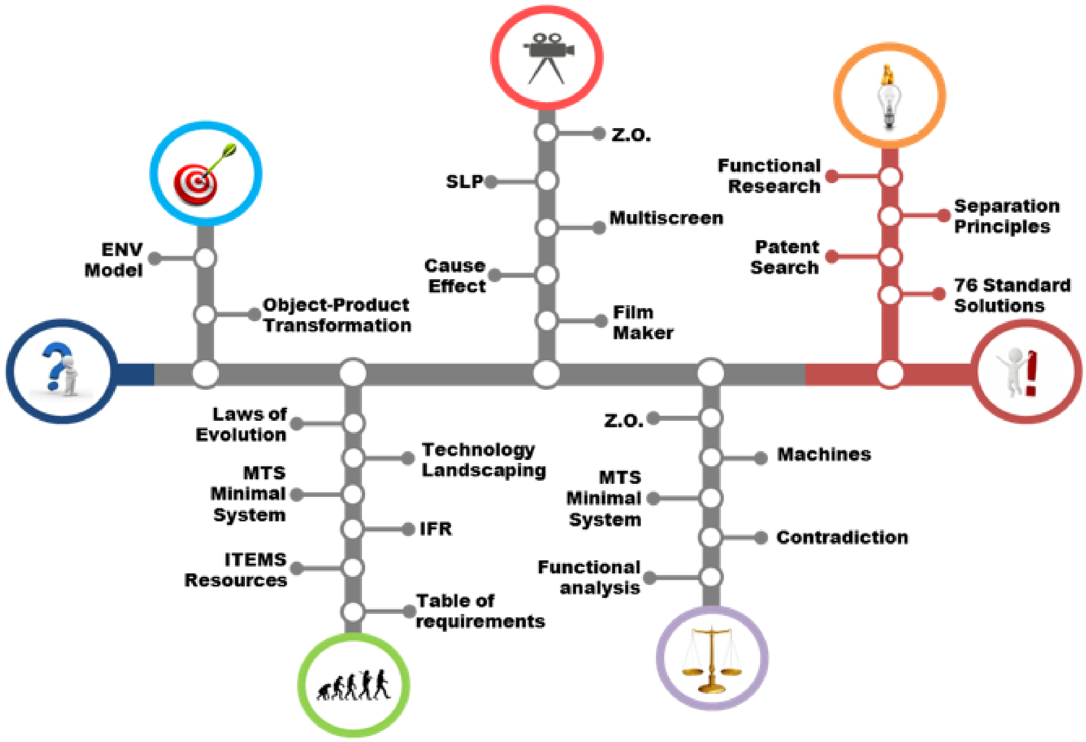


FIGURE 30: SRARK METHODOLOGY.

In the following, the five steps and the contained tools are presented in detail:

Functional overview

The aim of the functional overview is to collect and analyse the information about the product functionalities and the main useful function. To support this phase, the methodology suggests the use of two TRIZ tools:

- ***The Object-product transformation*** model helps in summarizing the main useful function through three elements: the object, or the entity that undergoes the action of the device, the product, or the object transformed after the action of the device and a verb that indicates the main useful function, or the transformation that "transform" the object into the product.
- ***ENV model*** (Khomenko et al. 2007 [110]) describes an element (object or product or other entity) in an univocal and objective manner, through three information: the name of the considered element, the name of the parameter that describe the element and a value to quantify the parameter.
  Inside Spark methodology, the ENV model is used to determine the main useful function, by describing the object and the product and by comparing their parameters.

Innovation strategy

This step helps in defining the scenario about the future developments of the device, by suggesting the following tools:

- ***IFR (ideal final result)*** is used to identify the ideal product of the object-product transformation, which is considered as term of comparison to evaluate level of development of the current device.
- ***Technology landscaping*** aims to create/catalogue the state of the art about the technologies able to realize the main function (on the basis of patents, technical catalogues and scientific literature) in order to provide the possible resolutive-directions and to highlight the "White space opportunities" or those technical areas not covered by patents.

The resulting scheme is organised in a hierarchical map based on a Function Behaviour Structure classification.

Figure 31 provides an example of technology landscaping, where the white space opportunities are heighted with "?".

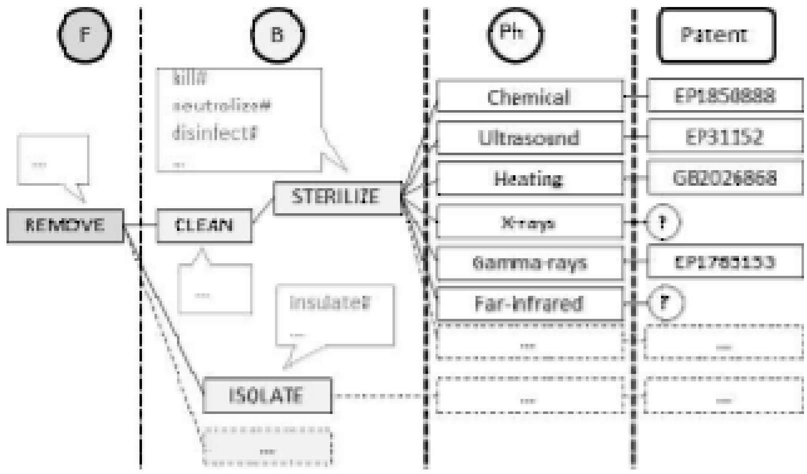


FIGURE 31: TREE-DIAGRAM OF CONTACT LENS STERILIZATION SHOWING DIRECTIONS AT THE STATE-OF-THE-ART AND THE POSSIBLE WHITE SPACE OPPORTUNITIES IN FORM OF (F)-(B)-(PH) TRIPLETS. (RUSSO ET AL. 2012 [33]).

- The ***Table of requirements*** collects the requirements of the device ant it orders them on the basis of importance and satisfaction parameters by using the "KOMpetitive Intelligence" technique (Russo and Duci, 2015 [47], Montecchi and Russo, 2012 [111]). The approach integrates knowledge extracted from patents, market analysis and scientific literature and it evolves through three phases: Information gathering, requirements evaluation and the definition of the innovation strategy.

Problem identification

In the third step, Spark suggests to deeper analyse the problem by discretising the dynamic of the problem during time and by dividing it into some simpler problems on which to work.

The tool of the Film Maker (Duci and Russo, 2014 [112]) is used in this phase to describe the dynamics of the current situation as a cause and effects chain, where each frame describes the effect of the actions of the previous frame.

Problem formulation

This step helps to formalise the problem in a more suitable way to be solved, i.e. through the contradiction model. The suggested tools are:

- ***TRIZ Functional analysis*** to formalize the previously identified sub-problem through the involved elements and shared actions (positive, negative, insufficient and excessive).

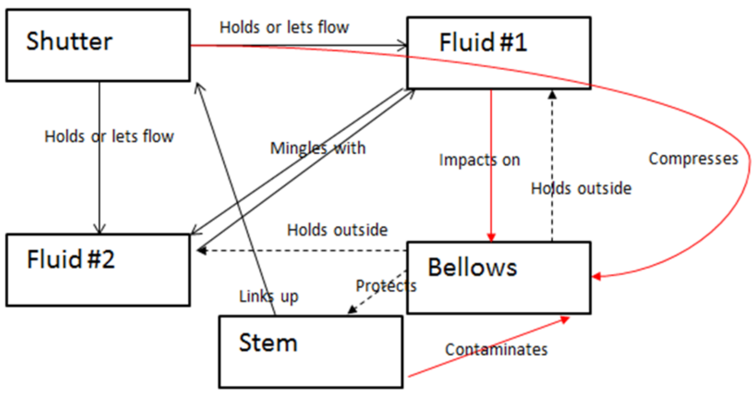


FIGURE 32: TRIZ FUNCTIONAL ANALYSIS FOR A VALVE.

- ***Physical Contradictions*** help in describing a problem where a device is not able to contemporary satisfy two opposite requirements, through the definition of a parameter of the technical system that opportunely designed can reach both the requirements. According OTSM model of contradiction (Figure 33), the two requirements are respectively called Evaluation Parameter 1 (EP1) and Evaluation Parameter 2 (EP2), while the Control Parameter (CP) is what is to be designed.

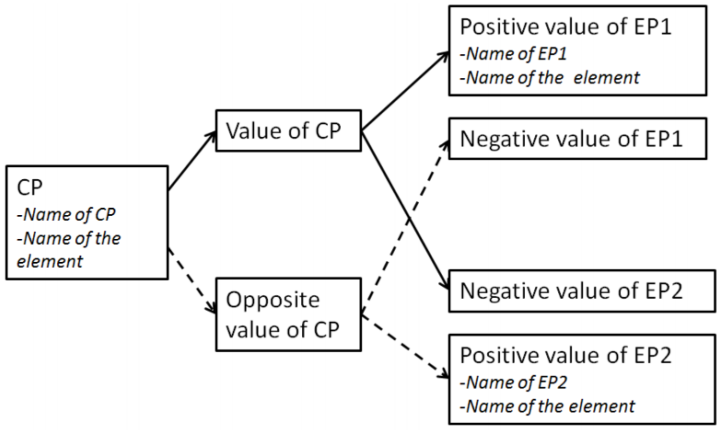


FIGURE 33: OTSM MODEL OF CONTRADICTION.

Problem solving

This phase contains the main TRIZ tools for idea generation:

- ***Separation principles*** support the problem solver during the solution of the contradictions by separating the conflicting elements inside the operative zone and the operative time.
- ***40 Inventive principles*** are a finite number of suggestions generally used to solve contradictions. Since the first publication (Altshuller and Shapiro, 1956 [113]), the inventive principles were improved several times by involving some aspects: ontology (e.g., Altshuller 1984 [15]), additions (e.g., Altshuller 1971 [114], Terninko 1998 [115]) and classifications based on physical attributes and mechanisms (e.g., Ross, 2006 [116]), degree of abstraction (e.g., Mann (2002)[117]) and suggested technologies (De Saeger and Claeys, 2008 [118]).
- ***76 Standard solutions*** were created by Altshuller starting from 1975 to solve common inventive problems that generally do not involve contradictions and they are divided, according to the last formulation provided by Salamatov (2005) [119], into the following 5 classes:
  - Class 1: Improving interactions and eliminating harmful effects;
  - Class 2: Evolution of systems;
  - Class 3: Transition to macro and micro-levels;

- Class 4: Measurement and Detection problems;
- Class 5: Helpers.

Spark limitations

The results deriving from Spark application during the years allowed to evaluate to identify the main advantages and limitations and to improve it. However, nowadays, the methodology already contains some shortcomings that can be summarized as follow:

- ***Method application:*** differently to TRIZ, Spark classifies all the contained tools into 5 fundamental steps. However, no suggestions about the order of application of the tools inside the steps is already missing.
- ***Application of the contained tools:*** the success of Spark depends also by the proper application of its tools, which is in part affected by the level of knowledge of the problem solver. In particular, un-expert users could not fully comprehend their essence, especially in the case of the 40 inventive principles and the 76 standard solutions, by compromising the success of the method.
- ***Addressed problems:*** Spark can support a huge multitude of different technical problems: product improvement, requirements evaluation, solving contradictions, physical investigation, etc. However, in some applications, such as new concept design, the methodology does not provide adequate support.

6. Proposals for a new set of guidelines for inventive problem solving

So far, a detailed analysis about different aspects of problem solving has been presented. A limited number of inventive problems have been identified inside a larger set of technical problems and some of the features of the supporting guidelines (structure and suggested approaches) have been analysed through literature surveys and empirical evidences collected during industrial practice and tests with the students.

These suggestions have then been applied to define a comprehensive set of guidelines to support inventive problem solving through the revision of the weakest part Spark methodology, according to the study carried out, and the development of specific integrations. In the following the resulting approaches are presented.

6.1. Introduction of a new Conceptual Design Scheme

The carried-out analyses about the addressed approaches highlighted the advantages of design models in supporting new concept design and product re-design. In this case, Spark methodology is weak due to the lack of a specific jargon and of guidelines that direct the user to the determination of key features for the design process (e.g., the determination of the behaviour and the manipulation of the device).

In order to overcome these limitations, a comprehensive approach to support conceptual design problems, including the most important elements of design (Function, Behaviour, Structure, Affordances, Signals), reformulated through a logical formalism has been proposed, and from it, a specific set of guidelines has been derived. This work has been carried out in collaboration with the University of Pisa and the results are reported in Spreafico, Fantoni and Russo (2015)[120] and have been presented during the conference ICED 2015. The resulting scheme has been applied to an industrial problem in collaboration with Tenacta-Imetect. It also led to the patent ITMI2013A001928 (Montecchi, Russo, Spreafico).

The scheme has been carried out through the following steps:

- STEP 1: the main involved elements have been identified through the literature analysis previously presented.
- STEP 2: a logical order of application of the main elements has been defined and a first deriving scheme has been determined.
- STEP 3: the scheme at STEP 2 has been enlarged by splitting all the considered elements into sub-elements in order to consider the double perception of the designer and the product user and the components of the structure of the product.
- STEP 4: a set of guidelines have been developed in order to explain the proposed design models at STEP 3 and how to use it to support conceptual design problems.

Figure 34 shows the new conceptual design scheme at STEP 2, its enlarged version at STEP 3 and the proposed guidelines.

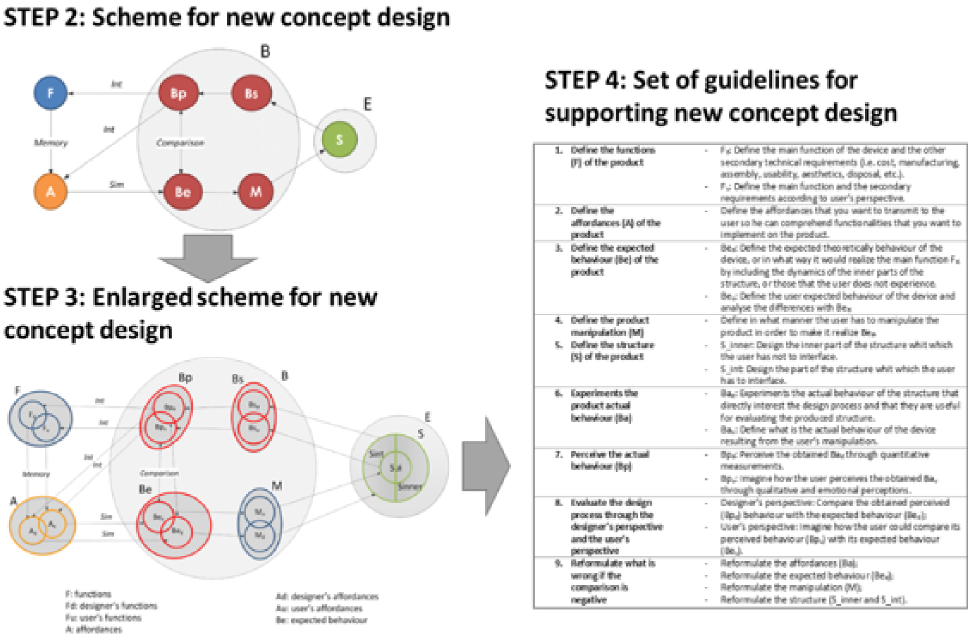


FIGURE 34: PROPOSED APPROACH FOR NEW CONCEPT DESIGN AND RELATED GUIDELINES.

In the following, the followed steps (2-4) are described in detail:

STEP 2: Scheme for new concept design

The overall scheme is constituted by a series of elements sets (e.g., the set of the functions, the set of the behaviours, the set of the structures) containing all the alternative entities to solve the problems and the relations among them. For instance, to realize the function F1 (e.g., cut the grass), included into the function set (F), two possible structure can be used (e.g., a blade and a rotating wire), both contained in the set of the structures

The starting point of the design process described in the scheme is the analysis of the functions (F), which are defined by the customers and the normative. The designer thinks then about the affordances (A) to implement on the structure that has already to be defined. Gero and Kannegiesser (2004)[75] call this process "Memory". After that, the designer simulates (Sim) the expected behaviour (Be) of the structure and thinks about the proper manipulations (M) of the device. The designer designs the structure (S) of the product and she/he realizes the physical prototype that interacts with the external environment (E). The designer experiments then the actual behaviour (Bs) through the prototype and she/he perceives this behaviour by obtaining the perceived behaviour (Bp). Through the comparison between the perceived behaviour and the actual behaviour, the designer interprets if the product can realize the functions and if the affordances are able to correctly communicate the product functionalities to the user.

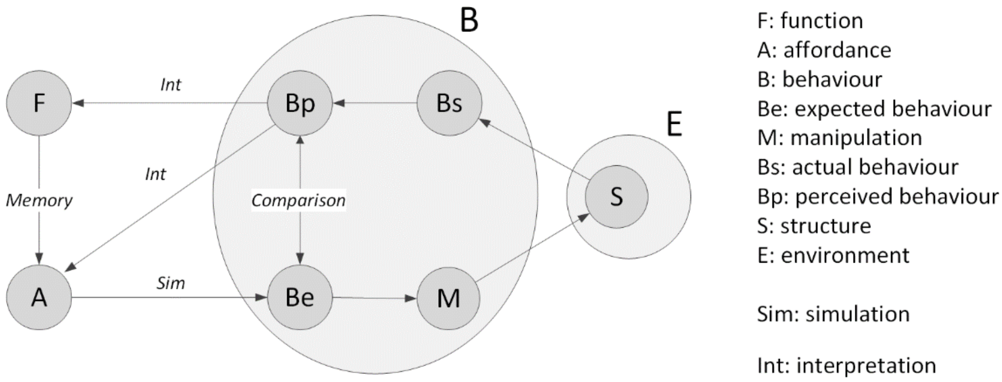


FIGURE 35: SIMPLIFIED PROPOSED SCHEME (SPREAFICO, FANTONI AND RUSSO (2015)[120]).

STEP 3: Enlarged scheme for new concept design

At this stage, all the elements of the previous scheme have been enriched with user's perspective. This leaded to the internal division within the sets of the entities into two subsets for each of them: the designer's subset and the user's subset. The first one contains all the elements designed by the designer, while the second one those interpreted or desired by the user. Some elements can be contained in both the subsets, while others belong only to one of them. In this scheme, the functions set (F) is divided into the functions intended by the designer (F_d) and functions assessed by the user (F_u), which can be different since the user might expect some functionalities which have not been designed on the device or because the user does not comprehend some of the present functions. The affordances set (A) is divided into designer's affordance (A_d) and user's affordance (A_u) that respectively represents the affordances implemented by the designer on the product and the affordances comprehended by the user by observing and interacting with the product. Even behaviour (B) is divided into the two subsets: designer and user starting from different affordances can simulate (Sim) different expected behaviours of the device: Be_d for the designer and Be_u for the user. In addition, also the designer's manipulation of the device (M_d) can be different from the user's manipulation (M_u) if the user manipulates the device in a not proper manner. The structure has instead been divided into tree subsets: the designed interface (Sint), the user's interface (Sui) and the inner interface (Sinner). Sint represent the part of the structure with which the user should interact, Sinner the one with it the user has not to interferes (e.g., the inner parts and the engine) and Sui is the part of the structure with which the user interacts. Sui can include parts of Sint and Sinner. The actual behaviour has been divided too into Bs_d and Bs_u and the perceived behaviours Bp_d and Bp_u by following the same logic of the previous subset divisions.

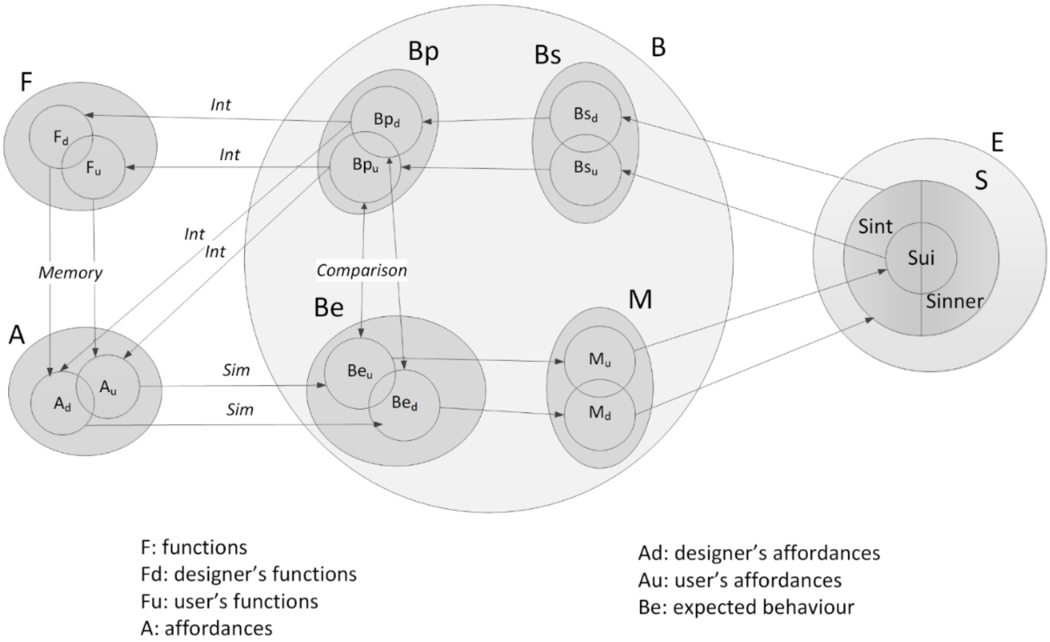


FIGURE 36: THE PROPOSED SCHEME WITH THE SUBDIVISIONS OF THE ELEMENTS BY CONSIDERING DESIGNER AND USER'S PERSPECTIVES ABOUT THE PRODUCT (SPREAFICO, FANTONI AND RUSSO (2015)[120]).

Through the proposed design scheme, the problem solver can design a new concept or redesign an already existing product by considering also the user's perspective at each step of the design process. For instance, when the designer chooses the functions of the device according to its perspective (F_d) has also to consider the functions required by the user (F_u) and the possible differences between them. This duality designer vs user involves all the stages in design process.

STEP 4: A set of guidelines to support new concept design

In order to support the problem solver in using the proposed scheme and to provide her/him a rigorous ontology to define each step of the methodology, a set of guidelines have been developed.

In particular, each set of features "X" in the design scheme (e.g., the set of the functions "F", the set of the expected behaviours "Be", the set of the manipulations "M", etc.) is divided into two distinct subsets: one contains the feature designed by the designer "X_d" (e.g., F_d, Be_d, M_d) while the other contains the features of the user "X_u" (e.g., F_u, Be_u, M_u). In general, the intersection between the two sub-set ($X_d \cap X_u$) represent the features implemented on the device by the designer and apprehended by the user. The area ($X_d - \{X_d \cap X_u\}$) contains instead the features implemented on the device and not experimented or comprehend by the user. The area ($X_u - \{X_d \cap X_u\}$) contains instead the features intended by the user and not considered by the designer.

