Denis Cavallucci *Editor*

TRIZ – The Theory of Inventive Problem Solving

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Preface

It has been two decades since the TRIZ theory overstepped the erstwhile Iron Curtain and spread into the world. Every continent, every country adopted it in a different manner, sometimes by glorifying its potential and its perspectives (the American way), sometimes by treating it with mistrust and suspicion (the European way) and sometimes by adopting it without questioning it further (the Asian way). Today, none of these models of adoption have really succeeded. Twenty years later, America is blaming the unkept promises that early TRIZ followers stirred up without much restraint. Asia caught up with the others and is even ahead now (TRIZ was developed there during the early 2000s) but is starting to get disillusioned about the way the theory was presented by people it trusted. As for the always careful Europe, it observes, analyses and tries to unveil the mystery of TRIZ, a model that amazes, disappoints and seduces those who see it as a new way to support the production of disruptive ideas. However, Europe's tergiversations and its timorousness of investing in research of methods made it lag behind Asia. I cannot compare us to the Americas (both North and South); however, in Europe, the TRIZ "wave" flooded the big companies with promises before interest began to decline due to a blatant gap between promises and reality.

The latest development is that Asia's fondness for TRIZ is also beginning to fade away, as the methods it employed were not the best, and by the time it tried to clear the negative opinion about it, it was already too late. In the end, Europe, because of the slowness of its decision-making process, has still a chance not to fall for the TRIZ model, like in the Americas or in Asia. It can learn from their failures, focus on the specificities of different countries (including countries within the same continent) and try to understand what went wrong with these models in order to better organize its approach in the years to come.

Before providing such an analysis and defining the trends that emerge from it, it is necessary to focus on our own progress. One preliminary question must be asked: within Europe, are there any differences or links in the way TRIZ was understood in France, Italy, Germany and England? I am convinced that this diagnosis, this assessment, this study about TRIZ practices in education, industry and research is necessary now that its decline has begun. What international indicators can be used to make these assessments? Insofar as multinational companies are concerned, specific attention is given to those that officially claim they are using TRIZ. The first is Samsung, closely followed by Posco, Hyundai, LG, Pioneer and Hitachi. With regard to the Americas, Intel, Boeing, Xerox and Ford need to be monitored carefully. In Europe, Whirlpool, Bosch-Siemens, PSA and Airbus can provide useful details on the way they have used TRIZ in the past few years. Regarding consulting practices, have they changed? Have they freed themselves from the classic TRIZ as the Russians have in order to reinvent it? Despite their association with numeric tools, only a few differences can be found besides the evolutions leading to oversimplification that have failed to make a compromise between being lighter and not losing the advantages produced by TRIZ. Another indicator regarding consulting practices is that in 20 years, not a single major actor in consulting has exploited it commercially. From this situation, we may understand that, on one hand, selling expertise about TRIZ would not yield enough money (its threshold is too difficult to reach and is too low), or, on the other hand, the preparation and the training of an expert would not be worthy in the end. Regarding scientific research, TRIZ is more critical. Either TRIZ preserves or even amplifies its capacity to become a subject for studies (in this case, its evolution seems unavoidable) or it is only seen as a packaged tool, thereby making its future bleak. Part of the answer resides in this work, at least with regard to the development of research in France. Another element of the answer resides in the indexation of scientific productions. When observing Scopus (one of the three leading international scientific production databases), the number of articles published in rank "A" journals (those with a decent impact factor) has grown since 2005, even though there has been a stagnation in the last 2 years. This means that the 150 scientific articles published annually by researchers in laboratories are supported by constantly developing knowledge, some of which will probably end up as a new practice/tool/method in companies after maturation. One can presume that TRIZ would have triggered something new, irrespective of the future acronyms that will come from research and that, in turn, will become the future of a discipline we call invention.

Invention is peculiar to human beings; some anthropologists argue that it distinguishes us from animals. Thus, it seems logical that a science of invention would offer a variety of digressions, each one likely to invade every discipline of the society. How does man invent (for human sciences)? How does the society assimilate these inventions (for sociology)? How do we invent new molecules (for chemistry)? How do we teach invention to the greatest number of people (for educational sciences)? How do we produce an algorithm to sketch the invention activity in the industrial process in R&D (for engineering sciences)? The list is almost endless, and it is understandable that no work can gather everything that has been accomplished in all of these areas as far as research is concerned.

The work that is presented in this book is compiled for engineers, educators at all levels, industrialists, managers, researchers and also political representatives. It provides a very partial and "snapshot" picture of the research conducted in the field of TRIZ. The span of the research encompassed all known francophone research laboratories producing regular research on TRIZ. Fifteen laboratories were questioned and thirteen out of them had indeed research tied to the subject of TRIZ that we were interested in for our project. Twelve accepted to send one or several of their postdoctoral researchers to present their work during a seminar, no matter its maturity or the completeness. Thus, we had a snapshot of the main research on TRIZ in French-speaking countries. Following this project was the idea to gather one chapter for every current thesis in order to observe and impart to the readers the breadth, richness and perspectives that research on TRIZ could bring to our society. Eleven research teams then proposed their achievements in the following chapters.

The first two chapters combines two fundamental aspects of invention: on the one hand, patents, of which we know that they gather a large amount of the traces of human inventiveness, and on the other hand, the laws of evolution of TRIZ, of which we know that the essential postulate makes it different from everything that is settled on in our consumer society—the demand from the customer that triggers the evolution of the product.

The postulate of the laws of evolution, a mix of Darwinism and Lamarckism, provides us with another scenario. What if the evolution of artefacts (i.e. what man conceives) was ineluctable? What surrounds the artefact (of which the customer is just a minor component) sets demands on the object and puts it under a whole set of constraints that makes its evolution according to a known scheme unavoidable. Chapter 1 attempts to analyse the potential links that would unite these contrains to the "roads" made by the laws of evolution of TRIZ, observable in the patents per population. Thus, in a meta-cartography, every patent could find its place in the phases of evolution of a technical object with respect to the laws of TRIZ. More, what if those markings created empty spaces seen as opportunities to question oneself about the opportunity of filling them? If such a thing were possible, it would get us some serious help in the scientific identification of opportunities for inventions yet to come.

Chapter 2 is also part of the exploitation of patents. In these authors' cases, different use is made of the mine of information called patents. In claiming that patents are mirroring human inventiveness and that they are a historical trace of technical progress, drawing a partial representation that allows artificial reasoning would considerably help the industrial R&Ds to address the true problems that have to be solved in a given context. We could thus avoid try-outs and time-consuming mistakes that prove costly and risky. This is the aim of Chap. 2: to model the knowledge in a given area as an introduction to creative thoughts. Just like networking can help numerical calculation, networking knowledge can help choice making in R&D. Patents seem to be, once again, a serious database for knowledge that has yet to be used.

Chapter 3 focuses at a macroscopic level on the design activity by returning to the basics of this exercise: defining a frame model. Complementary approaches of TRIZ are mentioned, such as C-K theory ("C" and "K" referring to Concepts and Knowledge) and its recent operational variations. Older models, such as the

Pahl-Beitz model, enlighten the chapter. A mix of the models follows in order to describe a new, hybrid, methodological approach that is still theoretical (the author incidentally reminds us that the approach still needs testing). An example concerning the design of a new street lighting system is provided to better grasp the sequence of underlying arguments of the approach. One can find in this example the difficulty linked to the multidisciplinary approach of this subject where design, technique, marketing and business considerations all combine. If C-K provides a concrete theoretical model about understanding the design of a creative act and TRIZ a set of methods to help the formulation and resolution of problems, these two approaches (TRIZ and C-K) have rarely cohabited within the same approach. The course choices given in this chapter based on a thesis are full of promises and could help the global efficiency in innovation progress.

Chapter 4 is about the inputs that TRIZ could bring to educational sciences. If invention training is still a significant challenge in that field of sciences, this chapter argues more strenuously for a contribution to the educational methods of teachers. Indeed, after an assessment of the educational methods on the inventiveness of young learners, the chapter deals with the teacher and his methods. For the first time in this work, an explanation of the acronym OTSM-TRIZ is provided, OTSM-TRIZ being an evolution of TRIZ towards an extrapolation of its basics in a generic form for education. When Altshuller was in his last phase of action, the idea of a discipline seen as a metascience of invention was born. Nikolaï Khomenko joined the adventure and led this line of research for many years. Some followed him and the acronym OTSM associated to TRIZ appears sometimes in the literature. This chapter provides an example of this ambitious project, which is centred on educational sciences. It covers the issues of education and provides a recap of its benefits to the learners. This chapter differs from others classic approaches directed at issues and provides experimentation in order for teachers to better grasp its inputs.

In Chap. 5, the reader is led to another universe: the universe of organization (or reorganization) of workshops. This chapter not only uses TRIZ to give its contribution but also one of its developments, Inventive Design Methodology, and especially one of its tools, the Graph of Problems. This tool usually used for the industrial design of a product/system was initially conceived in order to make an inventory of knowledge in a complex and multidisciplinary situation aiming at finding the contradictions. This chapter discusses its use in the reorganization of a workshop, with references to TRIZ and OTSM-TRIZ, which are the basics of the Inventive Design. The example given in this chapter shows that this approach improves the systematic nature of extracting information (a comparison with a classic approach is given with its results). With these results, the authors conclude that it is necessary to make this graph for its inputs in terms of efficiency in the global process are obvious, especially the risk of forgetting important issues and what that could lead to. There is no progress in research without a metric that allows the monitoring of the accomplished progress in regard to the goals aimed at. Such a metric does not exist yet when it comes to inventiveness in R&D (at least, those that exist are contested). This is the aim of Chap. 6: to understand and conceive indicators that will help create a metric of inventiveness for R&D project teams.

The chapter deals with the basics of the evaluation of performances and lists the criteria that allow a better understanding of how mathematics can help find an indicator that makes sense. The position of the research in invention metrics is transversal and is essential to the pursuit of research in Inventive Design. Indeed, how do we monitor and consider that a new method or a new practice is an input for the company? How do we state that what was produced is inventive or not, and in what proportions? How do we allow a company to enter in a logic of performance regarding the inventiveness of its R&D teams? All these questions are clumsily answered by measuring only the ROI, which we know diminishes the inventive dreams of project teams.

The next chapter deals first with the "contradiction" and formally highlights what a lot of TRIZ practitioners intuitively knew: using contradiction is indeed powerful but yet too intuitive. Chapter 7 concerns the basics of contradiction and the challenge of its resolution. However, it does not deal with it literally (as in most works on TRIZ) but mathematically and numerically so the description of mechanisms does not suffer from ambiguity. The mathematics of contradiction allowed the team that worked on this chapter to highlight the existence of a so-called generic form of contradiction. Authors explain how a set of components from a set of contradictions can be agglomerated in order to get a generic form and expression, the resolution of which impacts the process in a better way.

Chapter 8 covers another aspect of the process of Inventive Design: the feasibility of solution concepts. Numerous studies have already focused on the evaluation of ideas. They are often presented as statistical and matrix-like valuation (such as Stuart Pugh's work), but there is always a doubt regarding the feasibility of the idea (due to the qualitative aspects of the process). This doubt leads the decision-maker in a company to anticipate failure, and there is thus a risk that one idea can only lead to a technological deadlock and therefore to a financial one. Chapter 8 proposes an original process to rapidly estimate the feasibility of ideas by formal computation. This can reassure the company regarding the feasibility of an idea. However, formal computation (3D, finite elements) is not currently possible due to a lack of time and often of multidisciplinary competences in order to judge the idea objectively. The authors of this chapter suggest using 1D and 2D equations in order to help reduce computing time since all concepts of solution do not necessarily need a 3D computation to be credible. Moreover, in Inventive Design, the number of solution concepts is less important than conserving those with an inventive characteristic. Regarding the multidisciplinarity of the approach and the risk of the lack of competences to do a 1D/2D computation away from individual core competencies, an access and a simplification process to semi-automatic forms has been created. This chapter deals with the impact of simplification and acceleration of precomputation of ideas with a dual objective: find bad ideas at once and avoid abandoning good ones.

Chapter 9 reminds us that our world has swung into an informative and collaborative mode. Information systems are becoming more important in our daily lives. It seems legitimate to wonder about the consequences of this evolution for TRIZ and the way in which these methods and techniques can be applied more efficiently and usefully for society. A community is often referred to in this chapter: the computer-aided innovation (CAI) community from the International Federation for Information Processing (IFIP) where such subjects are largely debated. The authors first offer a review of the numerical contributions for TRIZ and what they bring to the CAI. Then, just like in Chap. 3, they offer a new approach that includes these considerations. This approach is original for it is based on the authors' previous work on case-based reasoning and has been complemented by other works from researchers on ontology and semantic analysis. They discuss an investigation of real cases and a software interface (internet + server) to highlight their contribution.

In Chap. 10, the authors deal with one of the limits of TRIZ: its low capacity to model a problem at the beginning of a study. This limit has been highlighted many times by the community, and several contributions have been put forward in order to resolve it. Two more elements are put forward in this chapter and a solution is offered. The first one is that TRIZ representations are not dynamic in time. Often an observation at a given moment will prove that a contradiction is true, but the fact that this contradiction can evolve, disappear or, at worst, reverse is not sufficiently analysed. The authors highlight the non-linearity of relations between factors and the oppositions between factors that influence each other. They suggest using a well-known tool for the numerical analyses: system dynamic modelling. The authors aim at combining this approach and TRIZ in order to solve this deficit of TRIZ. A case study is presented in order to illustrate this suggestion. Last but not least, Chap. 11 concludes this work by discussing creative activity. It first deals with the various approaches of creativity by sorting them into two categories: structured and exploratory methods. TRIZ is clearly part of the structured methods. Exploratory methods are then dealt with in order to describe the necessity, in the digital era, to offer them a support to better organize and widen the frame of creative activities and what they produce. Even if the computation part is not developed in this chapter, it provides a sketch of its architecture and main features.

The assessment of the research presented in this work is convincing: TRIZ has entered many different scientific disciplines and has allowed young researchers to explore new possibilities in their field of research. Its basics are universal. Thus, the observation of a problematic, no matter what the discipline it comes from, through the prism of contradiction, fosters a new way to apprehend it. Contradiction is a kind of syntactic universal language that allows knowledge from various disciplines to coexist within the same model of representation. It induces subsequent inventive reflexes, and thanks to their common pattern, "solutions" from one discipline can help find "solutions" for another one. Finding the knowledge from patents to supply TRIZ representations (Chaps. 1 and 2), supplying a new method inspired by TRIZ (Chaps. 3 and 9), solving its issues (Chaps. 8, 9 and 10) or measuring its impact within a team (Chap. 6) all converge to one idea: theory is the core preoccupation for many researchers who truly form a community nowadays. Chapter 4 is about educational practices, and Chap. 5 offers to review the ways in which issues are identified in workshops to better grasp their complexity. Two more fields (education and warehousing) that were never spoken of coexist within the same work, thanks to this project, and reflect only a tiny part of what this iconic theory has to offer. Twenty years later, TRIZ still surprises us.

Strasbourg Cedex, France Denis Cavallucci

Contents

Chapter 1
Finding Innovative Technical Solutions in Patents Through Improved Evolution Trends

Ulises Valverde, Jean-Pierre Nadeau, and Dominique Scaravetti

Abstract Patents represent a reservoir richly endowed with exploitable technical information, where a structured exploration of inventions can unveil essential knowledge for solving industrial problems. Several authors exploit patents using the evolution laws of the TRIZ theory to anticipate technological leaps, categorize patents in a TRIZ perspective, forecast technology, etc. TRIZ laws can be completed with Polovinkin's rules, design rules, better known as "design heuristics," and the rules of the art of engineering (engineering best practices). In this chapter, we propose evolution trends composed of all these elements and presented in the form of cards to assist users. After selecting pertinent patents, they can be classified into discovery matrices and analyzed in a timeline classification structured according to their technological branches. The evolution trends enable us to decipher the evolution in inventions being followed or to be followed by each technological branch. An in-depth analysis of several technological branches linked to the technical problem in question allows us to inspire users with original ideas, identify opportunities for innovation, and propose hybrid solutions. To illustrate our approach, we look for possible evolutions of current, deep offshore biphasic separation systems.

1.1 Introduction

Patent databases are truly a mine of information for designers. It is important that this information be structured in order to transform it into knowledge. Using functional analysis and functional energy decomposition, patents can be understood in a particular way. An initial analysis is carried out by crossing the physical phenomena involved with the technologies used. The search can then be developed using keywords from an energy study based on the first law of evolution of TRIZ.

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The next step is to use this knowledge, classified by timeline, to determine innovation opportunities. To this end, we draw up a list of studies on evolution trends in technical systems. Next, we describe our own method and structure the knowledge in the form of a discovery matrix, which shows the evolution of patents over time for each technology/physical phenomenon combination. Next, we propose evolution trend cards based on the TRIZ evolution laws, Polovinkin's rules, design heuristics from the I2M laboratory, and engineering best practices.

Our application case concerns the improvement of a biphasic separator deep offshore. Currently, according to oil production and reserves, the oil industry needs to exploit previously untapped reserves. Oil processing in offshore platforms at great depths leads oil companies to design complex separation systems. In some offshore oil fields gas/liquid separation is key. It is indeed essential to separate the gas from the liquid at the sea bottom in order to pump the viscous liquid to the surface. However, beyond a depth of 3000 m, voluminous biphasic gravity separators are a big problem and an industrial challenge. Existing systems are based on the principle of decantation, but several constraints must be considered, i.e., residence time, the sporadic production of liquid and gas, sand management, etc. In this context, our methodology aims to exploit patents and find possible innovative solutions.

This chapter is organized as follows. Section 1.2 addresses what already exists in terms of evolution laws, rules, and design heuristics for analyzing and evaluating a technical system. We give a few examples from various authors who exploit patents using the evolution laws for different purposes. Section 1.3 briefly presents a problem-solving methodology used to recover pertinent patents that will be classified in a discovery matrix. In Sect. 1.4, we continue with our evolution trends proposal that will be applied to a case related to biphasic separators (Sect. 1.5). We conclude with a discussion and future prospects.

1.2 State of the Art: Anticipating the Evolution of Technical Systems

A trend can be defined as the progressive routing of an entity. In an engineering context, it can be defined as "an early identification of the gradual transformation of a technical system." In effect, identifying the "technology trends" followed by a system provides designers with new ideas to innovate and, in some cases, enables them to solve complex technical problems.

Industrial property plays an essential role in problem-solving, innovation, and creativity; in fact, patents have served as a source of inspiration for deducing evolution trends followed by technical systems. Nowadays, several methods are used to exploit patent documents, such as evolution trends and several automatic techniques, frameworks, tools, etc., to assist design activities.

Table 1.1 TRIZ evolution laws

TRIZ Law	Description
Law of wholeness of system	The CTOC decomposition[a] comes from this law; it is to verify wholeness of the converters components, transmitter, operator, and control/command. An energy functional flow ensures the realization of the action
Law of energy conductivity	It is necessary to ensure continuity of energy flow among functional elements of the system (free energy path between components)
Law of coordination of rhythms	The frequencies and component behavior periodicity must contribute to a global optimum
Law of increase in the degree of perfection	Any system tends to evolve first by increasing complexity and then tends to be simplified
Law of uneven development of parts of a system's entities	Each entity has its own evolution, when the entity arrives at its decline, this blocks the evolution of the whole system
Law of transition from the macro-level to the micro-level	This law states the evolution to increased use of fields toward nanotechnology
Law of transition to a super-system	A system that has achieved its development limit will exchange functionalities with the surrounding environment. The final evolution is the integration into the surrounding environment
Law of dynamism and increase of controllability	The system passes from static to dynamic in order to act on the system; the energy fields go toward the immateriality to improve controllability
Law of increase of degree of ideality	The development of all systems tends to increase the degree of ideality (reduction of mass, volume, energy consumption, etc.)

[a]The CTOC method (Converter, Transmitter, Operator, Control/Command) was initially proposed by Pailhès et al. (2011)

The following sections address the origin of the laws, rules, and heuristics that make up our evolution trends proposal with some examples of their use.

1.2.1 Altshuller's Evolution Laws

In the 1940s, the Russian engineer and scientist, Genrich Altshuller, having studied more than 40,000 patents, developed objective laws (also known as the TRIZ evolution laws) that describe the evolution of technical systems and allow product designers to anticipate the evolution of a product. He relied on his observation, patent analysis, and the study of what exists (Altshuller 1984, 1994; Altshuller and Seredinski 2004). These laws are described in Table 1.1 by a former colleague of Altshuller, Salamatov (1996). The laws were originally presented in three groups: static, kinematic, and dynamic. In the context of this chapter, we have adapted the description of some of them.

In a more recent work, Mann (2002) sought to evolve the Soviet theory by adapting and complementing the classical TRIZ laws. He proposed a classification into 30 generic technical evolution trends and 20 commercial (business field) trends. Often encountered in the literature as Mann evolution trends, they refer to this author's classification into three categories: space, time, and interface.

Mann (2003) proposes a design method to support companies in identifying the relative maturity of their existing systems, and also in identifying areas where there is evolutionary potential. The author introduced the term "evolutionary potential," which is defined as the difference between the relative maturity of the current system and the point where it has reached the limits or bounds of each evolution trend. This method is mainly used for the evolution of complex technical systems. It enables industry, first, to identify areas where their technical systems can potentially evolve to create value and, second, to find out if the evolution limits of their technologies have already been reached.

Various patent analysis methods that look at technical evolutions are based on the TRIZ evolution laws. As a part of the design activities, these laws have been extensively used by many authors to identify evolution trends automatically in patent texts (e.g., Yoon et al. 2012; Park et al. 2013; Yoon and Kim 2011). In order to deduce technical evolutions, these authors exploit Mann's classification and propose several tools that use different computer techniques, especially in the field of computer linguistics.

By contrast, the evolution laws are also used by authors who employ nonautomatic methods. Based on the principle that the TRIZ evolution laws describe the state or situation of the evolution of a system or product, Zouaoua-ragab (2012) uses the evolution laws to predict future product generations. Drawing on the works of various authors, she has compiled several definitions of evolution laws, and models the first five laws. The aim of this approach is to guide designers toward the identification of the greatest number of possible developments of innovative products. This nonautomatic approach uses surveys and manual information extraction for data collection.

1.2.2 Polovinkin's Rules

The word "heuristic" (from the ancient Greek *Heurisko*) was coined by the French philosopher René Descartes. It means: "*Which serves to discover or the art or science of discovery and finding*."

The heuristic method was founded in the former USSR where it was used extensively. Professor Alexander I. Polovinkin selected different heuristics from the problem-solving best practices used by engineers and USSR machine designers (Polovinkin 1991). According to Polovinkin, heuristics or "decision rules" contain brief guidelines to show designers in which direction they should look or how to transform a prototype to solve a given problem. They encourage designers to think,

Table 1.2 The 12 groups of Polovinkin's rules (Polovinkin 1988)

Group	Rule	Number
1	Transformation of shape	16
2	Transformation of structure	19
3	Transformation in space	16
4	Transformation in time	8
5	Transformation of motion and strength	14
6	Transformation of matter and substances	23
7	Differentiation	12
8	Quantitative changes	12
9	The use of preventive measures	22
10	The use of reserves	13
11	Transformations by analogy	9
12	Increased ease of manufacture	16

but they do not give the answer. These heuristics are general and are issued to students, beginner engineers, and inventors (Polovinkin 1988).

The various works and examples by Polovinkin are difficult to find; they are in Russian, which means they cannot be understood and applied by an international public. Through the efforts of some contemporary authors, Polovinkin's rules have been translated into English (Savransky 2000) accompanied by several examples (Savransky et al. 2000) and translated into French by Scaravetti (2004). We have directly translated certain passages from the original Russian texts (Valverde 2015).

The basics of heuristics are linked with the basics of industry. They consist of 180 rules, classified into 12 groups (Table 1.2). These are general rules applicable to machines, tools, appliances, technologies, etc.

The purpose of these rules is to help make problem-solving more effective by reusing past experience to generate solutions to new problems. The rules act as explicit instructions, i.e., examples that represent solutions to past problems act as sources of descriptions for other problems. These rules have a global character and meaning, a large spectrum of application, and can be related to heuristics as being rules that have not been proved (or cannot be proven), but which need no justification as they leave no room for doubt.

Polovinkin's rules have the advantage that they can be implemented without a defined methodological framework. Their application enables the covering of a broad spectrum within the space of possible solutions because of the generic and universal character of the rules. However, there is no formalization of the design problem to be solved, which can consequently result in a somewhat ineffective application of the rules.

Let us consider some of the many examples described by Polovinkin where application of the rules is relevant and feasible:

- Regarding group 8, "Quantitative changes," Rule 8.1 states: *To change dramatically (several times, dozens of times, and hundreds of times) one or more*

Table 1.3 Excerpt from Polovinkin's rules, Rule 3 (de Carvalho et al. 2004)

Rule	Description
3	Transformation in space
3.1	To change traditional orientation of the system in space: horizontal instead of vertical or inclined; to turn the system on its side or upside down; to turn the system by rotation
3.2	To use a previously unused (i.e., an empty) space between subsystems. One subsystem can pass through a cavity that exists in the other subsystem
3.3	To unite known separate subsystems by locating one inside the other, as in Russian nested dolls (*Matrioshka*)
3.4	To change the settlement along one line by accommodation along a few lines or on planes. Inversion of expedient
3.5	To replace location on a plane by accommodation on several planes or in three-dimensional space; to proceed from one-layer configurations to multilayer. Inversion of expedient
3.6	To change the direction of action of an operation (or a whole process) or environment
3.7	To proceed from contact in a point to contact on a line; from contact on a line to contact on a surface; from contact on a surface to volumetric (spatial) contact. Inversion of expedient
3.8	To carry out interface on several surfaces
3.9	To bring instruments into the operative zone (the place where functions are fulfilled by tools) without moving other subsystems or the whole system
. . .	. . .

parameters of the object (its elements, the environment, etc.), for instance, a water jet of up to 10 megapascals erodes the soil. Increasing water pressure to 100 megapascals enables a water jet to cut stone and metal.

- The arc lamp was invented by the Russian inventor Pavel Yablochkov in 1875 (Julien 2000). In the original system, there were two carbon rods (arranged along a straight line, with one in front of the other or at an angle) and an electric arc was produced between them. To maintain this arc, the rods had to be brought close together so that they were at a (constant) distance, sufficient to ensure combustion. This was achieved using a special automatic regulator. Despite its success, in practice it had some major flaws due to the complexity of the regulators that were unreliable, and combustion of the electrodes was not uniform. At the time, a simple technical solution was required to ensure the correct combustion of the two-electrode lamp. To solve the problem, Polovinkin suggested using *the rules relating to transformation in space* (*3.1, 3.4, 3.7, and 3.9*) (Table 1.3). Yablochkov then realized that the electrodes should be placed close together in parallel, separated by consumable insulators.

de Carvalho et al. (2004) consider the TRIZ theory and its tools [the 40 inventive principles, the 76 standard solutions, Substance-Field (Su-field) and ARIZ[1]] to be a

[1]ARIZ is the acronym for the Russian: "Алгоритм решения изобретательских задач," translated into English as "Algorithm of Inventive Problem Solving."

very substantial, but unfinished, body of work, a methodology undergoing improvement which can be effectively completed by Polovinkin's rules. They present a smaller version with 121 heuristics classified into eight groups (the most relevant being in the TRIZ context), translated, adapted, and illustrated by different examples drawn from patent analysis. They introduce heuristics as rules, strategies, principles, or methods to increase efficiency in problem-solving. They claim that heuristics do not provide direct or precise answers, nor do they guarantee solutions to problems. Nevertheless, they do provide assistance that facilitates problem-solving.

To highlight the importance of these rules and of complementarity in design activities, it must be stressed that they complement the various existing approaches. A comparison by Savransky and Wei (2001) of the creative TRIZ principles and Polovinkin's rules shows that fewer than a third of the 121 heuristics compared are linked directly to the TRIZ principles, which means that the rest of the heuristics enhance these principles.

1.2.3 Design Heuristics

More recent work by the I2M-IMC department[2] (Calle-Escobar et al. 2014) uses Polovinkin's rules in a problem-solving context. The authors specify that, historically, problems have usually been approached either via the basic experience and know-how of the design engineers, or by arbitrary choices from suggestions by company managers (or key figures), or via the history of society. The authors stress the importance of establishing design rules backed by the knowledge of a number of stakeholders to guide designers through the choices they make. To achieve this, they suggest producing models that can be structured in the form of problem-solving strategies.

Heuristics refer to procedures or approaches that allow a designer to reach a solution to a particular problem. These heuristics are based on experience and observation rather than on an exhaustive process. In the design context, reference is made to technical or conceptual solutions that have been implemented and have already been tested in another domain or context, but which can be extrapolated to similar design problems. According to the authors, design rules are global in nature and have a wide spectrum of application.

They look at the eight groups proposed by de Carvalho et al. (2004) and also consider the ninth group defined by Savransky (2000) (Table 1.4).

The heuristics developed by I2M-IMC are based on TRIZ (evolution law, principles of innovation, standard solutions), Polovinkin's rules, and rules of the art of engineering and have been validated by different laboratory studies.

[2]Institute of Mechanics and Engineering—Bordeaux (I2M), Department of Mechanical Engineering and Design (IMC).

Table 1.4 Reduction of Polovinkin's rules to nine groups (de Carvalho et al. 2004; Savransky 2000)

Group	Name of the group
1	Transformation of shape
2	Transformation of structures
3	Transformation in space
4	Transformation in time
5	Transformation of movements and mechanical actions
6	Transformation of materials
7	Differential resources
8	Quantitative modifications
9	Transformations related to evolutionary trends

To explain how a group of heuristics is constructed, we demonstrate how to construct heuristics for the modification of a component (Figs. 1.1 and 1.2). This modification may be local, global, or an adaptation of the component.

- The first sub-branch (local modification) is for solving the problem at the place where it occurs. Innovation principle 3 (TRIZ, local quality) is used with the proposition of the location of a function. The introduction of a local substance is directly linked with class 1 (and, of course, also with class 5) of TRIZ standard solutions.
- For a problem linked with coupling physical phenomena, the designer uses traditional decoupling techniques which introduce a very well-known principle—that of segmentation. This is why, in branch A.2 (Fig. 1.1), we propose to segment in succession the overall structure, the components, and finally the internal flows. The following levels of branch A.2 concern segmentation typologies. These heuristics are the result of innovation principles (1, 3, 7, 17, 24, 26, 30, 40), evolution trend 6 (bi- and polysystems), standard solutions 223 and 226, and also rules of the art of engineering.

In studies carried out at I2M-IMC, there are 78 design heuristics. When grouped together they comprise a decision tree, part of which is shown in Fig. 1.3.

These heuristics are given in the form of problem-solving strategies expressed by a sentence constructed from the cause/effect analysis performed by designers (Calle-Escobar et al. 2014).

A succession of choices is then produced for the user in the tree diagram. For example, depending on the branch, the directions that the designer could opt for could give the following sentence:

"*Reduce the problem by acting on the system by modifying and adapting components by evolution of the shape in an alternative Symmetrical/Asymmetrical vision.*"

A.	**Through the modification of the components**
A.1.	**Locally**
A.1.1.	**Locating actions**
A.1.2.	**Introducing a substance (Locally)**
A.2.	**Globally**
A.2.1.	**Through the segmentation of the structure of the components**
A.2.1.1.	By layers
A.2.1.2.	Into identical elements, hollow elements, by dissociating their functions or interpenetrating them
A.2.1.3.	Through porous media or the introduction of a void
A.2.2.	**Through the segmentation of the components**
A.2.2.1.	Through the division into independent, removable, modular or adjustable components
A.2.2.2.	Through the division into independent, increasingly smaller elements (solid to pellets, to powder, etc.)
A.2.2.3.	Into identical components in order to increase effectiveness
A.2.2.4.	Into different components with identical functions, different functions, inverse or opposite functions
A.2.2.5.	Making them evolve from homogenous to heterogeneous (or vice versa)
A.2.2.6.	Into components with independent functions, optimized and/or conditional (according to available resources, life situation)
A.2.2.7.	Into components with opposite characteristics (insulating/conductive, rigid/deformable)
A.2.3.	**Through the segmentation of the flows**
A.2.3.1.	By introducing a permanent or non-permanent flow (according to life situations, available resources)
A.2.3.2.	Virtually (infrared vision, ultraviolet, vibrating behavior) or using images or reflections for a change of scale
A.2.3.3.	By passing from a planar contact (uniform mechanical field) to a point contact (discrete mechanical field) or vice versa
A.2.3.4.	By passing from a deformable system to a rigid system by changing the behavior of components: flexion to tension + compression (lattice), then tension or compression only (preload) (or vice versa)

Fig. 1.1 Heuristic (A), branches one and two

The designer then has to interpret this explicit sentence in the context of design, in order to express solutions.

1.2.4 Patent Exploitation Through the Evolution Laws of Technical Systems

Exploiting patents using Altshuller's evolution laws and inventive principles is the subject of research of many authors working on problem-solving and design activities. Most of them attempt to extract useful information from patent documents and link it with the TRIZ evolution laws (Yoon et al. 2012; Park et al. 2013; Yoon and

A.	**Through the modification of the components**
A.1.	**Locally**
A.2.	**Globally**
A.3.	**Through the adaptation of the components**
A.3.1.	**Through the evolution of the flow**
A.3.1.1.	**Dynamizing the component**
A.3.1.1.1.	Passing from a rigid to an articulate system (1, 2 or n articulations); to a flexible/ deformable system; to a fluid system (gas, liquid); to a field with controlled fields (or vice versa)
A.3.1.1.2.	Passing from a rigid to a deformable system through the modification of the behavior of the components, from traction or compression independently, to traction+compression (truss) and then flexion (or vice versa)
A.3.1.2.	**Through the coordination of rhythms**
A.3.1.2.1.	Coupling by phase, by opposing phase, by resonance or compensation
A.3.1.2.2.	Through the transformation of a continuous action into a periodical action (or vice versa)
A.3.1.2.3.	Through the modification of the frequency or amplitude of a periodical action or energy
A.3.1.2.4.	By increasing the frequency of vibration up to ultrasonic vibrations
A.3.1.3.	**Through the modification of movements between components**
A.3.1.3.1.	Through the substitution of a linear movement for a rotating movement (or vice versa)
A.3.1.3.2.	Through the introduction of internal movements
A.3.1.3.3.	Replacing sliders for bearings (or vice versa)
A.3.1.3.4.	With the purpose of not fighting against gravity (or centrifugal effects) or using gravity (or centrifugal effects)
A.3.1.4.	**Following the MATHEM logic of field evolution**
A.3.1.4.1.	Through the replacement or superposition of one mechanical flow for another mechanical flow (thermal, optical, chemical, acoustic, etc.)
A.3.1.4.2.	Through the utilization of a magnetic, electric or electromagnetic field
A.3.1.4.3.	Through the evolution of the field, from stationary to dynamic, constant to variable, random to structured (or vice versa)
A.3.1.5.	**For the reduction of deformations**
A.3.1.5.1.	Passing from a rigid to a deformable system through the modification of the behavior of the components, from traction or compression independently, to traction+compression (truss) and then flexion
A.3.2.	**Through the evolution of materials**
A.3.2.1.	**Towards standardization or diversification**
A.3.2.2.	**Towards porous materials (embedded or charged) or multimaterials**
A.3.2.3.	**Using coatings with different properties**
A.3.2.4.	**From rigid to deformable (or vice versa)**
A.3.2.5.	**From expensive to inexpensive (or vice versa)**
A.3.2.6.	**Using their differentiating properties (isotropic, anisotropic)**
A.3.2.7.	**According to their state (solid, liquid, gas, etc.)**
A.3.2.8.	**Changing phase**
A.3.2.9.	**Superposing the fields to modify their characteristics**
A.3.2.10.	**Towards materials with properties that change over time**
A.3.3.	**Through the evolution of the shape**
A.3.3.1.	**Changing the spatial dimension, from 1D to 2D, up to 3D (or vice versa)**
A.3.3.1.1.	Following the evolution: linear, circular, spiral (or vice versa)
A.3.3.1.2.	Following the evolution: linear, planar, curved (or vice versa)
A.3.3.2.	**Into an alternative vision**
A.3.3.2.1.	Symmetric/ Asymmetric
A.3.3.2.2.	Convex/Concave
A.3.3.3.	**Adapted to the materials**
A.3.3.3.1.	According to mechanical stress
A.3.3.3.2.	According to fabrication or industrialization
A.3.3.3.3.	In order to be coherent with the utilization of a coating
A.3.3.3.4.	Using shape memory
A.3.3.4.	**Optimized according to the requirements criteria**
A.3.3.4.1.	Mass
A.3.3.4.2.	Size
A.3.3.4.3.	Cost
A.3.3.4.4.	Requirements

Fig. 1.2 Heuristic (A), branch three

Kim 2011, etc.). Other authors attempt to classify patents according to the inventive principle or law that they follow (Loh et al. 2006; Li et al. 2012, etc.). In any case, the evolution laws are an interesting means to exploit patents.

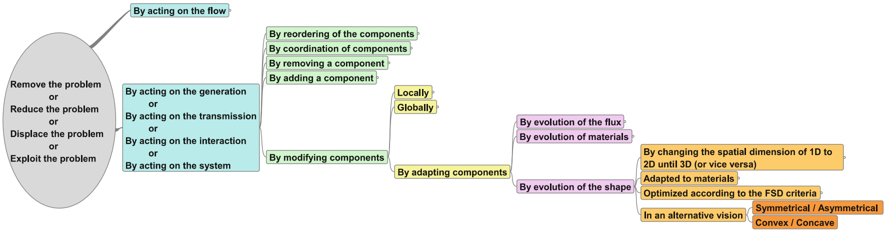


Fig. 1.3 Representation of one heuristic branch

A few relevant examples are addressed in the following subsections. These examples are neither the most current nor exhaustive; our aim is to highlight the relevance of laws, rules, principles, etc., in a patent exploitation context.