In particular, in order to support the designer during product design so that it can consider the user's interactions with the product, each guideline has been divided into two parts: part (a) suggests to the designer how to determine the features that the user does not experiments (contained in the area $X_d - \{X_d \cap X_u\}$), while part (b) suggest the designer how to determine the features that the user has to experiment (contained in the intersection $X_d \cap X_u$) in order to interact with the device in a proper way.

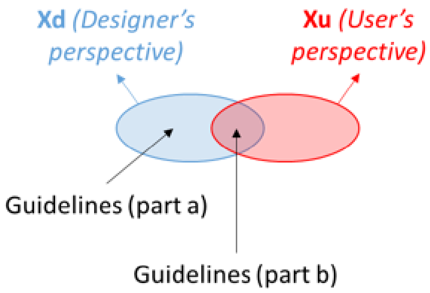


FIGURE 37: PART A OF EACH GUIDELINE SUGGESTS TO DETERMINE THE FEATURES NOT INTENDED BY THE USER, PART B SUGGEST INSTEAD THE FEATURES DESIGNED BY THE DESIGNER THAT THE USER MUST INTEND.

Table 20 contains the developed guidelines. In this case, for each guideline, the goal and the suggestions have been specified, without dividing, in this version, the first one into main goal and sub-goals and the suggestion into generic and specific. Some of the guidelines will be structured in a stricter way (e.g., by specifying the specific suggestion) in chapter 7.

TABLE 20: THE PROPOSED SET OF GUIDELINES TO SUPPORT NEW CONCEPT DESIGN.

Goals	Suggestions
1. Define the functions (F) of the product	- F_d: Define the main function of the device and the other secondary technical requirements (cost, manufacturing, assembly, usability, aesthetics, disposal, etc.). - F_u: Define the main function and the secondary requirements according to user's perspective.
2. Define the affordances (A) of the product	- Define the affordances that you want to transmit to the user so she/he can comprehend functionalities that you want to implement on the product.
3. Define the expected behaviour (Be) of the product	- Be_d: Define the expected theoretically behaviour of the device, or in what way it would realize the main function F_d, by including the dynamics of the inner parts of the structure, or those that the user does not experience. - Be_u: Define the user expected behaviour of the device and analyse the differences with Be_d.
4. Define the product manipulation (M)	- Define in what manner the user has to manipulate the product in order to make it realize Be_d.
5. Define the structure (S) of the product	- S_inner: Design the inner part of the structure whit which the user has not to interface. - S_int: Design the part of the structure whit which the user has to interface.
6. Experiments the product actual behaviour (Ba)	- Ba_d: Experiments the actual behaviour of the structure that directly interest the design process and that they are useful to evaluate the produced structure. - Ba_u: Define what is the actual behaviour of the device resulting from the user's manipulation.
7. Perceive the actual behaviour (Bp)	- Bp_d: Perceive the obtained Ba_d through quantitative measurements. - Bp_u: Imagine how the user perceives the obtained Ba_u through qualitative and emotional perceptions.
8. Evaluate the design process through the designer's perspective	- Designer's perspective: Compare the obtained perceived (Bp_d) behaviour with the expected behaviour (Be_d);

	and the user's perspective	-	User's perspective: Imagine how the user could compare its perceived behaviour (Bp_u) with its expected behaviour (Be_u).
9.	**Reformulate what is wrong if the comparison is negative**	- - - -	Reformulate the affordances (Ba); Reformulate the expected behaviour (Be_d); Reformulate the manipulation (M); Reformulate the structure (S_inner and S_int).

The proposed approach and Spark methodology thanks to some overlapping in Spark Step #1 "Functional overview" and Spark Step #2 "Evolutionary overview". In this way, the proposed approach can provide the strategy of use and the ontological formalism, while Spark tools can support the application of the approach:

- *The object-product transformation:* helps in defining the main useful function as the consequence of the transformation of the object (the element that undergoes the action of the device) into the product (the object transformed after the action of the device). The main useful function is the action performed by the device to transform the object into the product.
- *ENV model:* by redefining the object-product transformation in term of the modification of certain parameters of the object and of the environment, the designer can use the ENV model to quantify the main features of the object and the product.

6.2. Improving FMEA-TRIZ model for anticipatory failure investigation

The carried-out literature analyses confirmed the importance of the anticipatory failure investigation in inventive problem solving and they focused the attention on the shortcomings and the numerous open problems of the supporting approaches (FMEA and its improvements).

For these reasons, an integration between traditional FMEA and Spark has not been considered, but other methods, more suitable to be integrated with inventive problem solving, have been investigated: the Subversion Analysis developed by Mann (2002)[7] and implemented in the Anticipatory Failure Determination AFD by Kaplan et al. (1999)[121] and the scheme developed by Regazzoni and Russo (2011)[100].

By considering these approaches, a step by step procedure based on FMEA and including some TRIZ tools has been proposed and presented during ETRIA TRIZ Future Conference 2016, and from it, a set of guidelines have been derived with the aim to achieve the following objectives:

- Anticipate the analysis of the failures during the product design phase in order to facilitate the corrective actions.
- Ensure the integration with TRIZ and Spark tools in order to enhancing the analysis by better specifying the faults in relation to operative time and operative space.
- Change the modalities of determination of the failure modes in order to streamline the analysis.
- Make the anticipatory analysis approach more pro-active in order to better involve the problem solving and its creativity.

In the following, the two considered approaches are presented and then the proposed approach is explained.

Subversion analysis

In extreme synthesis, the method of the Subversion Analysis helps the problem solver in finding all the ways to destroy the current product; those are the failure mode. For this reason, differently to FMEA, during the Subversion Analysis, the problem solver is mostly involved in a creative and pro-active approach to find the failures: she/he uses TRIZ method not to invent a new system, but to provoke a damage, by using TRIZ tools, suggestions and resources. Once the failures have been determined, the approach suggest the use of TRIZ to solve them. The main steps of the subversion analysis are the following:

1) problem definition;
2) formulation of the inverted problem;
3) definition of the function;
4) identification of the failure modes;
5) description of the effect;
6) determination of the causes;
7) identification of the failure hypothesis;
8) research of the solutions.

Regazzoni and Russo's approach

Regazzoni and Russo (2011)[100] proposed a new paradigm to enhance risk management by integrating parts of FEMA and TRIZ and by adopting the logic of the Subversion Analysis. In this approach, some TRIZ tools helps not only in solving the identified failures but also in determining them. The main steps of the subversion analysis are the following:

1) ***Identification of the primary function*** of the product is carried out through the traditional TRIZ tools Energy Material Signal (EMS) model and Element Name Value (ENV) model.
2) ***Definition of elements and failure effects.*** In this phase a selection of the most important components and the possible related failure effects of the technical system and of the environment are determined and analysed through experts' interrogations and by using the proposed Element and negative effects tree.
3) ***Effects modelling with ENV model.*** In this phase the ENV model is used to identify the failure modes by increasing and decreasing the nominal values of the features of the described parameters in order to the realise the previously determined failure effects.
4) ***Assess risk via RPN.*** The risks of the failure modes are evaluated according to FMEA criteria for the calculation of the Risk Priority Number.
5) ***Subversion analysis.*** For the most critical failures, the possible failure causes are investigated by using the Substance-Field model to map the failures and the standard solutions to determine the possible causes.
6) ***Problem solving.*** The identified problems are solved by using TRIZ.

6.2.1. The proposed approach

In the following, the main steps of the proposed approach are explained in detail:

Main useful function determination

The starting point of the proposed approach is the determination of the main useful function. This because it helps in better defining the product and in determining in what way the Failure Effects affect its realisation. Step 1 of Spark methodology is specifically addressed in supporting the problem solver in this phase.

Failure effects determination

In order to determine the Failure Effects without using the entire bill of material, TRIZ functional analysis can be used in two ways: firstly, the analysis aims to mapping the main elements of the system by highlighting the actions shared between them in the current condition. Secondly the analysis can be adequately perturbed by simulating possible off-design conditions of the described elements in order to understand how these conditions change the shard actions by determining possible negative effects. The perturbed functional analyses can be used by experts to discuss the possible failure effects deriving from the off-design conditions. In the following the three steps of the methodology are explained in detail.

System map through TRIZ functional analysis

In order to map the main components of the technical system (or the component itself), the user and the external environment and the relations (positive, negative, insufficient and excessive) among them. The suggestion is to map with the functional analysis only the main element by maintaining an abstract level of detail in order to not complicate excessively the analysis. In this way, the elements of the functional analysis are generally assemblies of components rather than the basic components themselves, even if some of the most important ones still be considered if they play crucial role in the analysis, or if the analysed system is too simple.

Determination of the "perturbed" functional analyses (PFA)

Through this approach, the problem solver modifies one element at time of the functional analysis by hypothesizing an off-design configuration due to possible errors during the production phase or during the phase of use (an anomalous user's manipulation, an unconsidered variation in the environment condition, etc.). Since the elements can be both simple components and assemblies of components, the variation, the variations are in all the cases off-design conditions of the components, but in the first case the description is limited to the component itself (dimensional error in the screw core diameter), while in the second case the variation consider the entire assembly (excessive electrical consumption of a drill). In this way, the suggestion is to describe the assemblies as black boxes and their off-design conditions as the variations in their input and output parameters. In addition, since the aim of this procedure is to simplify the analysis of the system, the presence of the assemblies in the analysis should be more common of that of the single components.

In order to identify in what manner, the elements of the functional analysis can change, the designer can use the list of noise factors (environmental variation during the product's usage, manufacturing variation, and component deterioration) from robust design theory, to hypothesize the variations both of the components and of the assemblies.

Table 21 presents an example of Noise Factors adapted from Byrne and Taguchi (1987).

TABLE 21: EXAMPLES OF NOISE FACTORS (ADAPTED FROM BYRNE AND TAGUCHI, 1987).

Product Design	Process Design
Consumer's usage conditions	Ambient temperature
Low temperature	Humidity
High temperature	Seasons
Temperature change	Incoming material variation
Shock	Operators
Vibration	Voltage change
Humidity	Batch to batch variation
Deterioration of parts	Machinery aging
Deterioration of material	Tool wear
Oxidation (rust)	Deterioration
Piece to piece variation where they are supposed to be the same (e.g., Young's modulus, shear modulus, allowable stress)	Process to process variation where they are supposed to be the same (e.g., variation in feed rate)

All design parameters (e.g., dimension, material selection)	All process design parameters All process setting parameters

As consequence of the elements variation in the functional analysis, the shared actions between the considered element and the others and also the relations between the other elements can change in different ways: a sufficient action can turn for example in an insufficient one, a new negative action could manifest, etc. The task of the problem solver is to redefine the shared actions for each identified configuration.

The following graph (Figure 38) shows the logic of the perturbed functional analysis: for each perturbed element of the functional analysis, one or more perturbed functional analyses can be determined.

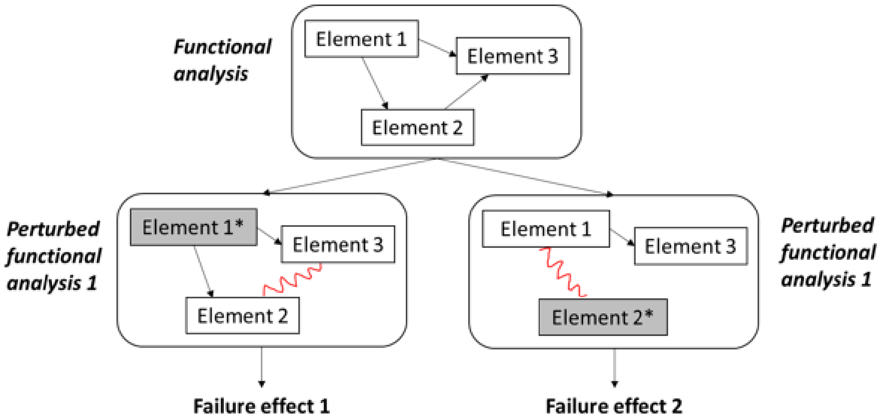


FIGURE 38: PERTURBED FUNCTIONAL ANALYSES-PFA.

In order to identify the changes in the relations between the elements and the failure effects deriving from these relation, the problem solver can use the Film Maker tool (Russo and Duci, 2014 [112]). This tool is used to describe the dynamics of the current situation by including the modified element, representing the complexity of the problem as a sequence of events. This tool is studied to highlight the cause-effect relationships that involve time, is composed of a sequence of states and are represented in frames on a time axis. In this sense, each state represents a picture of what is happening in a specific instant of time.

By using the Film Maker, we can represent at a high level of detail, in what way the variation of the considered element affects the relations with the others, and in particular by specifying when (in what precise instant of time) the changes occur.

<u>Failure effects determination</u>

Each perturbed functional analysis can be analysed by experts, which they determine one or more Failure Effects deriving from the modified elements and the modified relations between the elements (especially from the negative and the insufficient ones).

Also in this case the already performed Film Maker can be used to determine the Failure Effects, since they can be considered as the consequences of the modified actions that can occur in the same photogram of occurrence of the modified actions or in successive photograms.

In addition, once the photogram of occurrence of the Failure Effect has been identified, the problem solver can better analyse it by "zooming inside" in order to increase the level of detail in order to better circumscribe the Failure Effect also to a precise zone of occurrence in addition to the time of occurrence.

The following figure (Figure 39) shows an example that explain how the presence of the perturbed element "Presence of air bubbles in the paint" can turn the adhesion of the paint on the surface into insufficient (modification of the element of the functional analysis) and this leads to a possible Failure Effect (Peeling of the paint from the surface) during a further successive instant of time. In addition, the Failure Effect has been further analysed by identified the precise zone of occurrence of the Failure Effect, or the cavity between the beads.

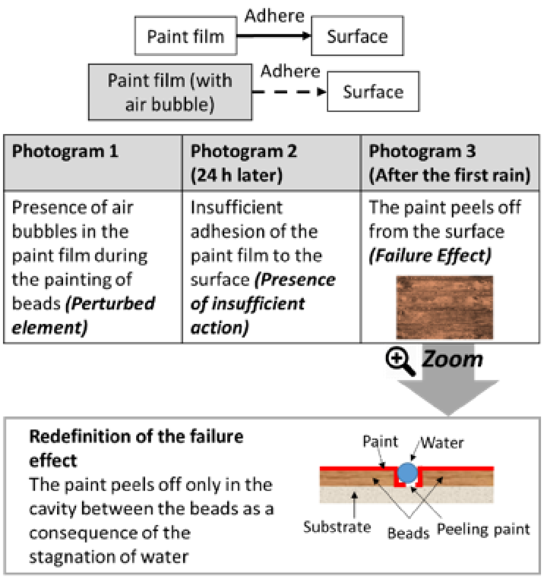


FIGURE 39: EXAMPLE OF DETERMINATION OF MODIFIED ACTIONS BETWEEN ELEMENTS AND FAILURE EFFECTS THROUGH FILM MAKER.

Through this approach, the problem solver can identify the Failure Effects without using the entire bill of material to determine all the possible Failure Modes. In addition, the proposed method is able to describe the Failure Effects in a more precise way, by identifying their time and the space of occurrence.

Failure Causes determination

Once all the Failure Effects have been determined, our suggestion for the problem solver is to evaluate them in order to identify the most critical ones, determining their Failure Causes and solving the related problem. The suggested approach for both the cases is TRIZ theory, according to the logic of the Subversion Analysis for the determination of the Failure Causes and in the traditional way to solve the problems.

Through the subversion analysis, the problem solver tries to voluntary provoke the Failure Effects by using all the resources and the physical effects available in the system. Those responsible are the Failure Causes.

Once the failure effects and the failure modes have been determined, the problem solver has to find their possible failure causes or the anomalies in the entities that constitute the system responsible of the off-design modification of the parameters of the elements mapped in the ENV model. These anomalies can be represented by the not provided manifestation of a certain physical effect or by a particular structural property not considered (cracks, blowholes, impurity in the materials, etc.). Spark methodology supports this phase by providing some specific tools to identify physical effects and structural resources (failure causes) to recreate the failure effect: e.g., TRIZ 40 inventive principles (e.g., #31 “Porous materials”) and KOMPAT effects DB.

Problem solving

Once the Failure Causes have been determined, we can solve the identified future problems by using part of Spark methodology in order to avoid their occurrence or mitigate their effects. In particular, Spark Step 4 “Problem formulation” is used to reformulate the problem in a more suitable way to be solved (e.g., physical contradiction). Spark Step 5 “Problem solving” suggests instead how to solve the identified problems through the application of the contained tools (e.g., separation principles, 40 inventive principles and 76 standard solutions).

6.2.2. The derived guidelines

On the basis of the proposed approach, a specific set of guidelines for the anticipatory failure determination have been determined. The guidelines are reported in the following table (Table 22).

TABLE 22: THE PROPOSED SET OF GUIDELINES TO SUPPORT THE ANTICIPATORY FAILURE ANALYSIS.

Goals	Suggested strategy (Generic suggestions)	Suggested tools (Specific suggestions)
1. Determine the main useful function of the device	Determine the device main useful function of the reason for which the system has been realized.	Use the MTS model and the ENV model
2. Identify the main elements of the system and their shared actions	Identify the main components that constitutes the system (the user, the product and its main components and the environment) and identify their relations.	
	Identify the shared relations between the elements.	Use Su-Field model to describe ideal actions, insufficient actions, harmful actions and excessive actions.
	Map the considered elements and their relations.	Use TRIZ functional analysis.
3. Perturb the functional analysis	Modify an element of the functional analysis by hypothesizing possible off-design configurations (Failure Mode).	Use the Noise Factor list as triggers
	Modify the relations between the elements as consequence of the modified element.	
	Repeat the procedure also for the other elements by obtaining other perturbed functional analyses.	
4. Determine the Failure Effects	Use the perturbed functional analyses as base of discussion to determine the Failure Effects deriving from each condition.	
	Represent the dynamic of occurrence of the identified Failure Effects, by identifying the instant of time of occurrence and the critical zone of occurrence of the Failure Effect.	- Use TRIZ Film Maker to represent the dynamic of occurrence of the Failure Effect. - When you have identified the frame of occurrence of the Failure Effect, zoom inside it in order to circumscribe its

		precise zone of occurrence.
5. Determine the Failure Causes	Try to provoke the Failure Effect (in the critical instant of time and zone) and the Failure Mode by using the elements of the system and of the environment	Use Structural resources DB, physical effects DB and TRIZ multiscreen to identify the possible resources (internal and external to the system) that cause the failure effects and the failure modes.
6. Evaluate the determined Failure Effects	Prioritize the most severe Failure Effects, Failure Modes and Failure Causes	Use Risk evaluation technique, (e.g., RPN index)
7. Solve the identified problems	Avoid the possible manifestation of the Failure Effects or mitigate its manifestation.	Use Spark step 4 and step 5.

6.3. A new set of Inventive principles based on FBS

Despite the many reformulations proposed in literature during the years, the 40 inventive principles are already considered too subjective and not fully understood, especially in industrial contexts. This can be due to the high degree of abstraction with which many of the principles are written that lead inevitably to a certain freedom of interpretation. Let's consider for instance principle #1 Segmentation and principle #38 Strong Oxidizers: the first one suggests us to divide the system into several parts and recombine them later, while the second one suggest the introduction into the system of ionized oxygen or enriched air instead of the regular air. As we can see, the level of detail is very different between the two principles: the principle #38 is sufficiently clear and univocal, the principle #1 no. If on one hand, the high level of abstraction of a guideline can ensure a major freedom of application and it can lead to a major number of solutions, on the other hand this ambiguity may lead not fully capture the contained inventive essence.

In order to overcome these limitations, all the 40 inventive principles have been analysed from the Function Behaviour Structure (FBS) perspective and new definitions of the principles have been proposed (see Russo and Spreafico (2015)[122]) in order to make the user more aware if she/he is acting on the function, the behaviour or the structure of the device.

The analysis of the principles has revealed that in many cases, a perfect match between the original Altshuller's definitions of the principles and the FBS ontology is already present: only few principles forces the user to simultaneously act both on the function, the behaviour and the structure of the device. For some of them, two FBS entities are considered in the original form, and others suggest only one FBS "direction" at time. Consider for instance principle #5 Combining, that in its original form suggests: (a) Consolidate in space homogeneous objects destined for contiguous operations and (b) Consolidate in time homogeneous or contiguous operations. According to FBS logic, the first part is related to the structure of the object, while the second one to the behavioural aspects. If we consider instead principle #31 Porous Materials, all the suggestions provided are strictly related to the modification of the structure of the object: (a) make your object porous, (b) use porous coatings, (c) use porous inserts and (d) if the object is porous, fill the pores with other substances, liquid or gas to achieve positive effects.

Let's take for instance the principle #1 Segmentation. If a system cannot fulfil its goal, the traditional principle #1 Segmentation suggests to divide it into several parts and to recombine them later. By analysing the principle from an FBS point of view, we can observe that this principle explicitly suggests to work on the structure of the system (e.g., independent parts, object sectionable, segmentation of the object). In fact, this principle does not provide any suggestion on how to achieve the goal by acting on the function or behaviour of the system. For this reason, this principle has been extended to the other two entities of the FBS theory (function and behaviour), without misunderstanding its original essence. Through the proposed reformulation, the behaviour of the device can be segmented in order to discretize the operative zone and/or the operative time by changing the dynamics of the system. Therefore, the physical effects related to the behaviour may occur in a heterogeneous and variable way and they can be also recombined to create new synergies. The proposed "segmentation of the function" suggests instead to subdivide the function into sub-functions inside the operative zone and the operative time. In this way, when a function cannot be entirely reached, its realisation in parts (e.g., through a sequence of parts of the function) could be convenient if able to guarantee the same final result. In order to show how this reformulated principle can act, an exemplary case dealing with a toaster is proposed in the following. In this case, the function coincides with the need to obtain a slice of baked bread, the behaviour is the way of toasting, while the structure is the toaster itself. The following figures (Figure 40 and Figure 41) show the application of the traditional principle #1 Segmentation and the application of the reformulated FBS principle.