1.2.4.1 Patent Classification According to the TRIZ Inventive Principles

Various authors have sought to link the patent classification based on the IPC code to the different visions of TRIZ, with the aim of assisting TRIZ users.

Loh et al. (2006) suggest an automatic patent classification using the 40 inventive principles of the TRIZ theory. Through machine-learning techniques, they show the results of classifying according to the first six invention principles from USPTO[3] patent documents.

Along the same lines, Li et al. (2012) present a more recent framework that incorporates models from machine learning, data mining, natural language processing, and patent citation metrics to extract patent data and classify them into several categories of inventiveness. They aim to classify patents according to their level of invention, known in the TRIZ context as LOI[4] (to characterize the creativity of a solution concept). To overcome the common problem in patent searches of the large quantity of nonpertinent patents retrieved, the authors present a framework to assist designers in the selection phase, ranking patents as pertinent or “high value.” The authors hope to integrate their approach into future Computer-Aided Design (CAD) systems to provide designers with the means to find alternative solutions (the most innovative) and to stimulate their creativity in the design phase.

[3]United States Patent and Trademark Office.

[4]The Level of Invention is defined as the degree of inventiveness, that is to say, the relative degree of system changes compared to a previous system.

1.2.4.2 Applying TRIZ Trends for Technology Transfer and Technology Forecasting

By definition, technology is systematic knowledge applied in order to modify, control, or order elements of the physical or social environment. This includes material systems and regulation and management analysis systems.

When considering the history of our society, we can see that over a long period of time, people have adapted to rapid technological change. Our great-grandparents were born in the age of horse-drawn carriages, then motor transport, they saw the first man walk on the moon, and now they are witnessing the radical change in computers and information technologies. However, despite the impacts of technological change, companies and individuals have not learned much about how to anticipate and plan technology (Roper et al. 2011).

Nowadays, anticipating technology is more than a mere desire; it has become a real need for industries seeking to forecast technological leaps related to their systems and products. *Innovate or die* has become the motto of several companies seeking to survive in a competitive environment. In this context, some researchers are working on the identification of different fields where technologies might be transferred and also on technology forecasting.

For instance, the identification of areas in which a given technology can potentially be applied assumes increasing importance for industries. Park et al. (2013) maintain that companies have insufficient understanding of the potential applications of their technologies in other domains due to the abundance of technologies and technical terminologies in different industrial fields. The authors note that industrial technologies can be linked to different areas of application by applying a functional point of view as the functions used are generally similar. Their approach, based on extracting SAO[5] structures, allows them to retrieve relevant information which is then transformed into knowledge to be used for future technology transfer. The authors adopted TRIZ evolution trends [redrawn from Mann (2002)] as criteria to evaluate technologies in patents. They claim that TRIZ evolution trends is a useful tool for technology evaluation and forecasting because almost every TRIZ trend follows the basic principle of the TRIZ philosophy, "*Increasing Ideality*," which means that technology systems evolve towards increasing benefits while reducing harm, and that most technologies and systems evolve only in this direction.

Finally, Technology Forecasting (TF) is a process that anticipates the generic or specific meaning of the technological evolution of a product or family of products, and is focused on inventions and their innovations.

For Verhaegen et al. (2009) TRIZ evolution trends enables them to predict improvements by identifying the "evolutionary potential" of a family of products described by Mann (2003). Their approach seeks to categorize patents according to several known trends (based on the intrinsic skill of TRIZ experts). They analyze

[5]Subject-Action-Object.

patents using an algorithm based on text mining and natural language processing, which extracts relevant information about a product, which is then compared with the TRIZ trends.

They collect the patents concerned (product or family of products) from IPC codes (or other classifications) and the different sections of text in the patent. The patents that are retrieved are then marked (with a tagger) for parts of speech (POS), in order to identify the adjectives. These are then used to identify the TRIZ trends concerned and the trend phases in the patents, a task that is not automatic. The authors say that their method can be incorporated into the product design specification phase to assist design engineers.

There is a real interest on the part of several researchers and industrialists in identifying and classifying evolution trends from patent documents. In more recent studies, Yoon and Kim (2011) describe an automatic approach that consists of extracting binary relations from patents using natural language processing and semantic sentence similarity (or semantic proximity[6]) to then determine the specific TRIZ evolution trends. Their approach lacks some precision in terms of correctly identifying trends. To improve the initial approach, they propose a system for using SAO structures (Park et al. 2012).

A timeline analysis of patents to identify key technological points (density of patents found in a short period) is one of the interesting features of this approach. This enables us to identify promising technologies in areas that are underdeveloped technologically. Based on this method, the authors designed a "Technology Intelligence[7]" tool. The authors claim that this "TrendPerceptor" can analyze large amounts of information from which it extracts what is useful and thus assists designers with decision-making (technology assessment and forecasting) (Yoon et al. 2012).

1.3 Selecting, Analyzing, and Classifying Pertinent Patents for Patent Exploitation

In our previous work (Valverde et al. 2014), we proposed a problem-solving methodology which uses mainly energy-based functional decomposition and physical phenomena to analyze patents iteratively and thus find innovative concepts. This method allows users to select relevant keywords using a detailed analysis of the problem's main function, related resources (available energies, external environments, space, time, etc.) and related physical keywords through functional

[6]This is the metric defined on a set of documents, terms or concepts. The notion of distance refers to the sense of similarity or semantic content.

[7]Technology intelligence is an activity that allows companies to identify opportunities and threats which could have either positive or negative effects. The aim is to systematically inform companies about the market environment, i.e. the latest techniques, competitors, potential partners, etc.

decomposition and a detailed physical analysis. The relevant selected keywords make up the knowledge base used to launch new searches, which in some cases focus the research and in others expand the research field. Pertinent recovered patents are classified into discovery matrices which can be exploited in timeline, allowing patent analysis in an evolutionary perspective (Valverde et al. 2016b).

This methodology was conceived in the IMC department (Valverde 2015), and brings together some aspects of the department's expertise and acquired knowledge. A brief description of this method is given in the next subsections.

1.3.1 General Description of the IMC Problem-Solving Methodology

The block diagram in Fig. 1.4 shows the procedure divided into three stages, each made up of several blocks or modules. It demonstrates the method proposed to find innovative solutions for a given industrial problem.

The first stage consists in defining the problem and the context. It is broken down into three blocks, the first being a detailed analysis of the function to be achieved, the second covers a thorough search of existing material, and the third relates to the recovery of the initial keywords to create a keyword database (knowledge base). First of all, the function to be processed is described in great detail, as we want to decompose the problem as much as possible in order to gain an exact understanding of the subject. We recover all the initial keywords linked directly to the problem but also to the context itself, i.e., external environments, areas of application, companies involved, etc. Secondly, a search of existing material is carried out, using the recovered and listed keywords. We provide the designer with the means to extend his search area into scientific journals, open archives, patent databases and search engines using automatic search tools designed for this purpose. A keyword database is created at this stage, and it is gradually added to each search iteration and reused to generate new requests.

In the second stage, a structural analysis of patents is carried out and the iterative search continues. The structural part examines in several phases and in detail the knowledge recovered in the previous stage, i.e., technologies and concepts. A single concept can be divided into several concepts represented by several functions. The exhaustive search for relevant keywords begins with an analysis of the functional flow required to carry out the function. The expected functioning will be described in a functional decomposition which will result in the selection of imposed or induced physical phenomena. These physical phenomena make up the knowledge base, along with improvement techniques and associated keywords. The energy-based functional decomposition gives us access to different keywords which lie outside the scope of the initial keywords. They derive from different types of converters from which we can select. This enables us to search for patents in different fields. The patent search based on keywords listed in the knowledge

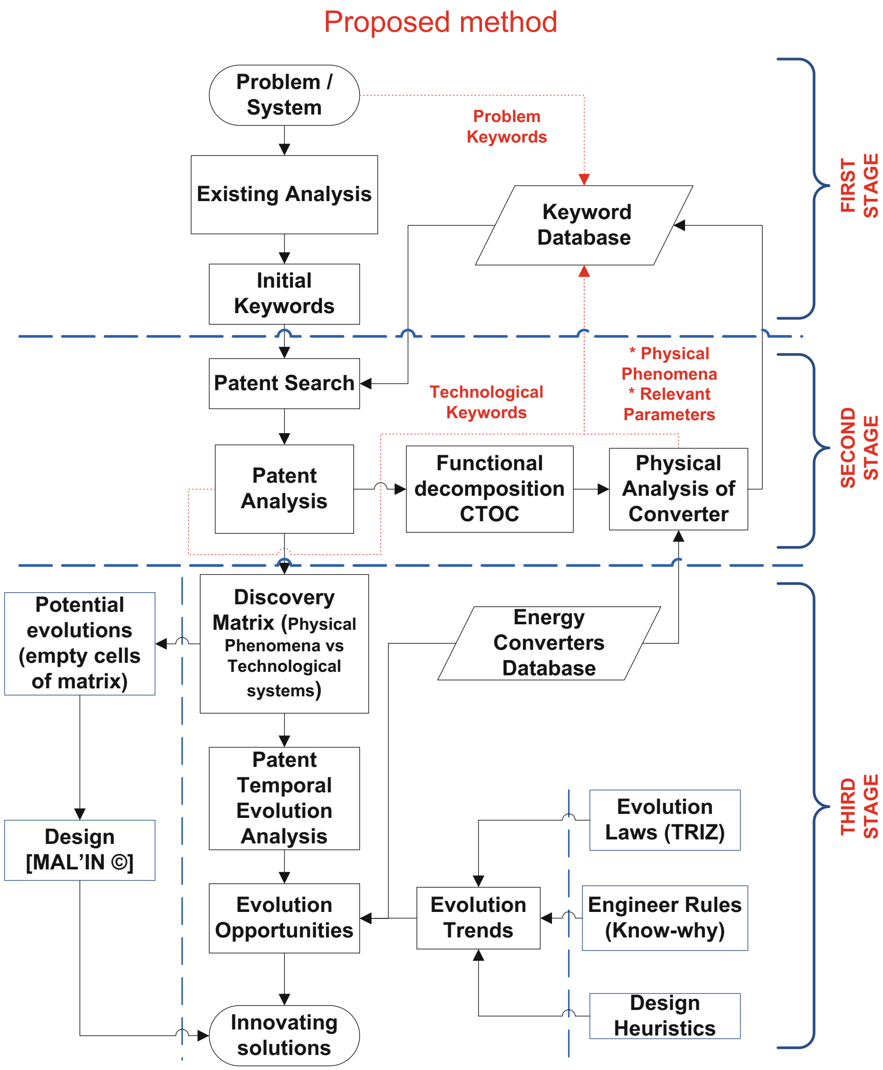


Fig. 1.4 Block diagram of the IMC method

base is carried out using the traditional patent databases. The search is therefore directed and framed. In this stage, a discovery matrix is constructed by crossing physical phenomena and the technological systems retrieved, so that the designer can classify the patents he considers to be pertinent. We then try to deduce evolution opportunities in order to move towards innovative solutions.

The third stage involves our innovation methods. It consists of exploiting the discovery matrix along three axes in order to define evolution opportunities and directions for innovation. First, we analyze empty cells, which correspond to concepts that are not found, are nonexistent or which lie in the public domain. The possibility must be validated with innovative solutions for problem-solving such as MAL'IN[8] (Pailhès and Nadeau 2007) (I2M-IMC). Pertinent patents are time-ranked to exploit the discovery matrix by evolution trends of technical systems. The second approach covers analysis by evolution trends constructed from the TRIZ theory evolution laws, rules of the art of engineering, and I2M-IMC design heuristics. The database of the physical effects of energy conversion completes the evolution opportunities in these systems, this is the third approach. This database is also used for the physical analysis in the second stage.

1.3.2 Formatting Patents for Exploitation: Discovery Matrix and the Timeline Classification

The discovery matrix has been presented initially as a classification tool of pertinent patents. It is constructed from a point of view of technologies vs. physical phenomena involved. Once the matrix contains a considerable amount of patents, it can be explored through an evolution trends perspective or from another point of view.

There are various possibilities for exploiting the matrix, i.e., by date of publication, by physical phenomenon, by technology used, by field of application, etc. The chosen classification provides users with various types of information, for example, classification by physical phenomenon shows the different phenomena used in the patented inventions, and reveals which physical phenomena are most used or least used to carry out the principal function.

Given the context of this chapter, it is appropriate to explore the matrix using a timeline to classify the patents. When the matrix has enough elements to analyze (convergence index of the method), we then carry out an in-depth analysis which provides the first opportunities for evolution in order to achieve innovative solutions.

The discovery matrix is used to carry out the timeline classification of pertinent inventions automatically. Figure 1.5 gives an overview of this concept. In certain cases, the timeline classification enables the designer to visualize obvious technological changes, e.g., changes in shape, addition of one or more components, division of elements of the system, etc. In other cases, the changes are less obvious, e.g., change in the frequency of an operation, improvement in energy flow, addition of materials, fibers, fabrics, etc. In all cases, a structured approach must be used to identify technological trends in order to gauge the next "technological leaps" in patented inventions.

[8]Software for inventive problem-solving, based on a method that combines functional analysis with idea-finding tools and concepts extracted from the TRIZ theory.

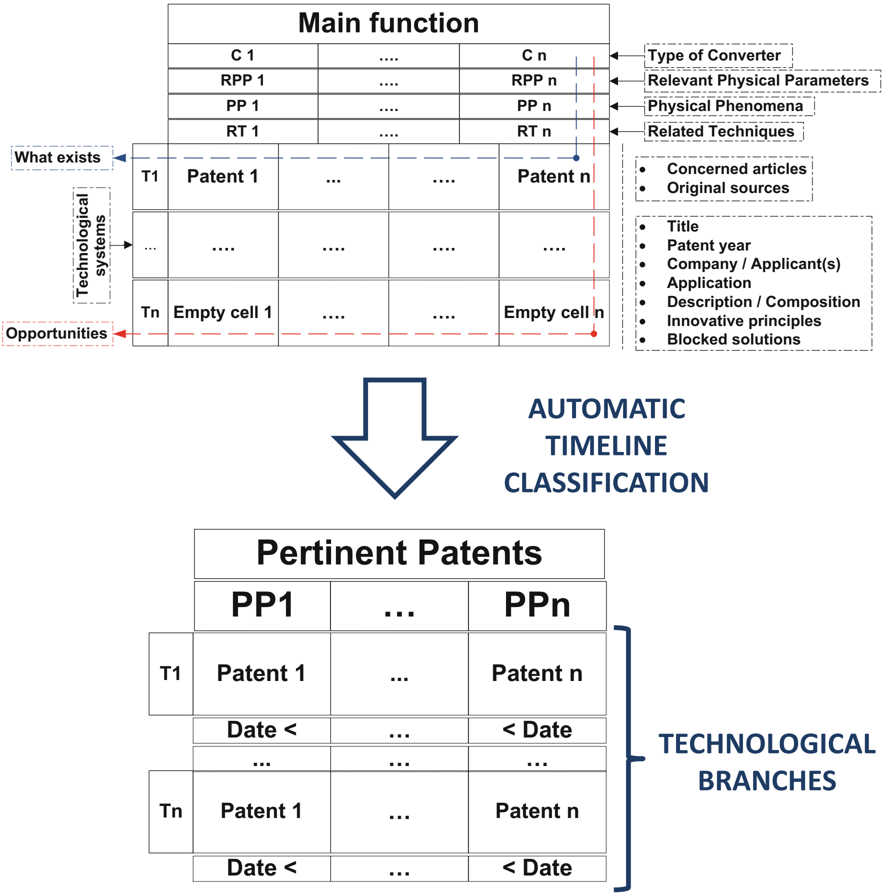


Fig. 1.5 Concept of the discovery matrix and patent timeline

1.4 A Proposition of Evolution Trends

In this section, our proposition of evolution trends is complemented by the rules of the art of engineering. These trends are presented in the form of eight cards which are part of an interactive tool to assist designers (Valverde 2015). To illustrate these trends here, we show some elements of the construction of Trend Four (T4). In the next section, we apply the evolution trends to a pair of technological branches in order to inspire possible hybrid solutions.

1.4.1 Rules of the Art of Engineering (Engineering Best Practices)

With several years of education behind them, years of experience in companies and techniques learned in the course of their careers, engineers acquire a specific know-how that we call the "rules of the art of engineering."

Our evolution trends integrate different professional practices by several professional bodies, the standards used, and research studies and experience acquired by the I2M-IMC department, all of which make up the knowledge base that enables us to find standardized solutions for design or for solving new problems.

To illustrate certain rules, we look very generally at studies carried out jointly by IMC and the company Galtenco Solutions on designing a new generation of pressure vessels for the oil industry.

Martinez (2014) introduces different concepts in the design of a system subjected to external pressure (or external loading). To model the problem, he defines a pressure vessel with two zones, one zone under stress and one zone unstressed. It is the zone under stress that is subjected to external stresses and links with the reference material (e.g., soil), while the nonstressed zone houses technical systems or is used for storage. In this context, he emphasizes the importance of understanding how to direct mechanical flows and absorb strain energy.

He uses various rules of the art of engineering from the department's knowledge base, of which some examples follow:

- Direct mechanical flow
  - Produce structures with bars working in traction or compression (lattice type); interactions should have a revolute joint behavior.
  - Produce shut-down systems and distribute stresses via segmented arcs which arch when compressed.
  - Produce granular areas to distribute stress locally.
  - Produce taut structures.
  - ...
- Produce a structure that is deformable locally to absorb strain energy and rigid overall for stability.
- Favor behavior in traction or compression for rigid structures and flexion behavior for deformable areas.
- ...

Table 1.5 shows an adaptation of several rules based on the work of Martinez. It covers various systems/technologies used as a source of inspiration in the design of a new generation of deep offshore pressure vessels (and which can be extrapolated to other issues). We are particularly interested in the design rules, some of which are included in our evolution trends.

It is important to clarify the main difference between heuristics and the rules of the art of engineering; the former describe proven findings, while the latter have a physical basis.

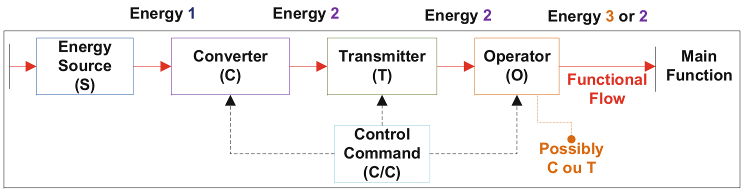
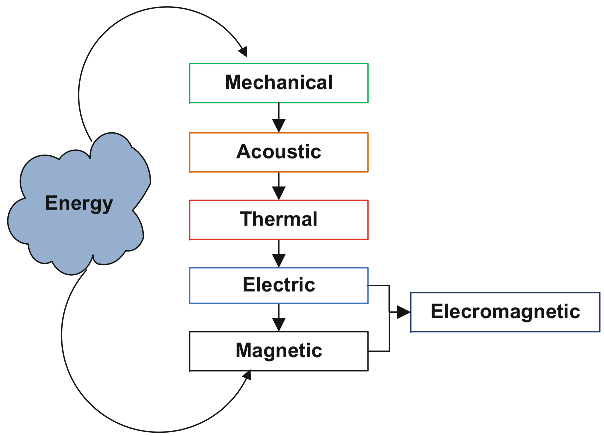
Table 1.5 Excerpt from engineering best practices related to pressure vessel design (Martinez 2014)

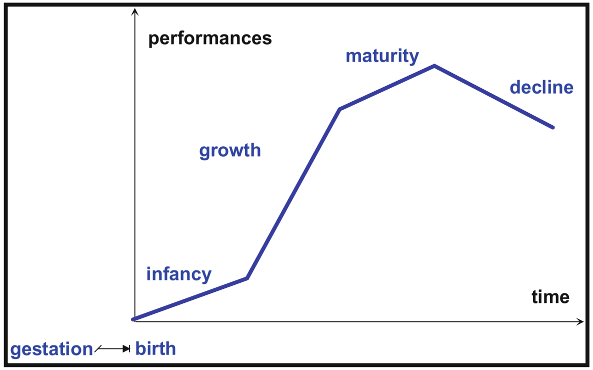
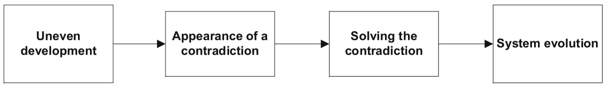
Domain/ Field	System/Object/ Product	Properties	Best practice
Aerospace and defense	Ceramics	Fragile nature, refractory properties, compressive strength, hardness	Prestress and/or confine ceramics to control their brittle behavior
Civil engineering	Segmented Arc (“Voussoirs” in French)/other modular elements	Discontinuous component at the microscopic level, mainly trapezoidal or rectangular geometry, usually made of concrete, etc.	To ensure the stability of the modular building elements, set up an external load that causes over-center locking (arching or “arc-boutement” in French) between components
Offshore and nuclear industry	Reinforced concrete vessel	Concrete has a fragile nature	Place steel bars to avoid shearing, preload them to increase performance
Deep water exploration	Ceramic submarine	Ceramic has a fragile nature, metal replacement for structural elements (steel and titanium)	To avoid bending stresses, split into several parts and introduce mobility
Military	Sandbags or Earthbags	Discontinuous component at the microscopic and macroscopic level, they do not have a linear-elastic behavior, low resistance facing tangential stress	Place fibers to avoid shearing
Pressure vessel	Stiffeners	Internal, external, rigid or deformable stiffeners, tubes, strips, sandwiches, mesh, honeycomb, composite, steel, etc.	Segmentation of the mechanical flow
Armors	Ceramic armor	Hardness, sintered material or powder, sometimes chemically bound to metals, plastics or composites	Prestress and/or confine ceramics to control their brittle behavior

1.4.2 Introduction of the Eight Cards of Evolution Trends

As we have already established, our eight evolution trend cards represent eight TRIZ theory evolution laws, some elements from the 12 groups of Polovinkin’s rules, several design heuristics, and several engineering best practices from different areas. They will be very useful in evaluating the different classified technologies that were found in the timeline of the patent analysis phase of the discovery matrix. Table 1.6 summarizes and provides a description of each group. Note that this classification is very similar to the eight TRIZ laws, because we have taken the foundations of these laws and expanded the original definition.

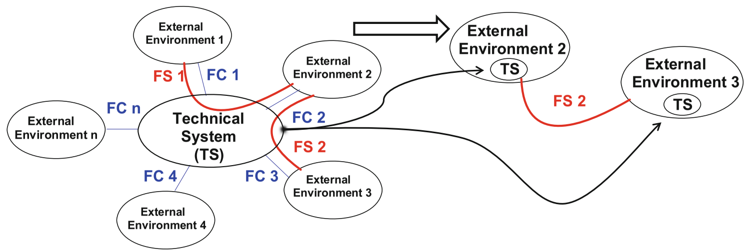
Table 1.6 Description of eight groups of the IMC evolution trends

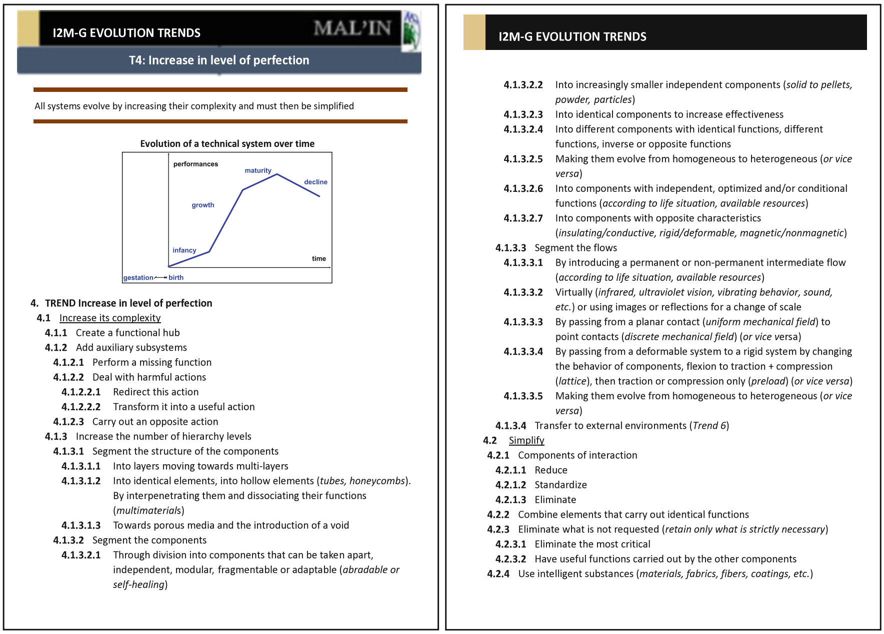
T	Title	Description
1	Source–Converter–Transmitter–Operator–Control/Command (SCTOC)	The realization of a function requires an energy source (internal/external). This energy is converted (converter), transmitted (transmitter), and used to carry out the action (Operator). A Control/Command entity ensures the correct performance of the main function 
2	Energy conductivity	A good system should effectively ensure the free passage of energy flow through the SCTOC components 
3	Coordination of the rhythms	The precondition for the evolution of a technical system is the voluntary matching or mismatch of the frequency, oscillations, vibrations, periodicity, or resonance of all parts of the technical system

<table>
<tr><td>4</td><td>Increased level of perfection</td><td>Every system evolves by increasing its complexity and must then be simplified</td><td>
</td></tr>
<tr><td>5</td><td>Uneven development of the entities</td><td colspan="2">Each entity of the system has its own evolution (nonuniform development of the system elements). The more uneven the evolution of entities, the more complex the system becomes. An entity that reaches its peak blocks the evolution of the system. Reducing complexity will simplify solving the technical and physical contradictions created

</td></tr>
</table>

(continued)

Table 1.6 (continued)

T	Title	Description
6	Transition to the external environments	The evolution of a system goes towards the elimination of what is not requested in order to keep only what is strictly necessary. Eliminating what is not requested leads to the removal of external environments. At the end of the process, the initial product is absorbed by the last two external environments involved in the main function. Intermediate evolutions can occur by exchanging functionalities with the external environments 
7	Transition from macro-level to micro-level	Once an operational entity cannot be improved at the macro-level, it is still possible to make it evolve at the micro-level. The concept of macro- and micro-levels is directly related to the observed structural level (solid, granules, powder, gel, liquid, mist, fields, molecules, atoms, ions, electrons, etc.). This trend leads to increased use of immaterial fields which replace the physical entities
8	Increased dynamism and level of controllability	To expand or increase the efficiency of a system, its entities must evolve from static to dynamic (movable) to increase their controllability. Various stages of evolution are possible: Uncontrollable entities become controllable, mechanical fields are replaced by electromagnetic fields, entities become mutually compatible. Generally, the evolution of the system moves towards a reduction in human intervention


I2M-G EVOLUTION TRENDS MAL'IN

T4: Increase in level of perfection

All systems evolve by increasing their complexity and must then be simplified

Evolution of a technical system over time

4. TREND Increase in level of perfection
- 4.1 Increase its complexity
  - 4.1.1 Create a functional hub
  - 4.1.2 Add auxiliary subsystems
    - 4.1.2.1 Perform a missing function
    - 4.1.2.2 Deal with harmful actions
      - 4.1.2.2.1 Redirect this action
      - 4.1.2.2.2 Transform it into a useful action
    - 4.1.2.3 Carry out an opposite action
  - 4.1.3 Increase the number of hierarchy levels
    - 4.1.3.1 Segment the structure of the components
      - 4.1.3.1.1 Into layers moving towards multi-layers
      - 4.1.3.1.2 Into identical elements, into hollow elements (*tubes, honeycombs*). By interpenetrating them and dissociating their functions (*multimaterials*)
      - 4.1.3.1.3 Towards porous media and the introduction of a void
    - 4.1.3.2 Segment the components
      - 4.1.3.2.1 Through division into components that can be taken apart, independent, modular, fragmentable or adaptable (*abradable or self-healing*)

I2M-G EVOLUTION TRENDS

      - 4.1.3.2.2 Into increasingly smaller independent components (*solid to pellets, powder, particles*)
      - 4.1.3.2.3 Into identical components to increase effectiveness
      - 4.1.3.2.4 Into different components with identical functions, different functions, inverse or opposite functions
      - 4.1.3.2.5 Making them evolve from homogeneous to heterogeneous (*or vice versa*)
      - 4.1.3.2.6 Into components with independent, optimized and/or conditional functions (*according to life situation, available resources*)
      - 4.1.3.2.7 Into components with opposite characteristics (*insulating/conductive, rigid/deformable, magnetic/nonmagnetic*)
    - 4.1.3.3 Segment the flows
      - 4.1.3.3.1 By introducing a permanent or non-permanent intermediate flow (*according to life situation, available resources*)
      - 4.1.3.3.2 Virtually (*infrared, ultraviolet vision, vibrating behavior, sound, etc.*) or using images or reflections for a change of scale
      - 4.1.3.3.3 By passing from a planar contact (*uniform mechanical field*) to point contacts (*discrete mechanical field*) (*or vice* versa)
      - 4.1.3.3.4 By passing from a deformable system to a rigid system by changing the behavior of components, flexion to traction + compression (*lattice*), then traction or compression only (*preload*) (*or vice versa*)
      - 4.1.3.3.5 Making them evolve from homogeneous to heterogeneous (*or vice versa*)
    - 4.1.3.4 Transfer to external environments (*Trend 6*)
- 4.2 Simplify
  - 4.2.1 Components of interaction
    - 4.2.1.1 Reduce
    - 4.2.1.2 Standardize
    - 4.2.1.3 Eliminate
  - 4.2.2 Combine elements that carry out identical functions
  - 4.2.3 Eliminate what is not requested (*retain only what is strictly necessary*)
    - 4.2.3.1 Eliminate the most critical
    - 4.2.3.2 Have useful functions carried out by the other components
  - 4.2.4 Use intelligent substances (*materials, fabrics, fibers, coatings, etc.*)

Fig. 1.6 Example of card showing evolution of trend four (T4)

As an example, Fig. 1.6 shows the card for trend four (T4). The increase in the degree of perfection establishes that all systems evolve by increasing their complexity and must then be simplified. This trend is illustrated with the different life stages of a technical system, from its birth until its decline.

On this card, design heuristics and rules of the art expand the level of detail of some evolution laws, giving us a more accurate view of the possible evolution of the technical system.

The S-curve in Fig. 1.6 is analyzed as follows: the first part concerns the birth of the product, i.e., the creation of the functional core, and then the product must evolve to reach new markets. In order to do this, it must increase in complexity to acquire new functions. Then, to retain its markets, it must become more simplified. The card defines the different stages and possible solutions.

The beginning of the evolution is an increase in complexity as the system must become multifunctional while avoiding any harmful effects. The performance of new functions will add auxiliary subsystems (T4.1.2). These auxiliary subsystems (T4.1.3) are necessary to perform any missing function while avoiding any adverse effects (TRIZ). These actions will then lead to the setting up of hierarchies and, of course, this will be with the aid of segmentation methods. The I2M-IMC heuristics already described will then be used to complete the trend analysis by classifying the segmentation of the structure of the components, the segmentation of the components or of the flows. The refinement of the different segmentation possibilities is borrowed from the rules of the art of engineering. We next come to simplification

(T4.2), which will reduce complexity by eliminating components or reducing them to a micro-level. The first components concerned are interaction components, which must be reduced, standardized, then eliminated. Next, the functional components are first segmented in the first phase, and must then be recombined or eliminated to retain only what is strictly necessary. Lastly, the final reduction consists in searching for solutions at the micro-level by using new materials which already incorporate functional possibilities.

The evolution trend cards are useful to assess technological evolution followed by technical systems found in relevant patents. In order to facilitate their use, the cards form part of an interactive tool that allows designers to browse more efficiently through the different trends.

The seven remaining cards can be found in doctoral studies by Valverde (2015). Concerning the application case of the bi-phasic separators, the utility of these evolution trends will become clear when pertinent patents are analyzed along a timeline.

1.5 Application Case: Deep Offshore Biphasic Separator

1.5.1 Context of the Problem

The application case relates to a biphasic separation system in deep offshore. Nowadays, offshore oil processing, at ever greater depths, has led the industry into the design of complex separation systems. Designers must develop separation systems with reduced mass and volume and improved performances, i.e., residence-time, slug[9] management, etc.

Several factors must be considered when devising a new biphasic separation system. Among the most important are:

- Hydrates or crystallized salts.
- Management of sand entrained by fluids.
- Thermal fluids (avoid cooling the liquid in order to prevent hydrate formation).
- Slug management: At low liquid and gas flow rates, the flow regime is generally stratified, with the gaseous phase flowing at a faster rate above the liquid phase. At higher flow rates, the gas may be entrained in the liquid and waves are formed at a gas-liquid interface. When they fill the cross section of the pipeline, these waves form liquid slugs. As the flow rate of the gas phase is generally much higher than that of the liquid phase, the liquid slugs are accelerated by the gas phase to the same velocity. Such liquid slug flow regime can cause unstable conditions and handling problems for downstream installations.

[9] Sporadic production of liquid and gas.

There is extensive literature on the design of biphasic separators for use upstream of the multiphase pumps. A large number of patents and articles dealing with the subject indicate that no separator with satisfactory performance has yet been achieved (Tor et al. 2012).

1.5.2 Structuring the Discovery Matrix and the Timeline Classification

Structuring the discovery matrix is possible once the first and second stages of the IMC methodology have been carried out. Performing these two stages gives us, first, a collection of pertinent patents selected and analyzed by designers. Second, several technical and physical concepts are recovered through an iterative implementation of functional decomposition and a detailed physical analysis. In the following section, we present the structure and elements that form one discovery matrix related to biphasic separators.

1.5.2.1 Discovery Matrix Columns and Lines Structure

Concerning the structure of columns, Table 1.7 shows, in general, the physical phenomena involved in separating a biphasic mixture, looking at the dominant liquid flow and the dominant gas flow. The discovery matrix is made up of the type of converter, the pertinent physical parameter, the physical phenomena, and the associated techniques.

The principal function of the matrix is defined as the separation of biphasic mixtures. Different types of separation have been identified (fluid dominant and fluid entrained), i.e., Liquid/Gas, Gas/Liquid, Liquid/Liquid, Liquid/Solid, Gas/Solid, etc. Table 1.7 considers only two cases to illustrate the method and the structure of the matrix. The last part of the structuring will be to cross the families (technological branches) of technologies found (Table 1.8) with the pertinent physical parameters and phenomena.

The lines of the discovery matrix are structured in five branches identified during the iterative phase of research and analysis of the IMC method. In Table 1.8, each branch or "technological family" is complemented by special features found when analyzing patent documents; they generally refer to the shape of the components (Fig. 1.7).

1.5.2.2 Discovery Matrix Timeline Classification

As previously mentioned, the discovery matrix may now be exploited either by physical phenomenon or by patent release date. In the context of this study, it is

Table 1.7 Columns of the discovery matrix, biphasic separators G/L and L/G case

Separation of biphasic mixtures: G/L case				
Gas/Liquid				
Converters (Cs)	Relevant physical parameters (RPP)	Physical phenomena (PP)	Related techniques (RT)	
Static	ρ[a]	Archimedes principle[b]		
Dynamic	ρ, ϒ[c] and Compactness (C[d])	Liquid inertia	Translation	Displacement in the opposite direction to movement of gas
			Rotation	Centrifugal
		Drop[e]		Limit friction
		Impact/Shock	Debonding	Dissociation
		Coalescence	Vibration	
Separation of biphasic mixtures: L/G case				
Liquid/Gas				
Cs	RPP	PP	RT	
Dynamic	ρ, ϒ and C	Diffusion	Pressure gradient	
			Rotation	Centrifugal
		Impact/Shock	Perpendicular to flow	In the flow direction
		Coalescence	Demister[f]	
			Vibration	
		Deflection/Deviation	Centrifugal[g]	
		Thermal gradient	Condensation	

[a] Density
[b] Gas/Liquid friction opposed to a buoyant force
[c] Acceleration
[d] Ratio between surface and volume
[e] Used as a resource, the law of gravity
[f] Removes entrained liquid droplets in a vapor stream
[g] Change in direction

relevant to display pertinent patents in a timeline classification with their related technologies ordered in technological branches (B) (Fig. 1.8). This classification is performed automatically using IMC method tools. Through this kind of arrangement, different technology changes or evolutions followed by biphasic separation systems can be deduced by simple observation and a brief analysis. To illustrate this general analysis by observation, consider two technology branches, vessels (branch 2) and cyclones (branch 4):

- Decantation tanks. In our classification, we see that from 1973 systems were already using deep offshore with heat exchangers to control fluid thermics (GB1309826). In 2003, we continue with gravitational systems which are hybrids with systems using other separators to manage entrained sand (hydrocyclones) (WO03078793). Until 2012, we see a change in shape and also the introduction

Table 1.8 Lines of the discovery matrix, biphasic separators, G/L and L/G case

Separation of biphasic mixtures				
Gas/Liquid and Liquid/Gas				
Branch 1	Branch 2	Branch 3	Branch 4	Branch 5
Helices, Spirals, Helical section, Propellers	Cyclone, Hydrocyclone, Venturi	Bulkheads, Baffles, Deflectors, Fins, Trays, Blades, Pipes, Tubes, Plates	Container, Reservoir, Tank, Vessel	Various: Heat Exchanger, Electrostatic (Electrodes), T-Junction, Chemical Agent
Characteristics				
Variable pitch, spiral, etc.	Cone, Cylinder ("Rotary"), etc.	Inclined, Circumferential, Maze, Snail Shell, Guidance, Curved, Rotating Stairs, Helical Spiral, Verticals, etc.	Sedimentation, Settling, Decantation	Combination of various technological systems (in our classification, fewest of these were found)

of elements inside the decantation tanks to improve their performance (US2012000643).

- Cyclones and hydrocyclones. In 1987, a rotational system (vortex type) appeared that separates oil droplets from water (US4702837). In 2000, we had hybrid systems based on cyclones and other components (i.e., electrodes) (WO0074810). In 2004, several hydrocyclones were used in parallel to optimize the separation process (EP1393812). Then in 2011, hydrocyclone systems (in series or in parallel) incorporate chemical agents (US2011042288). In general, we observe the use of cyclone systems downstream from other separation systems.

A more structured analysis using the evolution trends must be performed in order to deepen the analysis of concepts, decipher the potential technological leaps, inspire us with new ideas, and identify evolution opportunities or innovative solutions (if they exist).

1.5.3 Exploiting the Discovery Matrix by Means of Evolution Trends

The five technological branches (families) classified in the discovery matrix can be exploited now through an evolution trends perspective. A general analysis of these branches, as we have seen in the examples, shows an evolution over time, i.e., the shape, the arrangement of components, materials, etc. The evolutions followed by these branches are analyzed and compared with our knowledge base and then translated into evolution trends. To illustrate this point in the following subsections,

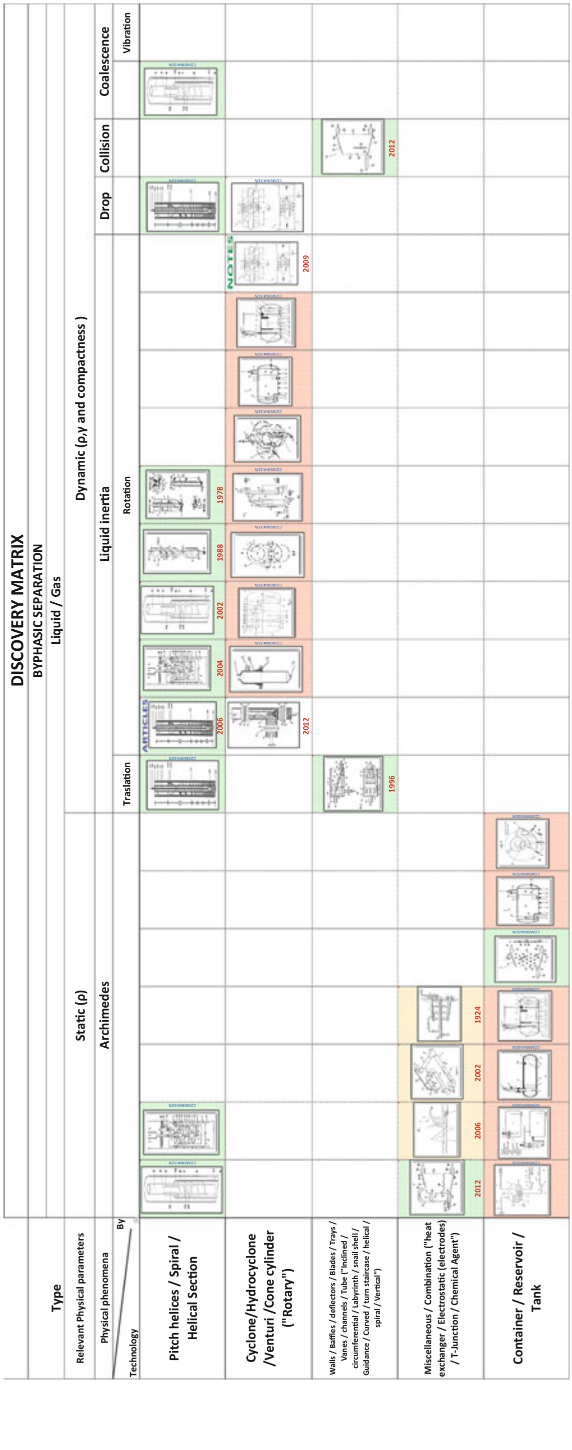


Fig. 1.7 Example taken from discovery matrix of biphasic separators (predominantly liquid stream) (*Green* useful, *orange* might be useful, *red* not useful, *white* not defined)

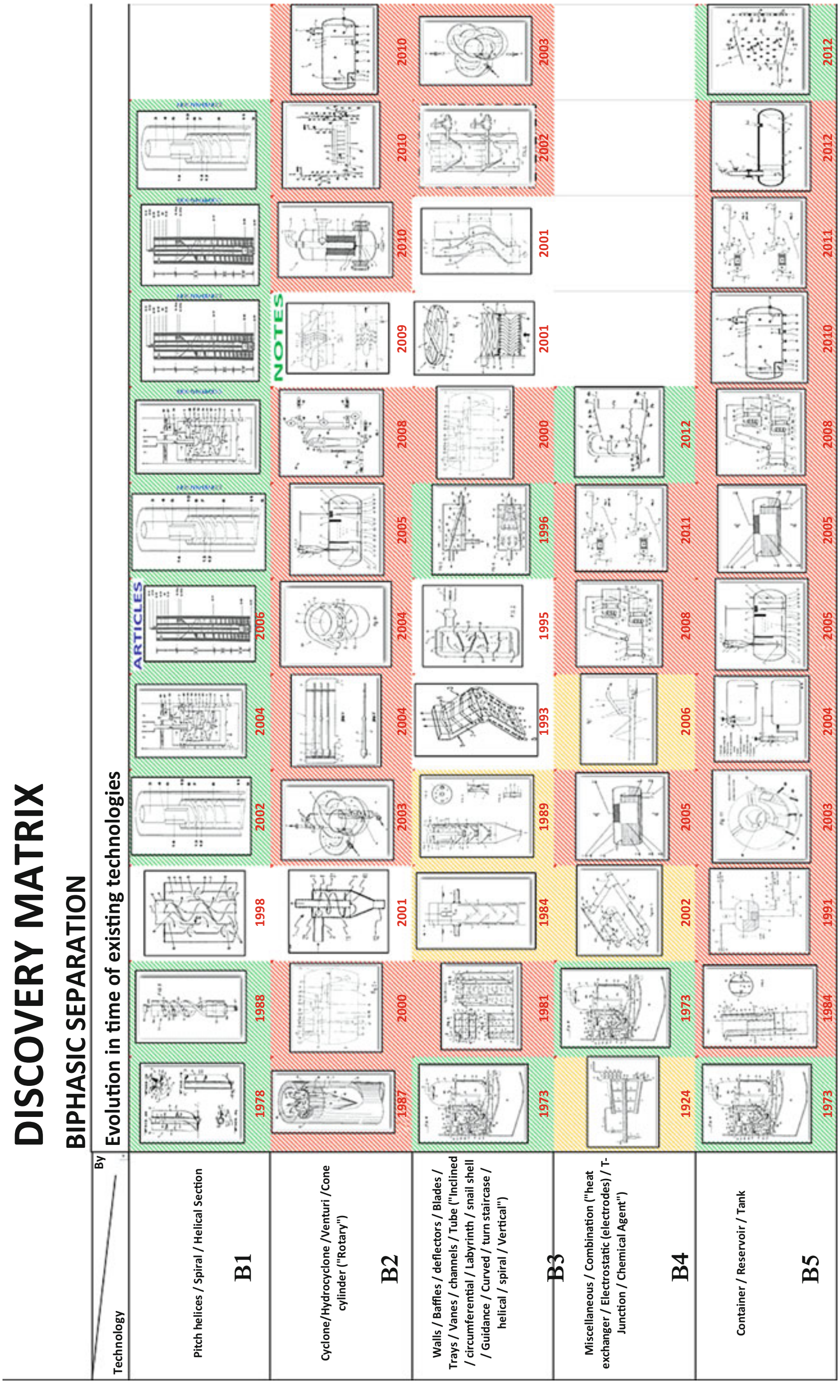


Fig. 1.8 Excerpt from patent timeline classification (*Green* useful, *orange* might be useful, *red* not useful)

we analyze branch 1 (helices, propellers, etc.), branch 3 (trays, deflectors, plates, etc.), and branch 4 (hybrid systems, combinations, etc.).

1.5.3.1 Analysis of Helical Systems (Branch 1)

From 1978 to 2006 (Fig. 1.9), patents dealing with biphasic separation by helical systems followed trend 6 (transition to external environments), T6.3 to be precise (evolving towards bi-poly-systems). In fact, we noticed that while the 1978 patent (CA1036077) consisted of a single type of helix with uniform pitch, all the others had several propellers with different characteristics.

Let us analyze the changes in each patent or group of patents according to the other trends (T1–T8).

A study of the completeness of the system (T1—Source, Converter, Transmitter, Operator, and Control) produces the following observations for all patents:

- The converter is always a pump.
- The transmitters are static.
- Separation is never controlled; this is an important area for change.

All helical systems generate losses through friction. Any reduction in these losses (T2—Energy conductivity) will favor systems that avoid systematic contact between the droplets and the metal structures, i.e., as soon as the droplets have been separated, they must be evacuated. Patent DE19650359A1 (Fig. 1.10a) recovers the droplets laterally, which reduces displacement. Patent RO119248B1 (Fig. 1.10b) uses gravity to help eliminate the droplets. The next change will be to eliminate these losses completely by letting the droplets fall (concept used in systems with plates).

The coordination of rhythms (T3) was present from the second patent that we found. There were double helices (in phase), helices with uniform pitch, and inverted helices (out of phase). These variations in pitch modified the displacement dynamics of the mixture. There are no dynamic components in these offshore systems; this avoids any problems in maintenance.

We noted that the complexity of the separator increased over time (T4—Increased level of perfection). Segmentation (T4.1.3—Increase the number of hierarchical levels) was used a lot, as mentioned previously. It is essential to incorporate hierarchy levels in order to avoid the risk of clogging due to the short-term transportation of large quantities of liquids (slugs), in other words, to anticipate when large volumes enter the system. We note that a hierarchy is in place in 2006 (Fig. 1.11) to deal with this problem: at the entrance the pitch of the helix is very steep. See Fig. 1.11 for an explanation of the hierarchy levels.

At first sight, trend T5, unequal development of entities, is not seen in the succession of patents in Fig. 1.9. If we put the systems into the context of offshore, we see that the helix diameters are small, which segments the separators. Offshore, having many separators is not an option. We therefore want a small number or even a single separator. There is therefore a contradiction associated with the

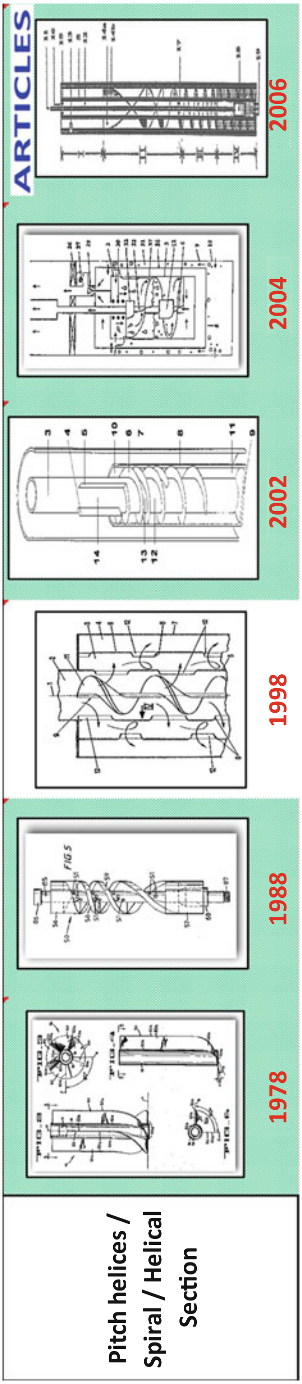


Fig. 1.9 Excerpt from the timeline of patents that contain helical elements (B1)

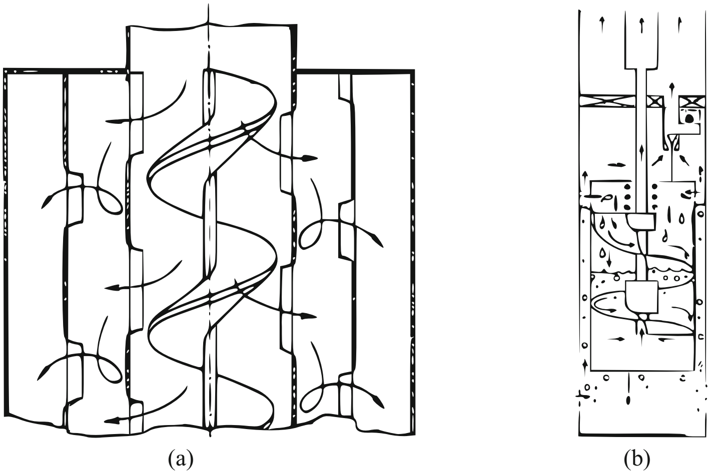


Fig. 1.10 (**a**) Patent DE19650359A1 (1998)—lateral recovery; (**b**) Patent RO119248B1 (2004)—recovery from below

development of small-diameter helices. For the concepts in our context to evolve, this contradiction has to be resolved.

There is no development expressed at the micro-level (T7—Transition from macro-level to micro-level) in the patents.

Trend T8 concerns the increase in dynamism and the level of controllability. From the beginning, we have seen that it is difficult to control separation efficiency. We must look at the effect of the evolution of the helices on separation. We note that the systems increase their dynamism by varying the shape (T8.4) of the helix and by segmentation which modifies the rhythm of droplet displacement up to Fig. 1.11, which includes two inverted helices with variable pitch (T3.1.2—Coupling in phase opposition). The increase in controllability now involves using new fields by superimposing effects that will initiate collisions and allow the droplets to coalesce. These fields, high frequencies for example, will be controllable.

1.5.3.2 Analysis of Plate Systems (Branch 3)

We now analyze patents involving plates Fig. 1.12. These patents have reached the public domain or will soon do so as the most recent is dated 1996.

Plate systems fall within trend T6 (Transition to the external environments), they have identical components with the same functionality to increase efficiency (T6.3.1), components that are following the concept of segmentation.

Analysis according to trend T1 (Source, Converter, Transmitter, Operator, and Control) is the same as for the helical systems, i.e., a lack of control.

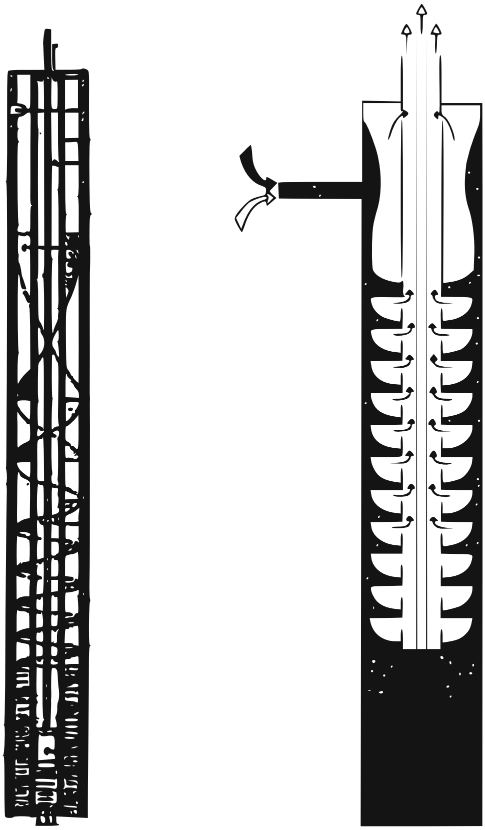


Fig. 1.11 Patent MY123978 (A) (2006): incorporation of hierarchy levels (Rosa et al. 2001)

However, energy losses (T2—Energy conductivity) are less as this is a hybrid concept: sliding along the plates and a drop between two plates, thus the liquid remains in contact with the plates for only a short time.

Apart from these two possibilities (slide and drop), no change in rhythm can be seen, which could be the case with changes in pitch. Similarly, there is no use of additional vibrating systems. Thus from the point of view of trend T3 (Coordination of the rhythms), there are possibilities for developments.

Increase in the level of perfection (T4) concerns segmentation, which is characteristic with plates (division into several entities, T4.1.3.1). This segmentation has evolved in the latest patents (Figs. 1.13a and 1.14) by incorporating the drilling of holes which will calibrate the droplets and cause them to fall. As in the case of the helical cyclones, the last patent (Fig. 1.14) includes management of the separation tables.

We observe no uneven development (T5) or transition to the micro-level (T7).

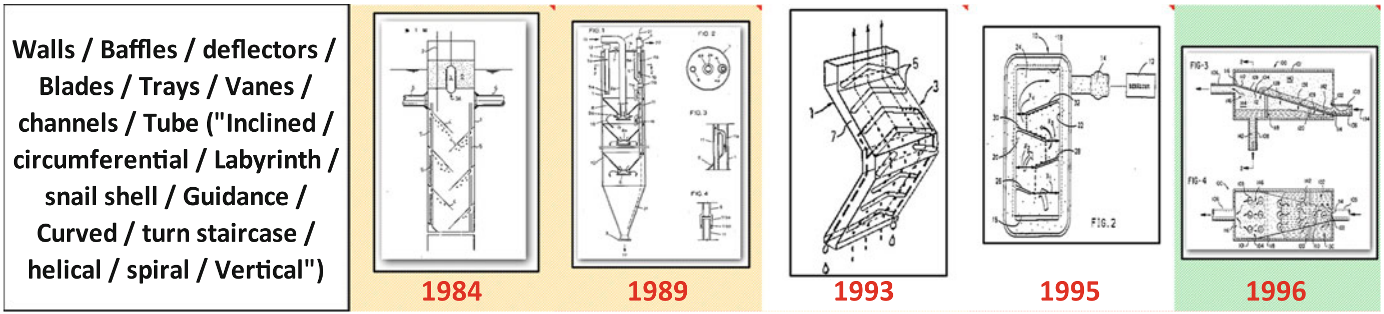


Fig. 1.12 Excerpt from the timeline of patents containing plate elements (B3)

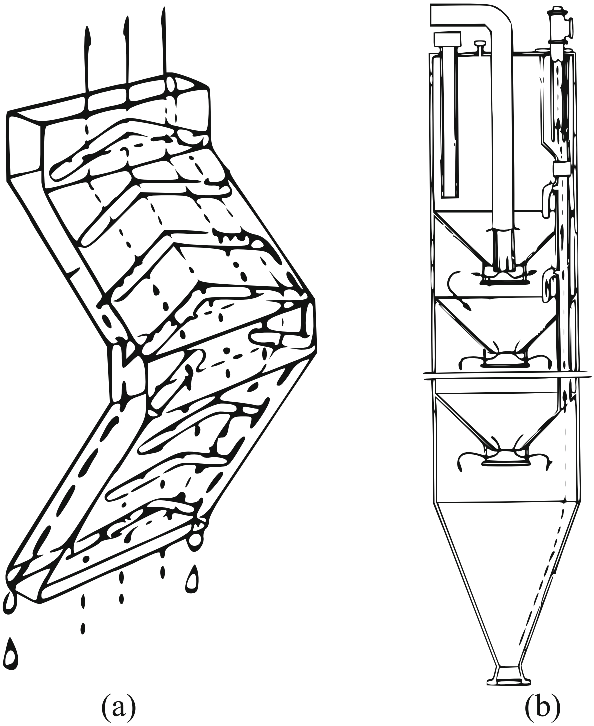


Fig. 1.13 (**a**) Patent DE4214094C1 (1993) Slugs management; (**b**) Patent US4816146A (1989): changes in shape

As was the case for the helices, we observe an increased dynamism as a result of change in shape (T8.4), from 2D to 3D (T8.4.4) until we find concave shapes (Fig. 1.13b, T8.4.3).

We paid particular attention to a patent invention from 1996 (Fig. 1.14) which is composed of polysystems and which is able to control slugs by means of an inverted plate.

1.5.3.3 Analysis of Hybrid Systems (Branch 4)

In this branch, we analyze patents concerning the combination of different concepts that produce hybrid systems to increase efficiency in the biphasic separation process. The combination of different technological systems allows designers to overcome the numerous constraints involved in offshore processes. Figure 1.15 shows branch 4, where we mainly identify storage tanks and T-junction systems combined with heat exchangers, storage tanks with hydrocyclones combined with chemical agents or high power electrodes, etc.

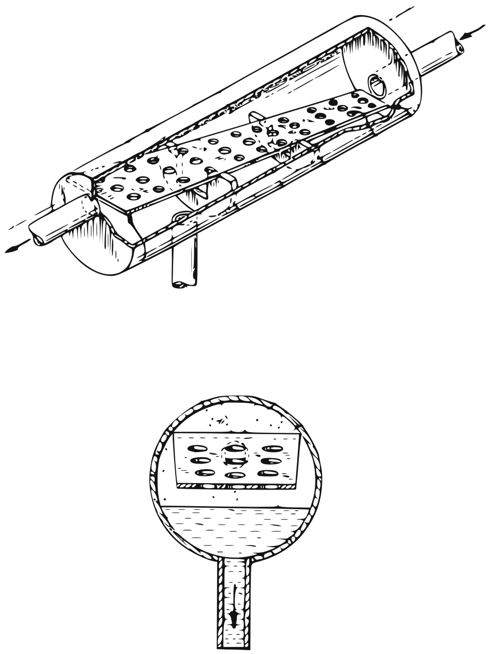


Fig. 1.14 Patent US5507858A (1996): Slugs management

Once again, the evolution trends help us in qualifying the main changes observed in patents with the aim of being inspired by the technical solutions found in the technological branches.

In biphasic separation, we identify two main axes used in subsea facilities: gravity (i.e., settling tanks) and centrifugal (i.e., cyclones) separation. In the 1970s, a third axis was formally observed: the biphasic separation by T-junctions. They attracted great interest among petroleum engineers, as many T-junction systems have been used in the vast networks of pipelines in offshore processes for separating biphasic mixtures (de Oliveira 1992). They are considered ideal systems in subsea installations because of their simplicity, the limited number of components needed, their possible reuse in other exploitation fields, and a simplified control. These systems achieve an efficiency of separation of 85%; however, they are extremely sensitive to two-phase flow behavior (Margaris 2007). In the technological branch 4 of Fig. 1.15, we observe that T-junction systems appeared in 1924 for stratifying two fluids; in 2002, they were used to dissipate fluid slugs from gas pipelines; and in 2006, we identified several vertical degassing pipes. In this time span, we find again Trend 4 (Increased level of perfection), particularly the increase in the number of hierarchical levels (T4.1.3) and segmentation (T4.1.3.1). From 2008, we began to observe the integration of different systems for different functions (T6.3.4), which means T-junctions combined with sedimentation tanks and centrifugal components organized in modular sections. Lastly, in 2012, we continue with the integration of various systems (T6.3.4) such as Tanks,

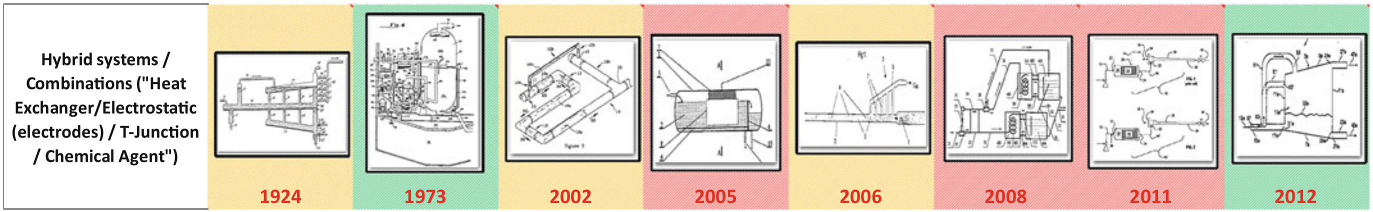


Fig. 1.15 Excerpt from the timeline of patents containing hybrid systems (B4)

T-junctions and Plates. We also note an evolution of the form (T8.4) through a modified settling tank adapted to deep offshore facilities (Compact separator) and several small tanks (segmentation principle, T4.1.3.1) linked in series to form a multi-stage separator to resolve the deep sea and slug problems, respectively.

Another hybrid concept is the integration of heat exchangers in order to thin liquids. Observing branch 4, we note in 1973 a system that combines settling tanks and heat exchangers for separating a three-phase mixture (gas, water, and oil). Heating is an interesting track because it allows prevention of the formation of hydrate plugs.

More interesting hybrid concepts found in branch 4 are the integration of high-voltage electrodes combined with settling tanks and baffles (2005). This invention uses an electrostatic field to promote drops coalescence. We note here the transition from a macro-level to the micro-level (T7) by the use of electric fields (T7.4.7). Finally, in 2011, we identified several settling tanks connected in series or in parallel (Segmentation T4.1.3.1), hydrocyclones (the vortex inside generates a centrifugal force), Coalescers (filters or baffles) and chemical agents to promote coalescence in the mixture. The chemical coalescent agents (polymers) or de-emulsifiers are used to coalesce insoluble particles (T7.4.6—Replace/Overlay mechanical flow by another, i.e., chemical, optical, acoustic, etc.).

1.5.4 Innovation Through the First Findings

The analysis of technological branches (from the discovery matrix classified in the timeline) using the evolution trends enables us to objectively identify trends followed by the patented inventions over time. This also gives some initial ideas and possible directions for innovation by taking into account the best solutions and looking toward hybridization (where several concepts are combined to carry out the desired function). Evolution trend analysis can also lead us to completely change the concept using new technologies.

1.5.4.1 Incremental Innovation: A Hybrid Solution

Our hybrid concept is illustrated in Fig. 1.16; it represents one of several possible conceptual solutions proposed to the oil industry. This hybrid concept is an alternative proposal to the use of a cyclone or a common settling tank (currently the most used).

Let us go over the essential concepts retrieved when analyzing by evolution trends: first, the incorporation of identical polysystems to increase the efficiency of an action (T6.3.1); next, trends toward segmenting one entity into several entities (T.4.1.3.1); then incorporating different systems with identical functions (T.6.3.2).

The constraints of working offshore generate a contradiction if we are using cyclones; our first proposal was based on the use of plates as this enables us to have

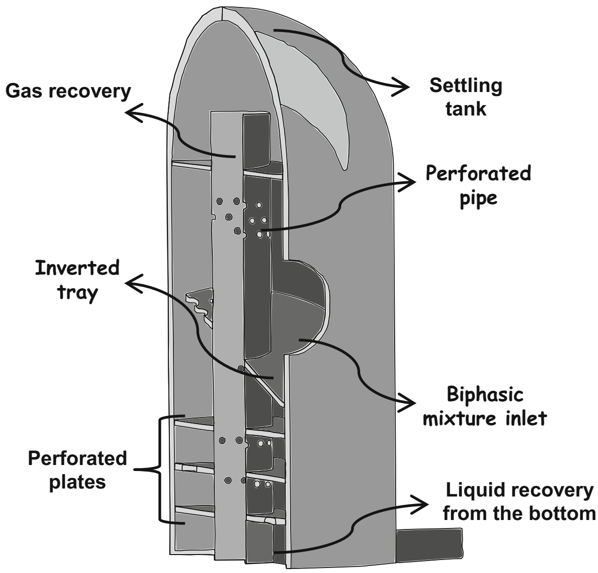


Fig. 1.16 First two-phase separator proposal

large diameters. Another restriction imposed by the oil industry was the use of settling tanks as those currently installed. Therefore, we should make a proposition based on an incremental innovation. The concept that was presented to the contractor involved a hybrid system, a gravity settling tank with plates, where fluid recovery is done from the bottom.

We start by taking relevant concepts found through patent analysis by evolution trends. Figure 1.16 shows a settling tank that incorporates horizontal perforated plates in order to refine the mixture separation; this concept was previously seen in Fig. 1.13 (trend towards identical polysystems—T6.3.1 and segmentation—T4.1.3.1). The mixture inlet is at the top, which means that it can then drop, thus promoting separation. The recovery of gas is done by means of a central tube; this solution is inspired by the lateral and internal recovery of Fig. 1.10a. Lastly, an inverted tray manages slug formation from the biphasic mixture due to the deceleration of the fluid; it also has perforations to promote biphasic separation before entering the horizontal plates where mixture separation will continue. This concept was inspired by the 1996 patent (Fig. 1.14) which will soon enter the public domain.

1.5.4.2 Breakthrough Innovation: Future Ideas

As seen previously, patent analysis by evolution trends offers us several interesting tracks that could inspire engineers in the design of a new biphasic separation device in order to go beyond what has been done up till now. The hybridization of technologies is a clear trend (T6.3.4) observed throughout the timeline of the discovery matrix. Work might continue on the integration of different solutions to increase separation efficiency, which could lead us to the reduction or even the elimination of components, thus increasing the level of perfection in the system (T4). In the timeline, we also observed a trend going from a macro-level to a micro-level (T7) which implies the replacement of physical components (static or dynamic) by fields. The application of an electrical field to improve biphasic separation is a current trend which will be increasingly used in the future.

1.6 Conclusion and Discussion

We have produced evolution trend cards for technical systems based on the TRIZ evolution laws, Polovinkin's rules, design heuristics by the I2M department and the rules of the art of engineering. These cards are used to analyze evolution opportunities based on the knowledge derived from studying pertinent patents. Selecting the pertinent patents was based on a method perfected by the I2M research institute. It is presented here in the form of a discovery matrix which crosses patented technologies with the physical phenomena involved in or suggested by the method.

By applying the technique to the design of a liquid/gas separator for deep offshore, the relevance of this analysis becomes clear. Directions for technological systems (lines of the matrix) or physical possibilities (columns of the matrix) were observed. The timeline classification and the trend cards indicate possible developments. By crossing solutions we were able to propose hybrid solutions, one of which is illustrated here.

Our aim now is to ensure the completeness of our evolution trends proposal by applying other design rules. It would be worthwhile to test our trend cards against the communities currently working on patent exploitation and thus measure their degree of detail in design activities.

Work is currently under way to improve searches in more substantial databases and by using special algorithms (Valverde et al. 2016a). To develop the information in our cards, further studies are needed based on different industrial fields, and this work has already started (transformation of marine energy and telescopic access platforms).

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Chapter 2
Automated Extraction of Knowledge Useful to Populate Inventive Design Ontology from Patents

Achille Souili and Denis Cavallucci

Abstract This chapter proposes an approach to extract and manage knowledge from patent documents for use by design engineers within the framework of the inventive design method (IDM). IDM is an extension of TRIZ, the theory of inventive problem solving, and is meant for complex situations. It uses generic linguistic markers to locate and extract IDM-related knowledge, such as problems, partial solutions, and parameters, to automatically populate IDM ontology.

2.1 Introduction

Analyzing the situation is a necessary first step when dealing with complex engineering problems. Furthermore, innovation is the foundation of technological advances in today's competitive economy. Patents contain important research results, and it is also possible to find within them a kind of history of the evolution of an artifact. In this context, engineers may very often need to analyze them in order to benefit from the knowledge contained therein to organize their inventive task. However, patents are lengthy and rich in technical terminology, and analyzing them may require a lot of effort. Thus, automating the process is very timely. To facilitate this, several patent analysis tools have been created. There are also patent analysis tools dedicated to highlight various values of patent document but very few of them are designed to extract information or knowledge contained in patent unstructured sections. The inventive design method (IDM; see Sect. 2.2.2.1) was developed to assist designers in their innovation process. One of the tasks in IDM R&D activities is the construction of a problem graph, which is a representation of known problems and potential solutions with their interactions. This chapter reports on an ongoing research to extract relevant knowledge for a (semi-)automatic

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problem graph generation. It shows that text mining can be a good technique to improve knowledge extraction from unstructured patent data.

To design new products and methods, industries are on a perpetual quest to find innovative methods and tools to assist R&D activities. On that score, TRIZ, the theory of inventive problem solving, which is primarily based on patent's analysis, turns out to be a relevant answer. Patents, together with scientific papers, represent the major part of the world's technical knowledge. Furthermore, according to the World Intellectual Property Organization, 90–95% of the world's inventions are found in patented documents. In addition, the European Patent Office also disclosed that "patents reveal solutions to technical problems, and they represent an inexhaustible source of information: more than 80% of man's technical knowledge is described in patent literature" (Yeap et al. 2003). Therefore, patents constitute a first choice media, when speaking of technological information. Thus, the observation of an artifact throughout the years enables the understanding of its evolution mechanism. In this context, and besides few contributions to patent mining, patents are underexploited in the process of designing new products. There is a field of research in building relevant methodologies using patent mining, aiming at better assisting R&D activities.

Patents turn out to be a good source of information for research. They are valuable to designers, industries, and businesses. When carefully analyzed, patents can also reveal important details on potential evolution of the artifact. This information can later be used to make decisions about the method or tool being developed. Unfortunately, the knowledge contained in patents remains underused by engineers who do not take the time to analyze and so benefit from their content. Unlike other traditional methods for solving inventive problems, IDM-TRIZ can overcome psychological inertia, an essential step in the innovation process. Its main goal is to bring the designer to come out of his field of study to find solutions by analogy, by looking for generic knowledge contained in the patent documents. However, experts currently do this research manually. Creating and updating the graph that represents all known problems and partial solution network is time consuming and requires a lot of effort. Therefore, it becomes necessary to make patents more accessible to engineers.

In this research, we seek to support effective and efficient patent mining and knowledge extraction by the use of text mining techniques. From visual and bibliometric analysis to semantic searches, many approaches exist in patent analysis. However, these approaches have not reached maturity yet. Despite their obvious efficiency, they are still domain dependent and do not always address unstructured data. The output is often a re-retreatment of surface data such as summaries, charts, maps, and tables (Cavallucci et al. 2010). Furthermore, great amounts of the work that aim at extracting knowledge from patent just perform quantitative techniques and try to display trends. Therefore, providing a tool that can effectively meet the designers' needs is very timely.

2.2 The Target Description

This chapter aims to describe an ongoing research to conceive a patent mining tool relevant to automatically extract IDM-related knowledge since engineers have been doing this manually until now. This research explores the use of text mining techniques to improve knowledge extraction. More specifically, it explores the use of generic linguistic markers to match and retrieve concepts likely to be of interest to IDM.

2.2.1 TRIZ and IDM Knowledge Model

IDM, like its mother theory, TRIZ, is based on logic, data, and research rather than intuition. It is primarily about technical and physical problems. TRIZ (Altshuller 1998, 2004) was developed and enunciated in 1946 by the Russian engineer and scientist Genrich Altshuller when he first discovered that objective laws govern the development of technical artifact. Stated after a study of nearly two million patents, the theory assumed the existence of universal principles of invention. This study led him to present his first three findings (Blossier 2002):

- First of all, some problems and solutions are recurrent in industry as well as in science. A predictive solution to these problems can be found by categorizing the contradictions existing in each problem. We will define the concept of contradiction later.
- Second, patterns of technical evolutions may also be recurrent across many different industries.
- Third, in general, creative innovation representing these technical evolutions emerges outside the field where they were developed.

The theory of inventive problem solving is different from other traditional approaches to problem solving that could rarely offer satisfactory solutions to the outcome of the implementation of a technique or a method and often disappoints the designer. Most of the existing tools offer analysis on patent surface data and do not tackle well the unstructured part of the patent document.

These approaches are:

- The trial-and-error approach that accepts compromise between system elements while seeking a solution randomly
- The "brainstorming" approach which is closely linked to individual skills
- The experimental design approach, which is complex and only allows finding solutions in a known direction

Unlike the above approaches, TRIZ avoids compromise when solving a problem. It focuses instead on an ideal solution that is the key to innovation (Cavallucci and Guiot 2008). It has now become universal, and apart from being primarily used for technical and physical problem solving, TRIZ is currently applied to solve nontechnical domain problems and situations.

2.2.2 IDM and Its Knowledge Model

2.2.2.1 The Inventive Design Method

IDM was developed to overcome the drawbacks encountered with conventional TRIZ (Dubois et al. 2004). Actually, TRIZ is not formalized and also has the disadvantage of not being able to be instantiated. Therefore, a modeling of TRIZ has been initiated within the LGeCo, Laboratory of Design Engineering, with the aim to provide assistance to inventive design experts.

In addition to TRIZ, IDM also derives from OTSM-TRIZ (Cavallucci and Khomenko 2007), and like OTSM-TRIZ, IDM uses contradictions to solve problems and shares its assumptions. There are three of them:

- Any problem solvable by TRIZ must be formulated as a contradiction.
- Technical systems evolve according to objective laws. The best solution is the one that complies with these laws.
- The best solution is the one that involves the least possible new resources.

Bultey et al. (2007) worked within the framework of this computer modeling on an ontology model based on substance-field concept analysis to stimulate problem solving through the use of description logics. An ontology of IDM was also built by Cavallucci et al. (2008). The next section presents IDM ontology and its different concepts.

2.2.2.2 IDM Ontology

Ontology may be defined as the standard representation of a domain or field of the important categories of objects or concepts, which exist in the field or domain, showing the relations between them. In other terms, ontology uses concepts and relations to organize domain knowledge and even to support knowledge extraction. IDM ontology, unlike other ontologies, is generic and is applicable in all areas without any restriction (Rousselot et al. 2007). Therefore, it differs from other ontologies applied to patents that are very specific and static. The main concepts of IDM were presented previously in Cavallucci et al. (2010). They are problems, partial solutions, and contradictions that include element parameters and values.