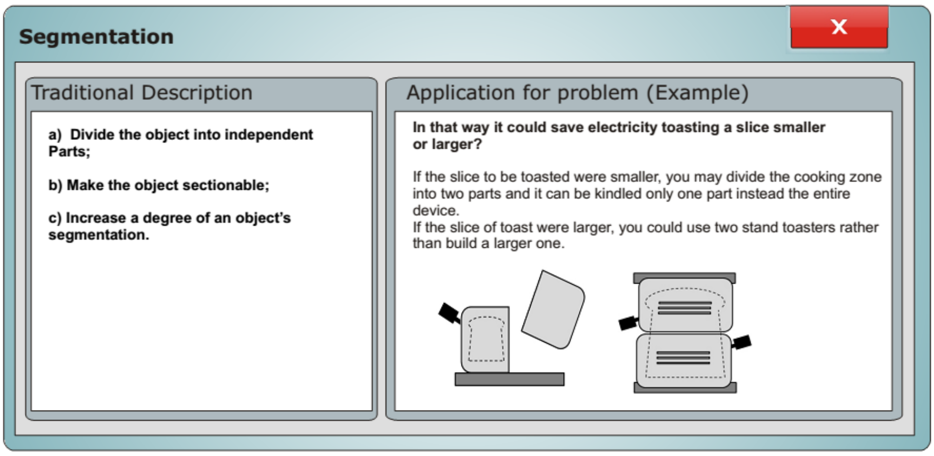


FIGURE 40: PRINCIPLE #1 SEGMENTATION (ORIGINAL FORM).

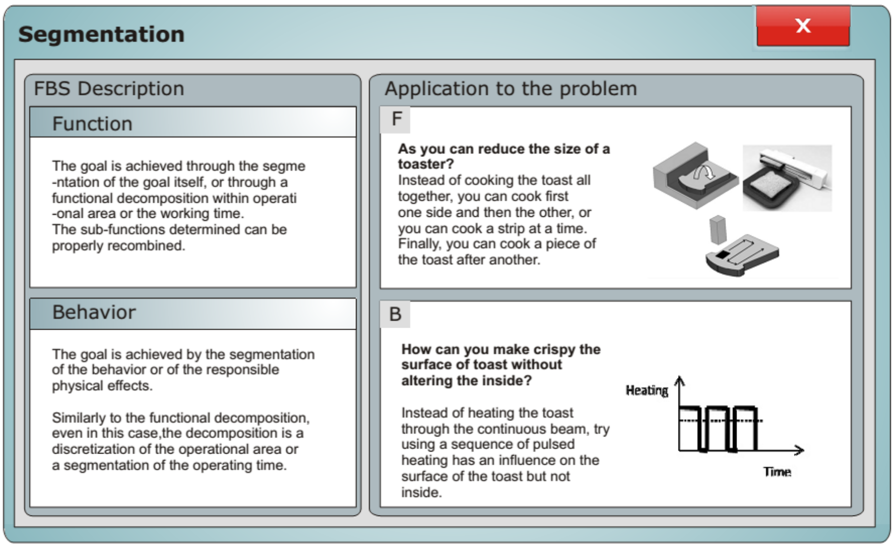


FIGURE 41: PRINCIPLE #1 SEGMENTATION (ACCORDING TO FUNCTION AND BEHAVIOUR FORM). STRUCTURE FORM IS IDENTICAL TO CLASSICAL ALTSHULLER'S DEFINITION IN THE FIGURE BELOW.

Table 23 contains the list of the most representative reformulated inventive principles, which have been divided into reformulated (REVISION) and new suggestions proposed (NEW).

TABLE 23: LIST OF MOST REPRESENTATIVE FBS INVENTIVE PRINCIPLES.

Altshuller's IP (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 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.	REVISION: 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 a specific part/time according to the local characteristics of the structure	REVISION: limit the goal (main function) only where/when needed
5. Combining a. Consolidate in space homogeneous objects destined for contiguous operations. b. Consolidate in time homogeneous or contiguous operations.	REVISION: 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.	REVISION: 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.	REVISION: 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.	REVISION: If your object is unreliable, prevent critical situations or compensate their	REVISION: If your object is unreliable, prevent critical situation changing the way	NEW: If your function/goal has to be changed and this is hard to

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.	harmful effects by modifying its structure or adding a new one.	to achieve the goal.	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. c. Use rotary motion. d. Use centrifugal forces.	REVISION: Change flat parts of the structure with a cavity or spherical curvature. Enter inside or outside of the device rollers, balls, spirals	REVISION: Use centrifugal forces	
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	REVISION: 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.	REVISION: Arrange the structure and / or the object in space rather than in a plane	REVISION: 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.	REVISION: 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	REVISION: If you need to use unavailable,	REVISION: If you need to use an	

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.	fragile, complicated, or dangerous object, substitute it with a physical or optical cheaper structure	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 of the object during operation.	REVISION: 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	REVISION: Remove a functionality when it becomes useless and eventually restore it later
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	REVISION: Change magnitude of the physical effect	

6.4. A new set of guidelines for measurement problems

The proposed guidelines are the result of 18 months of applications on diagnostic and prognostic in 3 companies with real case studies, involving different groups of professionals with and without TRIZ experience. During this activity, the guidelines of the class 4 (Measurement problems) of the traditional TRIZ 76 standard solutions (already included in Spark methodology) were firstly considered as possible candidates. These suggestions help the problem solver in measurement problems every time a direct measure is not possible. For this reason, they do not suggest sophisticated methods and tools of measure, but they face the measurement problems from another perspective: changing the problem or the target parameter to be measured.

In the traditional form, class 4 is organized in the following subgroups:

- Introduction of indirect measurement methods (3 solutions);
- Creation of a measurement system (4 solutions);
- Enhancement of the measurement system (3 solutions);
- Measurement of the ferromagnetic-field (5 solutions);
- Direction and evolution of the measuring systems (2 solutions).

In addition, the following general suggestions are proposed:

- Try to change the system so that there is no need to measure/detect;
- Measuring a copy;
- Introducing a substance that generates a field (introduce a mark internally or externally).

However, since their introduction, several efforts have been spent to improve them in order to overcome the difficulties in their application. Some authors (e.g., Khomenko, 2002 [123] and Souchkov, 1997 [124]) proposed new suggestions with the aim to facilitate their use. Other authors reformulated the standards by providing new notations (e.g., Kim, 2012 [125]) and new classifications (e.g., Mann, 2002 [7]). Several efforts have been spent in reducing the number of standards and the classes: Soderlin (2003)[126] proposed three main classes: improving the system with little or no change; improving the system by changing the solution; detection and measurement. However, despite the improvements proposed during the years, the standards solutions still struggle in the application of everyday engineering practice. Moreover, these works have only marginally interested the fourth class of the standards that still have the following limitations:

- the standards of these group acts at different levels of detail: some are too general (#4.1.1. Changing the measurement problem), others too specific (#4.3.2 Excite resonance oscillations).
- They do not have a hierarchical structure constituted by levels and sub-levels but they are all contained in the same class.
- They suggest only to use of certain resources for solving the measurement problems (#4.4.3. Introduce ferromagnetic additives in the substance), missing all the others.
- They do not integrate well with database of resources, physical effects and results from information retrieval (e.g., patent analysis).

For these reasons, a new set of guidelines for the measure problems has been developed. On the basis of what learned about the various contexts of application, the new guidelines are constituted by a less rigorous methodological formalism in favor of a leaner and more practical structure. In this way, they can be more easily applied, especially in industrial contexts. In particular, for achieving these aims the following sub-goals have been considered:

- Research of a schematic representation of the guidelines.
- Possibility of customizing the guidelines with a specific domain jargon.
- Integrating the standards with the databases of the resources (Physical effects DB and Structures DB).

To do this, the proposed schema, firstly presented in Russo and Spreafico (2016)[127], reorganizes all the suggestions into three main groups that express in what way a measurement can be performed:

1) Changing the problem in order to NOT measure the desired parameter (Altshuller's classes 4.1.1).
2) Maintain the technical parameter and measure it.
3) Measure a copy of the object (Altshuller's classes 4.1.2). Use substance database for selecting it.

In turn, if we maintain the technical parameter we can directly measure the interesting parameter X on it or performing and indirect measure (suggestion implicitly contained in the traditional standards) or the measure of a parameter Y influenced by X. In particular, the indirect measure contains all the other standards that have been revised.

Firstly, we must understand the meaning of relation between the parameters and the indirect measure. In logical-mathematical language, two parameters X and Y are related if Y=f(X) or X=g(Y), where the first one is named "dependent" parameter, the second one is "independent" and "f" is an expression that explains the linkage between them. While we perform a measure on a certain physical phenomenon (the degree of vacuum) or a physical object, X is a parameter that describe it and that we want to measure (the pressure of the gas inside an ampoule). Y is instead another parameter of the same phenomenon/object that we really measure because is more detachable than X. Given Y, we can obtain X through the expression Y=f(X). The nature of the relation f(X) depends on the degree of correspondence of the measure on X. The function f can be an analytical or a numerical expression that in case introduce a certain error on the derivative measure; other errors are introduced during the direct measure of X and Y.

Another clarification about the nature of X and Y regards the measured quantities. If we are interested on the absolute quantity ("measuring the value of the pressure of a gas") we have to entirely consider both X and Y; while if we are interested in a variation of the standard state ("measure the overpressure caused by …") we consider ΔX and ΔY and the relation between them is ΔY=g(ΔX), where the relation g is not necessary equal to f. This second situation is more used for detecting the anomalies in technical systems. For the explanation of the proposed method and for its use, the differences between X and ΔX are not important; on the contrary, this difference has to be considered during the evaluation of the measurement tools.

On the basis of these observations, the group of the guidelines for the indirect measure has been divided into two guidelines that suggest how to perform an indirect measure at a first level: (I) measure a field (F1) or (II) a substance (S1) directly influenced by the technical system, instead of the technical system itself.

In addition to these guidelines (that work at the step 1 of the indirect measure), other ones have been proposed for developing the suggestions provided by those already consider. The new guideless (step 2 of the indirect measure) can be used when the first-step guidelines cannot be applied due to insufficient magnitude of the field for performing the measure of the variation of the parameter or the substance cannot be detected. Two other guidelines suggest how to make an indirect measure at a second level: (I) measure a substance (S2) influenced by the field (F1), in turn influenced by the technical system and (II) measure a field (F2) influence by the substance (S1). The guidelines of the step 2 are a novelty respect the traditional standard solutions that they do not explicitly provided suggestions that work in this way.

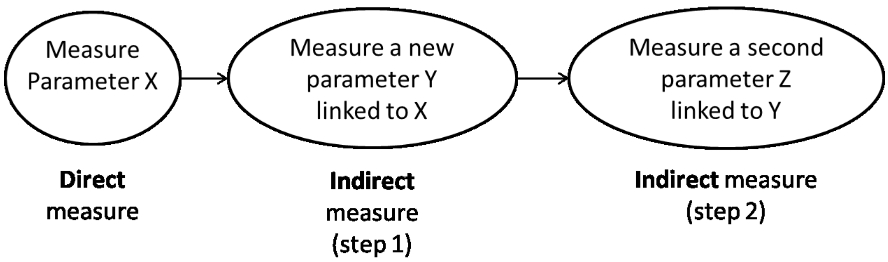


FIGURE 42: LOGIC SCHEME OF THE INDIRECT MEASURES (STEP 1 AND STEP 2).

Fields and substances can be already present in the technical system or they have to be introduced (activated). For their selection the effects DB and structure DB can be used.

Figure 43 represents the proposed scheme of guidelines for supporting measurement problems.

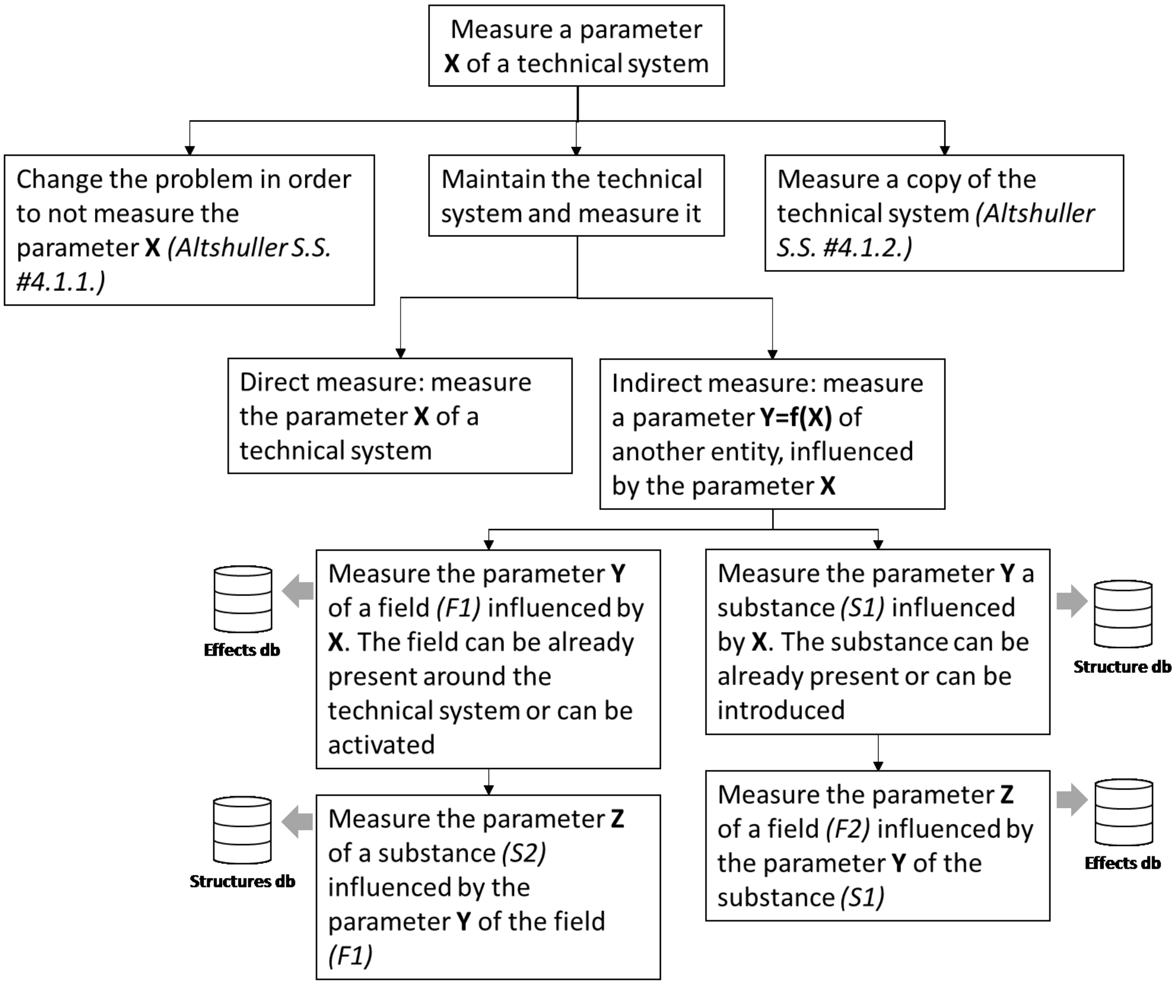


FIGURE 43: THE PROPOSED SCHEMA OF GUIDELINES FOR MEASUREMENT PROBLEMS.

The provided classification does not mention when and where the measurement take place (inside or outside the system), but a proper combination of introduced substances and fields allow us to do this in the more comfortable way (e.g., a remote wireless communication to measure parameters in dangerous places). In addition, for what concern the evaluation and the choice of the best measuring instrument, the discussion is more complex, often involving not technical criteria but more marketing and political choices, such as normative and other constraints.

6.5. Integration between FBS inventive principles and standard solutions

In classical TRIZ, 40 inventive principles and 76 standard solutions are generally considered as two independent tools that address different problems. The principles are generally more suitable for solving technical and physical contradictions, already reformulated, by suggesting how to segment the conflictual parameters in space and in time. The standards are instead applied independently for: improving the system with no or little change, improving the system by changing the system, supporting system transitions, solving measurement problems and providing strategies to simplify and improve technical systems.

However, some overlapping between the principles and the standards can be easily identified, which increases considerably if we consider the proposed FBS incentive principles, the standards for measurement problems and the 111 standard solutions provided by Russo and Duci (2015)[47]. Let's consider for instance the following principle #7 Nesting (function): "Add a functionality to the device by placing a new structure inside it" with this revised standard: "(H) If you have a missing action, (H4) Combine the system with another system".

Consequently, a unique and complete representation for the guidelines that support idea generation has been proposed. The resulting scheme is based on hierarchical structure proposed by Russo and Duci (2015)[47], enlarged with new groups for facing contradictions and measurement problems, and includes all the considered guidelines, specifically divided, recombined and redistributed. The suggestions provided for each group have also been distributed according to the level of detail according in line with what has been learned from the study on the structure of the guidelines: level 0 (4 faced problems/goal), level 1 (generic suggestion), level 2 (specific suggestion), level 3 (examples and results). In this way, the more abstract guidelines provide strategic suggestions for facing the problems while the more specific ones suggesting specific solutions at an operative level by integrating the "Helpers", already proposed by the 111 standard solutions. The helpers are specific suggestion regarding the adding and the modifications of substances and physical effects in the technical system. Let's consider for instance the helper "Add a substance" that suggest more abstract triggers such as "Add a present substance" or "Introduce chemical compound", derived by the standards and more detailed suggestions deriving from the principles, e.g., "Change flat parts of the structure with a cavity or spherical curvature. Enter inside or outside of the device rollers, balls, spirals".

The resulting scheme of guidelines addresses four kinds of problems (main goals): (1) Solving a contradiction, (2) Eliminating a harmful action or reducing an excessive action, (3) Improve an insufficient action and Replace a missing action and (4) Solving measurement problems. The goals suggest the sub-goals or directly the generic suggestions, that in turn can be applied through specific suggestions: some FBS inventive principles (e.g., "IP7: Nesting-Function") and the helpers (figure 45) that in turn contain other FBS principles.

In particular, for solving a contradiction also TRIZ separation principles have been added to the scheme in order to better organize the guidelines contained in this group. The guidelines provided in the scheme specify the resolutive directions for solving the problems and they suggest what helper can be used for developing them in the various cases. The helpers are divided into four sub-groups (F+: "activate a field", S+: "add a substance", F*: "modify a field" and S*: "modify a substance").

Figure 44 shows the proposed scheme of the guidelines for supporting idea generation:

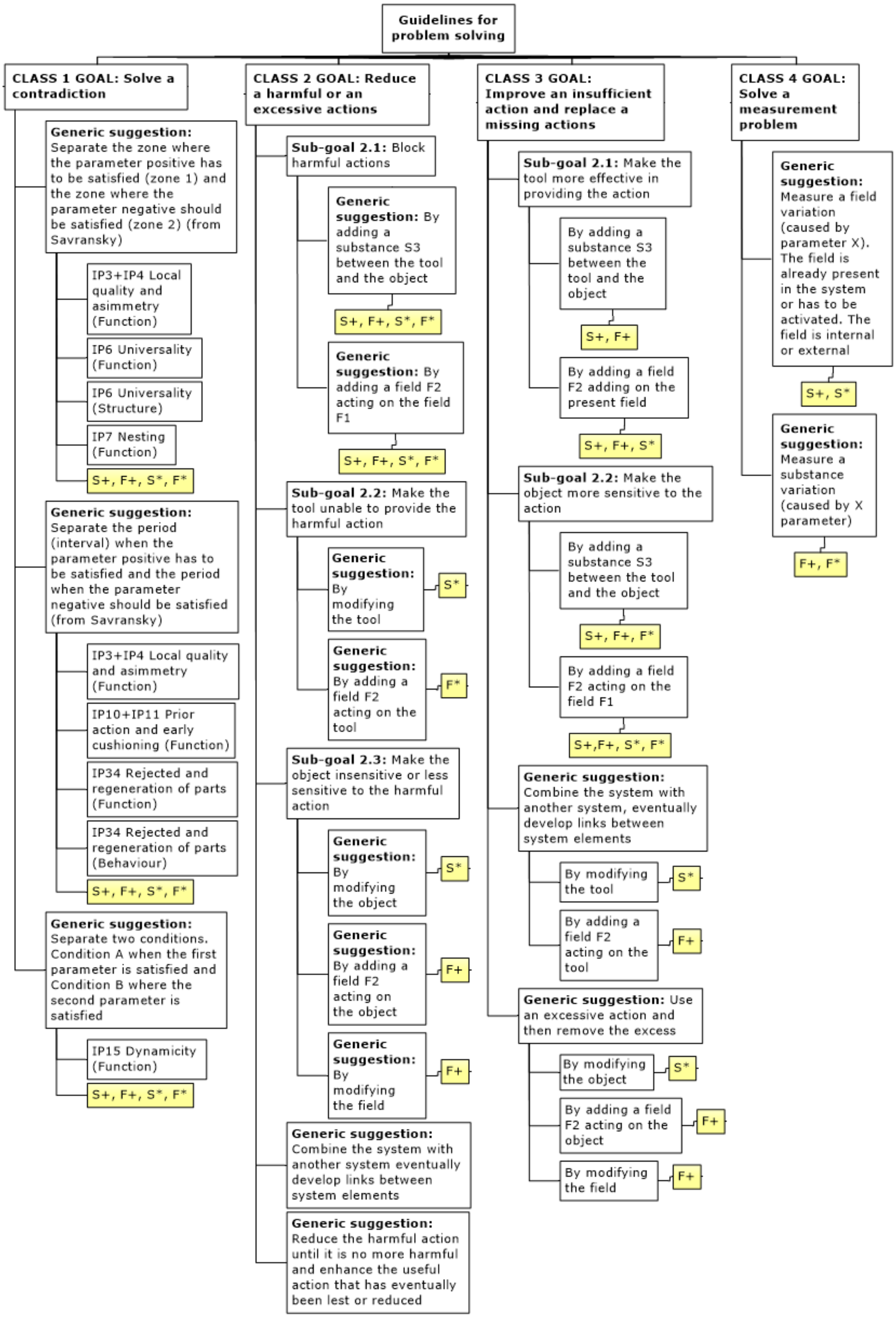


FIGURE 44: GUIDELINES FOR SUPPORTING IDEA GENERATION IN INNOVATIVE PROBLEM SOLVING.

The following scheme (Figure 45) contains the helpers.