Problems describe unsatisfactory features of a system or a method, while partial solutions bring progress or improvement to the method or artifact. A problem must represent the main problem. As for partial solution, it must be the simplest possible.

Parts or components of a system are called elements. They have parameters. Two types of parameters can be distinguished: parameters of action on which one can act and parameters of evaluation, which cannot be changed but remain useful to measure the results of a design choice.

Values are used to qualify parameters.

IDM proves to be an effective method that contributes to reduce the time spent in R&D during a design process.

2.2.3 The Nature of Patent Documents

A patent is an industrial property that gives to its holder the monopoly of the artifact being patented. According to the WIPO, the patent is an exclusive right to an invention, which is a product and a process that provides, in general, a new way of doing something or offers a new technical solution to a problem. Patent is generally granted for a maximum of 20 years, and the patent documents are structured according to the intellectual property code. Three main parts can be distinguished:

- The cover sheet: It contains the metadata of the invention, which are generally bibliographic: among others, the title of the invention, the date of application, the technical field, the date of priority, and the name and address of the inventor or the applicant. It may also include an abstract and illustration of the invention, which are very useful for identifying or classifying patent documents (Osenga 2006). Abstract is a summary that does not exceed 150 words that gives the gist of the artifact.
- The description section: It comes after the cover sheet. It presents general information on the prior state of the artifact as well as detailed information about the artifact or the process and its components. The description section is essential for the claims section (see next point) interpretation and the scope of protection sought by the inventor. The information about the technical field, the prior art of the artifact, the summary of the invention, illustrations, and the detailed description of the invention are also included in the description section.
- The claims section: This section is the legal basis of an invention protection. It specifies the limit of protection granted by the patent. There are two types of claims:
  - Independent claims, which set the characteristics of the invention for which protection is sought
  - Dependent claims, which complement the independent claims with additional specifications

In a nutshell, the patent document includes two main parts: a structured part and a non-structured part. It is very complex and specific. Brigitte Guyot, after a study on the patent text (Guyot and Normand 2004), concluded that it is a legal and scientific document. It contains complex syntaxes.

2.3 An Overview of Patent Mining Tools

The patent mining field is very young, and this section reports on major progress in the field of patent mining and more specifically in patent mining for TRIZ and IDM. Many approaches have been proposed to extract knowledge from patent documents and automate the TRIZ process. According to Trippe (2003), there is still no effective and generic instrument that is easily applicable, regardless of the domain. Tools dedicated to patent mining are very few. Some are related to TRIZ and have intended to automate knowledge extraction for patent documents. Such tools typically use hybrid approaches by associating statistics and linguistics. Feldman et al. (1998), for example, present a document explorer which implements text mining at the term level. A list of candidate keywords is produced after a basic linguistic preprocessing. Furthermore, Ghoula et al. (2007) expose a processing chain achieving automatic semantic patent annotation through a structural and domain ontology. Such approaches are promising for processing unstructured patent data.

However, the abovementioned approaches are limited in that they do not take into account artifact improvements. Hence, they do not give access to the invention process. The efficiency of TRIZ is obvious, and, with its development, many authors have tried to automate its application in order to use the inventive principles to solve problems in a variety of domains. One of these widespread approaches is subject-action-object (S-A-O), which is intrinsically linked to the concept of function, the understanding of which differs from one author to another.

For example, Savransky (2000) defines function as the “action of changing the feature of any product,” while for Cascini et al. action and subject refer to the components of a system where the action refers to the functions performed by and on the components. More precisely, they propose a method to automatically identify the contradictions subjacent to a given technical situation or system using patent mining (Cascini and Russo 2007). According to them, functional analysis can be used to identify problems or generate innovative solutions. In functional analysis, a problem is broken down into its component functions that are further divided into sub-functions and sub-sub-functions, until the function level for solving the problem is reached. Functional analysis is relevant for the representation of knowledge related to a patent’s key finding and the inventor’s domain of expertise.

2.4 The Proposed Methodology

The previous section reported on current progress made on patent mining and more specifically on patent mining for TRIZ. This section firstly presents the main approaches in knowledge extraction before exposing the methodology we use to extract knowledge relevant to IDM.

Two main approaches can be distinguished in the field of information extraction: data-oriented approach and knowledge-oriented approach. As a precision, knowledge extraction is used here to extract relevant information for IDM from the unstructured section/text of a patent.

Data-oriented approach consists in a statistical processing. In this approach, analysis results are represented as clouds or charts. This allows quick interpretation of results. The data-oriented approach includes:

- Factor analysis method, i.e., canonical approach, discriminant analysis, etc.
- Automated classification method, i.e., bottom-up and top-down methods, etc.

A patent document contains several items for analysis. It is made up of several parts. Some are structured, such as patent number, filing date, etc., and others are unstructured, such as claims, abstracts, and descriptions of the invention. From all these parts, it appears that it is the cover sheet that is predominantly processed by quantitative methods. As an example, the bibliometric method is known to be used for patent trend detection.

However, as Bereau and Dou (1997) mentioned, there is dissociation between the analysis of structured and unstructured parts. Data-oriented approaches fit well to structured data. Unstructured data requires other methods of processing such as knowledge-oriented method.

The data-oriented approach rests upon text mining and is based on linguistic analysis. This approach generally consists of text preprocessing, such as lemmatization, tagging, and segmentation, naming entities or recognizing concepts, and uses statistics sometimes.

The approach used in our study is knowledge oriented since the knowledge to be extracted is located in the unstructured parts of the patent document. More specifically, we propose to use a set of generic linguistic markers. Hearst (1992) demonstrated that in unstructured texts, it was possible to look for specific lexical relations, which are frequently expressed throughout the text. After developing a list of terms that reflects the desired relationship, expressions are grouped into representative patterns. Another study of Teufel (1998) tries to identify meta-speech markers to reveal the semantic and logical organization of text.

2.4.1 The Implementation

The underlying idea of our method is the use of generic linguistic markers as keywords to identify and extract knowledge useful for IDM. Unlike existing approaches in patent mining, our approach is domain independent. It performs the discovery of IDM knowledge using the patterns created from the observation of how IDM concepts are expressed syntactically in patent documents.

Hence, the starting point of our method is the building of the training patent corpus. The process was explained previously in Kerem (2009) and Souili et al. (2011). As a reminder, the corpus contains 100 patents from various domains ranging from engineering to chemistry. In order to deal with issues regarding representation and IDM knowledge model so as to produce an effective knowledge extraction process, our working model has been divided into two steps. The first step is the linguistic analysis that aims to produce both training information for further evaluation and the initial population of extraction automata. The second step constitutes the knowledge extraction itself. More precisely, this aims to apply our automata on test corpora and evaluate them to complete or extend the initial population with unseen extraction patterns.

2.4.2 The Linguistic Analysis

The linguistic analysis phase includes two main goals: to extract relevant information from patent documents and to use that information to build extraction automata.

With respect to text analysis, an essential principle in our method is to be able to make good use of the patent document structure for knowledge extraction. It is known that the patent document is very specific and has inherent complexities (Guyot and Normand 2004). So we have restricted our scope to some extent to study the parts of the patent documents, i.e., the cover sheet (mainly the abstract), the claim, and the description sections.

Linguistic analysis is useful to build relevant linguistic marker lists for the identification of IDM concepts. A text written in natural language consists of words. The latter allow the expression of ideas, the description of problems, or the presentation of solutions, and so on.

Two types of words can be distinguished: inflected words (names, verbs, determiners, pronouns, and adjectives) and uninflected words (interjections, conjunctions, and prepositions). Inflected words are words that have a morphological marker such as ablaut, consonant gradation, or affixes, indicating conjugation or declension. The uninflected form of a word is usually used as the lemma for the word. Lemma can be defined as an independent unit of the lexicon of a language. It is a sequence of characters forming a semantic unit and constituting a lexical entry.

However, it is insufficient to consider words as the basic unit in situations where they depend on each other to be understandable, for example, the expression "by means of." A possible solution could be the use of *N-gram*. *N-gram* was used by Shannon (1948). He used the concept of *N-gram* in a predictive system to predict a character following the sequence of characters previously entered. *N-grams* can be defined as the contiguous sequence of *n* items from a given sequence of text. They are typically collected from a text corpus. In this study, *N-grams* calculation was used to help disambiguate compound words or expressions for later use as markers. For example, the previous expression "by means of" is a trigram.

In the context of linguistic analysis implementation on patent texts and the development of lexical resources, we built two corpora. The first corpus (*Corpus A*) was used to train the data and the second one (*Corpus B*) to evaluate the extraction patterns.

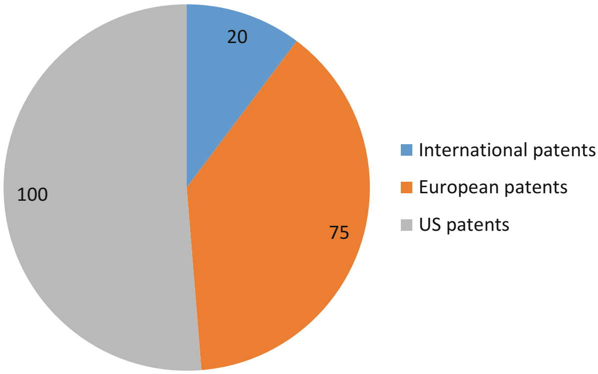


Fig. 2.1 *Corpus A* (training corpus)

Corpus A was built randomly and includes 195 patents (100 US patents and 95 international and European patents) published between 2000 and 2011 and retrieved from USPTO and Espacenet.

Corpus B includes 87 patents,[1] mostly written in English and published between 1975 and 2009. Patents included in *Corpus B* were collected following experts' manual analysis. Furthermore, they were selected due to their wealth with regard to relevant knowledge for IDM. In fact, *Corpus B* has already served for a manual knowledge extraction. This manual extraction took more than 5 days of full time work and involved four experts and a facilitator. The role of the facilitator was to guide experts in manipulating IDM concepts (Figs. 2.1 and 2.2).

Table 2.1 summarizes token analysis for each corpus. Patents are huge documents. According to the initial calculation obtained on corpora, the average length of sentences in the description section is 28.71 words, ranging from 18.88 to 48.18 words, with a standard deviation of 25.30.

As for the claims section, an average of 45.11, ranging from 20.88 words to 129.33 words, with a standard deviation of 48.49 was obtained.

Linguistic analysis is necessary to ensure relevant, clean, and complete information extraction. The analysis system adopted includes classical NLP steps, namely:

- Corpus preprocessing
- Stop word cleaning
- Linguistic marker weighting
- Part of speech tagging and lemmatization

All these steps are itemized in previous papers (Souili et al. 2013). In most of the cases, the *Unitex* platform, in fact, includes tools relevant to conduct the

[1]Eight patents from the set of 87 were written in French. We replaced them with their English translations available on http://fr.espacenet.com

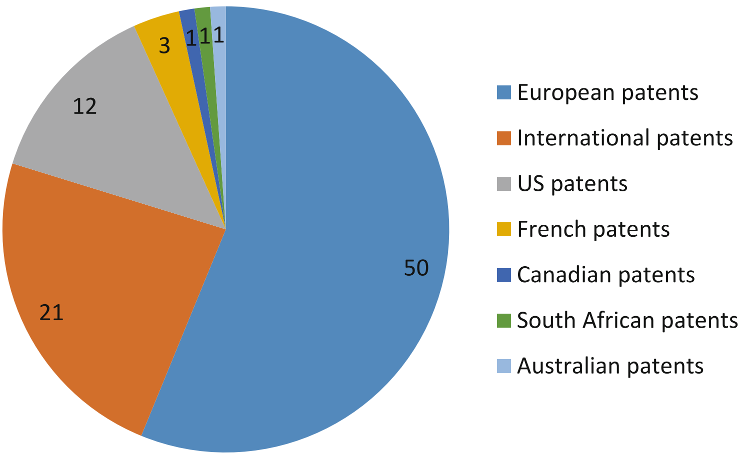


Fig. 2.2 *Corpus B* (evaluation corpus)

Table 2.1 Token analysis

	Corpus A[a]	Corpus B[a]
Main	1,742,600	1,104,946
Abstracts	32,251	20,450
Descriptions	1,502,514	634,445
Claims	240,086	103,122

[a]Tokens

abovementioned processes. After the parts of speech tagging and lemmatization steps comes the marker selection step.

2.4.3 The Linguistic Marker Selection

At this point, an identification of concepts relevant to IDM requires the study of their context of appearance in patent documents to derive clue words or markers. Thus, the classical approach in linguistics consists in a semasiological or inductive study (Hansen 1997) also known as classical corpus-based approach. This approach is to search for occurrences of a given linguistic data to compare its frequency of appearance in different bodies and determine the reasons for its presence in certain places of the text.

However, a significant limitation of this approach is its non-heuristic nature. Moreover, it is purely confirmatory. Sharing Pierard and Bestgen's (2006) point of view, one must indeed have a list of candidate markers to verify whether they are relevant. In this context, these authors propose instead the use of a more exploratory approach based on the automatic identification of expressions relevant to be markers of the desired structure.

Following this, and within the framework of candidate marker selection to extract knowledge relevant to IDM, we have used an approach based on the identification of recurring sequences of words, that is, N-gram. This approach is widespread in the field of phraseology (Hernandez and Grau 2003; Schone and Jurafsky 2001) and textual statistics (Lebart and Salem 1992). The method of identifying N-gram is to make a list of all N-grams with N ranging from 1 to 10 per sample, frequent enough in a text population. However, it happens that the number of recurring expressions collected is very important. In this case, it may be enough to set a minimal frequency to eliminate all words whose frequency of occurrence is lower than the threshold set. It is possible to make some observations with an N-gram analysis. We first note that several verbs of change used in gerund are used in co-occurrence with the preposition "for," for example, "for improving," "for generating," "for decreasing," etc. It also appears that the preposition "to" is also used with the verb of action used in the infinitive, for instance, "methods to generate...; a process to improve...." The prepositions "for" and "to" in both cases reflect the purpose, the intentional aspect, of the act of "generating" or "improving." A preliminary analysis of these co-occurrences reveals that these could be rich markers of partial solutions.

We then found that the "cause" marker is very productive. It is very often an indicator of parameters or can precede verbs of change. Thus, the nouns or noun phrases coming immediately after "caused by" are often parameters, for instance, "caused by presence of dross..." or "caused by the lowered level...." In addition, the verbs that follow "cause" are mostly verbs of change (flow, rise, change).

However, the patent documents remain very specific with complex syntax. It is not rare to find long sentences of more than five hundred (500) words. Moreover, several topics can be found in the same sentence, which complicates sorting. We also have the frequent use of complex compound names to express the maximum information with minimum words.

We noticed, for example, that verbs of change such as "create," "generate," "improve," "enhance," etc. are heavily used and introduce improvements. In contrast, verbs such as "deteriorate," "destroy," or conjonctions like "because", etc. induce problems. This also applies to nouns of change.

We noticed in addition to the previously mentioned regularities, some formulations such as "the present invention/process/apparatus" were carriers of partial solutions. As for problems, we have expressions such as "it is known that...", "resulting in...."

The study of sentence connectors such as "however," "so as to," "thus," "in order to," etc. reveals that they are used to ensure textual coherence and can be very productive in terms of relevant concepts to IDM, when they are used in the same context with nominal or verbal markers. Ghiglione et al. (1995) defines the connectors as formal marks for ensuring intersentence cohesion and textual coherence. Thus, connectors such as "however," "conversely" introduce contrast, while those such as "thus" and "as a result" express the result.

All these features of patent text allow the better identification of textual representations of the entity sought.

From this study, a set of linguistic markers were found interesting to find IDM knowledge.

Examples are the following:

- *Partial solutions*:
  - Nouns: *amelioration, enhancement, improvement, detection, etc.*
  - Verbs: *ameliorate, detect, enhance, etc.*
- *Problems*:
  - Nouns: *failure, flaw, imperfection, instability, limitation, etc.*
  - Verbs: *blemish, break, bug, complicate, crack, damage, deflect, etc.*
- *Parameters*:
  - Nouns: *noise, cost, effect, loss, stability, etc.*
  - Verbs: *cause, increase, decrease, avoid, control, detect, effect, achieve, permit, etc.*
  - Adverbs: *significantly, slightly, highly, effectively, substantially, etc.*
- *Values*:
  - Adjectives: *rapid, torsional, significant, slight, large, small, excessive, etc.*
  - Verbs: *cause, achieve, permit, prevent, produce, require, request, restrain, etc.*
  - Adverbs: *significantly, slightly, highly, expensively, inexpensively, etc.*
  - Nouns expressing quantity, quality, or intensity: *accumulation, elevation, etc.*
  - Most nouns ending with "ity" or "ness": *deformity, density, diffusivity, slowness, etc.*
  - Units of measurements: *mm, °C, inch, %, etc.*
- *Elements*:
  - Terms expressing a relation between elements: *comprises, comprising, consisting of, includes, including, consisting, consists of, consisting essentially of, characterized by, containing, having, which consists of, which comprises, which contains, constituting, adapted to, configured to, etc.*

Note that for partial solutions and problem linguistic markers, an advanced analysis shows that they can be classified into two main categories, taking into account two criteria, i.e., the structural value and the semantic content of the marker. They are concepts related to words. The semantic content may be defined as the image that a word in isolation carries. As for the structural value, it is determined by the relationship that a word has with another word in the context (Guiraud 1969).

All these observations led us to determine the way patents express IDM knowledge. They were translated as lexical patterns presented in previous studies (Souili et al. 2011, 2013). On this basis, we built a set of 634 automata to process patent document and extract relevant information to IDM. These automata can be classified as follows:

- List automata which contain lists of markers.
- Tool automata, which are used to clean and structure the corpus, these can include list automata.
- Tagging automata, which are used to tag and break patent text into segment; these can also include list automata.

The next step in our methodology is to apply all these automata on patent corpora to obtain XML output for the problem graph visualization.

Thus, we have a first run of automata dedicated to clean and structured text. Then, we have the filtering of relevant section of the patent document.

Thirdly, we have the identification and tagging of problems and partial solutions. The fourth series of automata are used to identify and tag the parameters and values before they are output as XML (Fig. 2.3).

Figure 2.4 displays an example of text processed with automata. The result is a structured text that fits with the IDM knowledge model. This tagged output is then used to display the problem graph (Fig. 2.5).

2.5 Results and Discussion

The evaluation of results is necessary in information extraction, since it allows to measure the performance of the implemented system. This section proposes to evaluate results obtained over trainings and evaluations. The first part of this evaluation involves applying traditional performance measure techniques on results before discussing in detail the extractions in order to identify the limits of our extraction methods.

2.5.1 Precision and Recall

The performance measure used to assess performance is the calculation of precision and recall. The assessment of extraction results was done with the help on an expert

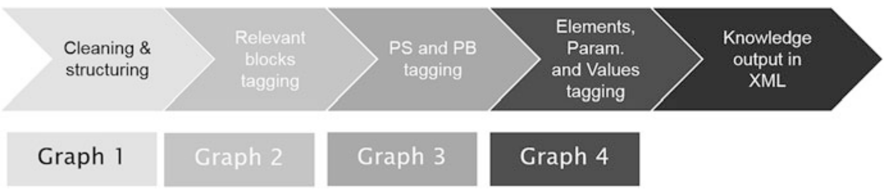


Fig. 2.3 Automata run in waterfall mode

[0001] CA 02838364 2013-12-31 = = = 23939-101 = SYNTHETIC BOTTLE AND PROCESS FOR MOLDING = THE SAME = This is a divisional application of application Ser. No. 2,688,582 filed May 30, 2008.
If the mixing amount is larger than 10 wt%, melting loss resistance of the nozzle will be deteriorated.
When the distance a is smaller than 3 cm, there is the danger that the metal will sink below the level 20, which would cause a disadvantageous oxidation of the metal.
TECHNICAL FIELD…………………………………………………………….

<seq>
If the <solupart> <param> **mixing** amount </param> is <val> **larger than 10 wt%** </val> </solupart> , <problem> <param> **melting loss** resistance </param> of the <elt>**nozzle** </elt> will be *deteriorated* </problem> .
</seq>
<seq>
When the <solupart> <param> distance </param> a is <val> **smaller than 3 cm** </val> </solupart>, *there is the danger that* the <problem> metal will sink below the <val> **level 20** </val> </problem> , <problem> which *would cause* a *disadvantageous oxidation* of the <elt>**metal** </elt></problem>.
</seq>

Fig. 2.4 Example of text processing and tagging

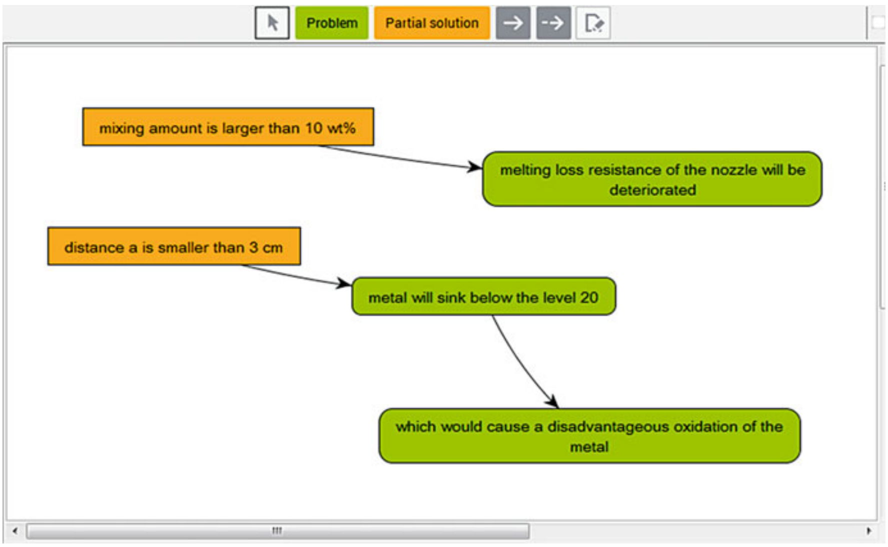


Fig. 2.5 Visualization as a problem graph

in the domain. The synthesis of their contributions allowed the evaluation of the recall and the precision of the extraction approach (Fig. 2.6).

The recall can be defined as the ratio between the number of relevant concepts retrieved automatically and those found manually.

$$\text{Recall} = \frac{\text{Number of relevant concepts automatically retrieved}}{\text{Number of relevant concepts found manually}}$$

As for precision, it is the ratio of the number of relevant concepts in all concepts automatically found and the total number of relevant concepts automatically retrieved. This ratio was calculated following the study of a sampling of the results obtained. These results were evaluated by experts. A ratio calculation of the relevant results on the total results obtained was then performed to obtain the precision grade.

$$\text{Precision} = \frac{\text{Number of relevant concepts in all concepts automatically found}}{\text{Total number of notions automatically retrieved}}$$

Tables 2.2 and 2.3 summarize the different results obtained on the corpora of study (Figs. 2.7, 2.8).

The preliminary analysis of these results shows that even if recall rates are low, precision rates are satisfactory. This situation is due in part to our decision to use strict algorithms in our approach. In addition, the use of linguistic resources leads to

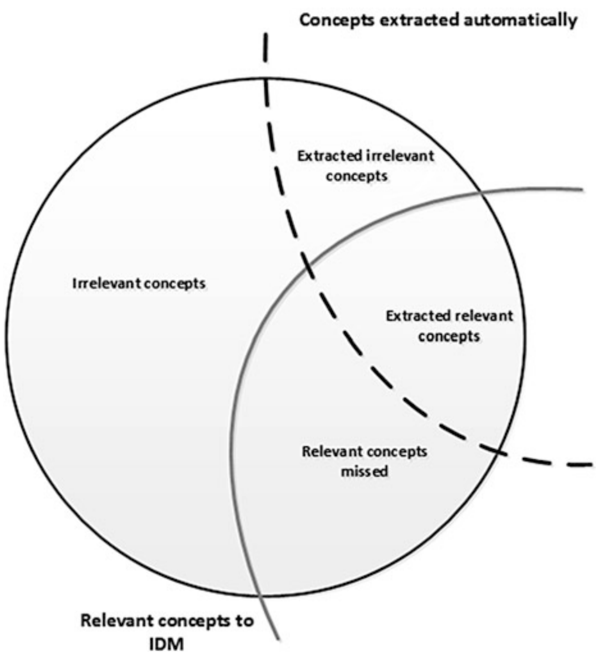


Fig. 2.6 Precision and recall

Table 2.2 *Corpus A* performance

	Recall (%)	Precision (%)
Partial solutions	32.10	73.30
Problems	40.29	87.13
Parameters	49.10	92.13

Table 2.3 *Corpus B* performance

	Recall (%)	Precision (%)
Partial solutions	44.22	73.53
Problems	46.10	86.10
Parameters	47.35	82.15

Fig. 2.7 Recall summary

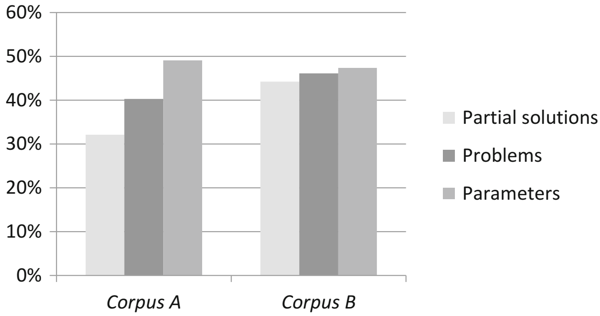
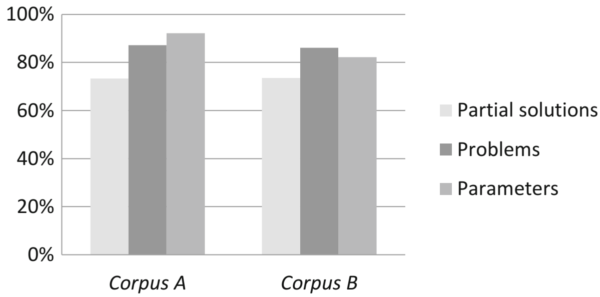


Fig. 2.8 Precision summary



better accuracy, but relatively low return rates. Indeed, the system is intended for conducting R&D activities in businesses. Therefore, it is crucial to avoid erroneous extractions.

However, beyond this traditional measure of results, we conducted a thorough analysis to identify the limits of the system. The following section presents our conclusions.

2.6 Discussions

Further analysis of extractions obtained throughout the study shows some limitations, including lack of completeness.

On one hand, low recall rates show that several relevant concepts were missed by the automata. Thus, the system is perfectible, and conducting more case studies could help us learn more about the patent text and improve the completeness of extraction algorithms.

On the other hand, precision rates are certainly satisfactory, but the further analysis of relevant extractions shows some limitations.

First of all, let us recall the IDM knowledge model according to which problems obey the syntax *Subject + Verb + Object*. As for partial solutions their syntax is *Infinitive + Object*.

Mainly five cases arise in analyzing extracted data:

First Case The extracted segment is longer or shorter than expected. Preliminary observations show that some long segments are in partial solutions in most of the cases. On the other hand, truncated segments are a problem. These situations lead to incomplete information for truncated extractions or the presence of irrelevant information for long extractions, for example, *and cannot move around in an individual drive slot in array*.

Second Case The extracted segment does not match the context of the study. Some extractions despite their relevancy deal with another issue and do not focus on the ongoing study.

Third Case The extracted segment does not respect the syntax of IDM. In this instance, extractions are relevant and focus on the ongoing study. However, they do not respect the standard syntax required by IDM knowledge model, for example, “the casting process is interrupted, thereby deteriorating the casting yield.” The previous sentence can be decomposed into two problems:

- A: “The casting process is interrupted.”
- B: “Deteriorating the casting yield.”

Problem B in this case, even if it is relevant according to IDM knowledge model, does not have the correct form. A proper formulation would be “The casting yield is deteriorated.”

Fourth Case Extracted segments include other unnecessary information. They are partially relevant. This situation is especially true for long extractions.

Fifth Case Extracted segments are partial or entire duplicates. The presence of duplicate impairs the quality of results. For example:

- *Alumina adheres and accumulates onto the surface of the bore of the continuous casting nozzle.*
- *Alumina tends to adhere and accumulate on the surface of the bore of the nozzle.*

In our research, we found that it was possible to optimize them by using, for example, Legallois' method (Legallois et al. 2011). This method is based on textual reduction and lexical repetition. It derives from Hoey's linguistic model (Hoey 1991). The method proposed by Dominique Legallois consists in identifying extracted segments that have at least three lexemes in common, for example, a verb, a noun, and an adjective. Then, it is possible to build sentence networks composed of similar sentences. The next step is to select the most relevant extraction for the representation of the problem graph. Another approach is from Yan (2014) and is based on semantic similarity measure. This may help to propose similar sentences to use when they reach a given threshold of similarity. All these approaches will help improve the general quality of the results obtained.

2.7 Conclusion and Perspectives

In this chapter, we first reviewed the existing literature in patent mining, specifically the contribution made so far on patent mining related to TRIZ. Then, we proposed our method to automate the retrieval of the IDM concept such as partial solutions, problems, and parameters. The premise of the method is to retrieve IDM concepts using generic linguistic markers. The challenge in this chapter is to contribute to the automation of knowledge extraction from patents to assist engineers in their innovation tasks during initial situation analysis stage of known problems and partial solution of an artifact or a method.

First, we set the conceptual framework of the research. Then, we presented the patent document and identified its major sections for the purpose of our research. The method we propose aims at automatically extracting relevant knowledge to feed the ontology of IDM. First results are satisfactory and lay down the basis for future research to benefit from the knowledge contained in patent documents.

Our extraction algorithms are still perfectible, and we need to conduct several other R&D case studies to improve them and assess their efficiency. The resources used for the extraction system were constituted following empirical observation of patent document. Then, it would be interesting to determine the final form of grammar rules automatically. A mathematical model would help to describe the level of complexity of the linguistic analysis of patent documents as well as the number of rules necessary to obtain better performance.

As a conclusion, it would be interesting to investigate other types of documents such as scientific reports or papers to benefit from other valuable sources of knowledge. Furthermore, a hybridization of the present method with machine learning is currently investigated to improve the performance of the model.

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Chapter 3
Modelling Industrial Design Contribution to Innovative Product or Service Design Process in a Highly Constrained Environment

Philippe Blanchard, Pascal Crubleau, Hervé Christofol, and Simon Richir

Abstract The purpose of this study is to build an *enhanced design* model applied to the conception of an innovative product in an SME environment. This approach includes C-K theory in the context of innovation.

In general, the industrial design process consists of four major steps:

- The *ego-design* phase, where the designer conceptualises a user need
- The *techno-design* phase, where the designer and engineer find solutions to materialise the concept
- The *eco-design* phase, where the social actors involved authorise it and then
- The *ergo-design* phase, where the user adopts the final product

A methodological reflection leads to the modelling of innovative *enhanced design* reasoning (where major actors are replaced by a bunch of various stakeholders).

The specific SME's case was successful. Using the model, the *enhanced design* project management was efficient. But some more complex application cases would help secure it. Using this approach, with appropriate information, should guide the SME design project manager in the general innovation process.

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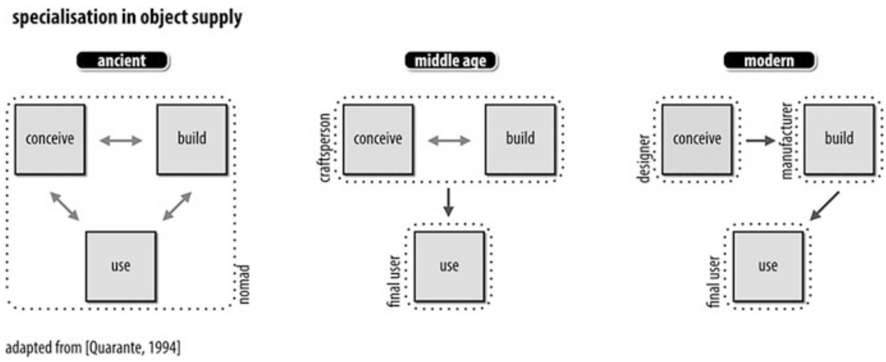

Fig. 3.1 Quarante's vision of the object/user relation

3.1 Introduction

One of the major advantages of man over the animal kingdom is his ability to imagine, make and use objects. In her influential book, Quarante (1994) studied the relation between an object and its user (see Fig. 3.1).

Consider a nomad in ancient times. He must conceive, build and use his everyday objects. If he tries a new constructive solution for a tent and it collapses, he would have to rebuild it using conventional means. Whereas, in the Middle Ages, techniques became more difficult to handle easily and craftspersons began to specialise in particular domains. Then if a *final user* wants an object, he should ask the appropriate craftsperson. This situation represents the first break between the final user and the object. The second break occurs in modern times. With the Industrial Revolution, objects are produced by a *manufacturer* instead of a craftsperson. But, frequently, the object's conception comes from a *designer*, which marks the second break between the final user and his object.

At first, the tool was the extension of the hand. Sometimes one could complain about the lack of performance of an existing artefact[1] for a desired task. Simon (1996) and Ulrich (2011) focused on that specific situation. They named the space between an ideal object and existing versions *gap*. Ulrich emphasises a *design phase* where the designer could imagine and *plan* a new device. Then, during the *production phase*, people built the new *artefact*. If that new proposition is not good enough, it will have to be reprocessed, possibly over several iterations, until the ideal is approached.

To be fully efficient, the design process should consider two different characteristics. First, in an industrialised civilisation, the *industrial design* approach is a good way to obtain impressive results. It could be suggested that product design is involved both in the *elegance* of the product itself and in the *elegance* of the methods used to achieve it. The second point deals with *innovation*. The final

[1]Artefact: human-made object (in opposition to a natural one).

response should be quite different from the original alternatives. Remember the *gap* between unsatisfactory real objects and the ideal one. Innovation can be likened to making improved products that were, at the beginning of the process, inconceivable.

The research question posed in this chapter deals with the methodology the designer could use in such a situation.

To limit the scope of the research area, the doctoral thesis presented in this chapter[2] was restricted to an SME[3] context. The core of the subject overlaps the areas of industrial design, innovation and SME. The design axis is related to the design process and the ability to create new knowledge. The innovation axis is dedicated to the result of that design process. The SME axis is representative of the design frame, the space where everything happens (especially as a resource provider).

As Günes (2011) mentioned, there is very little literature that combines design, innovation and SME contexts. The research goal was to provide an original design methodology for people concerned with innovative product development.

This chapter is structured as follows. In Sect. 3.2, the context of design is described through a presentation of the major stakeholders to help the reader understand the overall process and to help suggest some models. Sect. 3.3 consists of several tests of those models. Finally, Sect. 3.4 examines the impact of the validated model. Even if it will not be the main approach used, the TRIZ perspective will be discussed along those steps.

3.2 Process Modelling

To have a clear vision of the creative processes involved during the elaboration of new products through an industrial design approach, it has to be understood who are the key actors of that creative game and how they play together. In this section, it is shown how Quarante's proposition (see Fig. 3.1) could be extended by adding a fourth person. The section after that has a focus on the specific design process from various points of view. Finally, a bibliographic model of a generic design process is presented that has been extracted and built from the literature.

[2]Mark Irle (Ecole Supérieure du Bois) supervised its structure.

[3]SME: small and medium-sized enterprise.

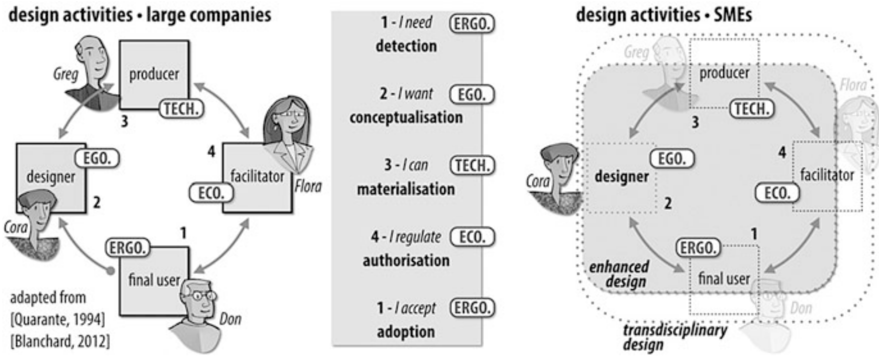

Fig. 3.2 Comparative design processes in two different contexts

3.2.1 *Design Playground*

The objective is to identify the different major stakeholders and how they interact. A good way to visualise this design playground is to use *personas*. Cooper (2004) introduced them in 1998. Thanks to their ability to quickly give an empathic and synthetic vision, their usage became very popular among creative consultants.

The general design process is extensively described in the doctoral thesis[4] and only a summary is given here (Blanchard 2015). At first, the design process in the context of a large company is presented (see Fig. 3.2).

From the *birth of industry* (1750–1850), the common user of manufactured products and the industrialist who made them can be identified. Consider Don[5] the final user and Greg the industry man. Greg's mission is to give Don products from his factory. These products are mainly characterised by both technical and technological approaches. It was decided to give them a "TECH" label. Don has just to buy them or not.

Later on, during the *Industrial Revolution* (1850–1900), Don became more and more demanding of Greg. He found the manufactured goods no longer matched his expectations (neither from an aesthetic point of view nor in terms of user-friendliness). As Greg was only specialised in manufacturing objects, he decided to rely on Cora, the design woman, to help him. She has to understand Don's needs, alter the design of the product and then give Greg instructions on how to make it.

In the next *modernism* sequence (1900–1970), the fourth persona mentioned earlier appears, Flora, who is a representative of the world of exchange, i.e. the "social" environment. The sequence now becomes: Greg asked Cora to work on a new product for Don. Cora is accustomed to finding the real harmony about

[4]Simon Richir (Arts and Métiers ParisTech) and Hervé Christofol (Angers University) were excellent research mentors.