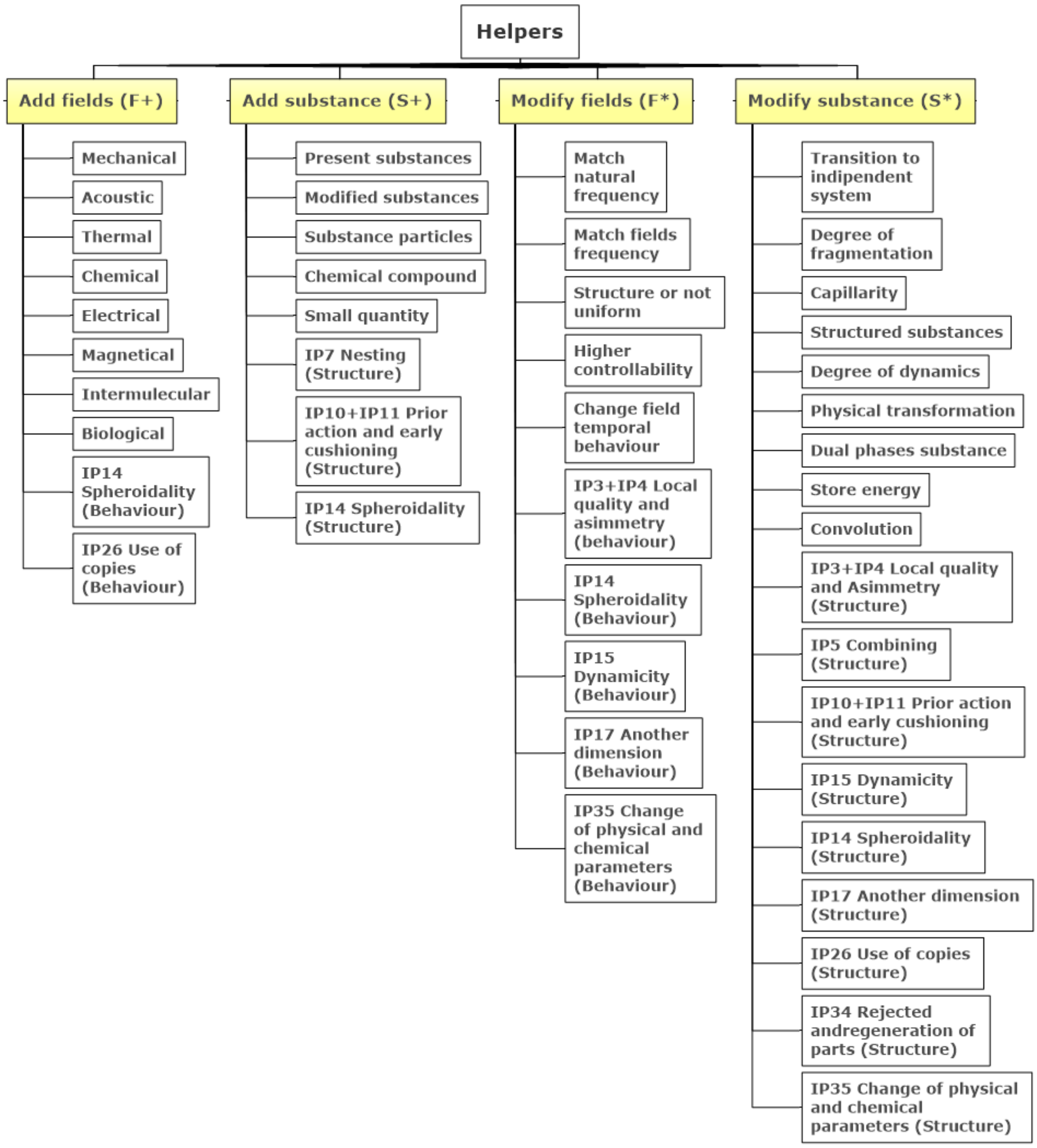


FIGURE 45: HELPERS.

7. Spark 2.0

In this chapter, Spark 2.0, a comprehensive approach for inventive problem solving based on Spark and integrating the proposed methods (Conceptual Design Scheme, FMEA-TRIZ model and the guidelines for idea generation), is presented. The objective of Spark 2.0 is to enlarge Spark domain of application to all the considered inventive problems, by conserving a unique step by step procedure. To define the approach, the main steps already presented of Spark methodology have been maintained while some of the contained sub-steps have been revised and integrated with the introduced approaches. On the basis of the proposed approach, a set of guidelines, to support the problem solver during its application, has been proposed.

The following scheme (Figure 46) summarizes the main methods considered to develop the proposed guidelines for problem solving.

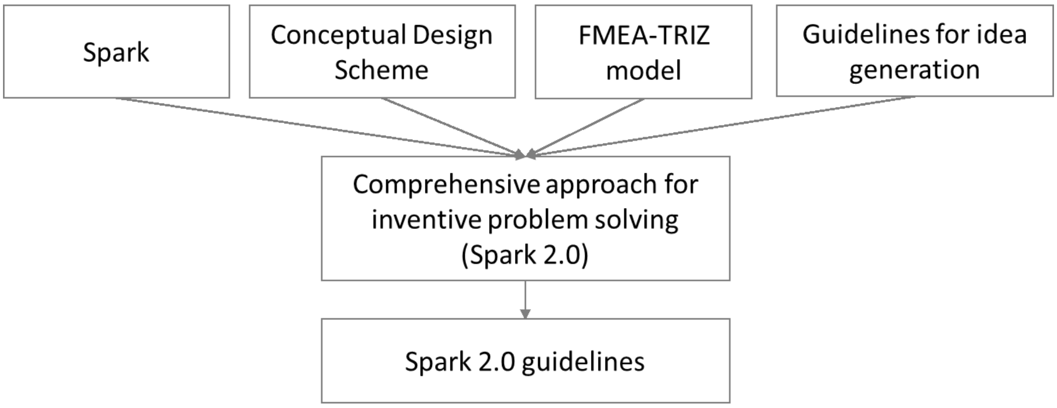


FIGURE 46: THE CONTENT OF THE PROPOSED GUIDELINES FOR INVENTIVE PROBLEM SOLVING.

The suggested approach for problem solving

In the following, the proposed comprehensive approach is explained step-by-step:

- ***STEP 1 Functional overview*** supports the problem solver in identifying the main useful function of the device. Starting from the definition of the requirements the problem solver focuses on the identification and description the “object”, i.e. the entity that undergoes the action of the device, without considering the device, already existing or to be designed. After that, she/he describes the “product”, i.e. the object after the transformation carried out by the device, and the main useful function as the transformation itself between the object and the product. In case the device already exists the problem solver can simply analyse the obtained product, during conceptual design, the main useful function will be experimented after the determination of the structure at step 2.
- ***STEP 2 Innovation strategy*** supports the definition of the most suitable structure of the device that has be achieved through design (for new concept design) or product improved (if the device already exists). The starting point of this phase is the definition of the ideal product or how the object should ideally transform, and consequently the ideal main useful function as the transformation between the object and the ideal product. Ideal product and ideal main useful function even if are not real and potentially unachievable due to the expense to obtain them are used as term of comparison for product improvement and the objective of new concept design.

In addition, during this step, the problem solver identifies where and when the ideal main useful function should be realized. This aspect provides the strategy for reducing the consumption of the involved resources.

Once the ideal product has been defined, the problem solver determines the expected behaviour of the device, or the most suitable sequence of states, among some possibilities, that describe the theoretical transformation of the object into the ideal product. At this point, the structure of the device for realising the ideal function according to the expected behaviour can be determined and produced. In new concept design, through the realisation of the structure and its testing we obtain the actual behaviour of the device. The comparison of the actual behaviour and the expected behaviour provide an evaluation about the current of ideality of the device.

- ***STEP 3 Problem identification*** supports the problem solver to find the possible problems of the current device on the basis of the actual behaviour or to identify possible future failures, if the comparison is currently satisfying.
- After that, the problem solver better describes the identified problems, by specifying the operative time and the operative zone of occurrence, she/he divides them into simpler sub-problems and she/he chooses one of them to be solved.
- ***STEP 4 Problem formulation*** helps in translating the selected sub-problem in a more suitable way to be solved, by providing a specific formalism based on the following main categories:
    - Presence of contradiction;
    - Presence of insufficient or missing action;
    - Presence of harmful or excessive action;
    - Presence of measurement problem.
- ***STEP 5 Idea generation*** supports the problem solver during the generation of the possible ideas for solving the reformulated sub-problems through the series of proposed guidelines, suggestions and triggers, organized according to the formulated problems.

Figure 47 shows the proposed approach:

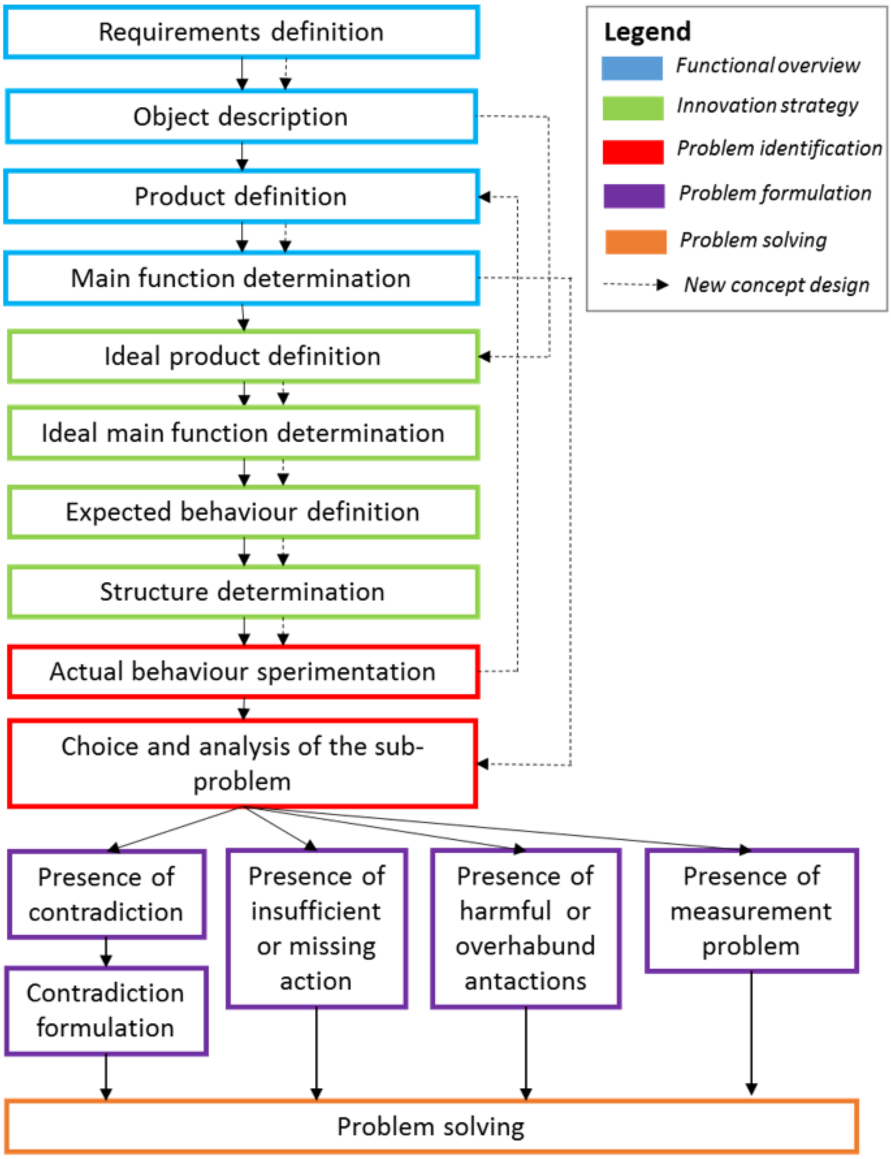


FIGURE 47: THE PROPOSED OVERALL SCHEME OF PROBLEM SOLVING.

7.1. SPARK 2.0 guidelines

On the basis of the proposed approach, the final set of guidelines has been derived. The structure of each guideline is constituted by the following parts:

1) The declaration of the main goal;
2) The generic and the specific suggestions (merged), or the strategies and the possible specific tools that can be used for achieving the declared goals and the explanations of use;
3) The indications about the choices of the successive guidelines, based on the progresses achieved during the problem solving path till to the current guideline and the outstanding problems.

Some guidelines (e.g., guidelines for step #4 “Idea generation”), after the declaration of the goal, address to the other guidelines (e.g., those contained in the map for idea generation (Figure 44) responding to the same goal), not reported again in the table below, which are more structured, by specifying in some cases the sub-goal, the generic suggestion and specific suggestions.

Table 24 shows the proposed guidelines:

TABLE 24: THE PROPOSED GUIDELINES.

Steps	Guidelines	
Functional overview 	**1. Determine the requirements**	**Goal** Define the technical requirements of the device manufacturing, maintenance, functioning and disposal, by including both those required by the designer and the user. **Strategy & tools** - Quantify the requirements' parameters. - Evaluate each requirement on the basis of customer's importance and satisfaction. - Order the requirements on the basis of the market potential. - Define the innovation strategy of the product or the way to improve it by working on its most important requirements. **What's next?** Use guideline #2
	2. Identify the object	**Goal** Identify the object that undergoes the main useful function of the device. **Strategy & tools** - Describe the main features of the object through quantitative parameters. - Use the following tools for describing the object: TOP model and ENV model. **What's next?** - If the device already exists and it has to be improved, use the guideline #3. - If the device has to be designed use the guideline #5.
	3. Determine the real product	**Goal** Determine and describe the real product or the real transformation of the object after the action of the main useful function of the device. **Strategy & tools** - Describe the main features of the product through quantitative parameters. - Use the following tools for describing the object: TOP model and ENV model. **What's next?** Use guideline #4
	4. Determine the main useful function	**Goal** Determine and describe the main useful function of the device or the action that transform the object into the real product. **Strategy & tools** Compare the values of the parameters of the object and the real product (Use the ENV model) in order to quantify the transformations of them that the device is able to operate. **What's next?** - If the device already exists, use guideline #5. - In new concept design case, use guideline #10.

Innovation strategy 	**5. Determine the ideal product**	**Goal** Determine the ideal product or the ideal transformation of the object able to fully satisfy all the requirements. **Strategy & tools** - Determine how the ideal product could be by using forecasting scenarios (Laws of Technical System Evolution) and quantify the features through parameters (use ENV model). **What's next?** Use guideline #6
	6. Determine the ideal main useful function	**Goal** Determine and describe the ideal main useful function of the device according to designer and user's perspectives. **Strategy & tools** - Compare the features of the object and of the ideal product and determine the ideal main useful function that transform the object into the ideal product. (Use ENV model). - Determine the operative zone and the operative time of occurrence of the ideal main useful function on the object. - Determine the affordances of the device according to designer and user's perspectives (See Guideline for NCD #2). **What's next?** Use guideline #7
	7. Determine the expected behaviour	**Goal** Determine the expected behaviour of the device or the sequence of states that describe the transformation of the object into the ideal product, without including the device in the description. **Strategy & tools** - Determine the kinematic and the dynamic of the transformation by including the morphological aspects (deformations) and the involved stress and forces. - Determine the required physical effects: use physical effects DB. - Determine the user's expected manipulation without defining the structure of the device, by defining the most suitable ergonomic aspects (posture and energy required). Evaluate the best expected behaviours and manipulations among those hypothesized: use Laws of Technical System Evolution and take advantage on practical evidences. **What's next?** Use guideline #8
	8. Determine the structure of the device	**Goal** - If the device does not exist, design the structure of the device that realize the main useful function according to the expected behaviour (See Guideline for NCD #5). - If the device already exists, describe the structure of the device. **Strategy & tools**

		- Define the interference part of the structure and the inner part of the structure. - Use MTS model in order to understand the degree of completeness of the system for summarising the elements of the system and comprehend its degree of completeness. - Use structure DB, patent DB and catalogues for identify and modify the component. **What's next?** Use guideline #9
Problem identification and reformulation 	**9. Determine the actual behaviour**	**Goal** Describe the actual behaviour of the device or the sequence of states that carry the transform the object into the real product. **Strategy & tools** - Test the structure of the device in its real functioning for producing the real product. - In case of new concept design, realize a prototype of the structure and test it. **What's next?** - In case of new concept design, use guideline #3 - If the device already exists, use guideline #10

	10. Evaluate the device and analyse of the sub-problems	**Goal**
		Evaluate the device by comparing the actual behaviour and the real obtained product with the expected behaviour and the ideal product respectively.
		If the comparison is not satisfying, identify the sub-problem to solve.
		Strategy & tools
		By analysing the chain of states of the actual behaviour, identify the photogram of occurrence of the fault and:
		- Find a sub-problem before the occurrence of the fault if you want to anticipate it.
		- Find a sub-problem contemporary to the fault for solving the problem when it occurs.
		- Find a sub-problem successive to the occurrence of the fault for mitigating the problem.
		- If the sub-problem does not contain the fault, choose another sub-problem and analyse it.
		Analyse the selected sub-problem through TRIZ functional analysis.
		What's next?
		- If the selected sub-problem contains:
		    o An insufficient action that can be improved without contradictions, use guideline #12.
		    o A harmful action, whose improvement implicates a contradiction, use guideline #13.
		    o A measurement problem, use guideline #14.
		- If the sub-problem does not contain the fault, find a possible future failure effect, by using guideline #11.

	11. Find failure effects, failure	**Goal**

	modes and failure causes	- Perturb the current situation of the sub-problem for determining the possible failure modes of the identified elements and the modified shared actions. - Determine the failure effects deriving from the modified situation of the sub-problem. - Determine the failure causes of the failure modes and failure effects. **Strategy & tools** Use guideline #3, #4, #5 for anticipatory failure investigation. **What's next?** If the identified failure causes are provoked by: - An insufficient, missing, harmful or excessive action, whose modification generate a contradiction with other parameters, use guideline #12 for formulating the contradiction. - A harmful or an excessive action that can be eliminated or reduced without a contradiction, use guideline #14. - An insufficient or a missing action that can be improved without a contradiction, use guideline #15. - A measurement problem, use guideline #16.
	12. Reformulate the problem as contradiction	**Goal** Reformulate the problem as contradiction by identifying two features of the device in contradiction, in which as result of the improvement of one of them, the other get worse. **Strategy & tools** - Reformulate the problem as technical contradiction: identify the two features as two engineering parameters (e.g., mass, length). o Consider the list of the 39 Engineering parameters). - Reformulate the problem as physical contradiction: identify a control parameter of the device that opportunely set leads to the improvement of one feature and the worsening of the other and vice-versa. In this case, the two features are two requirements of the device. **What's next?** Use Guideline #13.
Idea generation 	**13. Solve a contradiction**	**Goal** Find a solution able to solve the contradiction or to realise the two features at the same time. **Strategy & tools** - For solving technical contradiction: use contradiction matrix. - For solving physical contradiction: use class 1 (Solve a contradiction) of the guidelines for problem solving. **What's next?** Use Guideline #16 to evaluate if the problem has been solved, and find other possible problems.
	14. Reduce a harmful or an excessive action	**Strategy & tools** Use class 2 (Reduce a harmful or an excessive action) of the guidelines for problem solving. **What's next?**

		Use Guideline #16 to evaluate if the problem has been solved, and find other possible problems.
	15. Improve an insufficient action or add a missing action	**Strategy & tools** Use class 3 (Improve an insufficient action and replace a missing actions) of the guidelines for problem solving. **What's next?** Use Guideline #16 to evaluate if the problem has been solved, and find other possible problems.
	16. Solve a measurement problem	**Strategy & tools** Use class 4 (Measurement problems) of the guidelines for problem solving. **What's next?** Use Guideline #16 to evaluate if the problem has been solved, and find other possible problems.

7.2. Integration of Spark 2.0 guidelines with patent databases

The integration of the proposed guidelines with patent databases provides useful information for their application (e.g., behaviour, physical effects, technologies, structures and components) and it shows if someone has already found results compatible with the selected guideline. In order to achieve this aim, a semiautomatic built system for the compilation of the queries for each guideline has been studied, which are based on the suggestion provided and the information about the problem and the context of application, previously inserted by the user.

The queries are constituted by three fields: verb, object and a third additional field. The first one generally directly derive from the suggestion provided by the guidelines, the second one can contain information about the problem and the third one regards the context of application. Let's consider for instance the guideline #13.1.1 Solve a contradiction problem/Segment the structure, applied to the operative zone (e.g., the porthole) of a washing machine. The resulting query is: "SEGMENT" + "PORTHOLE" + "WAHSING MACHINE".

Table 25 summarizes the queries derived from some guidelines and information researched in databases:

TABLE 25: QUERIES DERIVED FROM SOME GUIDELINES.

Guideline	Generated query			Results from patent DB
	Verb	Object	3rd field	
#7 Determine the expected behaviour	Name of the main useful function *(Inserted by the user)*	Name of the object *(Inserted by the user in guideline #2 Identify the object)*	/	List of physical effects and field
#8 Determine the structure of the device	Name of the main useful function *(Inserted by the user)*	Name of the object *(Inserted by the user in guideline #2 Identify the object)*	Physical effect *(selected by the user from the results of guideline #7)*	List of structures
#9 Determine the actual behaviour	Measure OR Detect	Name of the Parameter or the requirement to be evaluated *(Inserted by the user in guideline #1*	/	List of tools for testing the parameters of the actual behaviour

		Determine the requirements)		
#14 Reduce harmful or excessive action *(example from Sub-guideline #14.2.2 "Block or deviate harmful effect through a substance")*	Block OR Deviate	Name of the harmful effect *(inserted by the user in guideline #9 Determine the actual behaviour)*	/	List of the substances
#15 Improve insufficient action or add a missing action *(example from Sub-guideline #15.1.1 "Increase the magnitude of a field by adding a tool between through the field)*	Increase	Name of the (insufficient) parameter of the field *(selected by the user from the results of the query of guideline #7 Determine the expected behaviour)*	/	List of compatible tools
#16 Solve a measurement problem	Measure OR Detect	Name of the parameter of the considered field *(selected by the user from the results of the query of guideline #7 Determine the expected behaviour)*	Name of the considered field	List of the technologies for measuring (substances and tools) the field
	Measure OR Detect	Name of the parameter of the considered substance *(selected by the user from the results of the query of guideline #8 Determine the substance)*	Name of the considered substance	List of fields (physical effects)

Future developments of this approach regard the implementation of this system inside the proposed web-based platform and the integration with already existent tools for query expansion and refinement (e.g., KOMPAT) and tools for the representation and the sorting of the results. KOMPAT is a software developed inside the V&K group at the University of Bergamo, able to transform a simple triad (as those proposed) into an effective query compatible with major patent databases (e.g., Espacenet and Wipo), through the automatic search of synonyms, hyponyms, hypernyms and the implementation of semantic rules. KOMPAT Effect DB is instead a tool for extracting from a poll of papers the physical effects implemented by the related devices and to represent them in a list.

7.3. Software implementation

A software implementation can provide several advantages to the proposed guidelines: improving user's interface, managing the addressed knowledge, customizing the suggestions in relation to the context of application, etc. In addition, since the proposed approach can be very complicated, especially if applied on complex industrial projects, the implementation become almost necessary. For these reasons a web based interface of SPARK 2.0 guidelines has been developed and the following objectives have been considered:

- ***Proposing the right guideline at the right time.*** The proposed approach aims to support different inventive problems, however, not all the guidelines are ever used for all the problems. For this reason, the software implementation must filter them according to the application context and in relation to the partial results achieved by the user during the application of the methodology.
- ***Simplifying the comprehension of the guidelines.*** In order to make the guidelines more comprehensible, especially for not-expert users, through the software implementation, their text can be customized through the collected data about the problem and the domain of application.
- ***Managing of the suggested tools.*** The interactive framework aims to suggest the most suitable tools and to explain how to use them to achieve the specific sub-goals during problem solving path and in relation to the context of application.