[5]Thanks to Jean-Michel Charruault for the character sketches.

designing objects. She can give them usability, aesthetics and smart characteristics in order to produce them quickly and cheaply. Don should be pleased with that new purchase because Cora was also able to include specific criteria suited to fulfilling Don's ego. Consequently, Cora is given an "EGO" label. As soon as Greg has made all his products, Flora has to check them to make sure that they respect all the marketing, legal and moral requirements. Only after that can Greg make and Don buy these products. Consequently, Flora is a facilitator between these two.

In the next period of time, *post-modernism* (1970–2000), people, like Don, were bored with over-standardised products. They desired more fantasy and individuality. The emphasis is rather put on product experiences. Designers, like Cora, have to carefully study Don's latent needs about his lifestyle. Due to the ergonomic approach, the "ERGO" label is given to this step.

Today's era (2000–) could be named *responsibility* where sustainable development and ethics emerge. Objects should have a *storytelling* dimension. The brand image overlaps the product itself. People can vote for a company when they buy its products (Don adopts the new designed objects). The message is that they have a good opinion of it. Otherwise, a boycott expresses a company's wrong social behaviour. In order to summarise both the economy dimension and the ecology one, an "ECO" label can be given to this situation. Flora is now a key actor.

Today, the design processes in large companies can be viewed as having five phases involving the four different personas and their associated labels (see Fig. 3.2).

- The *detection* phase: Don needs a new artefact because the actual objects are ERGOnomically poor.
- The *conceptualisation* phase: Cora explores Don's latent needs in order to imagine a brand, a new type of object. She wants to give it some EGO characteristics.
- The *materialisation* phase: Greg can make that new product, using a lot of TECHnical features.
- The *authorisation* phase: In this step, Flora works on how to publicise these products. She has to regulate them through the ECO axis.
- The *adoption* phase: finally, Don's acceptance and purchase of the product is the last step of that circle. This phase is concerned with the ERGOnomics of the product.

This circle represents a typical design process. It shows roughly each step in chronological order, but, real product development is more erratic and the succession of phases is a lot more blurred than is drawn in Fig. 3.2. Many feedback loops and shortcuts can occur along the new product design process. Depending on the situation, some steps could be dominant and some others dramatically reduced.

To gain a broader view about design, Aarts and Marzano (2003) noticed that *design* is often expressed as:

$$\text{Design} = \text{Form} + \text{Context}$$

Form is relative to the EGO label, while *Context* is represented by the fusion of the TECH, ERGO and ECO labels. So, *Design* (or industrial design) is not only about the form of an object, as it should also include the overall context.

Returning to Fig. 3.2 in the context of large companies, Cora's mission is to understand Don's needs, and to satisfy Greg's production capabilities and Flora's distribution requirements. She could operate on all of the labels: ERGO, EGO, TECH and ECO. In a large company, there could be an identified person[6] who has training and skills specific to each phase to help Cora.

In an SME context, things are quite different, even if the overall design process stays roughly the same (again see Fig. 3.2). Due to limited resources, either human or financial, there might not be a fulltime specialist[7] for each domain to work with Cora. This is obviously a constrained environment. So, to maintain the same kind of creative results, the designer (Cora) should "extend" her skills in each domain. Such a new designer could be named an *enhanced designer* doing an *enhanced design* job. This means that the designer must take the project from a front-end perspective to a back-end one. In a large company, Cora could either work with Don, Greg or Flora. But in that specific constrained context, Cora could just, parsimoniously, have meetings with Greg. She has to imagine Don's needs and Flora's requirements. Cora should combine various specialties and skills. Due to the number of different domain areas, the entire playground could be described as a place where transdisciplinary design operates.

3.2.2 Design Process

When Cora is placed in an SME context, she must be an *enhanced designer* who has a very tricky situation to manage: doing alone what an entire team could do in a large company. So, the question posed in the Ph.D. thesis is "how to do that *enhanced design* job?" First of all, the design activity should propose something really new. Innovations could come as very appropriate solutions. According to Schön's (1983) vision, designers and architects should consider:

$$\text{Innovation} = \text{Result} + \text{Methodology}$$

It is clever to work both for the result itself and the methodology used to obtain it. In that way, one can improve one's process skills and learn from them. In many situations, the solution should fulfil the desired performance, going beyond those of

[6]Sometimes, more than just one person, it could be a whole team.

[7]Even sometimes, nobody is identified to work with the designer.

the existing objects. What kind of creative process should be used to find all those innovations?

Cross (2008) identified two categories of design models:

- Descriptive models: description of design activities sequences. The focus is on finding concepts early in the general process. It usually refers to past design situations.
- Prescriptive models: prescription of more adapted design sequences (algorithmic and systematic ones). The focus is on in-depth problem analysis to be sure to have an exhaustive vision of the context. Jones (1981) detailed a systematic approach (analysis > synthesis > evaluation). The sub-problem decomposition and abductive reasoning are used to realise future designs.

To begin the literature review of descriptive models, in his last book, Lubart (2013) cited the four-step Wallas model (1926):

- The *preparation* phase: After the demand brief, people need to understand its context to gather a lot of information from the field. Frequently, a reframing of the brief is useful. This phase corresponds to the ground preparation for a gardener. Everything is made in a conscious mode.
- The *incubation* phase: Here, the designer's brain, unconsciously, operates on many distant knowledge connections. For the gardener, it is the time when the seed is already sowed.
- The *illumination* phase: Some of the brain's associations could arise to consciousness. Most of the time, they are quite surprising and they can trigger a WOW effect.[8] It matches the germination time.
- The *verification* phase: for this last period, the main objective is to validate the newly proposed concept and develop it.[9] In the greenhouse, it is linked to the growing time.

With the same goal of understanding the design challenge, Beckman and Barry (2007) and Brown (2008) attempted to clarify it. Beckman imagined two axes (see Fig. 3.3).

The horizontal one runs from *analysis* to *synthesis*. That means that in a design process, at first, one should take into account the context of the problem to solve through an analytical posture. Otherwise, there is a possibility of solving the wrong problem or not going deep enough into the problem. Then, the objective is to produce some answers and synthesise them. The overall objective is to understand what to solve (problem setting, exploration) and to solve it (problem solving, exploitation).

To do this, people take real facts and situations, then imagine some mental transformations (through creativity) and finally go back to reality with tangible propositions. This describes the vertical axis, from *real* to *virtual*. The *design*

[8] Other authors alternatively used Wahou effect, WOW factor or Eureka.

[9] As Edison noticed: "Genius is one percent inspiration, ninety-nine percent perspiration".

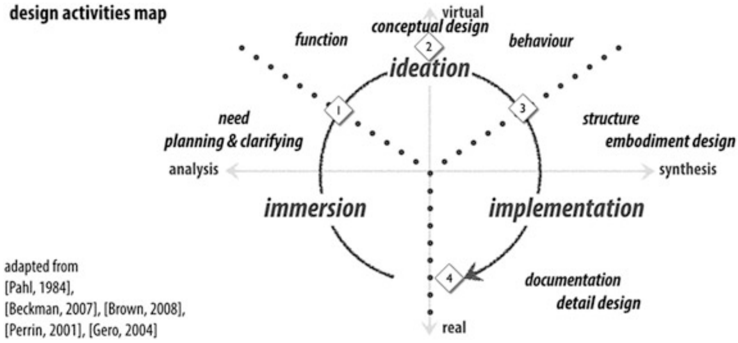

Fig. 3.3 Design process map

thinking process roughly traces a kind of circle from a *real* position, to an *analytical* one, to a *virtual* one and then be back again to the *real* position. The actual path is likely to be much more erratic than a perfect circle!

Brown did not divide this circle into quarters but into three. He called them:

- *Immersion*[10]*:* Framing the problem (test #1)[11] is for the validation of a vision (a reframed problem, a specification).
- *Ideation:* Finding concepts (test #2) and pre-projects (test #3) able to solve it.
- *Implementation:* Giving reality to the validated concept and its adoption (test #4).

Obviously, there are many situations where people can go directly from the beginning of the circle to the other end without even going to the virtual area. Be very careful about such an attitude! Even if it saves time, there is a great chance to solve either a wrong problem or to provide a wrong solution. The *5 Whys* technique[12] is a good approach for finding the underlying information that is not mentioned in the design brief.

Most of the time, a design brief is formulated with traces of a suggested solution in it. This should be avoided. For example, do not ask a designer to imagine a new *chair* but rather a new *way to sit down*. In doing so, products like the Sacco[13] or kind of swings could arise. The *functional analysis* method is built around this way of thinking.

Some prescriptive models followed. Years ago, Pahl and Beitz (1996) and Beitz[14] also focused on this creative process. They described four major phases of the design process (see Fig. 3.3):

[10]Originally, Brown uses *inspiration;* however, it is considered that *immersion* is more appropriate.

[11]In graphics, tests are represented by diamonds.

[12]Toyoda developed it within the Toyota Motor Corporation.

[13]The Sacco chair (designed by Gatti, Paolini and Teodoro) is filled with millions of polystyrene beads, very far from the common image of the chair.

[14]Following Hubka's and Eder's works on design science.

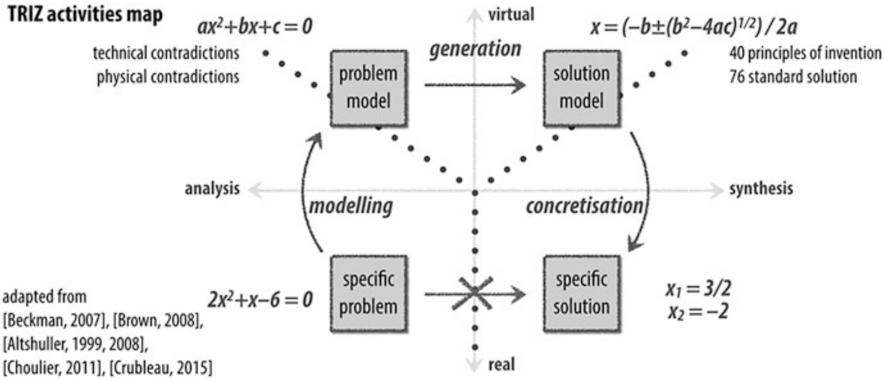

Fig. 3.4 The TRIZ process map

- The *planning and clarifying* phase: to analyse the problem and its context
- The *conceptual design* phase: to search for working principles
- The *embodiment design* phase: to develop and define the construction structure
- The *detail design* phase: to prepare production and operating documents

Perrin (2001) and Gero and Kannengiesser (2004) use another terminology (see again Fig. 3.3):

- a *documented* product
- has a *structure*
- that *behaves*
- in a way to fulfil *functions*
- that satisfies a *need*.

Altshuller (1999, 2008) introduced the TRIZ approach in order to systemise and make the design process more efficient. Among many authors, Choulier (2011) and Crubleau (2015) explored its characteristics in Fig. 3.4.

Quite often there is a mental wall in front of a problem which blocks the path to a solution. Or, maybe, one has to follow a definite process to solve it. Think about mathematical equations. As a *specific problem*, consider $2x^2 + x - 6 = 0$. It is difficult for common people to find, mentally, the *specific solution*. First, you have to find a model for the problem. Here, the *problem model* is $ax^2 + bx + c = 0$. Mathematical science gives us (generates) the answer through a *solution model*:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

This generic solution is still in the virtual zone, but moves to the synthesis side of the map. The final operation leads to the substitution of the variables by the current values. This is when the concretisation phase, on the real side of the map, is reached where the two *specific solutions* are:

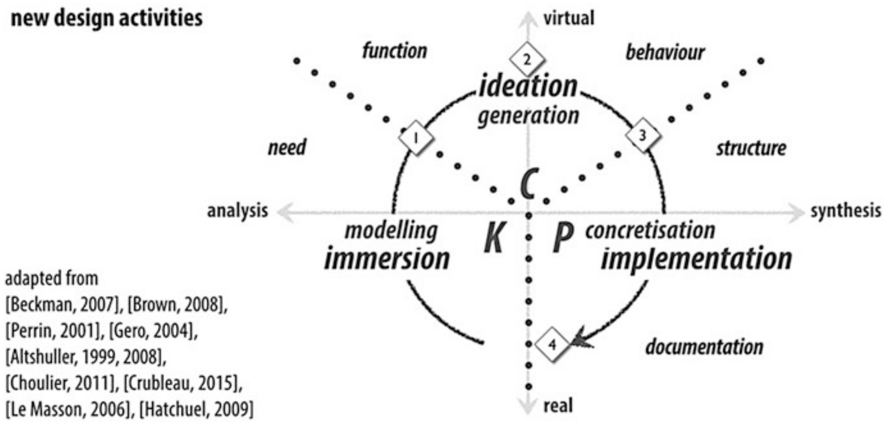

Fig. 3.5 New design process map

$$x_1 = 3/2 \text{ and } x_2 = -2$$

As detailed above, the design process maps three parts: *immersion*, *ideation* and *implementation* that make up the main process circle (see Fig. 3.3). Here, with TRIZ, there are, once again, three major steps:

- The *modelling* phase, from a specific problem to a problem model
- The *generation* phase, from that problem model to a solution model
- The *concretisation* phase, from that solution model to the desired specific solutions

TRIZ can help the designer avoid mental walls. It is very well suited for giving disruptive innovations. The three steps imply a systematic process. First, find the abstraction of the given problem. In the second, with the help of the innovation principles, the functional and contradiction analysis, the separation principles, the anticipatory failure identification and the prediction of technical developments convert the problem model into a solution model. Finally, in the third step, the solution model is transformed into an object or service for use in the real world. Now, these three items can be added to Fig. 3.3 (see Fig. 3.5).

Most design process methodologies deal with creativity and incremental innovations. Whereas for disruptive innovation, one can use TRIZ or another approach that is especially good at this, which is the C-K theory and its newest version (the KCP process). Hatchuel et al.[15] (2009) presented a two-column diagram. The right column "**K**" stands for the *knowledge* space where all the propositions have a logical status (true or false). The left column "**C**" describes the space of *concepts*,

[15]Benoît Weil and Pascal Le Masson are other contributors to that core research team.

design processes phases

DIO: design intermediary object

adapted from [Pahl, 1984], [Brown, 2008], [Perrin, 2001], [Gero, 2004], [Altshuller, 2008], [Choulier, 2011], [Crubleau, 2015], [Le Masson, 2006], [Hatchuel, 2009], [Vinck, 1995]

name	Pahl & Beitz	Perrin/Gero	Design Thinking	TRIZ	C-K Theory
1st phase NOW	planning & clarifying	need	immersion	modelling	K (knowledge)
DIO	design specification	mental prototype	"insight"	problem statement	C_0 (disjunction)
2nd phase WOW	conceptual design	function behaviour	ideation	generation	C (concepts)
DIO	solution principle	"object"	validated concept	analogous solution	conjunction
3rd phase HOW	embodiment design detail design	structure documentation	implementation	concretisation	P (propositions)

Fig. 3.6 Design process timeline

propositions with no logical status in "**K**." Finally, the "**P**" stands for *propositions*, how to set up a specific design strategy.

These three aspects can easily be placed in the new design map (see Fig. 3.5):

- ***K*** phase: When confronted with a problem, people have to gather information into a knowledge base (like the *immersion* phase).
- ***C*** phase: Then, with the crucial role of the C_0 (the root concept, consequence of a *disjunction* between **K** and **C**), people have to expand concepts (always **K** related). The main goal is to transform the C_0 with the addition or subtraction of many attributes. As soon as a new C_x that seems to have a logical status emerges, then there is a *conjunction* (and C_x moves to the **K** space). This is very similar to the *ideation* phase.
- ***P*** phase: Like in the *implementation* phase, people have to build and manage a design strategy.

So, a lot of different methodologies could be used for solving a design problem. Cora has many possibilities to act as a designer. Quite surprisingly, almost all methodologies have three steps in common. Figure 3.6 compares the phasing of five of the most frequent design methodologies.

Vinck and Jeantet (1995) identified the concept of design intermediary object (DIO). During design elaboration, people use DIOs like metaphors, analogies, sketches, drawings, prototypes, and so on. Some of the DIOs could have a landmark status between two following phases. In Fig. 3.6, these are referred to as crucial milestones.

Anyway, with very little reorganisation of Fig. 3.6, a three-period progression for each methodology can easily be seen.

- The first phase (NOW): The main objective is to have the best possible view, frame, of the context of the problem. Often, the brief is not functional enough to be sure to define the real problem to solve. The "NOW" expresses the actual situation, before the creative activity.

triads of subject matters in design

Emmanuel Kant	judgement	reason	moral
David Pye (1978)	the beautiful	the efficient	the useful
Bruce Archer (1979)	products	process	people
Nigel Cross (2001)	phenomenology	praxiology	epistemology
Alain Findeli (2008)	aesthetics	logic	ethics
Wolfgang Jonas (2011)	forms	processes	knowledges

[Jonas, 2011]

Fig. 3.7 Triads of subject matters in design

- The second phase (WOW): when everything is set up (the real problem and its context), there are many unconscious creative associations running. From time to time, some of them could emerge in the consciousness with a WOW effect. Even with this illumination of a mental prototype, it will probably still require work to improve it.
- The third phase (HOW): a virtually validated concept must then be created. The "HOW to make it real?" requires prototypes and tests.

Once again, the process is not so linear. There are a lot of side paths. For example, Ries (2011) on his *Lean startup* approach insists on the MVP[16] concept. How to test as early as possible new products even if they are still roughly designed and prototyped in order to persevere with the idea or pivot towards a new vision.

Surprisingly, the comparison table in Fig. 3.6 shows how often design methodologies can be divided into three common steps. Are there any other examples of this kind of sequencing? Jonas (2011) worked on that specific case. He identified numerous triads in the field of design (see Figs. 3.7 and 3.8).

In a first attempt (see Fig. 3.7), Jonas compared different occurrences of triads around design matters. Most of them are amazingly very close even from a large variety of times and authors.

In the second table (see Fig. 3.8), he focuses on various models of design processes. Again, there are a lot of analogies among them. The three-step progression seems to be quite universal: explore the field, experiment and then exploit it. Likewise, the suggested three-phase mapping in Fig. 3.5 is very coherent with Fig. 3.8.

Now that the design playground (with four actors and four labels) and the general design process (in three phases) have been described, a generic design process model can be extracted from the literature. This model could help structure the way in which to conduct a smart industrial design activity.

[16]MVP: minimum viable product.

triads of generic models of the designerly research process

J. Chris Jones (1970)	divergence	transformation	convergence
Bruce Archer (1981)	science	design	arts
Simon / Weick (1969)	intelligence	design	choice
Wolfgang Jonas (2007)	analysis	projection	synthesis
Tim Brown (2009)	inspiration	ideation	implementation
transdisciplinarity	system knowledge	target knowledge	transformation knowledge

[Chow & Jonas, 2008-2010], [Jonas, 2011]

Fig. 3.8 Triads of generic models of the designerly research process

3.2.3 Literature Model

Almost every author, in the design process theory field, uses specific diagrams to synthesise and illustrate their work. To make it quite simple to understand, Choulier (2008) suggests a graphic combination of the major ones. With some additional items, a generic literature design model (conventionally named "model #1") is presented in Fig. 3.9.

The traditional backbone of design methodology is contained within it. For example, the five steps demonstrated by Perrin (2001) are:

- 1—Needs: What is Don's request?
- 2—Functions: Which operations could fulfil his needs?
- 3—Structure: How a product architecture could enable these functions?
- 4—Behaviour: What product performance?
- 5—Definition: How can the product be made?

Design model #1 runs as follows:

Based on Greg's quest to satisfy Don's wishes, Cora has to develop a smart vision of the situation. In the first period (needs or immersion time), she gathers a lot of information from the field, the context of the demand. At this point, she lists all the perceived constraints. By reframing it, Cora is setting the real problem.[17]

In the next step (functions or the ideation's start), Cora searches for some first ideas. Thanks to the previous immersion in the field and some analogies, she uses *mental prototypes* in her thinking process. These "lightbulb" propositions are still roughly defined, functionally described and need to be further worked.

The third period (structure) helps Cora to refine the future product further. She has to compare (diagnose) the design construction with the original need. How does the new proposition fill the gap between the desired object and current design? She has to test it. If the later proposition matches, she has achieved her design goal, and

[17]Sometimes, very different from the initial demand.

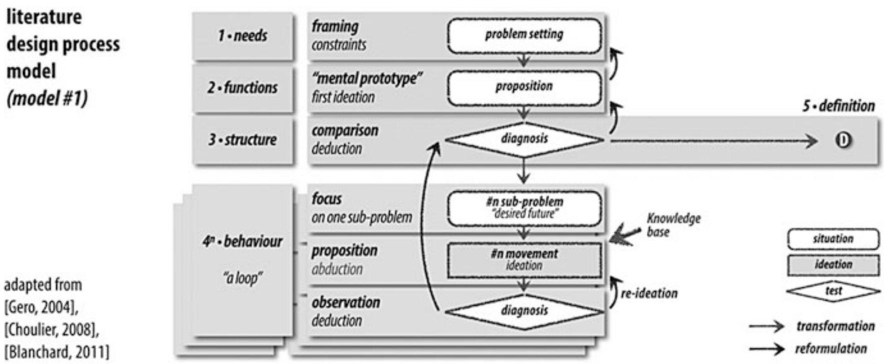

Fig. 3.9 Literature design model

the last activity (definition) should consist of precisely describing the newly imagined object. This happens very rarely. If the new product is far from fulfilling what it is supposed to do, Cora has to refine it with many iterations. She could start by analysing the actual proposition (the mental prototype), then enumerate and arrange all the dissatisfactions. These could be considered as sub-problems.

The fourth period[18] (behaviour or part of the ideation), which is an iterative loop, attempts to solve one by one all the previous dysfunctions. This period is itself internally composed of a three-step process:

- The focus is placed on the chosen major sub-problem.
- Then, with a great use of abduction reasoning and information taken from the knowledge base, Cora could ideate some new propositions.
- Finally, Cora has to diagnose (tests) the performance of that new idea once again. If it did not work well, then she has to repeat the proposition step until a smart solution arises. If a better smart solution does not appear, then Cora would have to imagine a new structure (third step).

If the sub-problem solution is validated, then she has to go in that same third step process with another sub-problem to solve. That iterative loop should be processed again and again until all the dissatisfactions are solved.

The fifth step (definition) occurs when all sub-problems have been resolved. Then Cora can document the final designed object.

Returning to the research questions of this chapter, is there any kind of similar loop categories, and, if so, how many are there? How a new design process model can be proposed? One way to go further in that direction is to test model #1 with real design cases.

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[18]The Perrin's steps are ordered as needs > functions > structure > behaviour > definition. It is posed that all dysfunctions have to validate a behaviour to confirm a structure.

3.3 Model Experiments

3.3.1 Toward an Experimental Design Model

Figure 3.10 contains 12 different design cases performed in a constrained environment. These will be used to identify the different design loops involved in the realisation of the final products.

Each example represents a real-life product or service requirement that has been used by the industrial partners involved. The authors contributed significantly to all of these design cases and so have first-hand experience of the contexts, the methodologies, the dead ends and eventual successes of each case. The knowledge and experience gained during these cases have been used to isolate the design loops within them. Figure 3.11 shows that nine distinct loop types (categories) were present and some were used twice (indicated by "**VV**") within the same design project.

The relative importance of a loop category can be induced from its frequency. Figure 3.11 orders the design loops by the number of times they have been used in the example projects. In addition, each column has been attributed with one of the four labels described above (Sect. 2.1 and Fig. 3.2).

What is not clear from the research literature design model (model #1 shown in Fig. 3.9) is how many loops are necessary and what type of loops are needed. Deduced from Fig. 3.11 table, Fig. 3.12 proposes a new design model (model #2) that has four poles (instead of loops), one for each design aspect, i.e. EGO., TECH., ECO., and ERGO.

In both Figs. 3.9 and 3.12, the focus is on the design thinking process for a generic situation. Figure 3.12 has been conceived in order to present a rounded square showing the previous four label directions (with their associated charac-

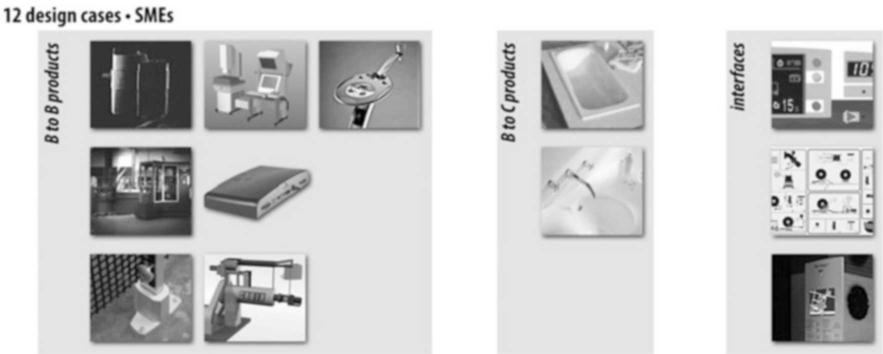

Fig. 3.10 Design cases

sub-problem category occurence • SMEs

design case	architecture	ergonomics	sensory	production	logistics	constraints	graphism	opportunity	marketing
Coyard	V		V	V					
Paulstra	V	V						V	
Tissmétal	V	V	V						
Delta Tech.	VV	V							
Axode			V	VV					
Croix	V	V	V						
Physiolab	V	V				V			
Néomediam	V	V				V			
Jacob Delafon	V		V						V
Hydrostop		V	V	V					
Perrot				V	V		V		
Ville d'Angers					VV		V		
total	9	7	6	5	3	2	2	1	1
	TECH.	ERGO.	EGO.	TECH.	ECO.	TECH.	EGO.	ECO.	ECO.

[Blanchard, 2014]

Fig. 3.11 Sub-problem category occurrence

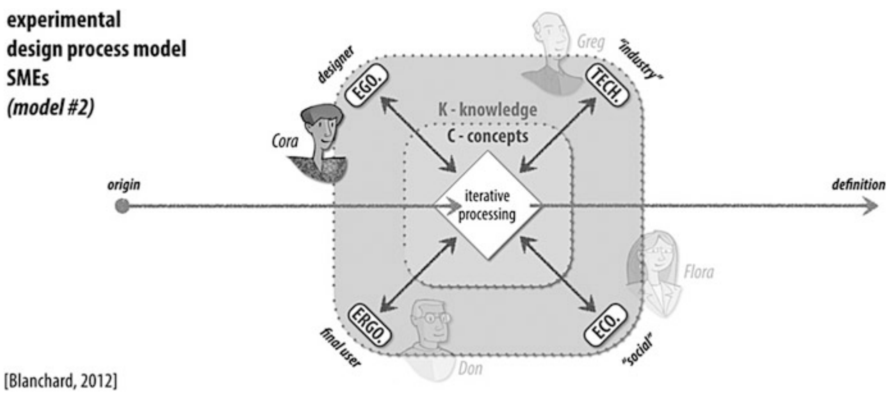

Fig. 3.12 A new model to test

ters[19]) that is easy to understand; the iterative loops have been removed. More precisely, there are three concentric rounded squares. The smaller (in white) represents the diagnosis table[20] where a proposition's performances are tested and the dissatisfactions are listed. The other round squares are a transformation of the classic C-K Theory diagram featuring the **C** space inside and the **K** space outside.

This new model (model #2) is tested with a real active design situation in the next section.

[19]In an SME context, due to constrained environment, some characters are shadowed to show the specific enhanced design situation.

[20]As in step 3 of the previous model (model #1 in Fig. 3.9).

Fig. 3.13 The urban lighting context

3.3.2 The Uniklic Design Case

A possibility arose to work with TMC Innovation on an urban lighting project (see Fig. 3.13). This company is an SME specialised in urban lighting and so it provided the opportunity to experiment the design model (model #2) described in Fig. 3.12.

The design problem was how to fix an LED strip to an existing lighting pole. A typical urban lamp consumes 100 W/h, which is quite a lot. Many cities have decided to turn off the city lighting during a part of the night to reduce public expenditure. Although it is undeniable that electricity costs are reduced, it also has an impact on citizen safety. An alternative possibility is, instead of lighting the whole road, providing enough light for pedestrians on the pavement. An LED strip that needs only 3 W/h would provide sufficient light.

TMC Innovation designed and built such a system as an option for new light poles. Each time a client orders a series of new poles, he can add that system, which would be directly installed at the factory during the production process.

The system was so appreciated by city representatives that they asked TMC Innovation to provide them with a system that could be retro-fitted to existing poles. This represents quite a big challenge for the design team. The solution they came up with is called Uniklic.

A design team was set up using people from within and outside the company. A three-step progression was scheduled:

1. During the immersion period, a large range of lighting solutions were investigated.
2. Then in the ideation period, a value analysis methodology was deployed. C-K theory diagrams helped identify three different solutions. When working on the last one, a *lightbulb* moment occurred. All that was methodically deployed in the third solution already existed in a very common product (but in a totally different environment). A fourth proposition was designed around that analogy and was prototyped and tested several times. The Uniklic product was developed, patented and won a design label (see Fig. 3.14).

Fig. 3.14 The Uniklic LED ring

3. The third period (implementation) is on-going and includes finding new uses and applications for the Uniklic solution.

   This Uniklic global design progression is very close to a TRIZ time approach:

1. In the first period, the context is explored with empathy and the aim is to frame the problem with fresh new directions. The DIO[21] of that time is functionally described. A problem model or a metaphor helps to illustrate it.
2. During the second period, both value analysis and C-K theory were used. The functional analysis gave a systematic view of the problem space, while the C-K diagrams helped draw the mind paths.
3. In the third session, most of the major innovations had already been made. This step is concerned with the development and industrialisation of an idea, i.e. going from an idealised concept to a tangible product. The overall design progression is drawn in Fig. 3.15.

It would appear that the experimental model (model #2 shown in Fig. 3.12) was used for each of these three periods. The path inside each diagram gives an idea of the way the project evolved and provides a kind of "fingerprint" for the project.

3.4 Benefits

The experimental model (model #2) has been helpful in the field[22] and induced the validated model (model #3). Some other SME's design projects (Dejoie, Sofame) helped further test model #2. Each attempt was successful.

[21]DIO: design intermediary object (see Fig. 3.6).

[22]Through the Uniklic design experiment.

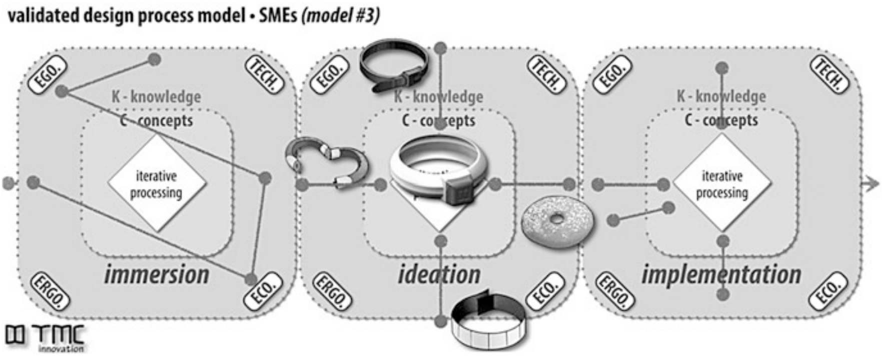

Fig. 3.15 Model #3 coming from the Uniklic design case

In addition to industrial cases, to assure an intuitive ergonomics, the model has been given to design and innovation students (EDNA[23] and ESB[24]). They are future users of that design tool and an easy population to observe. Again, the model's fundamentals were confirmed.

Figure 3.16 shows model #4 which synthesises the steps taken for each design case, i.e. model #3 shown in Fig. 3.14 applied for each case.

Here, the three independent diagrams (model #3) are placed on two axes. It seems that it is better to return to a circular graph instead of a linear one. Projects should always end with elements that can be used in other studies. Each C-K diagram is included in the three design thinking phases, because even if each of these phases has a specific role, the C-K approach combined with the given labels is very efficient. Each label direction should be investigated in each phase. So, the four labels have a double status, the common one in our basic C-K diagram and a meta-status in the circle representation.

To follow the aim to make an innovative design tool, the last figure (Fig. 3.16) can be filled with some different techniques used in each phase. The later model is convenient for the different phase planning. It constitutes a usable way to explain specific design processes to the whole team. It shows opportunities and minimises the risk of forgetting labels. The graphic representation used is a quick way for easy communication. Major abductive mindsets as well as unexpected feedbacks could appear. The model is easy to teach to new design actors.

This final model still has some limitations:

- It has not been tested in a large company.
- The Uniklic experiment was conducted by the authors who also designed this model. Would it work as well for anyone?

[23]EDNA: L'Ecole de design Nantes Atlantique (Nantes, France).

[24]ESB: l'Ecole Supérieure du Bois (Nantes, France).

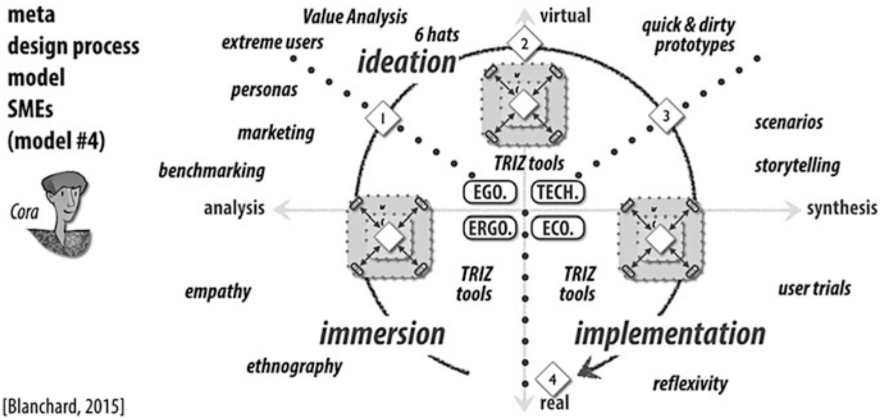

Fig. 3.16 A synopsis model

- It is not known if it is possible to extend the product design model to software design and service design projects.

During this Ph.D. research, emphasis was on *enhanced design*, but is there also an *enhanced research* activity?

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Chapter 4
Teaching Competence for Organising Problem-Centred Teaching-Learning Process

Renata Jonina, David Oget, and Jacques Audran

Abstract Problem-centred education (PCE) is a teaching-learning process which includes meta-subject tools as part of its content. The given tools, which find their origin in OTSM-TRIZ theories, allow to structure and reorganise information with the aim of identifying, analysing and solving problems in various domains. In the framework of PCE, students develop not only their subject-matter skills (language, maths, etc.) but also their problem-solving competence or inventive thinking skills. While research has shown that PCE has had a positive impact on learners, the empirical experience of helping regular school teachers learn to organise problem-centred teaching-learning process showed that while some teachers succeeded in introducing some changes in their classrooms, the majority of them failed to do so. This situation has brought to the foreground the problem of teaching competence required from a teacher for organising problem-centred teaching-learning process. This chapter will define PCE, highlighting the features which make it distinct from the existing problem-based and teaching for thinking approaches and will present the first results of the study on teaching competence required for organising problem-centred teaching-learning process.

4.1 Defining Problem-Centred Education

4.1.1 Educational Context and Problem-Centred Education

The need to develop students' higher-order thinking skills and problem-solving competence in the framework of school education has already been highlighted since the middle of the twentieth century. Nowadays, the requirement has shifted to the foreground of educational agenda due to the radical changes the world has been going through on its way from an industrial society to an information society (Lyotard 1984; Paul and Foray 2002), imposing on a person the demand to 'have

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a stock of information-processing skills, including literacy, numeracy and problem solving, and "generic" skills, such as interpersonal communication, self-management, and the ability to learn [. . .]' (OECD 2013a, p. 46). At the same time, the recent international research results highlight that neither modern students achive the desired results in terms of literacies and problem-solving abilities for successful functioning in a knowledge society (OECD 2013b, 2014), nor teachers seem to have relevant teaching competence for organising the teaching-learning process that would meet the needs of modern schools (Izglītības Attīstības Centrs 2008; Leat 1999; OECD 2005; Sawyer 2006; Sternberg and Martin 1988).

In the educational literature, the approaches and programmes which target the development of higher-order thinking skills and problem-solving competence are referred to as *approaches for teaching higher-order thinking* (Zohar 1999, 2004, 2008; Zohar and Schwartzer 2005), *approaches for teaching thinking skills* (Adey 1999; Adey and Shayer 1993, 1994; Avargil et al. 2012; Johnson and Siegel 2010; McGregor 2007; McGuiness 1999; Moseley et al. 2005), *inquiry-based instruction* (Baumfield 2006; Baumfield et al. 2005; Dostál 2015; Lehrer et al. 2008; Windschitl 2003), *problem-based educational approaches* (Barrows 1996; Barrows and Tamblyn 1980; Матюшкин 1972; Махмутов 1977; Мельникова 2002), *cognitive-activation instruction* (Echazarra et al. 2016, p. 35), *teaching for understanding* (Fennema and Romberg 1999; Perkins 1993, 1998; Perkins and Blythe 1994; Wiskey 1997) and the like. I apply the umbrella term 'teaching for thinking approaches' to refer to this family of approaches, programmes and methodologies. Having different theoretical backgrounds and being different in their specific focus, all teaching for thinking approaches rely on constructive or socio-constructive theory of learning, making students active participants of the teaching-learning process and involving them in constructing their understanding rather than practising rote memorisation and recall of information. In addition, all of them promote relevant thinking dispositions (e.g. being persistent, thinking flexibly, adopting a questioning attitude), encourage the language of thinking (such as summarise, estimate, conclude, imply) which allows associating thinking words with their relevant cognitive processes, develop meta-cognition and teach transferring of knowledge, skills, dispositions and strategies to students' everyday lives (Burke and Williams 2008). Moreover, all these approaches target to develop students' conceptual understanding of phenomena under study in the framework of the subject-matter teaching (be it science, math, languages or any other school subject). Hence, they blend subject-matter content instruction with explicit instruction about thinking skills and processes and are often called *infusion approaches* (McGuiness 1999; Moseley et al. 2005).