In the following, the software architecture and its main functionalities are presented.

Software architecture

The software architecture (see figure 1) of the guidelines software is constituted as follow: the web interface (defined using HTML, CSS and JavaScript) and achievable through a common browser, contains two kinds of pages "Page Guideline" and "Modules", with which the user interacts (action #1 and action #2). The Page Guidelines address (action #3) to the proposed guidelines and some of them suggest to the user the most suitable Module that in turn address to the tools (action #4). The user interacts with the Modules by inserting the data about the problem (e.g., the name of the device, the main useful function, etc.) and the context of application (e.g., the external requirements, the normative, etc.). The data inserted in the modules are memorized (action #5) in the Problem information DB, to whom, the Page Guidelines access (action #6) to customize the content of their contained guidelines in relation to the context of application. In addition, both the Page Guidelines and the Modules address to external databases (action #7 and action #8), such as patent DB and physical effects DB.

Figure 48 shows the software architecture:

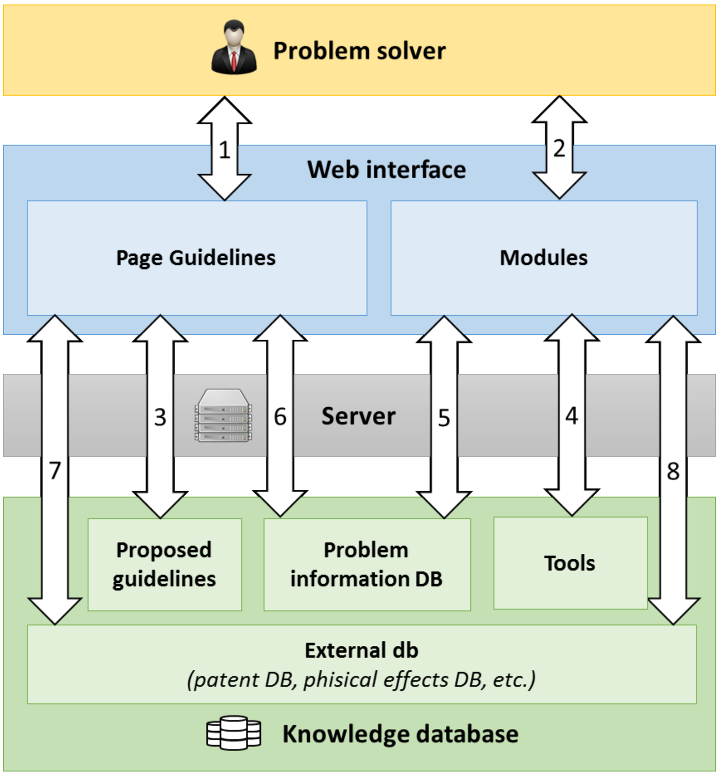


FIGURE 48: SPARK SOFTWARE ARCHITECTURE.

In the following scheme (Figure 49), part of the software navigation map is presented, including the Page Guidelines, the Modules and their relations. Observing the scheme, we can see that a Page Guideline can address to one or more Modules and successively to other Page Guidelines according to a determined path: for instance, the Page guideline #2 "Object definition" addresses to the ENV model Module and to the Page Guideline #3 "Product definition" and the Page Guideline #5 "Ideal product definition", according to the criteria previously explained in chapter 7.1. In addition, we can also see how the ENV model Module is used by three Page Guidelines in different moments and for achieving different purposes according to what suggested by the guidelines (see chapter 7.1.).

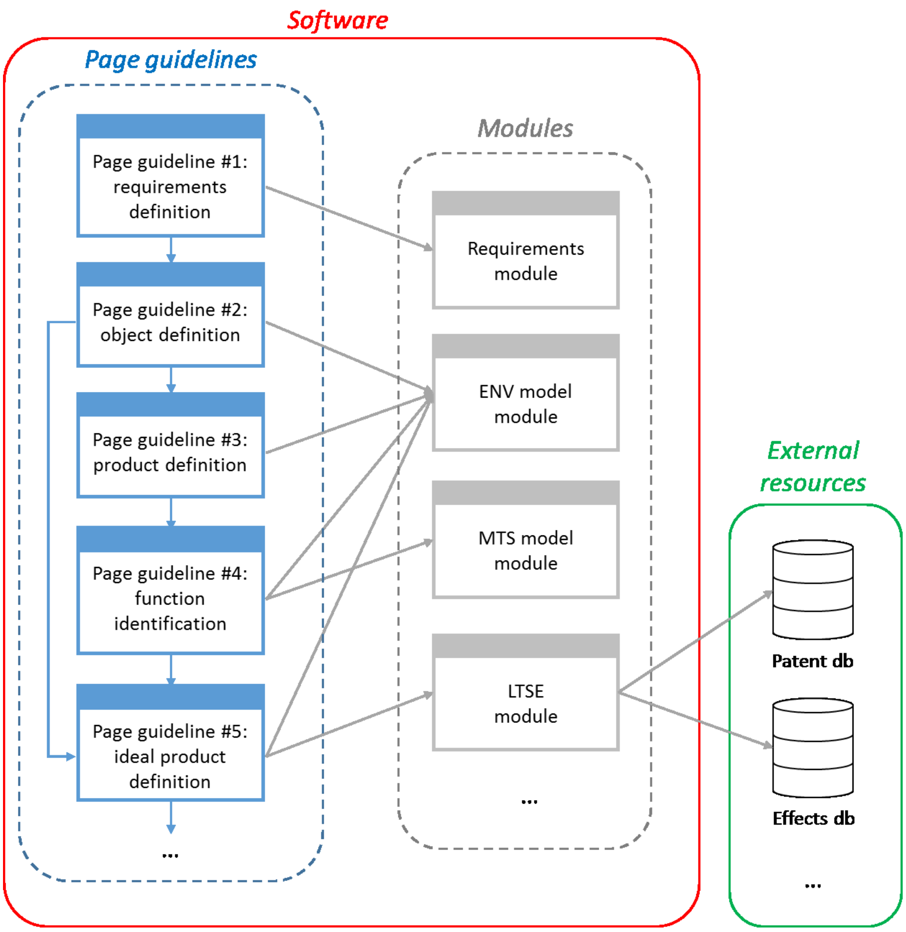


FIGURE 49: PART OF THE SOFTWARE NAVIGATION MAP.

Software main functionalities

In the following, the main functionalities of the proposed software interface are described in detail:

<u>Page Guidelines</u>

Each Page Guideline contains the proposed guidelines, it addresses to the related Modules, by explaining how to use them, and it suggests the subsequent Page Guidelines on the basis of the partial achieved results. In particular, the structure of the Page Guidelines is constituted as follow (see figure below):

- ***Main menu (Section 1)*** addresses to the main steps of the proposed approach by highlighting the selected one.
- ***Secondary menu (Section 2)*** addresses, according to an ordered sequence, to all the Page Guidelines contained in the selected main step. For instance, the step "Functional Overview" contains the following Page Guidelines: PG #1 "Requirements", PG #2 "Object", PG #3 "Product", etc. Each button contained in the secondary menu address to the related Page guideline: in the figure below, Page Guideline #2 is selected.
- ***Content of the Page guideline (Section 3)*** contains the text of the guideline (Section 4), the links to the suggested tools (Section 5) and the links to the possible subsequent guidelines (Section 6).

In figure 50, Page guideline #2 "Determine and describe the object" is presented:

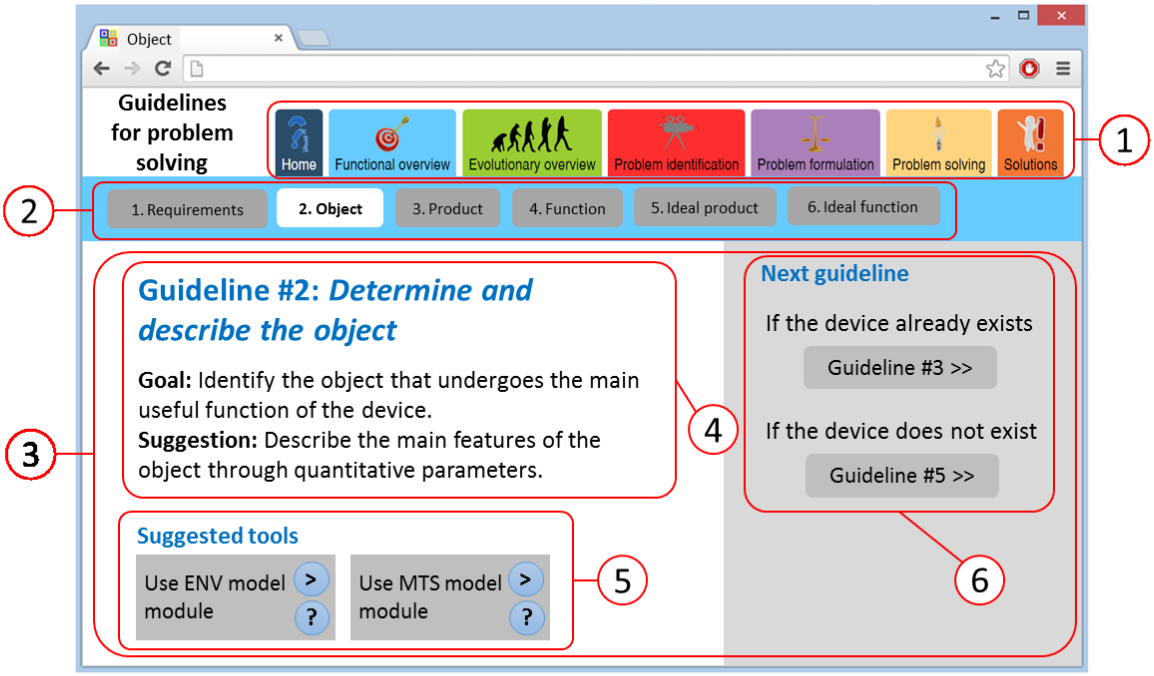


FIGURE 50: AN EXAMPLE OF PAGE GUIDELINE (PAGE GUIDELINE #2 "DETERMINE AND DESCRIBE THE OBJECT").

The Page guideline presented in Figure 51 is instead a more structured compared to the previous one. The contained guidelines include all the elements of the ontology presented in chapter 4.1.: goal, sub-goal, generic suggestions, specific suggestions and examples.

In addition, they are customized in accordance to the problem to be solved (the improvement of a nutcracker that does not crack a nutshell as required in the figure below) by using the information entered by the user in the Modules. As consequence, they specifically refer to the nutcracker, the nutshell and the action "To crack".

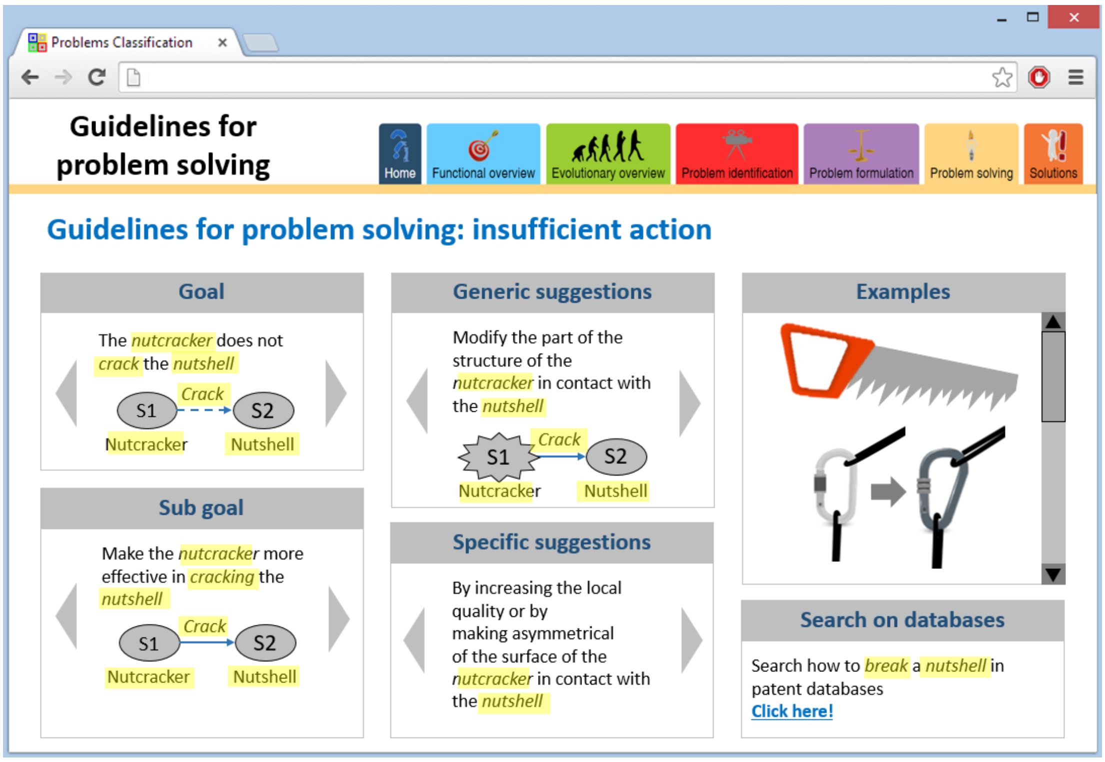
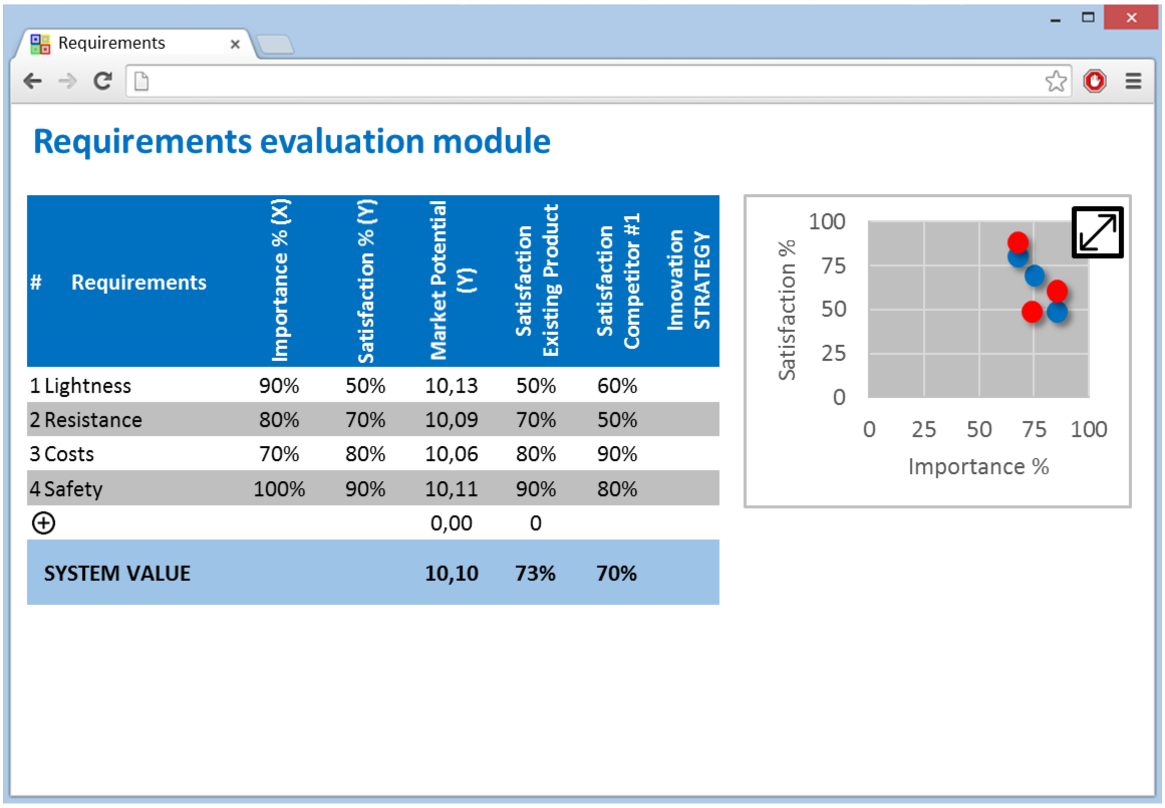


FIGURE 51: EXAMPLE OF CUSTOMISATION OF THE PROPOSED GUIDELINES.

Modules

The Modules contain the interactive versions of the tools (e.g., MTS model, ENV model, Requirements module) suggested by the guidelines. In there, the user can insert the data about the problem (e.g., requirements), which are memorized and reworked. As output, the modules provide the useful information in support of problem solving (e.g., the ranking of the requirements, the knowledge from the databases).

Figure 52 shows the Requirements evaluation module as example.



# Requirements	Importance % (X)	Satisfaction % (Y)	Market Potential (Y)	Satisfaction Existing Product	Satisfaction Competitor #1	Innovation STRATEGY
1 Lightness	90%	50%	10,13	50%	60%	
2 Resistance	80%	70%	10,09	70%	50%	
3 Costs	70%	80%	10,06	80%	90%	
4 Safety	100%	90%	10,11	90%	80%	
⊕			0,00	0		
SYSTEM VALUE			10,10	73%	70%	

FIGURE 52: THE REQUIREMENTS EVALUATION MODULE.

8. Case studies and tests

In this chapter, the following applications of the proposed guidelines are presented and the achieved results are discussed:

- Application 1 (New concept design): during this application, the guidelines have been applied to supporting the conceptual design of the structure of a new product, by spending a particular attention on the first two groups of the guidelines.
- Application 2 (Product improvement): almost all the same guidelines have been applied in a new perspective also in this case with a focus on the two first groups.
- Application 3 (Anticipatory failure investigation): the guidelines of the 3rd group (problem identification) have been specifically consider to improve the concept developed during the application 1 by investigating the possible problems related to the defined concept.
- Application 4 and application 5 (Idea generation): the guidelines of the 4st group have been applied to support idea generation in problems with and without contradictions, which have been specifically supplied with an advanced level of formulation, by providing the already identified problems that has to be solved.

8.1. Application 1: New concept design

8.1.1. Case study

The proposed guidelines have been applied by 1 academic researcher and 3 PhD students during a collaboration between the University of Bergamo and Tenacta-Imetec, an Italian industrial sector firm in the field of the home appliances, with the objective to design an innovative vacuum cleaner including a dust compactor in substitution of the traditional bag. The achieved results have been patented in Montecchi, Russo, Spreafico (ITMI20131928).

In the following, a summary of the results is explained in relation to the considered guidelines, in order to show in what way, the guidelines support a conceptual design of a new product. If the designer and user's perspective are presented separately.

Guideline #1 "Determine the requirements"

The requirements according to designer's perspective are: cost of the device manufacturing, size, shape and weight of the compactor, while those from user's perspective the requirements are: the compactness of the dust, the price of the vacuum cleaner and the required manual activating force.

Guideline #2 "Identify the object"

The object that undergoes the action of the compactor is the un-compacted dust, positioned in the collection compartment of the vacuum cleaner.

Guideline #5 "Determine the ideal product"

The ideal product of the object-product transformation is a compacted dust sample with a well-defined cylindrical shape and a compacted surface.

Guideline #6 "Determine the ideal main useful function and the affordances"

Both for designer and user's perspective, the main useful function is to compact the dust contained in the compartment collector in order to obtaining the compacted sample. While the affordances (Figure 53) are:

- Presence of a hand (Part A) on the upper part of the suction pipe for communicating to the user how to manipulate it as a lever for activating the compactor.
- Transparent window (Part B) positioned on the side of the vacuum cleaner for showing to the user when the dust collection compartment is full.
- Button (Part C) for pushing the dust from the collection compartment to the compactor.

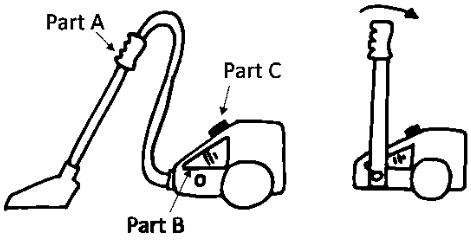


FIGURE 53: AFFORDANCES OF THE DEVICE.

Please note that the affordances have been identified without involving the structure of the dust compactor that has not already determined, by considering only the chassis of the vacuum cleaner.

Guideline #7 "Determine the expected behaviour"

The expected behaviour, according to designer's perspective, involved two phases: the insertion of the dust in the compactor, for which a vertical fall has been hypothesized, and the compaction of the collected dust, for which two dynamics have been investigated:

- ***Expected behaviour #1:*** The dust sample reduces the height by maintaining the diameter unchanged.
- ***Expected behaviour #2:*** The dust sample reduces the diameter by maintaining the height unchanged.

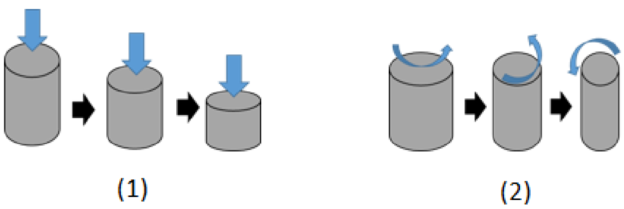


FIGURE 54: THE TWO HYPOTHESIZED EXPECTED BEHAVIOURS FOR THE COMPACTION OF THE DUST ACCORDING TO DESIGNER'S PERSPECTIVE.

As suggested by the guidelines, on the basis of practical experimentations, the expected behaviours #2 emerged as the best one, from an energetically point of view. The tests were conducted on two test machines, available at the laboratories of the University of Bergamo, able to realize the behaviours in the most aseptic way: an industrial press and a rolling mill.

The expected behaviour has also been investigated according to user's perspective (Figure 55), by hypothesizing two distinct operations: (1) the user pushes a button for inserting the dust into the compactor and (2) the user pulls the lever, using a certain force and rotating of a determined angle, to actuate the compactor.

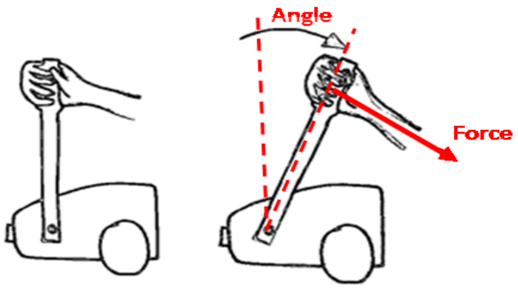


FIGURE 55: EXPECTED BEHAVIOUR ACCORDING TO USER'S PERSPECTIVE.