Despite a lot of positive features which characterise teaching for thinking approaches, none of them rely on any problem-solving theory that would serve as the basis for developing students' problem-solving competence (Sokol 2007; Sokol et al. 2008, p. 34, 2013a, b). The problem-centred education, on the other hand, relies on the General Theory of Powerful Thinking (OTSM) and the Theory of

Inventive Problem Solving (TRIZ)[1] (Altshuller 1984, 1986; Хоменко 1993, 2008; Хоменко and Аштиани 2007) and offers to integrate domain-dependent tools into the teaching-learning process (which in educational context I refer to as meta-subject tools) for managing information in the process of problem solving. The given domain-independent tools uncover the cognitive process which leads to solving a problem as it is viewed in OTSM-TRIZ. In the framework of PCE, these domain-independent tools are the ENV model, advanced ENV model (or the multiscreen model) and a set of ARIZ tools, such as for the analysis of the problem situation through identifying conflicting pair, contradiction, ideal final result and resources.

Therefore, on one hand, the problem-centred education can be considered to be a part of the teaching for thinking family since it shares its core features: the view on socio-constructive nature of learning, the content of education as a blend of subject-matter content and explicit thinking instruction, development of meta-cognition and promotion of relevant thinking dispositions. On the other hand, relying on the OTSM-TRIZ problem solving theories, the problem-centred education adds a new content into the teaching-learning process, namely, OTSM-TRIZ models and technologies, thus targeting the development of additional cognitive skills and dispositions, which in the framework of the problem-centred education are referred to as *inventive thinking skills and dispositions* or *problem solving competence* (Sokol 2007; Sokol et al. 2013a, b). Therefore, it would be legitimate to say that teaching competence for organising problem-centred teaching-learning processes can also be referred to as teaching competence for organising teaching-learning processes aimed at the development of students' inventive thinking skills and dispositions in the framework of the subject-matter instruction (see Fig. 4.1). In addition, it is important to highlight that even though thinking strategies are part of the content of the problem-centred education, these are not taught to students as it may be the case in different teaching for thinking approaches, but students are rather involved in building strategies through a series of problem tasks. As a result, students develop skills in building strategies and models rather than merely acquiring them.

Problem solving competence or **inventive thinking skills**: 'an ability and disposition to solve linguistic, sociolinguistic, pragmatic and other kinds of problems when no typical solution is available' (Sokol 2007, p. 56) and avoiding a large number of trials and errors (Sokol 2007, p. 46).

[1]From Russian *Общая теория сильного мышления (ОТСМ), Теория решения изобретательсктх задач (ТРИЗ)*

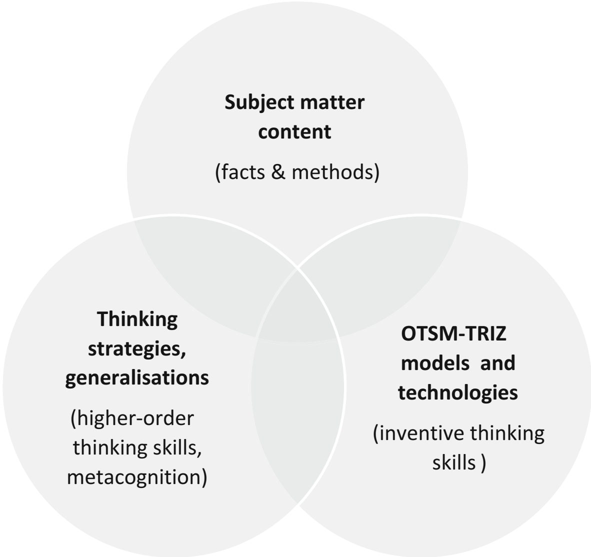

Fig. 4.1 The main content components of problem-centred education: general view

4.1.2 *TRIZ-Based Educational Movements and Problem-Centred Education*

Problem-centred education is an umbrella term and is also referred to as OTSM-TRIZ pedagogy (Терехова and Нестеренко 2012). It includes complexes of pedagogical technologies based on the system of OTSM-TRIZ models and technologies which I refer to as domain-independent tools or meta-subject tools. Currently, it includes three developed pedagogical technologies: (1) technologies for developing imagination, thinking and speech of pre-school children (Сидорчук 1998); (2) technologies of problem-centred education (Нестеренко 2006a); and (3) technologies of the thinking approach to language teaching and learning (Sokol 2007).

Problem-centred education should be distinguished from other so-called TRIZ-based educational movements.[2] Even though all of them set the priority of developing creative personality able to define and solve problems in different domains, and apply classical TRIZ, TRTL[3] and RTB[4] instruments as its theoretical basis, the content they offer to teach is different. If the classical TRIZ pedagogy keeps the classical TRIZ content as much as possible, then problem-centred education is

[2]For the comprehensive review of TRIZ-based educational movements, refer to (Терехова and Нестеренко 2012).

[3]TRTL, from Russian *Теория развития творческой личности*, Theory of the development of creative personality

[4]RTB, from Russian *Развитие творческого воображения*, Development of creative imagination

using the improved instruments of classical TRIZ and new OTSM instruments for working with interdisciplinary problems (Терехова and Нестеренко 2012, p. 40). Moreover, in the framework of problem-based education, the instruments are integrated in the subject-matter content. For instance, the thinking approach to language teaching and learning (Sokol 2007) offers technologies for developing inventive thinking skills while learning English as a foreign language.

Another aspect worth highlighting is the instruction or the organisation of the teaching-learning process as such which stands behind the content. Any content can be presented to students in the form of a lecture or a scattered set of tasks but fail to involve students in meaningful learning activity, which would eventually not lead to effective development of their problem solving competence. Problem-centred education relies on a socio-constructive view of learning (Vygotsky 1978; Леонтьев et al. 2005) and is based on the idea of a non-linear nature of learning and thus non-linear organisation of the teaching-learning process. This has certain implications on how the process of content acquisition is organised and may distinguish problem-centred education from other TRIZ-based educational movements.

Even though the line between TRIZ-based educational movements may seem blurred, the difference becomes much more apparent once the observation of the real teaching-learning process where students are involved in learning activities that lead to the development of their inventive thinking skills is made on a long-term basis.

4.1.3 Aims, Definition, Content and Instruction of Problem-Centred Education

4.1.3.1 Aims and Definition

The development of problem-centred education has been driven by the contradictions between a constantly increasing content of education which appears as a result of the general trend of the ever-increasing volume of information and speed at which it becomes outdated, of the reduced amount of time available for the acquisition of this content and of vagueness or even absence of information that students will need in the future.

Hence, the driving problem of education was formulated as follows: 'teachers must prepare students to the life that teachers know nothing about' (Мурашковска and Хоменко 2003, p. 32). The offered conceptual solution has been to move away from structuring educational content by division of content into subjects (see Fig. 4.2) to organising it through the study of a problem (Мурашковска 2004, p. 5) (see Fig. 4.3).

In other words, a problem should become a cornerstone, a pivotal component for the organisation of educational content and the central value in the system (Sokol 2007; Нестеренко 2006a, b, 2007), and the domain-independent models for

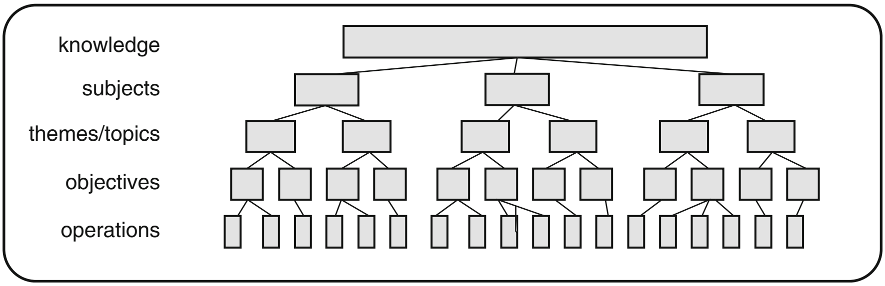

Fig. 4.2 Model of the structure of education content guided by division of content into subjects (Мурашковска 2004, p. 2)

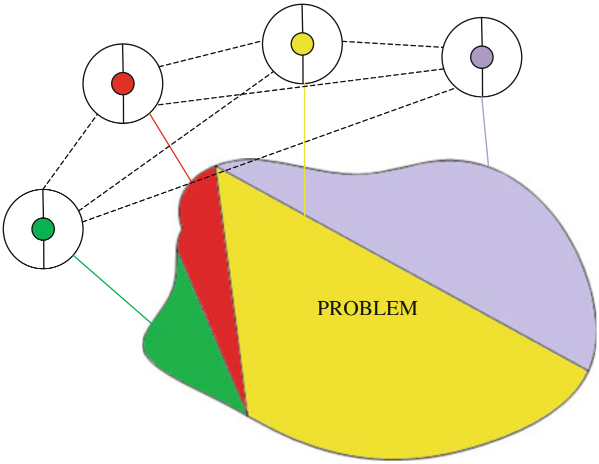

Fig. 4.3 Model of the structure of education content guided by the study of a problem (Мурашковска 2004, p. 8)

defining, analysing and solving problems should become its new structural content component (Нестеренко 2006a).

The aim of problem-centred education is then formulated as 'the development of a world view centred on a problem' (Sokol 2007, p. 43) and *problem-centred education is defined as* 'a teaching-learning process which includes meta-subject tools as part of its content; the given meta-subject tools allow to structure and reorganise information with the aim of identifying, analysing and solving problems in various domains' (Нестеренко 2006a, pp. 3, 13).

Problem-centred education has been explicitly aiming at helping learners develop skills which are necessary for coping with so-called non-typical (creative) problems in various domains, avoiding a large number of trials and errors (Sokol 2007; Sokol et al. 2008, p. 34), where a non-typical problem has been conceptualised as 'the one for which no solution exists or is not known to the

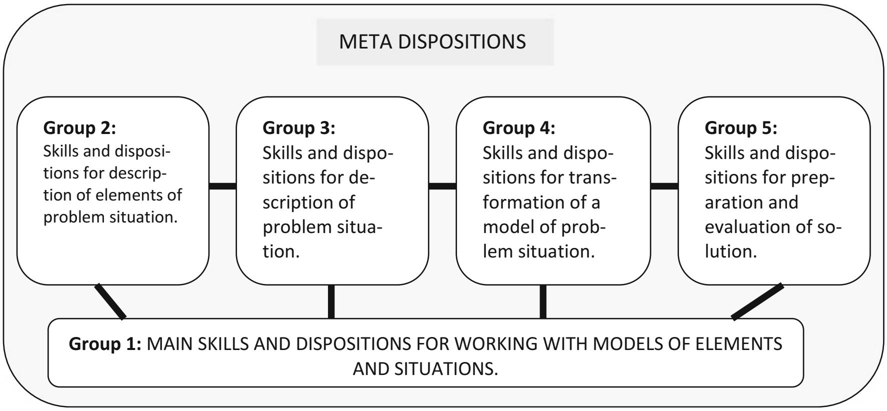

Fig. 4.4 Structure of inventive thinking (Sokol 2007, p. 46)

problem-solver' (Sokol et al. 2008, p. 34). The cognitive skills and dispositions which are targeted to be developed in the framework of the problem-centred teaching-learning process are referred to as inventive thinking skills (see Fig. 4.4).

Problem-centred education: 'a teaching-learning process which includes meta-subject tools as part of its content; the given meta-subject tools allow to structure and reorganise information with the aim of identifying, analysing and solving problems in various domains' (Нестеренко 2006a, b, pp. 3, 13)

4.1.3.2 Content

The content of problem-centred education contains three main structural components: (1) subject-matter or subject-specific information and (2) thinking strategies which form the building blocks of problem situations and (3) OTSM-TRIZ models and technologies referred to as domain-independent tools used to work with the subject-specific information, transforming problem situations into solutions (see Fig. 4.5).

The subject-matter content gets a new format. If subject-matter content is considered to have three structural components—(1) facts, which describe objects and processes; (2) strategies, which describe transformation of objects and processes, i.e. operations or algorithms of transformations; and (3) dispositions, which include beliefs, values and attitudes—then in the framework of PCE, students are working with the models of objects and processes and with the models of transformation and strategies.

A model is viewed as 'a system represented in mind or in a material world, which, being a representation or a reproduction of an object of the study, is able to substitute that object in such a way that the study of that representation/

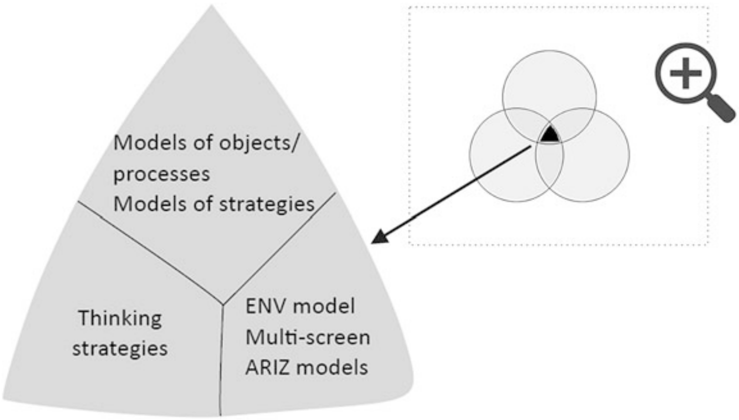

Fig. 4.5 The main content components of problem-centred education: specific view

reproduction allows us to discover new information about the object itself' (Штофф 1966, p. 19 in Нестеренко 2006a, p. 35). In other words, models are a schematic, rough representation of reality. They 'constitute a bridge between the observational and theoretical levels; and are concerned with simplification, reduction, concretization, experimentation, action, extension, globalization, theory formation and explanation' (Apostel 1961, p. 3 in Chorley and Haggett 2014, p. 24).

For example, instead of teaching students specific facts, such as specific historical events, they are offered a general model of a historical event which is described through a specific set of interconnected parameters. The next step is to build a model of any event which will further serve as a model for describing specific events, be it historical, economic, cultural or the like. The same holds true about procedures or methods for action. Instead of teaching students how to identify causes of a specific historical event, teachers can help students to build a more general model of how to identify causes of any fact, and this model will serve as a basis for various specific procedures (Нестеренко 2006a).

Building theoretical models allows efficient organisation and transformation of information in the process of problem solving. The developed models further serve as a basis for newly acquired information and as a result work on diminishing the amount of separate content components which traditionally have to be acquired in the subject-matter teaching-learning process. The focus of work shifts from finding a solution to building a strategy for developing solutions when dealing with a given type of tasks. However, the final result expected from students is not to learn all the developed strategies by heart but rather to learn HOW to build new strategies when students face a problem. In order to ensure the effective organisation of the above-defined teaching-learning process, students should be provided with meta-subject tools that would allow them to build specific models for specific learning contexts.

The meta-subject tools used in the framework of problem-centred education are the improved instruments of classical TRIZ and new OTSM instruments for working with interdisciplinary problems. These include the ENV model and the

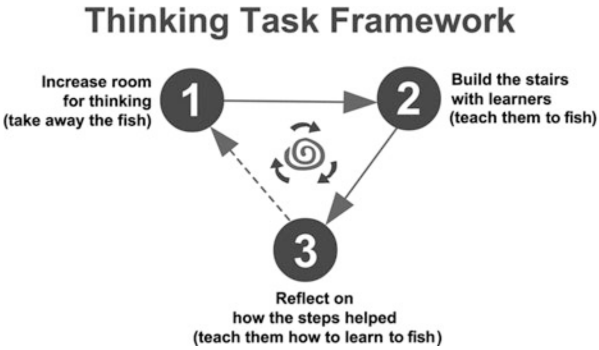

Fig. 4.6 The Thinking Task Framework (Sokol 2011; Sokol et al. 2013a, b)

advanced ENV model (or the full-scheme model), and a set of ARIZ models. Working with these meta-tools should lead to the development of the inventive thinking skills presented in Fig. 4.4.[5]

4.1.3.3 Instruction

PCE relies on findings from several psychological theories when it comes to building the teaching-learning process, the main ones being sociocultural theory of learning (Vygotsky 1978) and activity theory (Гальперин 2011; Леонтьев et al. 2005) including theory of developmental education (Давыдов 1996). Moreover, it takes into account an information-processing perspective on human cognition or schema theory (Anderson 1978, 1984) and various implications of cognitive approaches to learning (Adey et al. 2004; Anderson 2004; Bloom 1984; Emery and Wilks 1998; Ferretti et al. 2001; Higgins et al. 2004; Higgins and Baumfield 1998; Koufetta-Menicou and Scaife 2000; Krathwohl 2002; Li 2011; Naisbett 1997; Topping and Trickey 2007; Zohar and Schwartzer 2005), as well as implications of problem education (Кудрявцев 1991; Лернер 1982; Матюшкин 1972; Махмутов 1977; Мельникова 2002).

The main implications of these theories for problem-centred education are manifested in: (1) the instructional sequence, (2) method of teaching and (3) dialogic approach in teacher–student interaction.

Within the problem-centred teaching-learning process, the instruction is organised through the three steps represented in the Thinking Task Framework (Sokol 2011; Sokol et al. 2013a, b) (see Fig. 4.6).

In step one, 'increase room for thinking', students are given a problem task which causes a problem situation (Матюшкин 1972; Махмутов 1975; Мельникова 2002) or a cognitive conflict (Adey 1999; Adey and Shayer 1994) in students' minds. The second step invites a teacher to 'build the stairs with

[5]The detailed list of inventive thinking skills defined under each group presented in Fig. 4 can be found in Sokol (2007, Appendix 1.1).

learners', which can be interpreted as helping students build models with the help of meta-tools. This step involves applying psychological mechanisms of learning and managing the learning activity of students instead of merely letting them look for the solution following a trial-and-error method. In the psychological literature, the given process is referred to as scaffolding (Vygotsky 1978). It includes developing a system of sub-tasks which would keep challenging students cognitively and would involve students in learning activity leading to building a model or a strategy. This step also includes pursuing students' reasoning. The last step is reflection, when students are asked to reflect on the process (procedural steps that helped to build the models), on the meta-tools which helped build the model and on the model itself, its quality, application scope and limitations. In this step, as well as throughout the process, students are also involved in reflecting on thinking strategies that were used in the process.

Speaking about the method of teaching, it is worth making a distinction between the method of teaching and tools of teaching or resources of teaching (Лернер 1982). The teaching-learning process is the unity of the activity of a teacher and the activity of a learner. Tools or resources that a teacher can use in this process can be represented in different forms: graphical or pictorial (*images, graphs, videos, etc*.), in a form of tangible objects (*microscope, book, experimental material*, *etc*.) and in a verbal form (*story, lecture, explanation, etc*.). And a method of teaching is a way of organising learners' activity with the tools or resources, i.e. method of organisation of learners' cognitive activity. Any tool or resource can be used for the purposes of different methods. For instance, a simple picture can be presented to learners and accompanied by teacher's narration. In this teaching-learning situation, learners' cognitive activity will be limited to perception and awareness of new information. If learners are invited to answer questions about the picture they've just heard of, then their cognitive activity is involved in the reproduction of knowledge and possibly methods, and only when students are given a picture and a task connected to its analysis, their cognitive activity raises to problem solving (Лернер 1982). The main method of teaching in problem-centred education is the research method (or the method of inquiry).

The dialogic approach in teacher–student interaction means that a teacher should have competence in organising a qualitative dialogue with students while pursuing students' reasoning in the teaching-learning process.

The organisation of the above-defined problem-centred teaching-learning process requires specific competences from the teacher. The empirical experience[6] showed the lack of understanding exactly which competences are expected of a teacher for organising the problem-centred teaching-learning process and why

[6]Among other projects and professional development events, there were two international projects supported by the Nordic Council of Ministers in the framework of the Nordplus Horizontal programme which led to this conclusion:

- 2010–2012 Bringing Creativity and Thinking Skills in Educational Process
- 2012–2014 STEP to Thinking – Summer Schools for Teachers Professional Development

some teachers are more successful in this endeavour while others fail to change their usual teaching habits.

4.2 The Study of Teaching Competence for Problem-Centred Education

4.2.1 Teacher Competence and Teaching Competence

After analysing different approaches to defining teacher competences in Europe, the Thematic Working Group 'Teacher Professional Development' (The European Commission 2011, 2013) concluded that approaches vary a lot and range from general guidelines (for instance, in France, Hungary or Luxembourg) to detailed lists of specific competences (for instance, in Estonia, the Netherlands, the UK). Despite the differences, the international review of both policy documents and research studies done by the Thematic Working Group (The European Commission 2013, pp. 45–46) allowed to identify key aspects of teacher competences that are commonly mentioned in the majority of studies. These are regrouped in three areas or structural components: (1) knowledge and understanding, (2) skills and (3) dispositions (which include beliefs, attitudes, values and commitment).

As stated by Caena (2011; The European Commission 2013), teacher competences imply a wider, systemic view of teacher professionalism and consider the multi-faceted roles of the teacher on multiple levels—the individual, the school, the local community, and professional networks. Teaching competences, on the other hand, are focused on the role of the teacher in action in the classroom, directly linked with the 'craft' of teaching—with professional knowledge and skills mobilised for action. It can thus be defined as '[. . .] complex combinations of knowledge, skills, understanding, values and attitudes, leading to effective action in situation. Since teaching is much more than a task, and involves values or assumptions concerning education, learning and society [. . .]' (The European Commission 2013, p. 8).

We can, thus, assume then that in order to solve the problem of the lack of understanding of knowledge, skills and dispositions mobilised for action in a problem-centred classroom, a teacher in action has to be studied and a wider understanding of their underlying knowledge and dispositions be sought. The author has initiated a research which aims at studying teachers' experience of working with problem-centred education with the aim of identifying criteria and indicators of teaching competence required for organising the problem-centred teaching-learning process. The study described further on is a part of this larger research and is focused on studying instructional patterns of a teacher in action who is organising a problem-centred teaching-learning process.

4.2.2 The Study of a Teacher in Action Organising a Problem-Centred Teaching-Learning Process

4.2.2.1 Study Problem and Aim

The specific problem the study addressed was whether there is any core difference in classroom instruction between teachers who are experts in organising the problem-centred teaching-learning process and those who are non-experts.

The aim of the study was thus to identify instructional patterns of expert teachers who build their classroom instruction following the three steps of the Thinking Task Framework (see Fig. 4.6) and to compare them to those of non-expert teachers. In addition to identifying instructional patterns, the study focused on comparing the quality of teacher–student interaction of expert and non-expert teachers.

This chapter presents the results of the study on one expert teacher (referred further as T2-nk) and focuses only on the identification of her instructional patterns.

4.2.2.2 Research Base

The expert teacher whose lessons were analysed was a Russian as a mother tongue teacher, and she was the head of the Russian language department in the secondary school in Latvia (Daugavpils). The teacher was named as an expert since she had more than 3 years experience working with problem-centred education. In addition, she had more than 10 years experience working with Developmental Education (Давыдов 1996), and in 1997 she received the title of the best teacher of Russian as a mother tongue.

4.2.2.3 Data Collection Method

Permission was obtained from T2-nk to observe and film her lessons during which she was purposefully working through the three steps of the Thinking Task Framework organising the problem-centred teaching-learning process. During the first month, from September 2013 to October 2013, the researcher was attending and filming her lessons, occasionally recording the teacher's comments on her own lessons. As a result, 16 lessons (40 min each) were filmed with forms eight (two groups) and nine (two groups).

4.2.2.4 Data Selection Logic

Two consecutive lessons of T2-nk were selected for the purpose of the study analysis since the teacher introduced a new grammar topic. Non-structured interviews of the teacher on her own lessons were recorded. The next four consecutive lessons were selected since these were held with the same group of students and the teacher continued working with the same grammar topic. A non-structured interview of the teacher on her pre-last lesson was recorded. As a result, six lessons were selected for the analysis.

4.2.2.5 Data Analysis Method

In order to identify instructional patterns, the study adapted the analytic approach to modelling the teaching process developed by Teacher Model Group at the University of California at Berkeley, Graduate School of Education (Schoenfeld 1998a, b, 2000, 2011). The Teacher Model Group developed the model of classroom teaching (teacher in action). The core components of the model are based on the assumption that the teacher 'has' knowledge, goals and beliefs, makes decisions and takes actions. The model of the teacher, thus, contains representations of knowledge, goals and beliefs attributed to the teacher and the decision-making mechanism that suggests what actions the teacher is likely to take (Schoenfeld 2000, p. 249). The model has a descriptive nature and can be used to characterise, in extremely fine-grained detail, what happens in a given teaching session and used for making predictions about a teacher's classroom instruction in various circumstances.

4.2.2.6 Procedure of the Study

The study used the following procedure:

1. The researcher transcribed all the six lessons of T2-nk.
2. The first two consecutive lessons were then analysed together since they constituted one unit. The same was further done for two other lessons and then the two remaining lessons.
3. The first lesson was divided into six episodes and the second lesson into eight episodes (large action sequences), each containing a brief summary of that episode.
4. Each episode (large action sequence) was then parsed into smaller action sequences going down to the level of 'simple talk' (see Fig. 4.7 for an example of a parsed lesson). Each action sequence was characterised by triggering and terminating events, as well as beliefs, goals and knowledge attributed to the teacher.
5. The discussion on the parsing was held with the peer following the principles of competitive argumentation (VanLehn et al. 1984). The general idea of competitive argumentation is that 'it's the investigator's responsibility to consider all possible explanations of the situation being examined, and then look at the pro- and con- evidence for each. If every explanation but one is discredited, and that one is credible, then it's the best explanation' (from personal e-mail

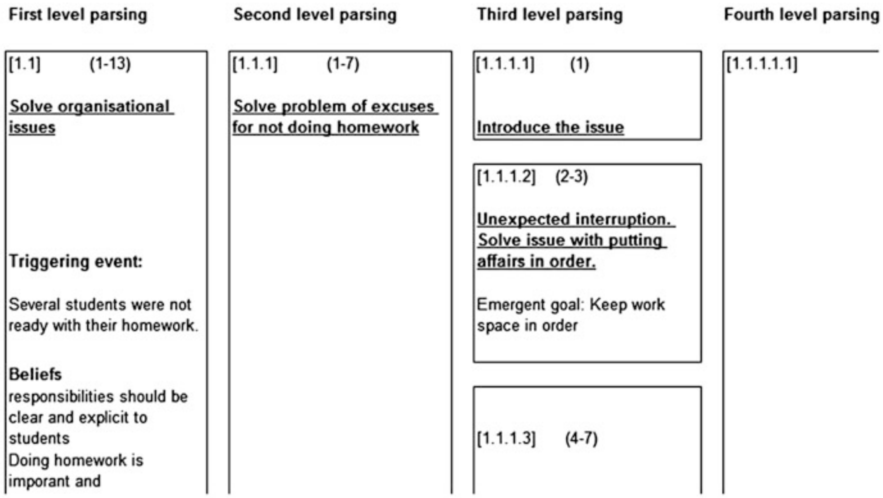

Fig. 4.7 Extract of one example of a parsed lesson

correspondence with Alan Schoenfeld, January 01, 2014). The first parsing was then refined through multiple iterations.

6. After the lesson was parsed, the researcher proceeded to identify the action sequences where the teacher organised learners' work with the system of tasks (a problem task and sub-tasks) following the instruction defined by the Thinking Task Framework. The guiding question was whether a specific pattern (routine) existed in how the teacher worked through these tasks.

4.2.2.7 Results and Discussion

Doing the same analysis for all the six lessons allowed me to identify a certain pattern in how T2-nk works through the system of problem tasks following the Thinking Task Framework (see Fig. 4.8). I refer to this pattern as a loop instruction.

As can be seen from Fig. 4.8, the teacher starts with offering students the main problem task, which involves students in the first learning activity in the form of an individual work, pair work or group work. As a result of this activity, students produce their first result, which is then discussed in a plenary session during teacher–student interaction.[7] The result of this interaction is involvement of students in the second learning activity during which they work on improving their

[7]The quality of this interaction is highly important, and as stated in the section on 'study problem and aim', it was also assessed following certain defined criteria. The results of this quality assessment are not reported in this chapter.

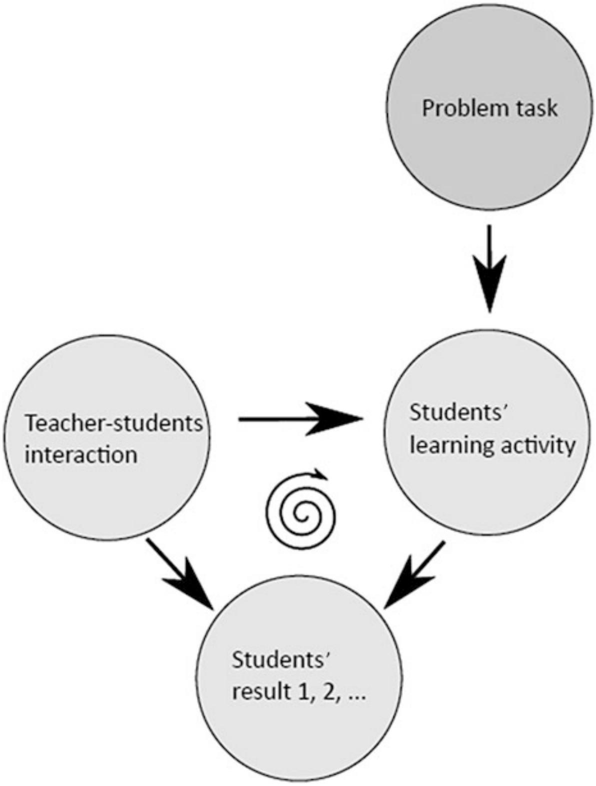

Fig. 4.8 An expert teacher's (T2-nk) instructional pattern for working through a system of problem tasks following the Thinking Task Framework in the framework of the problem-centred teaching-learning process

first result taking into account the conclusions of the plenary session. This is specifically during the second learning activity when the real learning happens place as students apply the new knowledge gained during the stage of the social construction of the meaning to the problem task. Students never start any other task before they work on improving their results in the first task. The given loop instruction can be repeated several times in the framework of doing one task.

I would assume that organising the instruction in the format of the loop allows planning enough time and steps for learners to build a model or a strategy. Moreover, it is specifically during the first teacher–students interaction that students have to be offered or reminded of the meta-subject tools which will help them build their model or strategy. I can tentatively assume then that the competence of organising the instruction in the form of a loop seems to be essential if one wants to work with problem-centred education.

The meticulous analysis of the expert teacher in action has to be repeated for other expert teachers as well before any conclusion on a common pattern can be made or any specific conclusions drawn. In addition, this pattern has to be compared to non-expert teachers' instruction in order to reveal the main difference between the two and identify those essential components of classroom instruction which make expert teachers succeed in organising the problem-centred teaching-learning process and which are missing in the instruction of non-expert teachers.

4.2.2.8 Conclusions

This chapter presented a brief overview of the essence of problem-centred education and the respective teaching-learning process.

This provided the implications on the general competences (i.e. knowledge and understanding, skills and dispositions) a teacher needs in order to be able to organise the defined process. These competences include both those which are specific for problem-centred education (PCE) and those which are shared with other teaching for thinking approaches and are part of the competences required for organising effective teaching-learning processes as such.

Among others, these essential competences include the following:

1. Aims and objectives of problem-centred education
    - Dispositions:
        - Belief in the need to develop students' worldview centred on a problem
        - Belief in the constructive nature of learning
2. Content of the problem-centred education
    - Knowledge and understanding of
        - The subject matter being taught
        - Mental modelling and strategy development
        - The meta-subject OTSM-TRIZ tools
        - Inventive thinking skills and their connection to the meta-subject OTSM-TRIZ tools
        - Thinking strategies and higher-order thinking skills
    - Skills
        - Skills to select the relevant subject-matter content, single out features common for specific types of tasks within that content and transform this content into a system of problem tasks (a problem task and sub-tasks) that would create and maintain cognitive conflict in students' minds and that requires developing a model or a strategy. The task should have the potential of applying the meta-subject tools for developing the model strategy.
3. Instruction of problem-centred education
    - Skills
        - Ability to organise the instruction following the three steps of the Thinking Task Framework: create cognitive conflict or a problem situation in a

student's mind, involve students in learning activity for building the solution and reflect on the process and result
- Ability to use the method of inquiry for organising students' learning activity
- Ability to hold qualitative teacher–student interactions.

The weakness of this list of competences is twofold: firstly, the list is not complete, and secondly, it is too general.

In order to address the given weakness, the author initiated a research that should result in measurable criteria and indicators of the problem-centred teaching competence. The first study presented in this chapter focused on classroom instruction and allowed to identify a specific loop instruction which seems to be one of the characteristics of teachers who are experts in problem-centred education. Further study is required in order to confirm the given hypothesis and to extend the understanding of teaching competence required for organising the problem-centred teaching-learning process.

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Chapter 5
Problem Graph for Warehousing Design

David Damand, Marc Barth, and Elvia Lepori

Abstract Warehousing plays a key role in supply chain performance (reactivity, flexibility, quality). In order to be competitive, reorganization of the warehouse is often required. The reorganization generally occurs via a design process based on two main stages. First, the designers have to precisely identify the design problems. Second, they have to design solutions to solve the problems. Academic researchers in warehousing design are used to studying all the different operations (receiving, storage, order picking, shipping) one by one while the warehouse design problems are linked together. As far as we know, the literature does not propose any model that capitalizes and links all the operations-related problems and solutions needed for warehouse designing. In this chapter, we propose a reference model as a graph including both the problems and the solutions advocated by a French third-party logistics (3PL) provider and quoted in the literature. The creation of such a model has been suggested in the state of the art in the literature. This model has been designed using a semantic and a syntax inspired by the TRIZ problem graph and with a taxonomy standardizing the vocabulary. The problem-solution graph is made up of 31 problems assessed by 31 evaluation parameters and 49 solutions defined by 73 action parameters. An industrial case study, in a French 3PL warehouse of 35,000 m^2 and 45,805 locations, proves the value of such a graph.

5.1 Introduction

The logistics costs of warehouses are determined to a large extent during the design and redesign phase. In general, based on a functional description, via a specific method, the design phase consists of selecting a layout of the four basic warehouse operations (receiving, storage, order picking and shipping) and a method for planning the operations related to these activities (Gu et al. 2010; Rouwenhorst et al. 2000). At each stage of the method, desired values of performance metrics (cycle time, storage costs, etc.) are required. Warehouse design as such is a complex

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task, in which, at each stage, compromises must be made between objectives that are often contradictory (Gu et al. 2007). Another difficulty is the large number of possible designs.

Warehouse design gets a great deal of discussion in the scientific literature. The literature defines six states of the art (Cormier and Gunn 1992; De Koster et al. 2007; Gu et al. 2007, 2010; Rouwenhorst et al. 2000; Tsui and Chang 1990). These works describe problems (e.g. the dimensioning of picking zones, ABC zones, the storage systems, etc.), performance metrics (e.g. material handling cost or space utilization) and solutions (e.g. number of routing methods). But the quality of design is linked to the degree of acknowledgement of all of the problems and solutions associated therewith (Rouwenhorst et al. 2000). To deal with this difficulty, this chapter proposes a reference model to be used as a decision support system (DSS). This reference model capitalizes all of the problems, solutions and their relations. This model is intended for third-party logistics (3PL providers). The DSS is developed on the basis of concepts of the OTSM-TRIZ theory (Cavallucci et al. 2010). To help the designer, the DSS is presented in the form of a problem graph.

The second section consists of a review of the literature. The third section describes the method for developing the reference model. The fourth section presents an assessment of the reference model in a case conducted in a French third-party logistics provider. Section 5.5 presents conclusions and perspectives.

5.2 Literature Review

Warehouse design problems have received a fair amount of attention. The authors analyse particular problems and solutions in the design of four basic warehouse operations.

In the design of the order picking operation, Roodbergen and De Koster (2001a) analyse the picker travel distance problem. The problem is assessed by travel distance metric. The solution proposed is a cross aisles layout.

Ratliff and Rosenthal (1983) propose to minimize the picker travel distance by an optimal order picking routing. In Petersen and Aase (2004), the solutions proposed are the routing policies and the volume-based storage.

In the design of shipping and receiving operations, Tsui and Chang (1992) minimize the distance travelled by the fork-lift driver by proposing a solution that assigns shipping and receiving doors. The problem in optimization analysed by Bartholdi and Gue (2000) rests on two criteria: the fork-lift driver travel distance and the number of fork-lift drivers in an area. The solution proposed is a cross-docking solution.

In the storage operation design, Berry (1968) minimizes the fork-lift driver travel distance by proposing a block stacking storage solution. In Pohl et al. (2009), the solution proposed is a cross aisles layout. Cardona et al. (2012) minimizes the storage costs by proposing a fishbone layout.

First, the aforesaid works analyse particular problems, describe particular performance metrics and propose particular solutions. Their contribution to warehouse design is not negligible. However, these works focus on analysis rather than on synthesis. The analysis is oriented mainly to a study of the order picking operation. The authors analyse the picker travel distance. The solutions that get the most attention are the implementation of picker routings and the storage layout in pick locations. No study encompasses the four basic warehouse operations. Design decisions are closely coupled and cannot be analysed in an isolated manner.

Second, the available decision models are not unified and are not interoperable. For example, with respect to minimization in picker travel distances, one observes:

– Various syntaxes to describe a problem: “to minimise the total distance travelled by pickers” (Bindi et al. 2009, p. 2); “minimizing the travel distance required to pick a number of items from their respective storage locations” (Vaughan and Petersen 1999, p. 1)
– Various syntaxes to describe a performance metric: “average travel distance of a picking tour (or average tour length)” (Petersen and Aase 2004); “total travel distance” (De Koster et al. 2007)
– Various syntaxes to describe a solution: “order picking tour” (Ratliff and Rosenthal 1983); “routing order picker” (Roodbergen and De Koster 2001a)

The interactions between warehouse operations are not clearly explained (Gu et al. 2007). Only occasionally does the literature mention the consequence of a solution, and therefore the relationships between problems–solutions–problems. For example, Petersen and Aase (2004) analyse the minimization in picker travel distances by defining an optimal order picking routing. The authors point out that the implementation of this particular solution may lead to errors in the order picking system and might have an effect on the business’s fill rate. The literature’s models are not designed to bring out the reference problems and solutions and their relationships.

The contribution that is sought is a structure that collects data for capitalize reference problems (PB), reference solutions (SOL) and reference relationships based on particular analyses (PB, SOL and particular relationships). To that end, the contribution is dual: the preparation of a data collecting language (syntax, semantics, taxonomy) and the representation of data collected in the form of problem graphs called reference model.

5.3 The Reference Model

This chapter presents the reference model’s structure and its implementation in 3PL warehouses. The reference model is designed in four stages (Fig. 5.1).

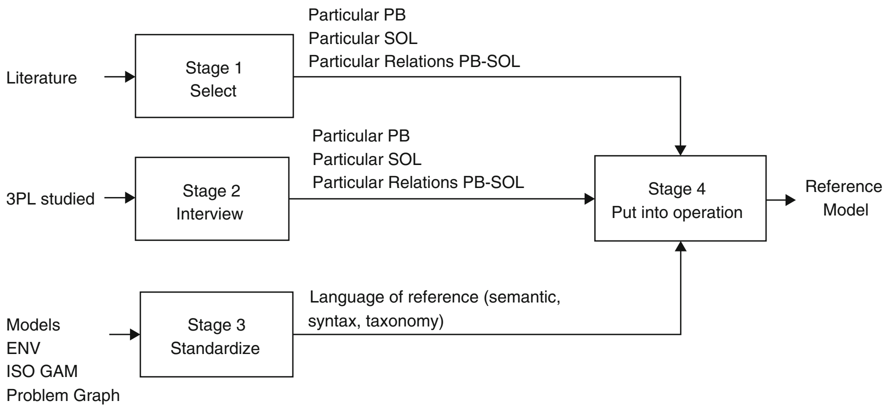


Fig. 5.1 Reference model design

5.3.1 Stage 1: Select

Stage 1 consists of selecting scientific articles related to warehouse design. The databases consulted are ScienceDirect, Scopus, Ebsco, Taylor & Francis and Web of Science. The key words are warehouse/warehousing layout, warehouse/warehousing design, warehouse/warehousing routing, warehouse batching, picking layout, picking routing and picking batching. The literature reviewed regarding warehouse design includes (Cormier and Gunn 1992; De Koster et al. 2007; Gu et al. 2007, 2010; Tsui and Chang 1990; Rouwenhorst et al. 2000). The bibliographic references of the following websites are consulted: http://www.fbk.eur.nl/OZ/LOGISTICA/lit.html and http://www.roodbergen.com/warehouse/.

Because of the specific characteristics of 3PL, two types of problems are excluded:

– The parametrization of inventory levels in warehouses. The inventory levels are determined by customers of 3PL.
– The design of automated storage and retrieval systems (AS/RS). These systems reduce the flexibility of warehouses and may be costly for companies with heterogeneous storage operations (Gray et al. 1992) such as 3PL.

The journals thusly identified are listed in Table 5.1.

At the end of this first stage, 136 scientific articles published between 1965 and 2015 are selected (Accorsi et al. 2012; Bartholdi and Gue 2000; Bartholdi and Hackman 2008; Bassan et al. 1980; Battini et al. 2015; Berglund and Batta 2012; Berry 1968; Bindi et al. 2009; Bottani et al. 2012; Boysen and Stephan 2013; Bozer and Kile 2008; Brynzér and Johansson 1996; Cardona et al. 2012, 2015; Caron et al. 1998, 2000a, b; Çelk and Süral 2014; Chan and Chan 2011; Chen et al. 2010, 2013; Chen and Wu 2005; Cheng et al. 2015; Chew and Tang 1999; Chuang et al. 2012; Cormier and Gunn 1992; Daniels et al. 1998; De Koster et al. 1999, 2007; De Koster and Van Der Poort 1998; Francis 1967; Frazele and Sharp 1989; Gademann

Table 5.1 Journals identified

Journal title	Journal title
IIE Transactions	*Material Flow*
International Journal of Production Research	*Decision Sciences*
European Journal of Operational Research	*Transportation Science*
Computers and Industrial Engineering	*Applied Mathematical Modelling*
International Journal of Production Economics	*Discrete Applied Mathematics*
International Journal of Operations and Production Management	*Expert Systems with Applications*
International Journal of Logistics Research and Applications	*Flexible Services and Manufacturing Journal*
Transportation Research Part E	*Logistics and Transportation Review*
International Journal of Physical Distribution and Logistics Management	*Omega*
The International Journal of Advanced Manufacturing Technology	*Management Science*
Operations Research	*Engineering Optimization*
Computers and Operations Research	*Facilities*
Computers in Industry	*International Journal of Computer Integrated Manufacturing*
Production and Operations Management	*Industrial Engineering*
Interfaces	*The Journal of Industrial Engineering*

et al. 2001; Gademann and Velde 2005; Gibson and Sharp 1992; Goetschalckx and Ratliff 1988a, b, 1991; Gray et al. 1992; Gu et al. 2007, 2010; Gue 1999; Gue et al. 2012; Gue and Meller 2009; Hall 1993; Harmatuck 1976; Heragu et al. 2005; Hong et al. 2012a, b, 2013; Ho et al. 2008; Ho and Tseng 2006; Hsieh and Tsai 2006; Hsu et al. 2005; Hung and Fisk 1984; Hwang et al. 2004; Jane 2000; Jane and Laih 2005; Jarvis and McDowell 1991; Kallina and Lynn 1976; Kulak et al. 2012; Lai et al. 2002; Larson et al. 1997; Le-Duc and De Koster 2005, 2007; Lin and Lu 1999; Liu 1999; Mallette and Francis 1972; Malmborg and Bhaskaran 1990; Malmborg and Krishnakumar 1987; Manzini et al. 2007, 2015; Marsh 1979; Matusiak et al. 2014; Moder and Thornton 1965; Mowrey and Parikh 2014; Muppani and Adil 2008; Oh et al. 2006; Önüt et al. 2008; Öztürkoğlu et al. 2012, 2014; Pan and Shih 2008; Pan et al. 2012, 2014; Pan and Wu 2012; Parikh and Meller 2008, 2009, 2010; Petersen 1997, 1999, 2002; Petersen and Aase 2004; Petersen et al. 2004, 2005; Petersen and Schmenner 1999; Pohl et al. 2009, 2011; Rana 1990; Rao and Rao 1998; Rao and Adil 2013a, b; Ratliff and Rosenthal 1983; Roberts and Reed 1972; Roll and Rosenblatt 1983; Roodbergen and De Koster 2001a, b; Roodbergen et al. 2008, 2015; Roodbergen and Vis 2006; Rosenblatt and Roll 1984; Rosenwein 1994, 1996; Rouwenhorst et al. 2000; Ruben and Jacobs 1999; Sadiq et al. 1996; Schleyer and Gue 2012; Schuur 2015; Stadtler 1996; Tang and Chew 1997; Theys et al. 2010; Thomas and Meller 2015; Tsai et al. 2008; Tsui and Chang 1990, 1992; Van Den Berg 1999; Van den Berg et al. 1998; Van Nieuwenhuyse and De Koster 2009; Vaughan and Petersen 1999; Vis and Roodbergen 2011; Walter et al. 2013; White and Francis 1971; Won and Olafsson 2005; Wutthisirisart et al. 2015; Xu et al. 2014; Zhang and Lai 2006; Zhang et al. 2000, 2002).

5.3.2 Stage 2: Interview

Stage 2 consists of formalizing the expertise of designers of 3PL. The 3PL that is studied is a French 3PL. Its turnover in 2015 was 1.066 M euros. The study covers 21 warehouses of this 3PL. Its customers are mainly in the food processing, mass distribution and health sectors. Sixteen designers of this 3PL are interviewed. The interviews are spread out over a period of 6 months. Each interview lasts an average of 2 h. The interviews are transcribed in a document of 152 pages. A study of the documents referring to the 3PL's quality system and the warehouse visits are added to the interview data.

All of the data show two principal disparities. The first disparity resides in the definition of problems and solutions. According to the expert interviewed, problems in warehouse design are defined differently. For example, two experts address the problem of minimization in picker travel distances as follows: "…travel the least distance between two picks… (expert 1)"; "…limit the distance for order picking… (expert 2)". The second disparity resides in the vocabulary that is employed. For example, in certain situations, the term pallet may give rise to different interpretations by experts. It may refer to empty pallets or pallet loads. In other situations, the verbs "stack" and "put away" are used indiscriminately. But these two verbs describe a different action. "Stack" means "piling boxes and containers on top of each other", and "put away" means "recording the movement and identification of the location where the material has been placed" (APICS The association for Operations Management 2008).

5.3.3 Stage 3: Standardize

Stage 3 consists of defining a reference language. Standardized problems and solutions are called, respectively, reference problems and reference solutions. The semantic and the syntax are constructed on the basis of three models defined as business modelling: the ENV model (Element, Name of the Feature, Value of the Feature) to define the resources, the Generic Activity Model (GAM) to define the operations and the representation by problem graph to construct the relationships between reference problems and solutions.

The first "ENV" model is defined in OTSM-TRIZ (Cavallucci and Khomenko 2007; Khomenko and Ashtiani 2007): Element, Name of the Feature, Value of the Feature. The elements are resources of the system studied. Resources designate all of the means, equipment and persons that are necessary for the operation of a warehouse (e.g. Cardona et al. 2012): the storage units, pallets and boxes, the

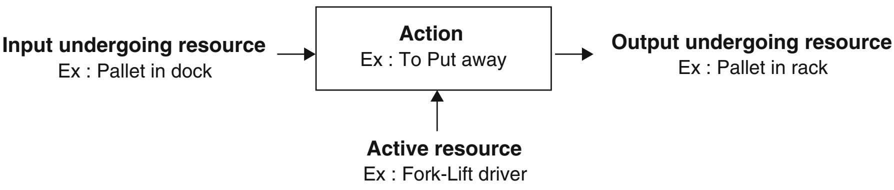


Fig. 5.2 Description of a warehouse operation

storage systems (racks), the doors, the operation areas, the handling equipment and the personnel (fork-lift drivers, pickers). The features are parameters qualifying the elements. The features are performance metrics or action parameters (control). The value quantifies the parameter (Zanni-Merk et al. 2009). The values of performance metrics may be values that are measured (V_m) (performance achieved) or desired (V_d) (objective).

The second "ISO GAM" model is defined in ISO/TR 10 314. An operation is an active resource that performs an action on an undergoing resource (Fig. 5.2).

The third "problem graph" model is defined in Cavallucci et al. (2010). This model characterizes a network of relationships between problems and solutions. Figure 5.3 shows the entity-relation diagram characterizing the graph's data.

The assembly of the three models above (ENV, ISO GAM, problem graph) enables the construction of a reference language (syntax, semantic) adapted to the reference model.

The Semantic and Syntax of a Reference Problem A problem is evaluated by a performance metric or indicator (PI). The syntax of a performance metric is comprised of a performance metric, an active resource and a measurement unit. The syntax proposed for a performance metric is described as follows:

"Performance metric; active resource; measurement unit".

If the PI's measured value does not reach a desired value, the problem is identified. Based on the ENV and GAM models, the semantic proposed for a reference problem is defined by the following phrase:

"The measured value (V_m) of a performance metric of an active resource performing an action on an undergoing resource is less or more than the desired value (V_d)".

The syntax, without any link between the words, is then described as follows:

"Performance metric; active resource; action; undergoing resource; $V_m >$ or $< V_d$".

As an illustration, the semantic and syntax of a reference problem constructed on the basis of the aforesaid problem ("...limit the picker travel distance... (expert 2) is respectively the following": "the measured value of the distance travelled by the picker to pick boxes exceeds the desired value"; "Picker travel distance; picker; to pick; boxes; $V_m > V_d$").

The Semantic and Syntax of a Reference Solution A solution is defined by one or more action parameters of a resource. The value of the action parameters is

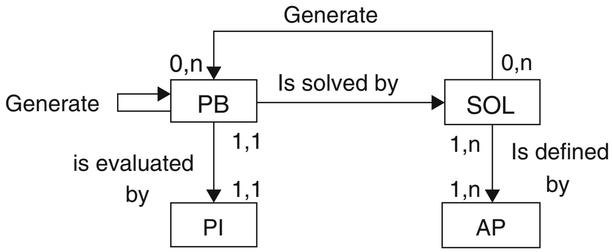


Fig. 5.3 Elements and relationships between elements in the problem graph

Table 5.2 Methods and reference verbs of methods

Methods	Reference verbs
• Algorithm	• Define
• Constant	• Define
• Direction of variation	• Reduce; increase
• Interval	• Include; not included

defined by using a method as a formula, an algorithm or a selection. The semantic proposed for a reference solution is defined by the following phrase:

"The value of the action parameters of resources determined pursuant to a method". The syntax proposed, without any link between words, is then described as follows:

"Method; value; action parameter; resource] & [Method; value; action parameters; resource] & [Method; value; action parameters; resource] & [...] & [. . .]".

The method is characterized by five reference verbs shown in Table 5.2.

For example, the foregoing problem ("Picker travel distance; picker; to pick; boxes; $V_{\mathrm{m}} > V_{\mathrm{d}}$") is solved by the cross aisles layout in the order picking area. The syntax of the reference solution is as follows: "[Define; value; Number; cross aisles] & [Define; value; length; cross aisle] & [Define; value; identification (x, y); cross aisle]". This type of solution is parameterized by using an algorithm that defines three action parameters: the number, the length and the identification of the cross aisles.

Figure 5.4 recapitulates the reference elements and the relationships between the reference elements of the problem graph.

Reference Taxonomy The reference taxonomy enables the standardization of vocabulary that is used to describe the reference problems and solutions. The reference vocabulary derives (in the order of preference) from the APICS dictionary, then from reviews of the scientific literature on warehousing and, finally, from manuals regarding warehouse design and management. The resulting taxonomy is comprised of 73 terms. It is structured with the protected software recommended by W3W, in the SKOS language (Appendix 6).

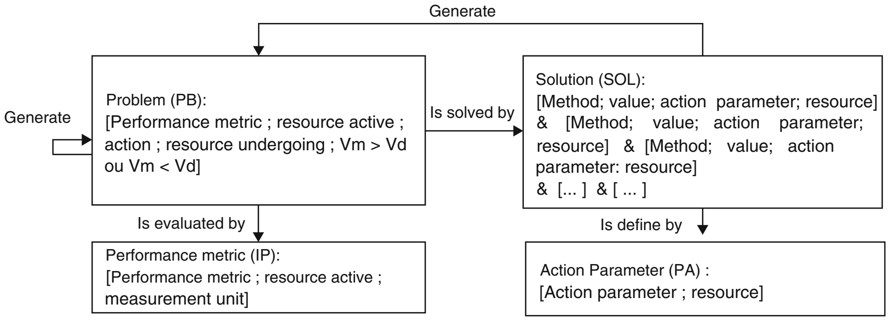


Fig. 5.4 Standardization of graph problem elements

Table 5.3 Number of elements and relationships between the elements of the reference model

Elements and relations between elements (Fig. 5.4)	Stage 1	Stage 2	Stage 4	# Appendix
Number of PB	19	12	31	01
Number of SOL	31	18	49	02
Number of relations: PB-PB: PB generate PB	6	36	42	03
Number of relations: PB-SOL: PB solved by SOL	53	52	105	04
Number of relations: SOL-PB: SOL generate PB	15	31	46	05

5.3.4 Stage 4: Put Into Operation

All of the elements (particular problem, particular solution and the relationships between particular problems and solutions (stages 1 and 2) are transcribed in the reference language (stages 3 and 4, Table 5.3).

The resulting reference model includes:

- 31 reference problems (PB).
- 49 reference solutions (SOL).
- The 49 solutions are characterized by 73 action parameters.
- The results of stage 2 supplement the results of stage 1.
- 105 PB-SOL relationships: 1 problem may be solved by solutions ($i = 1 ... 8$). For example (Appendix 4), PB22 is solved by SOL 45 or SOL 43 (Fig. 5.5).
- 42 PB-PB relationships: 1 problem may generate i problems ($i = 1 ... 4$). For example (Appendix 3), PB10 generates PB23 (Fig. 5.6).
- 46 SOL-PB relationships: 1 solution may generate i problems ($i = 1 ... 4$). For example (Appendix 5), SOL45 generates PB16 (Fig. 5.7).

Through the PB-SOL and SOL-PB relationships, PB-SOL-PB transitive relationships may be deduced. For example, PB22 is solved by SOL45, which generates PB16 (Fig. 5.8).

The significant number of elements and relationships that exists in the model reference requires computerization. For proper coverage of all of the reference

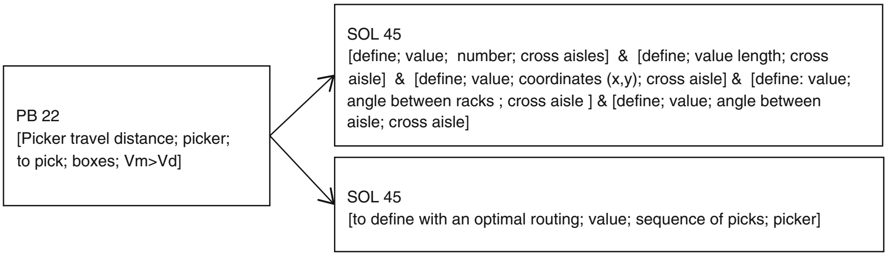


Fig. 5.5 Example of PB-SOL relations

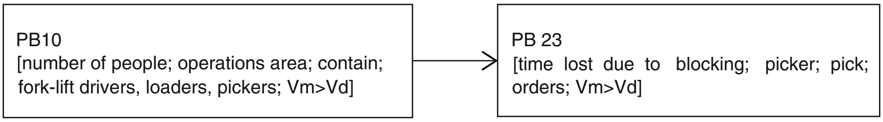


Fig. 5.6 Example of a PB-PB relation

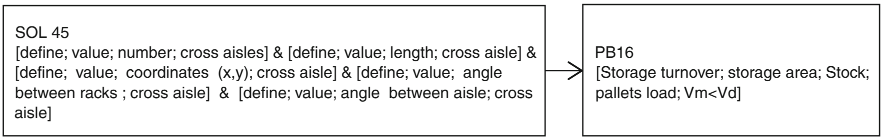


Fig. 5.7 Example of a SOL-PB relation

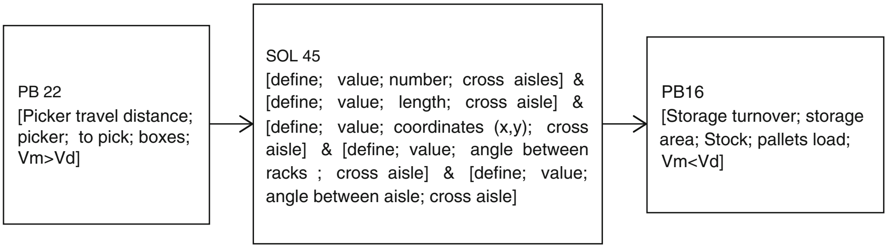


Fig. 5.8 Extract of a PB-SOL-PB relation

problems and solutions, the reference model is implemented in the Systematic Tool for Efficient Problem Solving (STEPS) software (http://www.time-to-innovate.com). The problems and solutions are sorted and grouped according to the four warehouse operations. This grouping helps highlight visually the interactions between operations. Figure 5.9 is a screen capture of the complete problem graph in the STEPS software. The problems and solutions are documented by description sheets attached to the software. As the scientific literature and expertise evolve, the problem graph is updated by conducting the four stages of Fig. 5.1. For this purpose, a learning module for integrating new problems and new solutions in the knowledge base was developed.

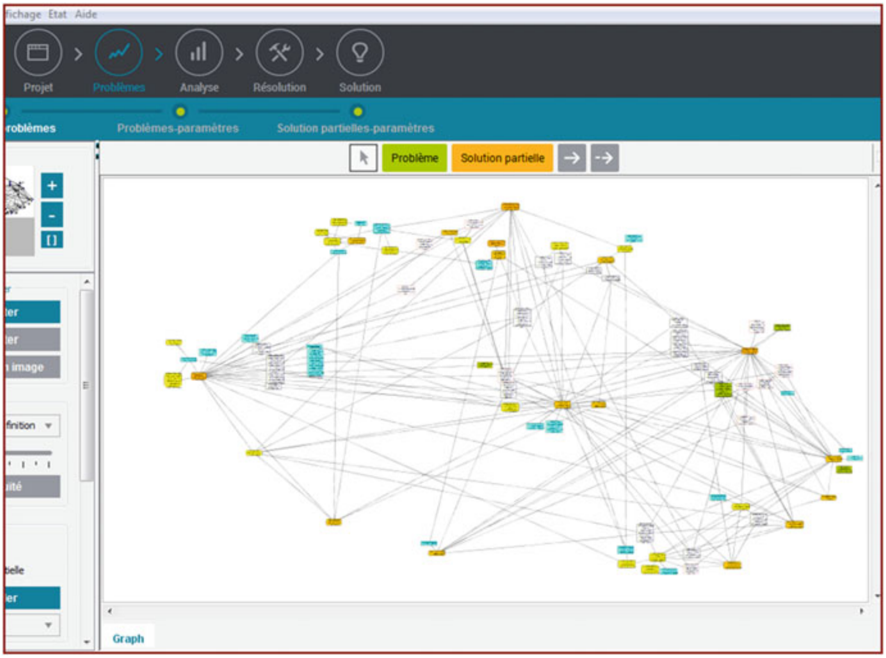


Fig. 5.9 Designed problem graph, screen capture from the STEPS software

5.4 Example of Application

An example of application involves a warehouse dedicated to a customer in mass distribution. Four operations are carried out in the warehouse: receiving, storage, order picking and shipping. The warehouse has 247 employees; it has a surface area of 35,000 m^2 with 45,805 storage locations and 62 doors. The volume of the business consists of 110,000 boxes picked per day, 3800 incoming pallets per day and 1600 outgoing pallets per day. The customer has the following needs: a 20% increase in the quantity of goods to be stored and in the number of pick orders. The warehouse's present capacity is not sufficient to satisfy the customer's needs. A designer is responsible for a warehouse redesign. The project consists in identifying the problems to be solved and the solutions to be envisaged.

In order to understand the interest in using the reference model, two experiments are conducted:

– Experiment 1: Identification of particular problems and solutions without using the reference model.
– Experiment 2: Identification of particular problems and solutions by using the reference model.

5.4.1 Experiment 1: Without the Reference Model

The experiment is conducted in three stages:

– Stage 1: Analysis of customer requests and visiting the warehouse
– Stage 2: Identification of problems by an expert
– Stage 3: Proposal for solutions by an expert

5.4.2 Experiment 2: With the Reference Model

The experiment is conducted in three stages:

– Stage 1: Identification of problems by using the reference model. The 31 reference problems are analysed one by one. For example, the following problem is addressed: “the measured value of the picker’s productivity in picking boxes does not reach the desired value”. Other problems may be identified on the basis of the relationships between elements of the problem graph, as PB-PB relationships. For example, the measured value of the distance travelled by the picker to pick his boxes does not reach the desired value.
– Stage 2: Identification of solutions on the basis of PB-SOL relationships. For example, the solution that is used consists of defining a fixed value at the specific pick locations as a function of the turnover rate of the stored article.
– Stage 3: Identification of problems induced by the application of a solution based on SOL-PB relationships. For example, the preceding solution may deteriorate another performance metric as it generates a flow convergence in an area. The measured value of the number of persons in an operations area consisting of fork-lift drivers, loaders and pickers will no longer reach the desired value. The designer is warned of the potential occurrence of such a problem and, hence, will check this metric upon application of the particular solution to his warehouse.

5.4.3 Comparison of Experiments 1 and 2

The results of these two experiments are given in Table 5.4.

The compared results of these two experiments show the contribution of the reference model. The model enables systematic identification of additional information at a rate of 50–90% with an average of 76%. For example, experiment 1 shows that the designer does not systematically define the performance metric associated with a problem or all the PA associated with a solution. The designer’s mode of expression is not formalized. The problems and solutions are highlighted by the observation of operations in the warehouse. The time difference between the

Table 5.4 Comparison of experiments 1 and 2

Elements	Experiments 1	Experiments 2	Difference %
PB	10	20	50
PI	6	20	70
SOL	6	17	65
AP	4	37	89
Relations PB-SOL	7	37	81
Relations SOL-PB	1	10	90
Relations PB-PB	6	36	83

two experiences is negligible given the quality of the result, duration and cost of the layout design project.

5.5 Conclusion and Perspective

In the scientific literature on warehouse operations design, authors deal with particular problems by bringing particular solutions. They point out that there is no global and systematic approach that gives a summarized view of the reference problems and solutions for the design of a warehouse.

The result of this research is a reference model for warehouse design. This reference model enables amassing of reference problems and solutions appropriate for standardized design of the four warehouse operations. A syntax, a semantic and a taxonomy are designed for each element of the problem graph. This model is comprised of reference problems and solutions that are standardized on the basis of particular knowledge of the scientific literature and the French 3PL. The knowledge contained in the scientific literature and that of experts supplement each other. Standardization of the reference model provides a global view of the knowledge by linking the elements to each other. The reference model that is designed is comprised of 31 reference problems. These reference problems are assessed by 31 performance metrics. The problems are solved by 49 reference solutions. These solutions are defined by 73 action parameters. This reference model is used in the context of a particular design of the 3PL that is studied and demonstrates the contributions it provides thereto. Utilization of the reference model enables the designer to search for solutions and assess problems in a comprehensive manner and guides him in his reasoning.

The study of the 3PL's 21 warehouses has helped formalize problems, solutions and relationships between problems and solutions that do not presently exist in the scientific literature: +12 PB, +18 SOL, +36 PB-PB relationships, +52 PB-SOL relationships and +31 SOL-PB. The design of the structure of the reference model provides supplementary information for future scientific research and other 3PL.

In that regard, the problem graph may be used for research on planned development of logistics platforms. The contradictions between parameters comprising the problem graph may be brought out and linked to the contradiction networks.

Appendix 1: Problems and Performance Metrics Extract

# Problems	Problems	Performance metrics
1	Time to retrieve and put away; fork-lift driver; retrieve or put away; pallets load; $V_m > V_d$	Time to retrieve and put away; fork-lift driver; (min)
	Berry (1968)	
2	Travel distance to retrieve and put away; fork-lift driver; retrieve or put away; pallets load; $V_m > V_d$	Travel distance to retrieve and put away; fork-lift driver (km)
	Cardona et al. (2012), Oh et al. (2006), Gue and Meller (2009), Lai et al. (2002), Rosenblatt and Roll (1984), Berry (1968), Tsui and Chang (1990, 1992), Mallette and Francis (1972), Roberts and Reed (1972), Bassan et al. (1980), Larson et al. (1997) and Gue (1999)	
. . .	. . .	. . .
31	Replenishment rate; replenisher fork-lift driver; replenish; full pallets load; $V_m > V_d$	Replenishment rate
	Accorsi et al. (2012), Van den Berg et al. (1998), Bartholdi and Hackman (2008) and White and Francis (1971)	

Appendix 2: Solutions and Action Parameters Extract

# Solutions	Solutions	Action parameters
1	[define; value; number; racks] & [define; value; groups number; racks] & [define; value; number; aisle] & [define; value; length; aisle] & [define; value; width; aisle] & [define; value; angle between cross-aisle; racks]	Number; racks
		Groups number; racks
		Number; aisle
		Length; aisle
		Width; aisle
		Angle between cross-aisle; racks
	Rao and Adil (2013a, b), Roodbergen and Vis (2006), Cardona et al. (2012) and Öztürkoğlu et al. (2012)	
. . .	. . .	. . .
48	[Define with return (U), traversal (S), (N), midpoint, largest gap; value; sequence of picks; picker]	Sequence of picks; Picker
	Theys et al. (2010), Hwang et al. (2004), De Koster and Van Der Poort (1998), Petersen and Schmenner (1999), Pan et al. (2014)	

Appendix 3: Problems Generate Problems Extract

↗	PB1	PB2	PB3	PB4	PB5	PB6	PB7	PB8	PB9	PB10	PB11	PB12	PB13
PB1			X										
PB2	X		X										
PB3													
PB4					X	X	X		X				
PB5						X							
PB6													
PB7													
PB8		X											
PB9													
PB10	X		X										
PB11		X	X							X			
PB12													
PB13													
PB14													
PB15													
PB16													
PB17													
PB18											X		
PB19		X				X							
PB20													
PB21													
PB22													
PB23	X		X										
PB24													X
PB25													
PB26													
PB27		X											
PB28										X			
PB29													
PB30													X
PB31													

↗	PB18	PB19	PB20	PB21	PB22	PB23	PB24	PB25	PB26	PB27	PB28	PB29	PB30	PB31
PB1														
PB2														
PB3														
PB4														
PB5														
PB6														
PB7														
PB8														
PB9														
PB10				X		X	X							
PB11														
PB12														
PB13														
PB14														
PB15														
PB16														
PB17														
PB18														
PB19					X									X
PB20					X				X					
PB21														
PB22				X			X							
PB23				X			X							
PB24				X										
PB25														
PB26							X							
PB27									X					
PB28									X					
PB29									X		X			
PB30														
PB31									X					

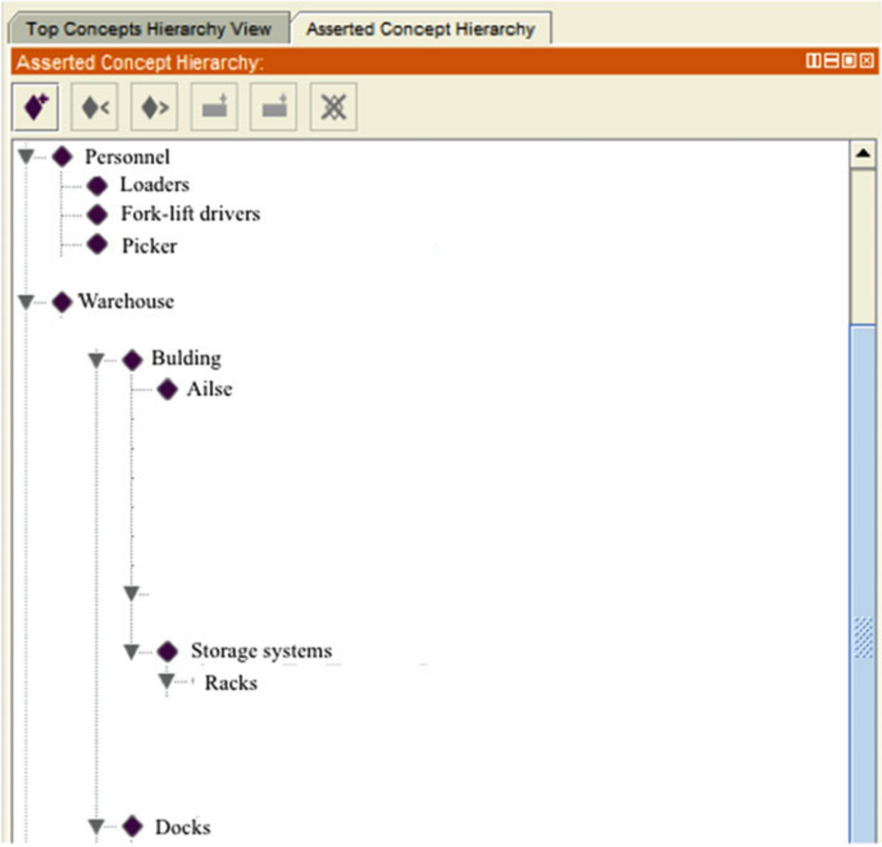
Appendix 4: Problems Solved by Solutions Extract

↗	SOL8	SOL12	SOL2	SOL25	SOL28	SOL38	SOL39	SOL45	SOL47	…	SOL35	SOL37	SOL40	SOL43	SOL46	SOL48	SOL49	SOL10	SOL6	SOL14	SOL16
PB1																					
PB2		X						X	X										X		
PB3																					
PB4										X											
PB5																		X			
PB6																					
PB7																		X			
PB8																					
PB9																					
PB10	X	X		X	X	X	X	X	X												X
PB11									X												
PB12									X												
PB13			X																		
PB14				X																	
PB15																					
PB16									X												
PB17																					
PB18																					
PB19		X																			
PB20									X												
PB21																					
PB22						X		X	X		X	X	X	X	X	X	X				
PB23				X				X									X				
PB24					X	X	X		X		X		X		X	X	X				
PB25						X							X				X			X	
PB26					X		X														
PB27																					
PB28					X		X														
PB29																	X		X		
PB30																					
PB31																					

Appendix 5: Solutions Generate Problems Extract

	PB1	PB2	PB3	PB4	PB5	PB6	PB7	PB8	PB12	PB13	PB14	PB15	PB16	PB17	PB18	PB19	PB20
SOL8																	
SOL12																	
SOL2																	
SOL25																	
SOL28																	
SOL38																	
SOL39																	X
SOL45													X				X
SOL47																	
SOL13	X	X															
SOL1																	
SOL3	X			X			X										
SOL44											X						
SOL4																	
SOL5														X			
SOL19											X						
SOL20																	
SOL34																	
SOL29																	
SOL33																	
SOL36																	
SOL41																	
SOL30		X															
SOL21		X															
SOL42																	
SOL26																	
SOL17																	
SOL18																	
SOL23			X														
SOL9															X		
SOL27																	
SOL7																	
SOL15																	
SOL11																	

Appendix 6: Taxonomy Extract, Protégé Screenshot



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Chapter 6
Key Indicators of Inventive Performance for Characterizing Design Activities in R&Ds: Application in Technological Design

Ali Taheri, Denis Cavallucci, and David Oget

Abstract This chapter is a synthesis of the contributions made by scientific authors about the evaluation of creativity and inventive activities, which aims to establish a baseline for measuring inventive performance. Although some lessons of this work have been published in a Ph.D. thesis, journals, and proceedings of international conferences, it provides an overall view of our findings during recent years in the form of a framework, namely, inventive design performance measurement system (IDPMS). The chapter introduces some new observations, citing related discussions for defining the key indicators of inventive performance. The purpose is to give a better understanding about the evaluation of creativity that leads to revising the research roadmap.

6.1 Introduction

Nowadays, our industries suffer from a lack of sustainable growth through innovation; however, most aspects of innovation management have been studied and formalized during the nearly 70 years of research work. Dert (1997) and Lundin and Midler (1998) were the first who considered innovation as a substantial factor for sustainable economic benefits and competitive markets. Recognizing innovation as a sustainable advantage stimulated companies to enhance their innovation capability that propounded innovation management as an increasingly covered topic in scientific literature.

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After 60 years focusing on four research themes of innovation management [individual innovation (1940s–1950s), organizational-driven innovation (1960s–1970s), external source-based innovation and outsider involvements (1970s), and innovation portfolio, integrated, and systematic innovation (1980s–1990s)], at the beginning of the twenty-first century, researchers admitted that innovation management needs a totally new paradigm to improve on its performance (Qingrui et al. 2000; Von Hippel 2007; Xu et al. 2007). Sustainable advantage through innovation occurs when all innovation projects launched within a company are capable of crossing competitive frontiers by proposing and implementing new ideas successfully (Dert 1997; Lundin and Midler 1998). The adverb "successfully" in this definition refers to the wealth creation and improvement of the competitive condition (Martins et al. 2011). A brief review of the literature on this issue shows that most studies have focused on the financial, managerial, and organizational dimensions of the development and marketing phases of innovation process and only very few studies on the design phase and inventive efficiency. However, invention is the basis of innovation, and inventive performance has been the most important factor to provide a higher level of sustainability.

With this introduction, the chapter will highlight the principal criteria of inventive performance from the perspective of innovation management.

6.2 In Search of Inventive Activities

In the engineering design, the innovation process is known as a process for developing new products [new product development (NPD)]. It consists of six stages, including idea generation, idea definition, idea evaluation, development, prototyping, and commercialization and marketing, with the target of achieving market success. According to the stage-gate model of Cooper and Elko (1995), between every two consecutive stages, there is a gate that verifies the achievement of requirements and validates output results to go to the next stage (Fig. 6.1).

In the innovation process, the design phase (the stages before development) poses a major threat to innovation performance index because the activities of the earlier stages deal with a fuzzy situation due to the fuzzy nature of creative behaviors and/or creativity, particularly when ideation is experienced in a high-level view.