Guideline #8 "Determine the structure of the device"

In order to realize the selected expected behaviour (by considering all the phases and the designer and user's perspectives), both the Inner Structure and the Interference Structure have been designed. The Inner Structure (Figure 56) is constituted by the following components:

- A piston for pushing the dust in the compactor.
- The compactor constituted by 4 rollers, a wrapper, a cover and a cam. The rollers are dragged by the cover (in turn moved by the lever (suction pipe) through a gear) and they approach and rotate inside a cam by compacting a wrapper.
- The transmission is constituted by a joint with toothed wheels that actuates the cover with the movement of the lever.

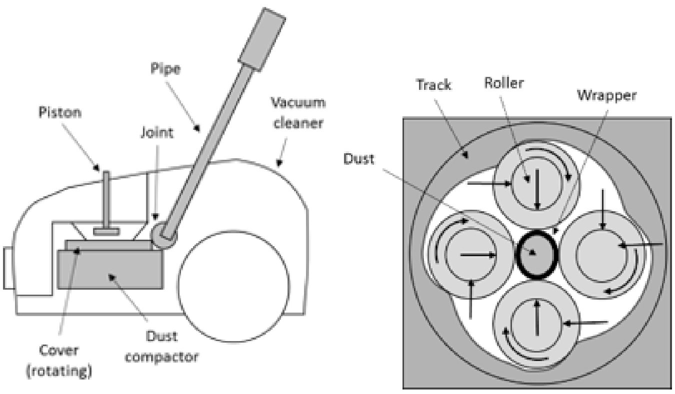


FIGURE 56: (A) PART OF THE INNER STRUCTURE AND (B) THE COMPACTOR (WITHOUT THE COVER).

The Interference Structure (Figure 57) is instead constituted by two components: a button positioned on the top side of the vacuum cleaner for actuating the piston and a handle on the top side of the lever (suction pipe).

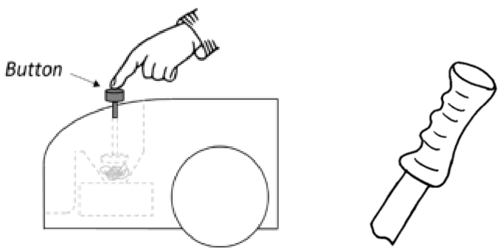


FIGURE 57: INTERFERENCE STRUCTURE, (A) PARTICULAR OF THE BUTTON AND (B) THE HANDLE.

Guideline #9 "Determine the actual behaviour"

The structure was built and tested by producing a series of compacted samples. In addition, the right rotation of the rollers and the wrapper, the approaching of the rollers and the required actuation energy have been verified.

Guideline #3 "Determine the real product"

Through the experimentation of the actual behaviour, the real product of the device has been obtained. Even if the produced samples (see Figure 58) have not the perfect cylindrical shape as the ideal product, they were sufficiently compact and resistant to the touch. The evaluation of the real product has been carried out both considering engineering parameters and marketing aspects: the weight and the shape of the sample and the force required for the actuation have been respectively detected through a digital scale, a calibre and a torque wrench. The user's manipulation on the device has been compared to normative for human ergonomics and to the results of virtual simulations with human modelling. In addition, the device and the produced sample has been evaluated by 4 professionals from the marketing area of the company, which evaluated the achieved results in a positive way.

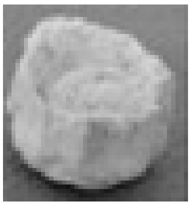


FIGURE 58: AN IMAGE OF THE REAL PRODUCT OBTAINED.

Guideline #10 "Evaluate the device and analyse the sub-problems"

A possible structure of the device has been proposed and tested with success. Since no particular problems have been determined, the anticipatory failure investigation of the device, presented in the following, has been considered to improve the device.

8.1.2. Test

The proposed guidelines have been tested for supporting the innovative design of the vacuum cleaner with the dust compactor also by 18 MsD students in engineering, whit the aim to investigate their main advantages and limitations. In the following, some details about test execution are presented and then the achieved results are discussed.

Test participants

The test has been carried out by 36 MsD students follow a university course named "Methods and tools for product lifecycle" (i.e. PLM-Product Lifecycle Management) during the master's degree in engineering. Only half of the students had a previous knowledge of TRIZ theory provided by another academic course.

Test execution

During the test, the students have been divided into two groups, equally distributed between students involved and not involved in TRIZ, and each of them individually solved the problem in 1 hour by providing one solution. The students of one group used the guidelines while the others (control group) not. A general explanation about the problem and the delivered guidelines has been provided to all the students before the test execution.

Achieved results

The solutions achieved with and without the guidelines have been quantitatively evaluated on the basis of the following criteria:

- Function realisation parameter (3 points) includes:
  - Realisation of the function (1 point): the complete realisation of the function (1 point) and the partial improvement of the function (0,5 point) have been evaluated on the basis of the similarities of the proposed solutions with the one identified by the researchers during the industrial collaboration, presented before.
  - Realisation of the function "compactness" in the precise operative zone (e.g., the surface of the sample) where is required (1 point) and not in all the body of the sample (e.g., the core), where is not required.
  - Use of the resources: 1 point has been assigned to the solutions proposing a better utilisation of the already available resources for realising the function (e.g., engine vibrations); 0,5 points have been assigned to the solutions proposing the use of unexploited external resources.
- Secondary requirements (2 points for each one) have been evaluated on the basis of their realisation and the use of the resources.
- The feasibility (1 points) and the degree of novelty (1 points) of the proposed solutions have been evaluated on the bases of patent databases and technical brochures.

Table 26 sumarizes the achieved results:

TABLE 26: OVERALL RESULTS OF THE PROPOSED TEST.

	Control group (No guidelines)			Group with guidelines		
	TRIZ knowledge	Not TRIZ knowledge	Total	TRIZ knowledge	Not TRIZ knowledge	Total
Function (3 pts)	2,0	1,3	1,7	2,6	2,3	2,4
Requirement 2 (2 pts)	1,7	1,3	1,5	2,0	2,0	2,0
Requirement 3 (2 pts)	1,9	1,5	1,7	2,3	2,2	2,2
Requirement 4 (2 pts)	0,3	1,3	0,8	1,2	1,8	1,6
Feasibility (1 pts)	0,5	0,6	0,5	0,8	0,9	0,8
Novelty (1pts)	0,4	0,4	0,4	0,8	0,6	0,6
Total (9 pts)	6,8	6,4	6,6	9,7	9,8	9,6

As we can see by the achieved results, the solutions achieved through the help of the guidelines are generally better than the others, both for students already involved in TRIZ and for others. In particular, these solutions better achieve the main useful function and the secondary requirements. In addition, they are more feasible and innovative.

More in detail, the students that applied the guidelines describe the main useful function in a more conscious way, by better contextualising it in the required operative zone. This trend is particularly accentuated for the students without TRIZ background as we can see by the following table (Table 27).

TABLE 27: AVERAGE EVALUATIONS OF THE FUNCTION REALISATION IN THE OPERATIVE ZONES FOR THE PROPOSED SOLUTIONS (MAX 1 POINT).

Control group (No guidelines)			Group with guidelines		
TRIZ	NON TRIZ	Total	TRIZ	NON TRIZ	Total
0,4	0,1	0,3	0,9	0,7	0,8

Discussion of the results

In general, the use of the guidelines to support new concept design increases the quality of the proposed solutions, both for students involved in TRIZ and for the others that achieved the greatest improvements. The students with the guidelines demonstrated an improved consciousness about the design variables, which leaded to better define the main useful function and the secondary requirements and to better exploiting the available resources. In addition, these students (with the guidelines) proposed solutions more various and with higher degrees of novelty and feasibility, compared to the others. More in particular, the following advantages have been identified:

- The guidelines helped the students to better focus on the definition of main useful function though a more complete comprehension about the object-product transformation and thanks to the identification of the precise operative zone of realisation of the function. Let's consider for instance the description provided to the function "Compactness": the students without the guidelines identified it with a uniformly compact sample in the entire volume. The great part of the students with the guidelines identified instead the specific areas of the sample where the compactness is really required, such as the edges of the samples, where the risk of disintegration is higher, and the surface (see Figure 59).

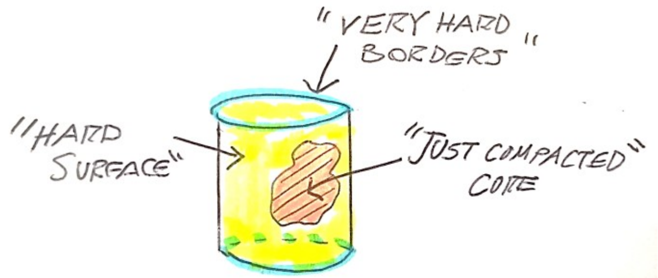


FIGURE 59: EXAMPLE OF DESCRIPTION OF THE MAIN USEFUL FUNCTION BY IDENTIFYING THE OPERATIVE ZONES OF THE DUST SAMPLE, PROPOSED BY A STUDENTS WITH THE USE OF THE GUIDELINES.

- The use of the guidelines seems also to guarantee a better realisation of the secondary requirements in addition to the main useful function. Almost all the students without the guidelines, difficulty realised all the secondary requirements with the proposed solutions, which are generally similar between them. The students with the guidelines proposed instead solutions that implement different modalities for realising the secondary requirements.
  Let's consider for instance the solutions proposed for the requirement #3 "Human activation of the device" (see Figure 60). The major part of the students without the guidelines proposed different kinds of buttons for actuating the compactor and some of them suggested the use of springs for reducing the required force. The students with the guidelines proposed instead different kinds of levers, hands, pedals and also a sort of chair; two of them suggested to exploit the rotating movement of the wheels of the vacuum cleaner. The variety of the solutions can be due to the major knowledge about the physic of the problem acquired by the students through the guidelines.

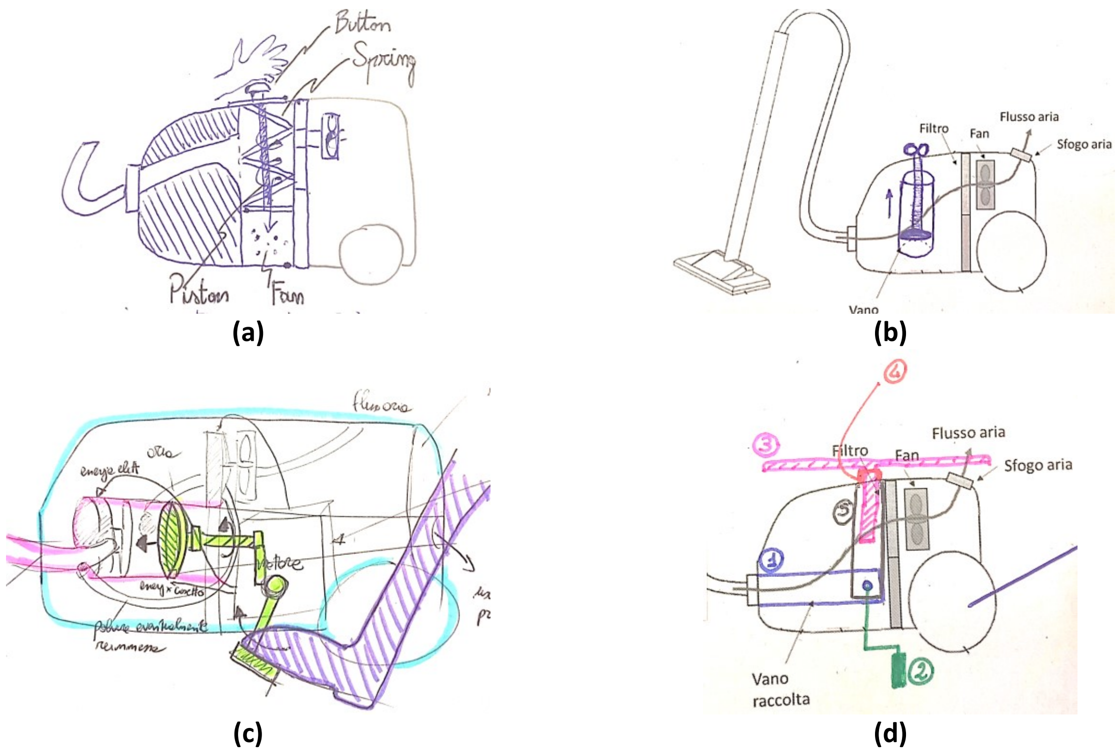


FIGURE 60: PROPOSALS FOR REALISING THE SECONDARY REQUIREMENTS: HUMAN ACTIVATION OF THE DEVICE. SOLUTIONS (A) AND (B) HAVE BEEN FOUND WITHOUT THE GUIDELINES, SOLUTIONS (C) AND (D) WITH THE GUIDELINES.

- Finally, the students with the guidelines demonstrate an increased perception about the design process and the related problems, by solving them during the design phase. As consequence, the solutions provided are generally more feasible compared to those provided by the students without the guidelines.
  In addition, the provided solutions are also characterized by a greater degree of novelty compared to the others, which are generally similar to the technologies already available on the market. Let's consider for instance the use of the water in the vacuum cleaner. This idea has been provided both with and without the guidelines, however, in the first case the solutions is constituted by a pump that sprays a water spray jet only on the surface of the dust sample after the compaction, while in the second case a little water container is designed for collecting and aggregating the dust without compacting it as in the case of already existing water vacuum cleaner (see Figure 61).

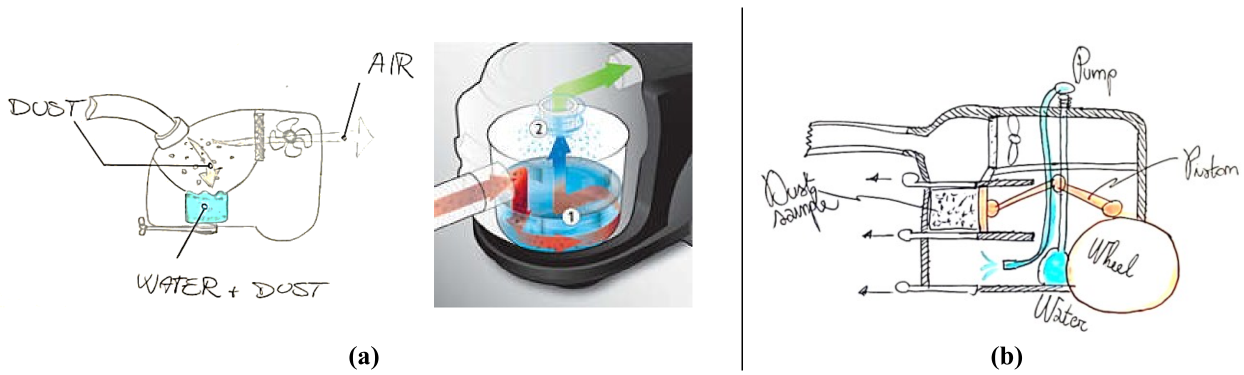


FIGURE 61: TWO EXAMPLES OF DUST COMPACTOR THAT USE WATER: (A) DETERMINED WITHOUT GUIDELINES AND (B) DETERMINED WITH THE GUIDELINES.

8.2. Application 2: Product improvement

In order to test the efficacy of the proposed guidelines to support product improvement, a case study about the improvement of a tradition nutcracker has been proposed to 36 MsD students in engineering. The specific objectives of the test are: evaluating if the guidelines can improve the realisation of the main useful function and the secondary requirements of the device, through a better exploitation of the available resources, and only when and where is more appropriate. In addition, the qualitative level of the proposed solution (novelty and feasibility) has been evaluated. In the following, the details about test execution and the achieved results are explained in detail.

Case study

The proposed case study deals with a common nutcracker that is not able realise the main useful function as required: the nutcracker cracks the nutshell of a nut in an insufficient manner so that the user is not able to extract the content. The secondary requirements of the device (a low force of activation and the integrity of the content of the nut after the cracking of the shell) are currently achieved by the device and they have to be guaranteed also during the improvement of the device.

FIGURE 62: THE ASSIGNED PROBLEM: A NUTCRACKER DOES NOT BREAK A NUTSHELL AS REQUIRED.

Test participants

The proposed guidelines have been tested by 36 MsD students of a university course named "Methods and tools for product lifecycle" (e.g., PLM-Product Lifecycle Management) during the master's degree in engineering. Only half of the students have a previous knowledge of TRIZ theory, thanks to previous course in the university. Each student proposed one solution to the problem.

Test execution

During the test, the students have been divided into two groups, equally divided between students involved and not involved in TRIZ. All the students solved the assigned problem individually in 1 hour. The students of one group used the guidelines while the others (control group) solved the same problem without any help. A general explanation of 15 minutes about the problem and the guidelines has been provided to all the students before the test execution.

Results

The results achieved during the proposed tests are the following:

- The improvement in function realisation is evaluated as follow: 1 point for the complete realisation of the function and 0,5 points for the partial improvement.
- The realisation of two secondary requirements has been evaluated by providing 2 additional points.
- An additional point has been assigned to the solutions that propose a smart use of the already available resources, while 0,5 points have been assigned to the solutions proposing the use of unexploited external resources.

- The qualitative level of the solutions has been evaluated through their feasibility and novelty, by providing 2 additional points. These parameters have been evaluated on the basis of a patent and technical brochures analyses.
- An additional point is provided to the solutions that realise the function only where it is more appropriate (e.g., instead of cracking all the surface of the nutshell, dividing it along the joint line to obtaining the same result).

Table 28 summarizes the total overall average values of the proposed solutions, achieved by the two groups.

TABLE 28: OVERALL RESULTS OF THE PROPOSED TEST.

	Control group	Group with guidelines
Students with TRIZ background	4,8	5,6
Students without TRIZ background	4,1	5,9
All students	4,4	5,8

On the basis of the obtained results, both the students with and without TRIZ background proposed better solutions by using the guidelines; the second ones in particular encountered greater improvements. In the following table (Table 29) the results of all the considered evaluations criteria are summarized.

TABLE 29: TEST RESULTS (MEAN VALUES).

	Control group (no guidelines)			Group with guidelines		
	TRIZ knowledge	**Not TRIZ knowledge**	**Total**	**TRIZ knowledge**	**Not TRIZ knowledge**	**Total**
Function realisation	1,0	0,9	0,9	1,0	0,9	0,9
2nd requirement realisation	0,9	0,7	0,8	1,0	0,9	0,9
3rd requirement realisation	1,0	0,8	0,9	1,0	1,0	1,0
Use of resources	0,5	0,5	0,5	0,6	0,6	0,6
Feasibility of the solution	1,0	0,9	0,9	0,9	0,8	0,9
Novelty of the solution	0,1	0,2	0,2	0,7	0,8	0,8
Solution realisation in the operative zone	0,3	0,1	0,2	0,4	0,9	0,7

On the basis of the achieved results, the following observations can be stated:

- Almost all the proposed solutions improved the realisation of the main useful function, but the students with the guidelines identified smarter solution to do it, by better exploiting the available resources for obtaining the same final result. Lets' consider for instance that almost all the students with the guidelines suggest to crack the nutshell through the reduction of the breaking area, along the division line of the two parts of the shell, while the others, except in one case, suggest instead to maintain the current surface to break or also to increase it increase the surface.
- As consequence of the function identification, the students with the guidelines provided solutions better able to realize the secondary requirements such has the lower force of activation of the nutcracker.
- The solutions proposed with the help of the guidelines are also more innovative than the others that, in almost all cases, are similar to already existing product, available on the market. For some of them, only remoted correspondences in patent databases have been found, while a solution is completely new.
- Finally, the students with the guidelines improved the nutcracker in a more conscious way, in order to realize the identified main useful function where/when required, as consequence the modified specific and strategic parts of the nutcracker such as by proposing a blade able to creep inside of the

division line of the shell and to exert a localized pressure. On the contrary, the students without the guidelines modified instead different parts of the nutcracker mostly random, without achieving a specific objective. Some of them modified the length of the handles, other insert additional parts, such as a complicated nutcracker constituted by four handles that close simultaneously, which complicate, also unnecessarily, the initial structure. Still others work on the contact zone but a too superficial level, e.g., by increasing the surface roughness.

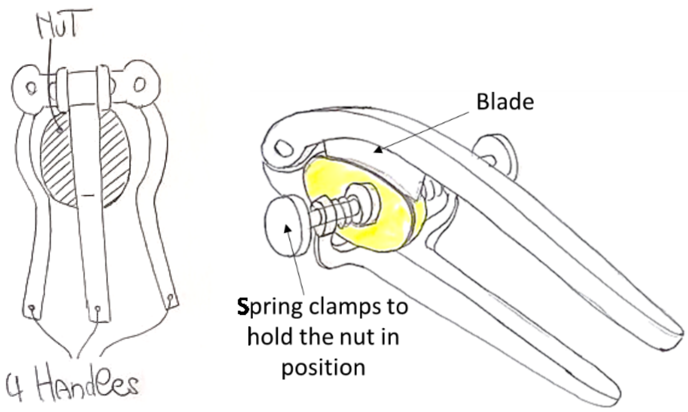


FIGURE 63: EXAMPLES OF TWO PROPOSED SOLUTIONS: (A) ACHIEVED WITHOUT THE GUIDELINE AND (B) ACHIEVED THROUGH THE GUIDELINES. NOTE THAT SOLUTION (A) IS MORE COMPLEX AND IT BREAKS ALL THE NUTSHELL TO EXTRACT THE CONTENTS WHILE THE SOLUTION (B) IS MORE SIMPLE AND IT AIMS TO "DIVIDE" THE NUTSHELL BY CRACKING IT ONLY ALONG THE DIVISION LINE, PROBABLY BY REQUIRING A LESS FORCE OF ACTIVATION TO THE USER.

8.3. Application 3: Anticipatory failure investigation

8.3.1. Case study

In order test the proposed guidelines in supporting problem investigation, the continuation of the design of the innovative vacuum cleaner, presented in application 1, has been considered and the defined concept has been improved by using the 3rd group of the guidelines for the anticipatory failure investigation. In the following case study, the achieved results are explained in detail by referring to the specific used guidelines.

Guideline #10: ***System map through functional analysis***

Among all the possible components of the device, some of them have been selected for the analysis for describing the current functioning of the device: the user's acts by pulling and rotating the pipe that moves the joint, which rotates the cover of the compactor. This cover rotates inside the track and it drags the four rollers. Rollers rotate around the axis of the device and they revolve on themselves. At the same time, they approach each other by compressing the wrapper that contains the dust, thanks to the internal shape of the track. The dust is inserted inside the wrapper with a piston actuated by the user. Figure 64 shows the functional analysis of this device.

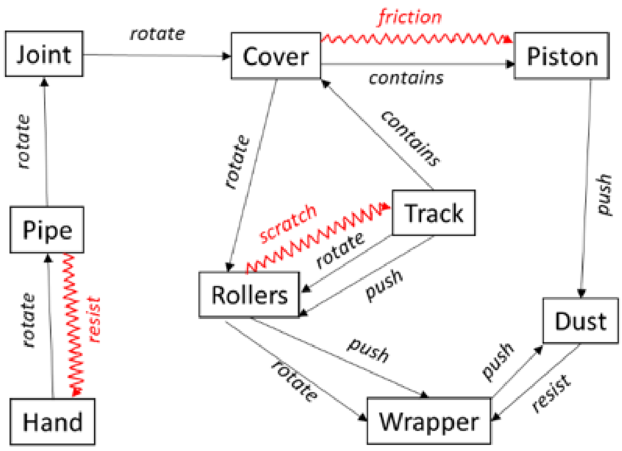


FIGURE 64: FUNCTIONAL ANALYSIS.

Guideline #11: ***Failure modes determination***

The guidelines suggest to consider one by one all elements and their modifications according to noise factors and to determine the relative perturbed functional analyses. In this chapter the redesign of Wrapper is presented.

In the following figure (Figure 65), the obtained perturbed functional analysis for a "Thinned Thickness" of the Wrapper affected by the noise factor "Deterioration of material" is considered. The functional analysis showed new interactions between (1) Thinned Wrapper that insufficiently pushes the dust, and between (2) the pipe that insufficiently resists less to the user manual actuating.

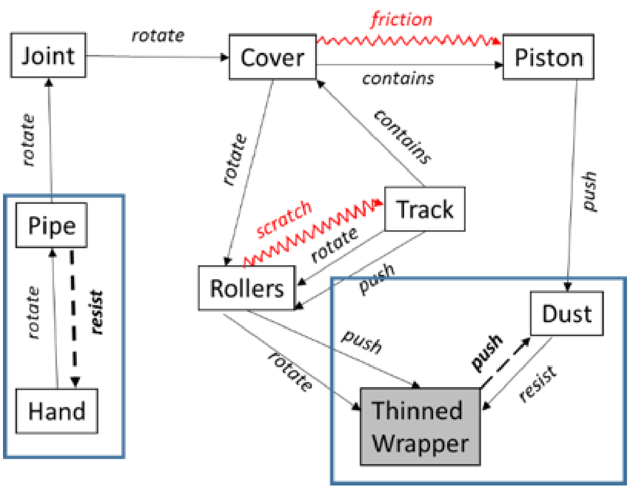


FIGURE 65: PERTURBED FUNCTIONAL ANALYSIS FOR DUST COMPACTOR OBTAINED THROUGH THE MODIFICATION OF THE WRAPPER ACCORDING TO THE NOISE FACTOR "DETERIORATION OF MATERIAL".

Guideline #11: ***Failure Effects determination***

On the basis of the determined modified interactions in the proposed perturbed functional analysis, the Failure Effects depending by the "Thinned Wrapper" have been determined and compared to those found by using the traditional FMEA and by considering the same Failure Mode. Table 30 summarizes the results.

TABLE 30: DETERMINED FAILURE EFFECTS DERIVING FROM THE FAILURE MODE "THINNED WRAPPER" BY USING TRADITIONAL FMEA AND THE PROPOSED APPROACH.

Failure Effects	Traditional FMEA	Proposed approach

Not compact dust sample (caused by the insufficient push of the Thinned Wrapper on the device)	✓	✓
User injury (caused by the unexpected low resistance of the pipe and due to the reduced resistance in the compaction in turn caused by the insufficient push of the Thinned Wrapper on the device)		✓

In particular, among the determined Failure Effects, the "Not compact dust sample" has been investigated in order to compare the successive steps with the traditional FMEA on the basis of the same Failure Effect.

The selected Failure Effect has been then analysed by using the Film Maker (Figure 66) by supposing the presence of a thinned thickness in a part of the wrapper. This cause an infiltration of the corresponding part of the Wrapper and the contained dust in the space between the rollers when they approach.

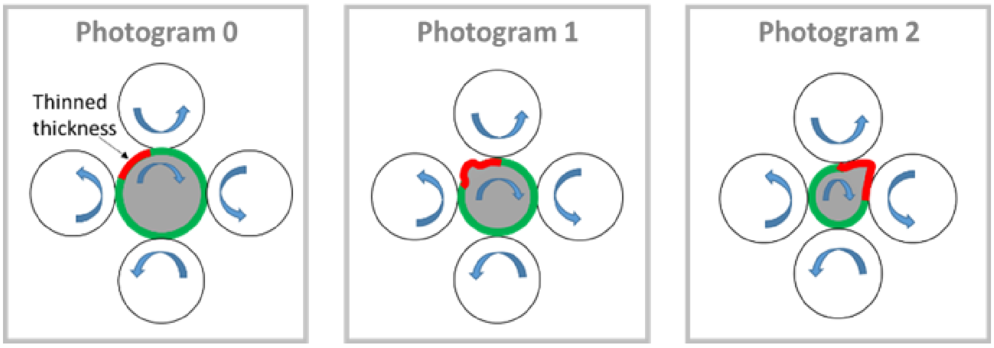


FIGURE 66: FILM MAKER OF THE FORMATION OF A NOT COMPACT DUST CAUSED BY A LOCAL THINNED THICKNESS OF THE WRAPPER.

Guideline #11: ***Failure Causes determination***

At this point, the Failure Causes for the considered Failure Modes and Failure Effects, in accordance to the dynamics of manifestation of the Failure Effect (temporal and spatial) can be investigated. As result, this analysis leaded to the determination of new Failure Causes compared to those found with traditional FMEA.

The following table (Table 31) compares the identified Failure Causes for the considered Failure Mode and Failure Effect by using traditional FMEA and the proposed approach.

TABLE 31: FAILURE CAUSES OF THE FAILURE MODE (THINNED WRAPPER) AND FAILURE EFFECT (NOT COMPACT DUST SAMPLE) BY USING TRADITIONAL FMEA AND THE PROPOSED APPROACH.

Failure Cause	Traditional FMEA	Proposed approach
Needle in the dust (provokes the local damage of the Wrapper)	✓	✓
Excessive space between the rollers (causes the penetration of the damaged part of the Wrapper between the rollers and the local reduction of the compactness of the dust sample)		✓

In particular, by considering the presence of a needle in the dust, the previously described Film Maker has been completed by adding the photograms (-2, -1) before the realisation of the considered Failure Mode and Failure Effect (Figure 67).

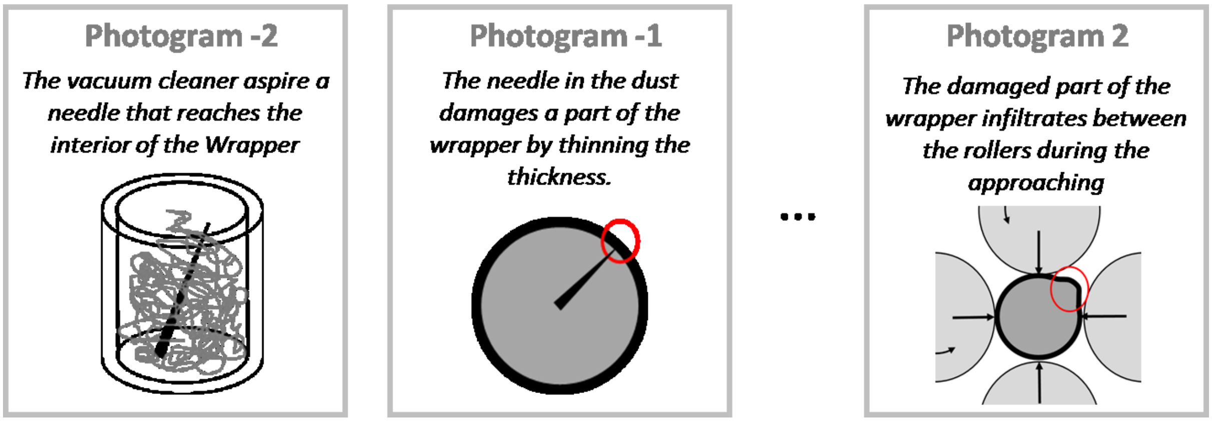


FIGURE 67: COMPLETE FILM MAKER.

Each photogram of the Film Maker highlights a possible problem to solve: in photogram #-2, we have to prevent that a needle goes inside the wrapper, in photogram #-1 we have to avoid that the needle inside the wrapper could damage it and in the photogram #2, we have instead to prevent that the damaged wrapper can infiltrate between the rollers. Several resolutive directions can be found for each photogram, e.g., a filter in the first case, a reinforced wrapper in the second one an increase in the number of the rollers. In order to show how to identified resolutive directions can be developed by using the proposed approach, in the rest of the chapter, the successive guidelines are applied to photogram #2.

The improvement of the problematic situation described in photogram #2 by using the identified resolutive directions cannot be realized without imply additional problems. A compactor constituted by a greater number of rollers with smaller diameter is not able to compress the dust sample as required because of the reduction in approaching of the rollers. For this reason, the considered reolutive direction imply a possible contradiction, which has to be reformulated and solved. The successive guideline to be considered is then guideline #12.

Guideline #12 “Reformulate the problem as contradiction”

In order to find a correct level of compactness of the sample even if the wrapper is less rigid, the current guideline suggests to reformulate the problem as a technical contradiction. To do this, two alternative solutions (see Figure 68) have to be defined and compared: the current one and an alternative one, which does not present the same problem.

- Solution A: the current compactor produces a sample with a high density on the centre and a lower density on the boundary.
- Solution B: a hypothetic dust compactor constituted by more rollers with a minor diameter is not able to compress the dust on the centre with the same value of density of the situation A, cause of the geometrical constraints of the rollers that are not able to sufficiently approach each other.

However, on the boundary of the sample the value of the density increases because the wrapper is confined in more points.

The control parameter that lead from the situation A to the situation B can be identified as the roller radius, which is high in the first one and low in the second one.

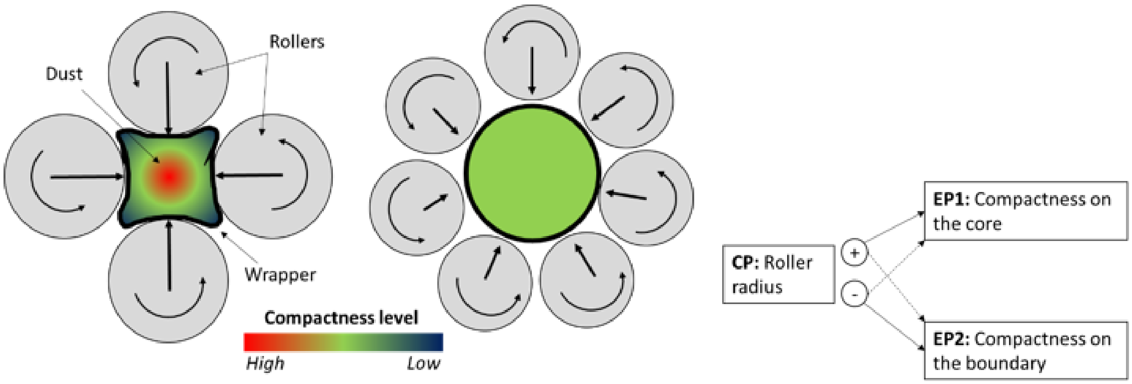


FIGURE 68: SITUATION A AND SITUATION B AND TRIZ CONTRADICTION.

Guideline #13 "Solve a contradiction"

In order to solve the identified contradiction, the inventive principle #1 Segmentation can help by suggesting for instance to use different rollers with different diameters, high and low (Figure 69). The solution can be found in the patent application (ITMI20131928).

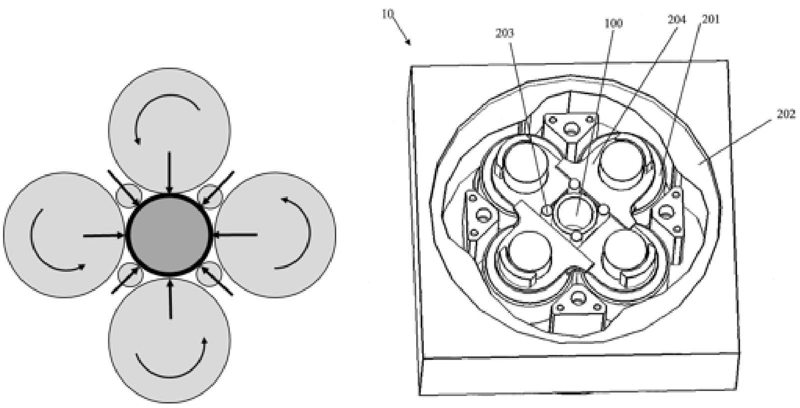


FIGURE 69: (A) SOLUTION OF THE CONTRADICTION AND (B) IMPLEMENTATION IN THE PATENTED SOLUTION (MONTECCHI, RUSSO, SPREAFICO (ITMI20131928)).

8.3.2. Test

During the test, the considered device is a variant of the presented dust compactor, which differs from the previous one in the behaviour and in the structure. In extreme synthesis, in the new device (see Figure 70), the lever actuates with a gear (not represented) a sprocket (#220) on which a belt (#210) wounds in #214. The belt is fixed through glue to ta matrix (# 230) in #212. When the belt is pulled, it compacts the dust contained in #100, collected inside from the collector compartment (#260) by a piston (#250), superiorly bound by the frame itself.

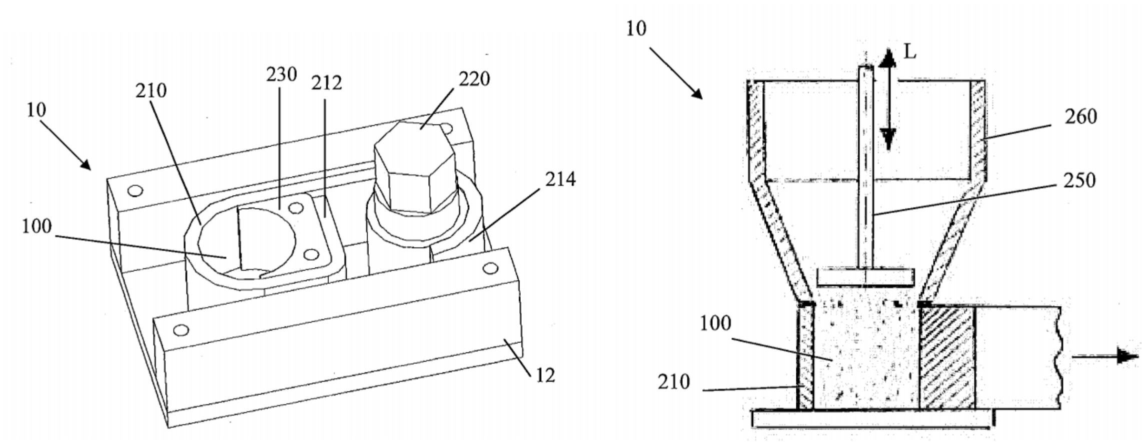


FIGURE 70: CONSIDERED DUST COMPACTOR (MONTECCHI, RUSSO, SPREAFICO (TMI20131928)).

During the test, 4 MsD students in engineering and 4 PhD and academic researchers with a previous knowledge in previous knowledge in FMEA, TRIZ and Spark, faced the same problem by using the proposed guidelines for weeks. The achieved results have been compared to those found by a control group through the use of traditional FMEA.

The objective of this test is to verify the efficacy of the proposed guidelines in comparison to the application of the traditional FMEA on the same devices. In particular, the specific objectives are:

- Verifying if the guidelines are able to not omitting any failure provided by the traditional FMEA.
- Verifying if the guidelines are able to help the problem solver in identifying a greater number of failures (Failure Modes, Failure Effects and Failure Causes) compared to the traditional approach.
- Verifying if the guidelines are able to better contextualize the identified Failures Effects in their specific space and time of occurrence.

Results

In the following graph (Figure 71), the number of the results found by the control group through the use of traditional FMEA and by the other group through the proposed approach are resumed in terms of Failure Modes, Effects and Causes.

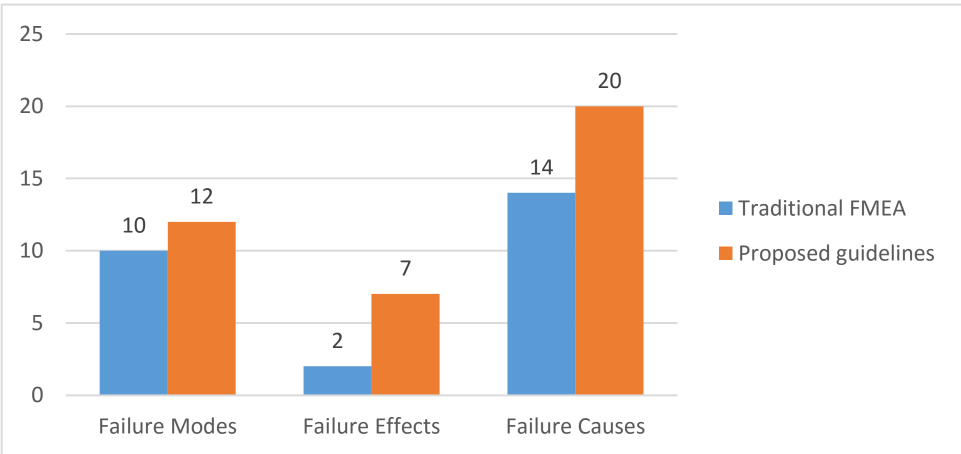
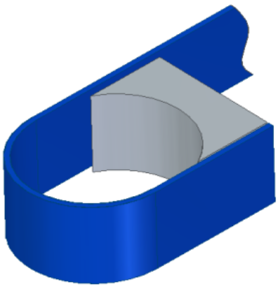


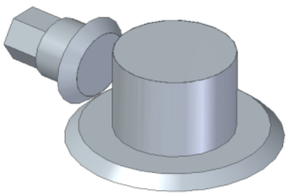
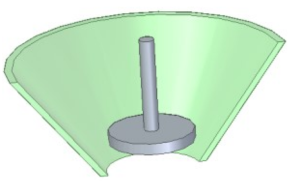
FIGURE 71: COMPARISON BETWEEN THE NUMBER OF FAILURES IDENTIFIED THROUGH TRADITIONAL FMEA AND THE PROPOSED APPROACH.

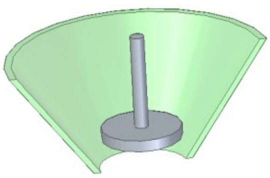
As we can see by the graph, the proposed guidelines have been able to support the identification of all the failures determined by the control group through the traditional FMEA, in addition to some additional unknown failures (Failure Modes, Failure Effects and Failure Causes).

In particular, the specific results achieved by using the proposed approach and the traditional FMEA are summarized in the following table (Table 32), where the improvements to the failures and the additions, identified through the proposed guidelines, have been highlighted.

TABLE 32: FAILURE MODES, EFFECTS AND CAUSES DETERMINED BOTH THROUGH TRADITIONAL FMEA AND THE PROPOSED APPROACH (WHITE), AND THE MODIFICATIONS (BLUE) AND THE ADDITIONS (YELLOW) IDENTIFIED ONLY BY USING THE PROPOSED GUIDELINES.

Elements	Failure Modes	Failure Effects	Failure Causes
Dust compactor	Perforated belt (FM#1)	Sample with reduced density (due to the dust leakage) (FE#1)	Stone or needle in the dust sample (FC#1)
			***Stone stuck between the belt and the side of the matrix (FC#2)***
	Dilated belt (FM#2)	Sample with reduced density (due to the excessive dust mass collected) (FE#1)	Belt material degradation (FC#3)
		Blocked belt between the sprocket and the containment wall due to the belt overlap on the sprocket (FE#2)	
	Belt out of position (closer to the matrix), (FM#3)	Reduced dust quantity collected in the belt (FE#3)	- Shifted matrix (FC#4) - Misaligned sprocket (FC#5)
		User injury (whiplash injury) due to the reduced lever resistance offered by the reduced dust mass collected in the contract belt (FE#4)	***Infiltration of the dust or stone between the belt and the sprocket during the wilding (FC#6)***
	Rotated matrix (FM#4)	Sample with reduced density (since the matrix is not able to constraints the belt as it should) (FE#1)	Broken fixing screw (FC#7)
		Blockage of the belt since it is pinched between the rotated matrix, the spill dust and the wall (FE#2)	
	Dirty matrix with excessive adhesion with the dust (FM#5)	Reduced dust quantity collected in the belt ***in the posterior surface of the sample; not***	**Presence of lubricant or aspirated colloids (FC#8)**

		cylindrical shape of the sample (FE#3)	
Transmission (gear, lever) 	Misaligned gear (FM#6)	Sample with reduced density (since the belt cannot be completely pulled) (FE#1)	- Bumps on the lever during the use tilts the gear in perpendicular direction to that of actuation (FC#9) - Presence of compacted dust between the gear teeth (FC#10) ***A stone in the dust sample overstressed the belt that tilts the sprocket (FC#2)***
	Broken gear teeth (FM#7)	***- The belt does not return to its original position consequently the next sample cannot accommodate the required dust amount in the anterior part (FE#5)*** ***- User injury (whiplash injury) due to the reduced lever resistance offered by the reduced dust mass collected in the contract belt (FE#4)***	***Engine vibrations causes rubbing and breakage of the teeth (FC#11)***
Collection compartment and piston 	Misaligned compartment (FM#8)	Sample with reduced density ***on the top side since the piston does not reach the end position by blocking the dust leakage in the collection compartment (FE#1)***	- Frame deformation (FC#12) - Collection compartment deformation (FC#13) - Broken of the compartment fixation (FC#14)

	Entrance hole smaller diameter (FM#9)	Sample with reduced density ***on the top side since the piston does not reach the end position by blocking the dust leakage in the collection compartment (FE#1)*** ***Piston broken part of the edge of the hole by reducing the diameter if pulled too strong by the user. Part of the edge falls into the sample by compromising in part its density (FE#6)***	- Particles bonding (FC#15) - Constructive errors (FC#16) - Collection compartment deformation (FC#13)
	Entrance hole larger diameter (FM#10)	Sample with reduced density ***on the top side since the piston does not reach the end position by blocking the dust leakage in the collection compartment (FE#1)***	Particles pinched between the piston and the hole (FC#17) ***The misaligned piston ruined the collection compartments (FC#18)***
Piston 	Misaligned piston (FM#11)	Sample with reduced density ***on the top side since the piston does not reach the end position by blocking the dust leakage in the collection compartment (FE#1)*** ***The piston wears the walls of the compartment hole by enlarging its diameter (FE#7)***	Frame deformation (FC#12) - ***Particles bonding inside the sliding guide during the suction (FC#19)***
	Piston with larger diameter (FM#12)	Sample with reduced density ***(part of the dust in the sample returns to the compartment during the compaction since the piston does not reach the end position) (FE#1)***	Particles bonding on the piston border (FC#20)

Discussion of the results

In general, during the proposed applications and tests, the guidelines proved their validity in supporting anticipatory failure investigation, by helping in determining unknown failures and by improving their description in comparison to traditional FMEA. In particular, by specifically referring to the specific achieved results, the following specifically considerations can be stated:

- ***Failure Modes determination:*** The additional determined Failure Modes are circumscribed to more precise areas e.g., "Broken gear teeth" by exploring different possibilities of failures than the traditional ones, typically more related to morphological aspects (misalignments, larger/smaller dimensions) and macroscopically damages (e.g., broken belt).
- ***Failure Effects determination:*** The new determined Failure Effects are referred to the new determined Failure Modes or to the already determined ones, even if they hypothesize unexpected related damages, such as the user's injury, e.g., "Whiplash injury due to the unexpected less resistance offered by the lever to the actuation, in turn caused by the less dust amount contained in the belt out of position". In particular, the second aspect can be due to the ability of TRIZ functional analysis to better define the cause and effect chains, especially those afflicting the user, which is considered an integrant part of the analysis.
  In addition, the new identified Failure Effects are generally described in a more precise way, by better specifying the zone of occurrence; let's consider for instance the following effect: "Reduced dust quantity in the posterior surface of the sample".
- ***Failure Causes determination:*** The use of the guidelines increased the number of the determined Failure Causes, both for the already determined Failure Effects and for the new ones. In particular, the identified Failure Causes highlighted how possible not previously considered dangerous physical effects, such as the vibration of the engine, could affect the technical system (e.g., broking the gear teeth). In addition, some of the determined causes are not specifically related to the elements of the technical system, as in the traditional FMEA, e.g., collected external particles and liquids. Also in this case, the guidelines helped in describing the Failure Causes with a deeper level of analysis, by better circumscribing the zone and the time of occurrence (e.g., the presence of colloids and lubricants on the inner part of the matrix increases the adhesion of the dust). Finally, some of the identified causes seem generally less obvious than those determined through traditional FMEA, predominantly related to deformation and wear.

8.4. Application 4: Idea generation in problems with contradiction

In order to test the efficacy of the guidelines for enhancing idea generation in problems with contradictions, the last group of them, whit a particular focus on "FBS inventive principles", has been tested by involving students and researchers. The two addressed problems have been deliberately supplied in a sufficiently abstract way in order to allow multiple directions of intervention on different levels of detail (function, behaviour, physical effects and structure). For this reason, the problems have been formulated at the functional level, focusing on a description of how to meet the customer's requirements.

Test participants

In order to identify how the personal background and the level of experience of the problem solver can influence the application of the method, the test have been proposed to two kinds of students:

- 10 MsD students follow a university course named "Methods and tools for product lifecycle" (i.e. PLM-Product Lifecycle Management) during the master degree in Mechanical Engineering and Management Engineering. Only half of them, have a previous knowledge of TRIZ theory, thanks to previous course in the university background.
- 5 PhD students involved in TRIZ and dealing with product and process innovation through engineering design, problem solving and CAE methods.

Case study

In order to provide an evaluation of the principles as impartial as possible and not influenced by the kind of faced problem, two different case studies have been proposed:

- ***Hair dryer:*** the function 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. Less energy intensive models which do not guarantee the same quality of the more energy-consumptive competitors are available on the market. The objective of this case study is to provide a hairdryer equally efficient and performant.
- ***Joint for high voltage cables:*** in this problem two functions have to be satisfied: (1) "Ensure the physical continuity of the cables" and (2) "Ensure the electrical continuity of the cables". The material of the joint also ensures the continuity of the electric arc. The actual connection of the cables is realized on the ground because of the difficulty of welding in suspension.

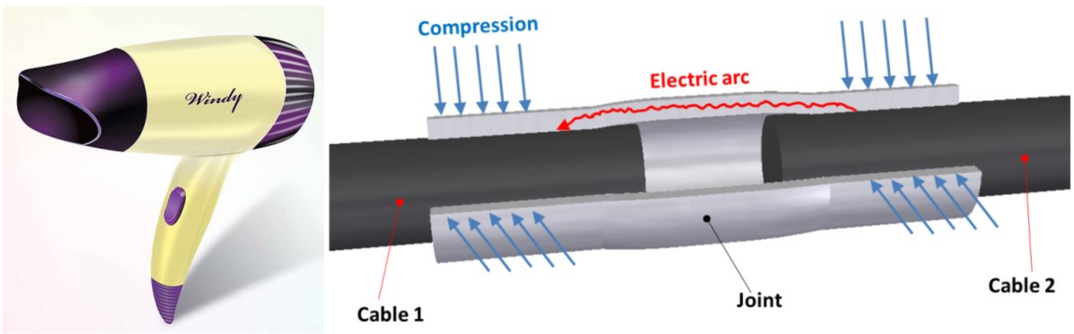


FIGURE 72: THE TWO PROPOSED CASE STUDIES (A) THE HAIRDRYER AND (B) THE JOINT FOR HIGH VOLTAGE CABLES (SCHEMATIC REPRESENTATION).

Test Execution

The students and the researchers solved the assigned problems in two sessions.:

- ***1st session (1h):*** by using traditional TRIZ 40 inventive principles;
- ***2nd session (1h):*** by using the reformulated FBS inventive principles after a training session (0,5 h) during which the key concept of FBS theory has been explained.

Test results

In the following the results of the test are discussed in relation to the total number and to the quality of the proposed solutions:

Number of solutions

Table 33 summarizes the total number of solutions determined in each session by MsD students and PhD students.

TABLE 33: NUMBER OF PROPOSED IDEAS FOR EACH SESSION.

	Session 1 (Traditional inventive principles)		Session 2 (FBS inventive principles)	
	Total solutions	**Individual solutions (per person)**	**Total solutions**	**Individual solutions (per person)**
MsD students	12	1,2	24	2,4 (+100%)
PhD students	22	4,4	26	5,2 (+18%)

As we can see by the achieved results, through the application of the FBS inventive principles, both MsD and PhD students found a major number of total solutions. In particular, the second ones found a great number of solutions compared to the MsD students in each session, especially during the first one. This fact can be attributed to their major knowledge about TRIZ and the traditional 40 inventive principles. However, the FBS inventive principles allow to the MsD students to reach a major percentage increase in the number of the new solutions compared to the traditional inventive principles.

Quality of the solutions

The proposed ideas have also been evaluated on the basis of their qualitative level by considering the following parameters:

- ***The precision of the solution*** has been evaluated on the basis of the degree of structuredness of the proposed solutions, by considering the following criteria: the presence of the sketches, the number of the involved physical effects, the description of the behaviour and the structural aspects, the identification of the operative zone and the operative time of the solutions.
- ***The novelty of the solution*** has been evaluated on the basis of the possible correspondences in the reference literature (patent analysis and technical catalogues).
- ***The feasibility of the solution*** has been evaluated by 3 university researchers on the basis of the feedbacks provided by the R&D researchers of companies that realize the considered products.

Each of the three parameters has been evaluated with a ranking from 1 to 3 points, while the resulting parameter (Quality) is constituted by their sum. Table 34 shows the evaluations of the results:

TABLE 34: QUALITY OF THE SOLUTIONS, IN TERMS OF PRECISION, NOVELTY AND FEASIBILITY, FOR EACH PHASE.

		Session 1 (Traditional inventive principles)				Session 2 (FBS inventive principles)			
		Precision	**Novelty**	**Feasibility**	**Quality**	**Precision**	**Novelty**	**Feasibility**	**Quality**
MsD students	**Mean value**	1,17	1,25	2,50	4,92	1,58	2,08	2,54	6,21
	St. dev.	0,58	0,62	0,52	1,38	0,58	0,72	0,51	1,10
PhD students	**Mean value**	1,50	1,73	2,14	5,36	2,27	2,81	2,73	7,81
	St. dev.	0,51	0,83	0,71	1,00	0,53	0,40	0,45	0,90

On the basis of the determined results, the following observations can be stated:

- With the application of the FBS inventive principles, the students (both MsD and PhD) propose solutions qualitatively better respect the use of the traditional inventive principles. In particular, the MsD students propose solutions with a significantly increased degree of novelty. Also the precision of the solutions is increases in the second session due to a more consciousness about the operative zones and operative times of the problem. PhD students improve all the three parameters.
- PhD students propose solutions with a high qualitative level in both the sessions. This fact can be attributed to their high level of preparation.
- Finally, by considering the standard deviation of the results, both the PhD students and the MsD students seem more focused in finding solutions with similar qualitative levels, with the help of FBS inventive principles.

8.5. Application 5: Idea generation for Measurement problems

The last part of the guidelines, regarding idea generation for problems without contradictions, has been applied during an industrial collaboration for solving measurement problems for several interesting parameters of a circuit breaker (see Figure 73). All the achieved solutions come from the guideline #16 "Solve a measurement problem" and in particular from the Step 1 ("*Measure the parameter Y of a field F1*" and "*Measure the parameter Y of a substance S1*") and the Step 2 ("*Measure the parameter Z of a substance S2*" and "*Measure the parameter Z of a field F2*"). This because these guidelines are the more suitable for the considered application.

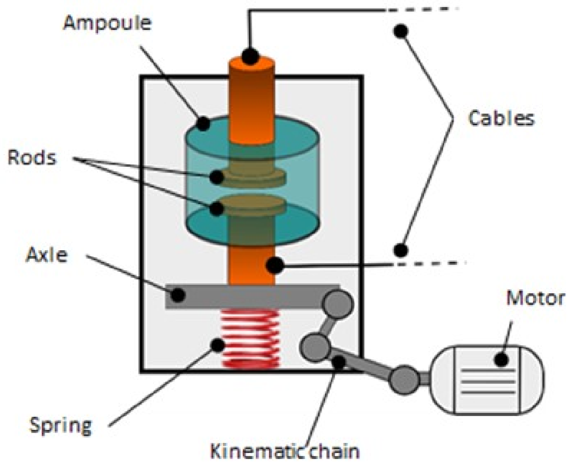


FIGURE 73: SCHEMATIC REPRESENTATION OF A CIRCUIT BREAKER (ONE PHASE).

Test participants are 7 PhD students in mechanical engineering with TRIZ background. The scheme of the guidelines has been applied (for 1 week) by each researcher after a detailed common literature analysis on patents, scientific contributions and catalogues in the field of the circuit breaker. Each of them used the scheme of the guidelines for solving a specific measurement problem (e.g., measure of the vacuum degree inside the ampoule, measure of the energy consumption of the motor, measure of the spring condition, etc.) of the circuit breaker.

Evaluation of the results

Total number of the solutions

The solutions suggested by the guidelines have been divided into two kinds: (1) new solutions with no correspondence in literature and (2) solutions patented or applied in other industrial fields (not circuit breaker); and they have been compared with the solutions achieved through the information retrieval.

Table 35 shows the results:

TABLE 35: TEST RESULTS (NUMBER OF PROPOSED IDEAS).

	Phase 1: information retrieval	**Phase 2: application of the scheme of the guidelines for measure problems**		
Addressed problems	**Total solutions**	**New solutions**	**Solutions patented in other fields**	**Total solutions**
Problem 1	9	9	0	9

Problem 2	18	6	6	12
Problem 3	13	8	3	11
Problem 4	6	8	0	8
Problem 5	7	5	2	7
Problem 6	5	3	0	3
Problem 7	8	11	8	19
Total solutions	***66***	***50***	***19***	***69***
Mean value	***9,4***	***7,1***	***2,7***	***9,9***
Standard deviation	***4,6***	***2,7***	***3,2***	***5,0***

Figure 74 summarizes the results:

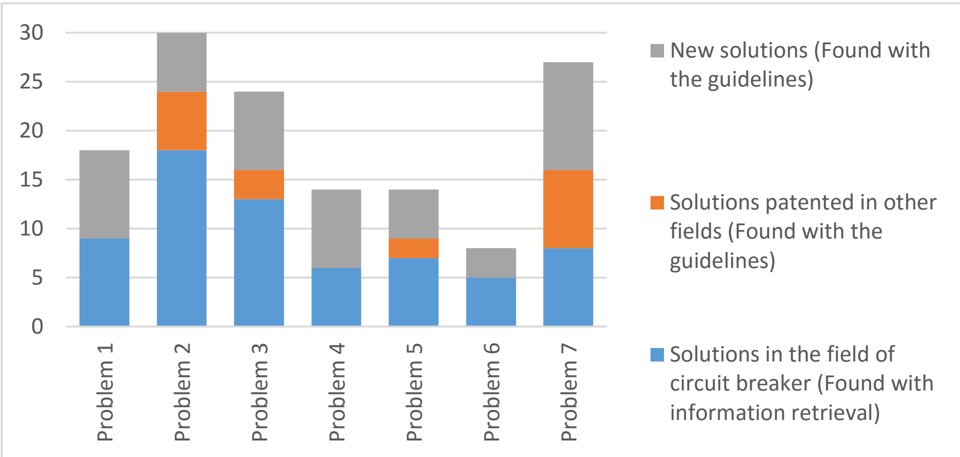


FIGURE 74: TEST RESULTS (NUMBER OF PROPOSED IDEAS).

The achieved results confirmed the validity of the suggested guidelines in supporting the identification of new solutions, in addition to those previously found with information retrieval. In particular, large part of the provided solutions are totally new, with no correspondence in other technical fields.

Level of detail of the solutions

The results have also been catalogued according to the level of detail in order to investigate which of the two steps of the scheme is more commonly used:

- Solutions from Step 1 suggest the measure of an introduced substance or field, which is influenced by the interesting parameter.
- Solutions from Step 2 suggest the measure of an additional substance or field, in turn influenced by the substance/field of the step 1.

Table 36 shows the results:

TABLE 36: TEST RESULTS (LEVEL OF DETAIL OF THE PROPOSED IDEAS).

	New ideas (Found with the guidelines for measurement problems)			Ideas patented in other fields (Found with Standards)
Addressed Problems	**Step 1**	**Step 2**	**Total**	**Step 1**
Problem 1	8	1	9	0
Problem 2	5	1	6	6

Problem 3	2	6	8	3
Problem 4	3	5	8	0
Problem 5	4	1	5	2
Problem 6	2	1	3	0
Problem 7	5	6	11	8
Total solutions	***29***	***21***	***50***	***19***
Mean	***7,25***	***5,25***	***12,5***	***4,75***
Standard deviation	***2,116***	***2,517***	***2,67***	***3,2***

The following graph (Figure 75) shows the obtained results:

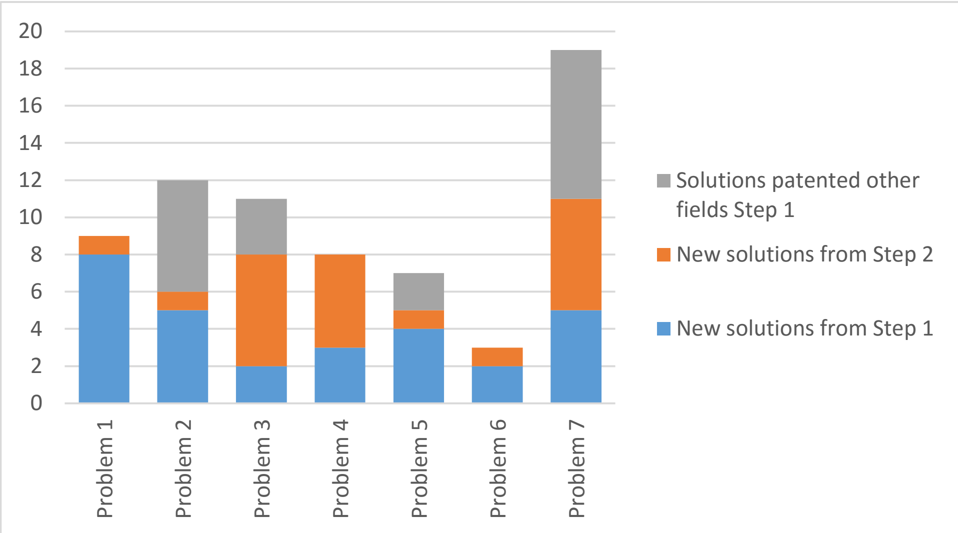


FIGURE 75: TEST RESULTS (LEVEL OF DETAIL OF THE PROPOSED IDEAS).

Overall, the achieved results are equally distributed between the two levels of detail (step 1 and step 2). In particular, all the solutions found, with the guidelines and with correspondences in other fields, derive from step 1, while the unknown solutions are also from step 2 and they are typically more structured, by simultaneously involving multiple physical effects and structures.

8.6. Discussion of the results

The proposed tests showed different applications of the proposed approach and the related guidelines in the considered problems, by highlighting the main improvement made to the main phases of Spark:

- The guidelines helped the users, especially those not involved in TRIZ, in improving the identification of the main useful function, by focusing attention on the identification of the required operative zone and operative time. Through the guidelines, the users have also been more conscious about the expected behaviour of the device, which has been used both to design the structures of new devices and to identify the weaknesses and the problems of the already existing ones.
- The identification and the description of the problem have also been improved through the introduction of the specific guidelines for the anticipatory failure investigation that enlarged the set of identified problems, by leading the user to work also on unknown criticalities, otherwise not taken into account. In addition, the guidelines supported the problems solvers in better identifying the critical zone and the critical time of the problem.
- The idea generation phase has also been improved both for problems with and without contradictions. In particular, an increased number of solutions have been determined and their

qualitative level has been improved through the identification of unknown resources and the better exploitation of the already considered ones. In addition, the proposed solutions have been characterized by increased novelty and feasibility.

9. Conclusions

In this Ph.D. thesis, the key features to create good guidelines have been investigated on the basis of literature review, empirical evidences collected during the collaborations in industrial projects and tests with students. The identified features have been applied to develop specific guidelines with the aim to improve Spark methodology.

During this activity, first of all, a restricted number of inventive problems, including new concept design, anticipatory failure investigation/robust design, elimination of harmful effects and product improvement, have been identified within a broader set of technical problems, and have been considered as domain of application.

Then, the main features of the guidelines for problem solving have been analysed. They are: the structure of single guidelines (order of the provided suggestions, text, examples and graphical representations), the organisation of multiple guidelines (e.g., hierarchical maps, random lists), the advantages of software implementation (e.g., text customisation, interactive examples) and the most suitable strategies and tools suggested by the guidelines (e.g., use of models, database interrogation). In particular, specific literature surveys, involving papers and patents, have been carried out on Design models (e.g., FBS), anticipatory failure techniques (FMEA) and problem solving techniques (TRIZ), with a focus on the presented case studies. During the analysis I focused attention to comprehend how the structure and the content of the guidelines change in relation to: (1) the kinds of addressed problems by analysing the correspondence with the considered problem domain; (2) the different phases of the problem solving activity (problem identification, problem formulation, idea generation, etc.) and (3) the kinds of users (professionals and students) with regard to their specific methodological and technical background.

After that, a set of guidelines have been defined in order to improve Spark methodology by integrating two proposed models (the comprehensive design scheme and the FMEA-TRIZ model) and reviewing some steps, with the aim to ameliorate the comprehension and the efficacy and enlarge its domain of application to all the considered inventive problems.

The proposed integrations have been: (1) the comprehensive conceptual design scheme to improve function identification in Spark through the identification of the most important elements of design activities (function, behaviour, affordances, manipulations, structures, signals) and the relations among them; (2) the FMEA-TRIZ model that enlarges the efficacy of problem investigation in Spark by adding the possible future failures of the device, through a step divided procedure based on traditional FMEA and involving some TRIZ tools (e.g., function analysis, resources and subversion analysis).

The revisions have been: (1) FBS inventive principles, or a new version of the traditional TRIZ 40 inventive principles revised through a rigorous FBS ontology, which have been divided into sub-principles specifically acting on the function, the behaviour and the structure of the device; (2) a scheme of guidelines based on 76 standards solutions, revised through a less rigorous methodological formalism (Su-Field model) and organized in a more practical structure.

The resulting comprehensive set of guidelines has been organised into four main groups (i.e., Functional overview, Innovation strategy, Problem identification and formulation and Idea generation) and all the guidelines have been built with the same structure including: goal declaration, suggestions, tools, examples and reference to the subsequent guidelines.

Subsequently I studied the integration between information retrieval techniques and some modules of modified Spark (e.g., idea generation) and I proposed a method that automatically translates the suggestions provided by the guidelines into functions and it creates queries containing the information provided by the user (e.g., the name of the product to innovate) for databases interrogation. The result is a list of suggestions (e.g., physical effects and technologies) to innovate the product.

The guidelines have been embedded in the software platform I developed as a web application through HTML, CSS and JavaScript languages. The platform is based on a direct interaction with the user, through data entry about the problem (e.g., name of the device, description of the negative effects) and the context of application (e.g., the requirements), the selection of the guidelines, through navigation menu, and the customisation of the visualized guidelines according to the collected data. In addition, the software platform directly addresses to the databases for the research of information. These features made the guidelines more comprehensible, especially for R&D technicians, and more practical.

Finally, the proposed guidelines have been tested with some real industrial case studies, by involving students in engineering, with encouraging results: (1) Function identification has been improved through a more precise description (e.g., including functional verbs) and the identification of the required operative zone and time; (2) Problem identification has been improved with an increased user's awareness about the dynamic of occurrence, the critical zone and the critical time and through the determination of the possible future failures of the device; (3) Idea generation has been improved through the determination of a greater number of solutions, characterized by an increased qualitative level in terms of novelty, feasibility, and resource exploitation.

Future developments

Future developments will regard the continuation of the ontological analysis of the guidelines, a further development of the proposed guidelines and an enlarged test campaign. In particular, the following activities have been planned for the next months:

<u>Developing a set of rules to write good guidelines</u>

The analysis of the features of guidelines will be enlarged to a wider pool of considered documents from literature and from practical evidences. The collected features of the guidelines will be formalized within a rigorous set of rules.

<u>Continuing the development of the proposed guidelines</u>

The proposed guidelines will be improved through the development of the linguistic formulation and the identification of specific examples with the aim to facilitate their comprehension especially for novice users and with different scientific and technical backgrounds. In addition, the software platform will be updated in order to improve the integration with knowledge databases and the user interface providing a more intuitive interaction style.

<u>Massive application of the guidelines</u>

So far, the proposed guidelines have been tested on a restricted number of industrial case studies for limited periods of time and involving almost exclusively students. In the next months, they will be applied on more complex industrial projects, including all the stages of product development, and by professionals, with the aim to investigate all the advantages and limitations of the guidelines not yet highlighted.

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