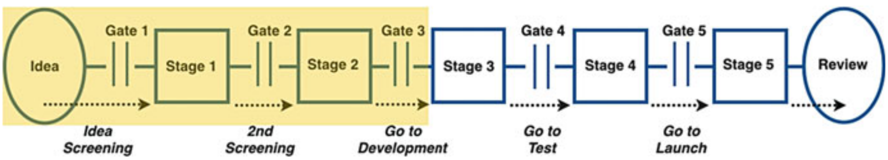

Fig. 6.1 The innovation process

Table 6.1 The terms used for mentioning design activities in the literature of design study[a]

Knowledge forms	Activities	Activities	Activities
Problems	Definition	Observation	Screening
Needs	Problem-solving	Invention	Analyzing
Requirements	Understanding	Decomposition	Decision-making
Existing solutions	Thinking	Identification	Evaluation
Data	Analyzing	Specification	Testing
Information	Formulation	Conception	Selection
Experiences	**Cognition**[b]	Expansion	Collection
Idea/Preconcept	Decoupling	Conjunction	Experimentation
Solution	Modeling	Disjunction	Verification
Concept	Elaboration	Exploration	Validation
Model	Enrichment	Divergence	Action
	Ideation	Synthesizing	Reflection
	Creation[b]	Designing	Modeling
	Prediction	Discovering	Clarification
	Proposition	Establishment	Determination
	Searching	Inspiration	Programming

[a] The activities of the design phase along the innovation process
[b] **Ideality** can cover each one of the engineering evolution law

Reviewing the terms used by scientific literature for mentioning design activities concludes that all the related activities are involved with cognition and creation; cf. Table 6.1.

Cognition includes all mental abilities related to knowledge processing (Hubka and Elder 2012) through attention, memorizing, judgment, evaluation, reasoning, comprehension, learning, problem-solving, and decision-making (Newell 1982; Lester 2009; Blomberg 2011). The creation here is about creative ability and artistic or intellectual inventiveness, which gives new meaning to existing facts (Balon 1999; Wallisch 2003). Creation in technological design is on a continuum with invention. Technological design occurs through a joint effort with art, science, and inventive activities (Weber and Perkins 1992), i.e., design without inventive activities is nothing but art. An inventive activity looks for combining available knowledge in a new and meaningful way to improve job performance through a rational use of available resources. However, inventive activities derive from the consideration of contradictions (Altshuller 1999).

6.3 Essential Elements of a Measurement System

Developing a standard set of indicators, metrics, measures, or benchmarks, in its initial phase, needs to be defined through three concepts: the level of measurement, dimensions, and uncertainties. Thus, any measurement system is judged by

Table 6.2 The levels of measurement for representing an object's magnitude

Levels of measurement	Description
Nominal	A nominal scale includes qualitative scales for differentiating between items (subjects) by classifying their characteristics, categories, and what the items belong to. The nominal scale type classifies subjects with the aim of explaining sensory measurements. So a nominal measurement is based on the modeling of qualitative data (Schofield 2007; Crotty 1998)
Ordinal	In an ordinal scale of measurement, data can be sorted in a rank order without presenting a relative degree of difference between them, e.g., in particular, IQ scores reflect an ordinal scale in which all scores are meaningful and a ten-point difference may carry different meaning at different points of the scale (Sheskin 2003; Bartholomew 2004). The ordinal types can include dichotomous data as truth values (sick versus healthy) and nondichotomous data as opinion (completely agree, mostly disagree, and completely disagree)
Interval	The interval scales allow measuring the degree of difference between subjects, but not the ratio between them, e.g., the Celsius temperature scale possesses an arbitrary-defined zero point
Ratio	In a ratio scale, the measurement is carried out by the estimation of the relationship between a continuous numerical magnitude and a unit numerical magnitude of the same kind (Wentworth 1922). The ratio scales possess a nonarbitrary zero point, e.g., the Kelvin temperature scale is a ratio scale. Most measurements in the physical sciences and engineering are done on ratio scales

verifying these meta-measurement criteria (VIM 2004). The level (scale) of measurement refers to the data types of representing the magnitude of an object.

In inventive design, the object is an idea. This is the term used by the US Supreme Court for naming the results of inventive activities (Schulze and Martin 2008). The nominal, ordinal, interval, and ratio are the four levels of measurement represented by Steven in 1946 (Stevens 1946); cf. Table 6.2.

A standard measurement needs its dimensions for tracking and quantifying. Here, dimension means the unit of measurement that presents a definite magnitude of quantity for estimating the amount of measurement. Within a standard measurement system, each dimension consists of an object (property), a standard magnitude, and a standard symbol (VIM 2004); cf. Table 6.3. Since the measurement of inventive performance includes qualitative evaluations with quantitative presentations, the property and standard magnitude will express in terms of degree, grade, range, and/or rate for describing the class of performance in a ranking order. Measurement uncertainty is concerned about the logic and the accuracy of measurement. In this regard, the measurement system should be modeled considering risk and a detailed comprehension about evaluations.

Table 6.3 The constituent elements of dimensions in measurement systems

Elements of dimensioning	Description
Property	A property is what belongs to the objects of measurement. Any property possesses an attribute that is expressed as a relative value of the chosen unit for measurement, e.g., considering length as a physical property
Unit	Units are the standard magnitudes for measuring properties. A unit in a measurement system is defined as a constant value that allows expressing different quantities of measurements, i.e., multiple values of the unit value, e.g., in the SI (the international system of units), the unit of length measurement is one ten-millionth of the distance from the Earth's equator to the North Pole (at sea level), which is known as meter (unit symbol)
Unit symbol	A unit symbol is what a measurement uses for expressing the value of a property, e.g., meter (m) that expresses SI-based measurements of length

6.4 Appropriate Level for the Analysis

Design performance can be analyzed at different organizational levels. In the literature, the firm level, project level, process level, and activity level are the prevalent organizational levels that have been discussed and considered for performance analysis (Schainblatt 1982; Cooper and Elko 1995; Wilson et al. 1994; Loch et al. 1996; Werner and William 1997; Cordero 1990; Kim and Oh 2002); see also Fig. 6.2. But which organizational level is more appropriate for analyzing inventive performance?

Reviewing the advantages and disadvantages of each organizational level confirms that the project level is the most appropriate level for inventive performance analysis. However, the activity level is the fundamental level of NPD projects. O'Donnell and Duffy (2005) implemented their performance analysis on the activity level. Their decision was emanated from the fact that design activities are fed by individuals' creativity (O'Donnell and Duffy 2005). As mentioned before, an inventive activity is linked with the cognitive and creative acts of individuals (Nijstad and Stroebe 2006). Although the performance analysis at the activity level provides detailed information on what is going on during creation, the issues caused by this consideration are not negligible. For example, specifying the boundaries of an activity is not easy to be clarified as O'Donnell and Duffy (2005) also did not specify the boundaries of a design activity for their analysis. Moreover, as they did not prepare a practical example of applying their measurement method, it can be concluded that the activity level is not the appropriate level for analyzing inventive performance. Furthermore, choosing the activity level leads us on to a second difficulty that arises with the definition of the results of an activity. This issue can be extended to the definition of resources used and all entries of an activity, which needs to verify a huge amount of data and information.

The process level presents the particular processes that are defined, scheduled, and implemented for organizing activities. Using the term "particular" for a process refers to the appropriateness of the process to achieve a specified goal through

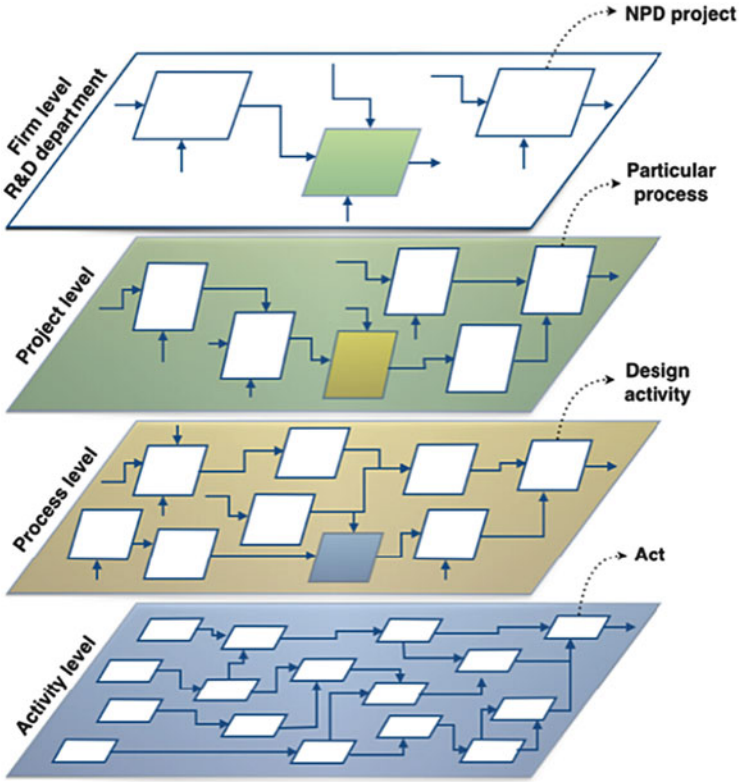

Fig. 6.2 The most prevalent organizational levels for design performance analysis

specific methods and technics. The particular processes in design projects should be able to enhance cognitive and creative activities. Although considering the process level as an intermediate level for performance analysis imposes less complexity vis-à-vis the activity level, this organizational level also involves the analysis with a large amount of data and information. However, the project level provides a much less complex condition and involves the analysis with the resultants of activities in the lower levels (the process and the activity levels). This is why the project level is the most prevalent level for analyzing organizational performance. Indeed, choosing the project level ensures a detailed and comprehensive performance analysis.

The firm level also provides a complex condition for performance analysis. R&D departments within companies are not only responsible for fostering and managing NPD projects but also operations research, marketing, manufacturing, and production. Hence, performing the analysis at this level may involve us with any other activities related to NPD projects, but not inventive activities, which provide a wide range of data and so a complicated analysis. In addition, the distance between the firm level and the detailed levels (the activity and process levels) puts at risk the accuracy of inventive performance measurement.

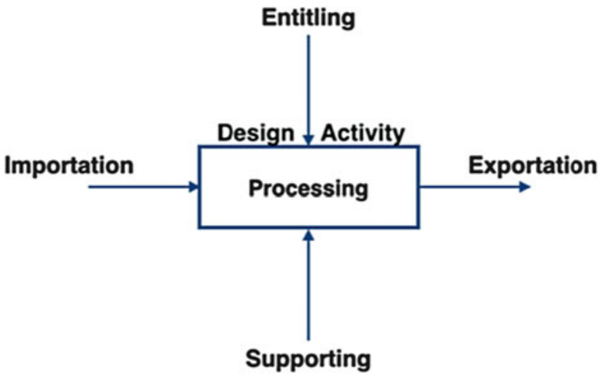

Fig. 6.3 The five operations of a design activity

6.5 Design Activities

Activities are the fundamental components of projects. Here, understanding the meaning of design activities gives a better performance analysis. Apart from the specified modality for design activities (inventiveness), a design activity can be described through the five operations: processing, importation, exportation, entitling, and support; see also Fig. 6.3. The objective of defining these operations is to understand what is going on between design activities, with a reasonable accuracy in the scope of the project level.

6.5.1 Processing

In the literature, a design activity is made up of rational and cognitive acts (Newell 1982; Hubka and Elder 2012). The input and output materials of a design activity are knowledge, and its task is knowledge processing for knowledge creation (O'Donnell and Duffy 2005; Popadiuk and Wei Choo 2006; Helfat et al. 2000; Pitt and Clarke 1999; McAdam et al. 2006; Von Krogh et al. 2006; Blomberg 2011). Several authors have recognized design activity as an interdisciplinary study of the mind and its processes (Blomberg 2011). Among the few works on how knowledge processing and knowledge creation are carried out during the design phase (Nonaka 1994), C-K theory provides one of the best descriptions with a real portrayal of what happens within a team (Hatchuel and Weil 2009). In this respect, knowledge processing for design is explained as an imputation system that in addition of ideation looks for attributing logical status to the initial concepts without logical status. Along this imputation process—which is known as knowledge creation—design activities are supported by knowledge acquisition and scientific research (McAdam et al. 2006); see also Fig. 6.4.

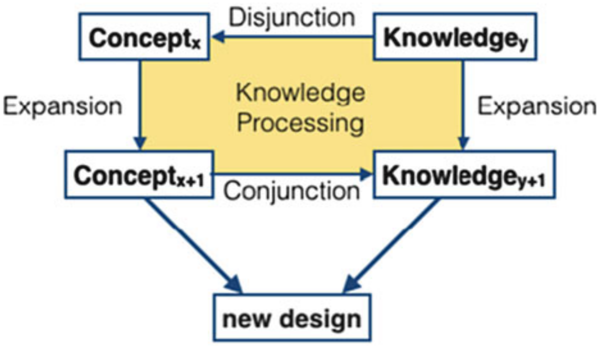

Fig. 6.4 The design square or the design loop in C-K theory

The scope of a unit of knowledge processing can vary from an activity to project level (including a set of activities); cf. Eq. (6.1).[1] In this circumstance, the resultants of all entries and exits—of all activities at the activity level—appear at the project level (O'Donnell and Duffy 2005).

$$\Psi_i : \text{the knowledge processing by design activity}\, i \tag{6.1}$$

6.5.2 *Importation and Exportation*

These operations refer to the importation and the exportation of knowledge into/from a design activity. C-K theory explains well the importation and exportation into/from design activities through considering concept and knowledge spaces (concept expansion, knowledge expansion, disjunction, and conjunction) (Fig. 6.4). At the project level, the inputs and outputs are respectively the initial and final states of knowledge before and after processing; cf. Eqs. (6.2, 6.3)[1]. Moreover, according to the literature on psychology and creativity, germination time and growing period are not the proper moments for analyzing the performance of design teams (Hindo and Grow 2007) (Fig. 6.5).

$$I_i : \text{the input knowledge of design activity}\, i \tag{6.2}$$

$$O_i : \text{the output knowledge of design activity}\, i \tag{6.3}$$

[1] {$\forall i$: might be one or a set of activities}.

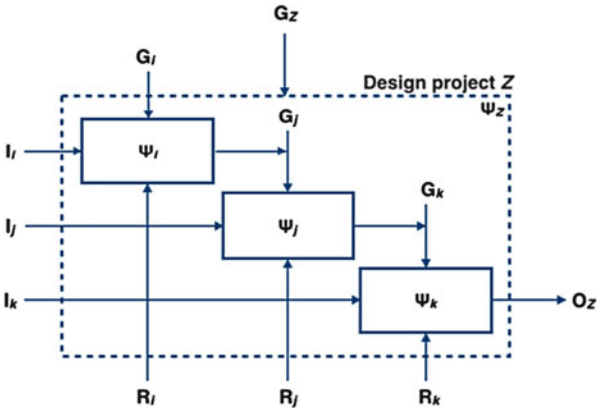

Fig. 6.5 Relationships at the project level

6.5.3 *Entitling*

Entitling a design activity within an NPD project refers to the assignment tasks to that activity regarding project goals. The goals of project level are distributed over the lower organizational levels by defining processes and scheduling the required activities; cf. Eq. (6.4)[1]. Concerning innovation projects, inventiveness is the generic goal of any activity and/or process.

$$G_i : \text{the goal of design activity}\, i \tag{6.4}$$

6.5.4 *Support*

The human resource is the main motor of design activities, and its absence cripples the whole knowledge processing for inventive problem-solving (Frankenberger et al. 2012). Supporting a design activity refers to what the knowledge processing needs to ensure the achievement of activity goals. In this respect, the human resources, particular processes (proper methods), tools, software, environment, and all equipment used for carrying out design tasks are the resources of knowledge processing for design; cf. Eq. (6.5)[1]. For analyzing design performance at the project level, all resources used during the earlier stages should be considered.

$$R_i : \text{the resources used for carrying out design activity}\, i \tag{6.5}$$

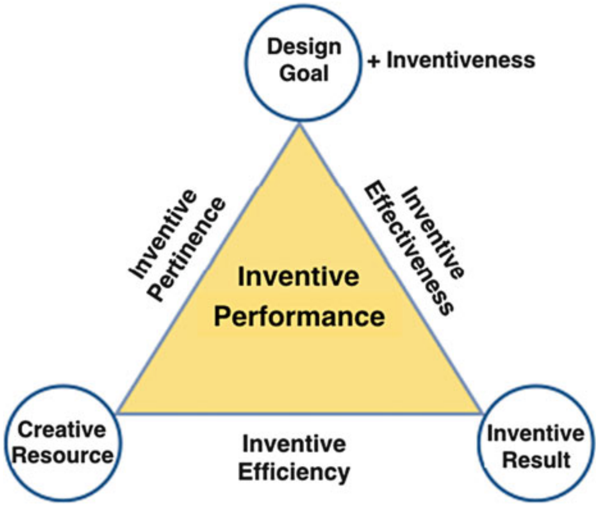

Fig. 6.6 The key elements of analyzing inventive performance

6.6 Inventive Performance

Reviewing the studies on design performance reveals that such analysis depends on three elements: the effectiveness of carrying out design tasks, the efficiency of design activities, and the pertinence of resources and knowledge used for fulfilling activities. Attributing inventiveness to performance analysis involves the performance elements to conduct the analysis regarding inventiveness; see also Fig. 6.6.

6.6.1 Inventive Effectiveness

Effectiveness is defined as the capability of producing desired results (O'Donnell and Duffy 2005; LLC 2011). In other words, effectiveness means the capability of realizing design intent according to what has been imagined or intended. In this respect, the term design intention is explained as what has been expected to be achieved in a deep and vivid impression (LLC 2011). Thus, effectiveness in design signifies "the degree to which result (output) meets project goals" (O'Donnell and Duffy 2005). Indeed, design effectiveness looks for the evaluation of the quality of outputs at the end of the earlier stages of innovation projects (Shah 2003). Thus, design effectiveness expresses how much the outputs of an NPD project conform to project goals. The effectiveness value of a set of design activities is evaluated by

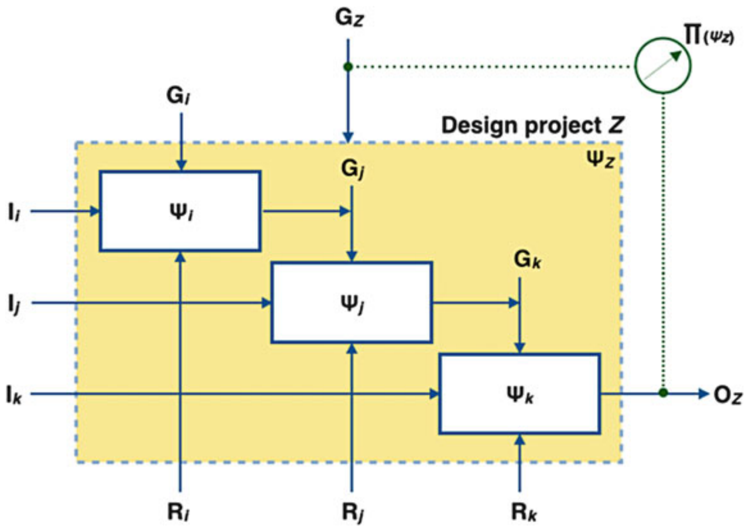

Fig. 6.7 The comparative relationship for evaluating design effectiveness at the project level

comparing outputs and goals; cf. Eq. (6.6)[2,3]; see also Fig. 6.7. By this definition, project goals have the role of reference points by comparison.

$$\Pi(\Psi_i) : O_i == G_i \tag{6.6}$$

An inventive design project, alongside achieving a certain goal specified for the project, should generate inventive results. Here, the term *inventive* as the adjective of activities emphasizes that the dominant goal for all outputs is *inventiveness*. In this regard, the question to ask is this: What are the criteria for measuring inventive effectiveness (inventiveness-based effectiveness)? Regardless of user satisfaction and/or the economic competitive advantages, inventiveness is considered as a subjective goal to obtain through design activities. Indeed, inventive effectiveness can be obtained by carrying out design activities in a creative manner. However, inventive outputs (inventions) remain as the main demonstrators of the accomplishment of inventive activities. In the literature on design measurement, inventiveness has the same meaning as creativity (Wunsch-Vincent 2011; Demirkan and Afacan 2012; Shah 2003; Sarkar and Chakrabarti 2011; Dean et al. 2006; Shah et al. 2000). Among the different criteria of inventiveness discussed in the literature (cf. Table 6.4), novelty and usefulness seem essential for admitting an inventive design (Sarkar and Chakrabarti 2011). That is because most listed criteria about

[2] Π (Ψ_i): the effectiveness value (Π) of design activity i

[3] $O_i == G_i$: comparison between the outputs and the goals of design activity i

Table 6.4 Different characteristics of inventive effectiveness in the literature

Criteria of inventive effectiveness	Author
Originality	Stein (1953)
Novelty	Guilford (1950)
Originality, usefulness, valuable	Barron (1955)
Novelty, solution, elaboration and synthesis	Bessemer and Treffinger (1981)
Novelty, appropriateness	Amabile (1996)
Originality, utility	Runco (1988), Runco and Jaeger (2012)
Originality	Redmond et al. (1993)
Originality, usefulness	Woodman et al. (1993)
Novel, valuable	Weisberg (1993)
Rarity	Eisenberger and Selbst (1994)
Novelty, non-obviousness, relevance, workability, thoroughness	MacCrimmon and Wagner (1994)
Originality, purpose, implementation	Wagner (1996)
Novel (unexpected, original), appropriate (useful, adaptive)	Sternberg and Lubart (1999)
Originality, appropriateness (usefulness)	Reiter-Palmon and Illies (2004)
Novelty, non-obviousness, relevance, workability, specificity	Dean et al. (2006)
Novel, valuable (technical, engineered), utility (usefulness)	Sarkar and Chakrabarti (2008)
Originality, fluency, flexibility, elaboration	Torrance (1965)
Novelty, utility	Batey (2012)

inventiveness or inventive design—such as appropriateness, valuable, adaptivity, or unexpected—refer to novelty and/or usefulness, and some others such as fluency and elaboration have yet remained as the ambiguous concepts even after reviewing their definitions.

In addition to these criteria, Altshuller et al. in their works (Altshuller 1984, 1988) discussed technological evolutions and defined nine evolution laws for engineering design (Table 6.5). Among these laws, ideality seems to be the most significant notion, and this emanated from the fact that ideality is the common consequence of implementing each one of the eight other evolution laws. Thus, each evolution law, in its turn, looks for leading design activities to get closer toward an ideal system. Laws 2, 3, and 8 directly and laws 1, 5, 6, 7, and 9 indirectly affect approaching ideality systems (Table 6.5) (Cavallucci et al. 2009). The influence of considering the evolution laws to enhance ideality is so obvious that the theory of inventive problem-solving (TRIZ) (Altshuller 1988) is known as a holistic method for generating a portrait of ideal systems (Cavallucci and Eltzer 2011; Cavallucci et al. 2010). Therefore, ideality is considered as a principal criterion for evaluating inventive effectiveness, alongside novelty and usefulness.

On the other hand, according to intellectual property (IP) laws, three criteria exist for verifying the patentability of technological systems. Although IP offices are established nationally, multinationally, and internationally, the patentability criteria of industrial properties for granting patent agreements are almost similar and generally based on meeting novelty, usefulness, and nonobviousness through

Table 6.5 The evolution laws of technological design by Altshuller (1988)

TRIZ evolution laws for engineering design	Description
1. Completeness of systems	This law describes the minimal requirements of a technological system. Accordingly, any technological system requires these four parts to be completed: engine, transmission, worker, and control. The lack of each one of these parts for defining a system demolishes the signification of a system. However, the control part is not essential
2. Energy conductivity	This law is about the energy flow through a system's parts (components), i.e., the completeness of a system is verified by optimizing the flow of energy through different parts for maximizing the ratio between the transmitted and consumed energy
3. Harmonization	This law looks for maximizing the performance of a technological system by coordinating system's parts
4. Ideality	This law is concerned with the ideality value of technological systems. By technological evolution, systems tend to approach an ideal design or improve the ratio of system performance and system cost
5. Irregularity of evolution	This law describes that different parts (components) within a system evolve irregularly
6. Integration with supersystems	This law implies the tendency of new designs to be integrated with their supersystems, i.e., technological systems tend to merge with their supersystems
7. Integration with micro-level	This law describes the transitions from macro-level to micro-level. The law refers to the advantage of using properties of dispersed material (e.g., tools) and particles of physical fields within technological systems
8. Dynamization	This law describes the dynamic growth by technological evolution, when technological systems, in order to achieve higher performance, tend to be more flexible, adaptable (by changing the working conditions and requirements), and changeable (in terms of structural entity)
9. Substance-field interactions	This law is concerned with the improvement of technical performance of systems by using the elementary rules (including physical effects) of inventive standards (70 standards of TRIZ). Considering physical effects (substance-field interactions) helps systems to be more controllable

Ideality [bold] covers the signification of all other Engineering Evolution Laws

new designs (Table 6.6). Indeed, these three criteria must be met in a substantive condition with design outputs (Kuznets 1962; Robertson et al. 2009; Mishra 2014; Nuvolari and Alessandro 2006). Among the IP criteria, nonobviousness seems a little ambiguous, which needs to be discussed and clarified.

In the literature, the term nonobviousness possesses various interpretations due to unclear definitions in the law. The lack of a clear understanding of nonobviousness poses difficulties for recognizing patentable concepts. In 2003, the Federal Trade Commission (CFT 2003) defined nonobviousness as an idea generation with a level beyond the expectation of skilled users. Here, the question is: What does the expectation of skilled users for the next evolution mean? The

Table 6.6 The patentability criteria of industrial properties in different IP laws

Intellectual property office	The prescribed criteria for the validity of patentability
Europe	*Novelty*: an invention must be strictly new. It must not be found at a previous date in any matter (TP/P) *Inventiveness*: any invention must involve an inventive step, i.e., an ordinary brain with experiences in the art should not be able to derive the claims *Industrial application*: an invention must have an industrial application or be susceptible of industrial application
USA	*Novelty*: an invention must be new *Utility*: an invention should be useful *Nonobviousness*: an invention must not be obvious to anybody having ordinary intelligence and knowledge on the subject matter
Japan	*Novelty*: an invention must not be publicly known, publicly used, and publicly available through an electric telecommunication line *Inventive step*: an invention at the time of the application should not have been easy to make for a person who is ordinarily skilled in the field of art to which the invention belongs *Industrial application*: an invention must be specified for a concrete application use
India	*Novelty*: an invention must be a new TP/P (technological products/processes) during the examination procedure, i.e., invention is disqualified by any indication of prior use *Nonobvious*: an invention as a new TP/P involves an inventive step *Useful*: an invention even though obtaining novelty and nonobvious features cannot be patented unless and until it has some use to mankind
WIPO	*Novelty*: an invention must be new (novel) *Inventive step* (be nonobvious): an invention should not be obvious to a person who is skilled in the art at the time the patent application was filed *Industrial application*: an invention must be useful

meaning of user expectation is not the same as the decision-makers' anticipations for a hedonic future (Kahneman and Snell 1990). The expectation of skilled users is in relation with the term "expected world" by Gero and Kannengiesser (2004), which refers to an ideal condition for the incredible and conceptual ideas proposed by designers. In this respect, the expectations of skilled users should be translated as the intuitive predictions of experts about new generations in a product family. The intuitive predictions are typically nonregressive. Experts with both singular and distributional information (knowledge) often make the extreme predictions on the base of the information whose reliability and predictive validity are known to be low (Kahneman and Tversky 1977). The lack of reliability and/or the low predictive validity in the expected world derives from the concepts without logical status. Hatchuel et al. (2010) also, in C-K theory, try to explain how the credibility gap between an expected world and a real world is filled through the associations from existing knowledge even after knowledge expansion (by research and development). Accordingly, since the term nonobviousness is used to highlight the achievement of new solutions (new ideas) in real the world (with logical status), the knowledge of a skilled user is assumed to be equal to all existing solutions (with logical status) at the moment of proposing a new solution. In addition, in the words of IP laws, the occurrence of nonobviousness depends on the existence of an inventive step during the design phase (the earlier stages of NPD processes) (Barton 2003). According to Altshuller (1984), an inventive step at the design phase occurs when at least one technical contradiction is configured and considered for solving after reviewing existing solutions (Salamatov et al. 1999). By considering all these views, nonobviousness is defined as the proposition of a new solution (an idea with logical status) through considering an unsolved contradiction or beyond the existing solutions of a solved contradiction. Indeed, considering a contradiction at the problem modeling step of any problem-solving process is necessary but not sufficient for obtaining an inventive step.

So, we can be conclude that the value of inventive effectiveness in engineering design depends on the novelty, usefulness, and ideality values of the outputs of inventive problem-solving. Recognizing the principal criteria of evaluating inventive effectiveness leads the study to further steps, such as:

1. Understanding each of the inventive effectiveness criteria (novelty, ideality, and usefulness)
2. Developing an integrated measurement system for evaluating the inventive effectiveness criteria
3. Defining the evaluation method and related indicators

6.6.2 Inventive Efficiency

Efficiency, in general, refers to the productivity rate of any process (Chiou et al. 1999). It presents the extent to which the resources allocated to a process—such as time, cost, and efforts—have been used as well as possible when the specified goal has been achieved completely. In the literature, the efficiency of any system, process, operation, and organization is defined as "the ratio of useful work performed to the total resources expended" (Sim and Duffy 2003). In technological design, the useful work of activities results in knowledge gain (K^+) by using the required resources (R) in performing the activities; cf. Eq. (6.7)[4,5,6]; see also Fig. 6.8.

$$\eta\,(\Psi_i) = \frac{K_i^+}{R_i} \tag{6.7}$$

[4] $\eta\,(\Psi_i)$: efficiency value (η) of design activity i

[5] K_i^+ : knowledge gain by design activity i

[6] R_i : resources used by design activity i

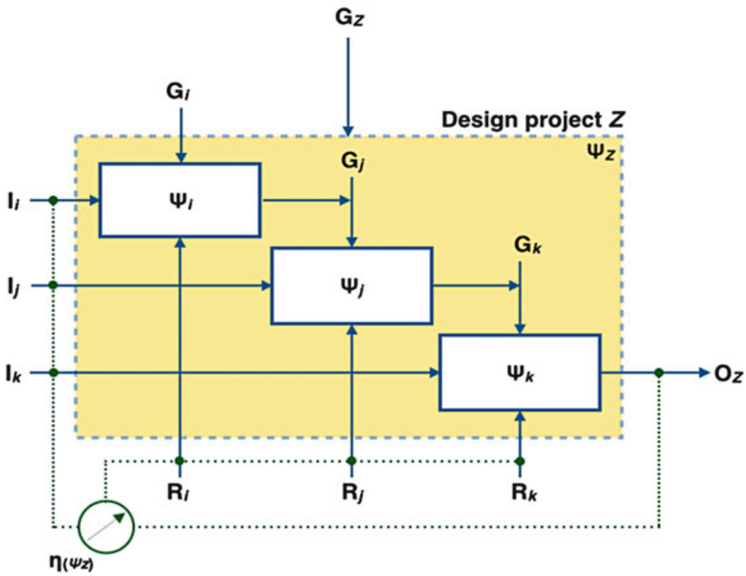

Fig. 6.8 The relationships for measuring efficiency at the project level

The knowledge gain from a design activity is the amount of technological evolution which is obtained by comparing the output knowledge with the input knowledge (design effectiveness). This comparison, concerning the measurement of inventive efficiency, must be implemented according to inventive effectiveness criteria. Indeed, the amount of technological evolution regarding inventiveness is considered equal to the value of inventive effectiveness; cf. Eq. (6.8).

$$K_i^+ = \{(O_i - I_i) == G_i\} = \Pi(\Psi_i) \tag{6.8}$$

The consumption rate of resources used by design activities is another necessary criterion for measuring efficiency. Here, the consumption rate refers to the consumption level of the resources allocated for performing design activities (Duffy 2012). Since different activities may use various resources, all resources have been summarized into three criteria as time, cost, and human resource for avoiding the complexity of managing diverse data and data conversion. Moreover, as the human resource is the engine for performing design activities and the other resources are in service to the human resource, its combinations with time and cost are considered as the significant measures for analyzing creativity through cerebration; cf. Table 6.7.

Thus, the value of inventive efficiency of an activity may be presented on the basis of various criteria of resources used. Table 6.8 presents the different measures of inventive efficiency.

Table 6.7 The generic criteria of resources used (R) by a design activity

R in detail	In general	Sign	Unit	Description
• Duration of using methods • Duration of using materials • Duration of using tools • Duration of using minds	Time	t	Hour	How much time has been spent for performing inventive design activities during a design activity?
• Cost of methods used • Cost of materials used • Cost of tools used • Cost of team • Cost of environment	Cost	c	Euro	How much money has been spent for performing an inventive design activity?
• Salary of designers	Human resource	hr	Cerebration (minding)	How many brains have been engaged for inventive minding for a design activity?
• Duration of using minds	Man-hour	mh	Man-hour	How much work has been performed by a designer in 1 h?
• Cost of using minds/hour	Man-hour cost	mhc	Euro	How much money has been spent for a man-hour?

Table 6.8 The different measures of inventive efficiency regarding different resources used

Resources used (R_i)	η (Ψ_i)[a]	Measures of inventive efficiency
Time	$= {}^{\Pi\Psi_i}/_{t_i}$	Inventive efficiency of design activity i (IE_i)t
Cost	$= {}^{\Pi\Psi_i}/_{c_i}$	Inventive productivity of design activity i (IP_i)
Human resource	$= {}^{\Pi\Psi_i}/_{hr_i}$	Inventive creativity of design activity i (IC_i)
Man-hour	$= {}^{\Pi\Psi_i}/_{mh_i}$	Inventive frequency of design activity i (IF_i)
Man-hour cost	$= {}^{\Pi\Psi_i}/_{mhr_i}$	Net inventive productivity of design activity i (NIP_i)

[a] Inventive efficiency of design activity i

6.6.3 *Inventive Pertinence*

Pertinence, as the third element of design performance, severely affects the other elements of performance analysis (effectiveness and efficiency). This effect arises from the fact that pertinence signifies the degree to which a resource enhances design activities to meet project goals; cf. Eq. (6.9). In other words, pertinence looks for recognizing the resources in consonance with achieving project goals; see

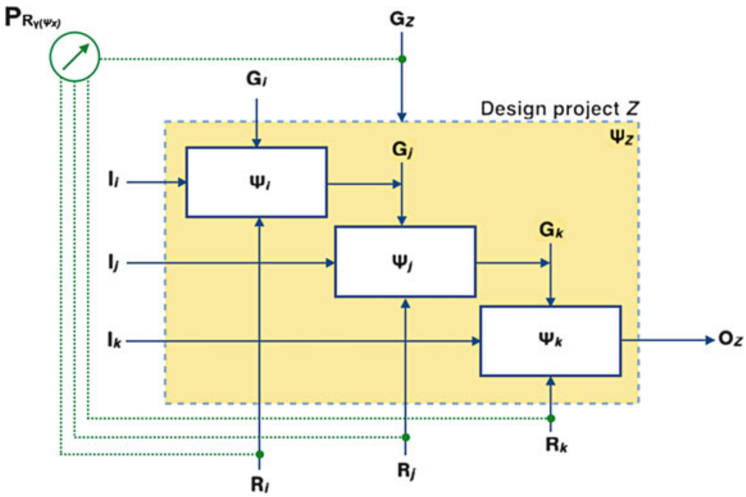

Fig. 6.9 The relationships for measuring inventive pertinence

also Fig. 6.9. Concerning inventive design, the resources must be qualified for supporting creativity and/or inventive activities. Although a few works have been devoted to analyze the pertinent resources of creativity through empirical studies, none of them are comprehensive with ranking resources against each other.

$$P_{R_y}(\Psi_i) : \text{the pertinence value of resource used } y \text{ for design activity } i \tag{6.9}$$

6.7 Conclusion

Since the common mistake of several studies about design performance arises from a misunderstanding of the key criteria, this research contributes to scientists' understanding of analyzing inventive design performance that has today become an increasingly covered topic in scientific and management literature. The first objective of this work was to provide the baseline for developing invention metrics. The second objective was to raise the attention of designers, engineers, and R&D managers on inventive performance and its criteria for enhancing design activities and approaching sustainability.

In this work, the meaning of inventive activity within innovation projects was explained, the elements of analyzing design performance were presented, and the appropriate level for this analysis was discussed. A design activity was presented with five operations which give a detailed understanding of design projects. Moreover, the main criteria of inventive performance were studied with respect to their definitions. The relationships for measuring each criteria were also discussed and figured out.

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Chapter 7
Optimization Methods for Inventive Design

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Abstract The work presented in this chapter deals with problems of invention where solutions of optimization methods do not meet the objectives of problems to solve. The problems previously defined exploit, for their resolution, a problem extending the model of classical TRIZ in a canonical form called "generalized system of contradictions." This research draws up a resolution process based on the simulation-optimization-invention loop using both solving methods of optimization and invention. More precisely, it models the extraction of generalized contractions from simulation data as combinatorial optimization problems and offers algorithms that provide all the solutions to these problems. In addition, it provides heuristics to select variables and their relevant values involved in generalized contradictions and/or useful for optimization. The contributions concern theory and practice of the inventive design. The work also explores cross-fertilization between optimization and TRIZ.

7.1 Introduction

The work presented in this chapter is part of research efforts conducted over the last 15 years in the Laboratory of Design Engineering (LGECO) within the context of applying the theory of inventive problem solving, also known as Teorija Reshenija Izobretateliskih Zadatch (TRIZ), and its extensions in different domains. Details regarding the proposed algorithms and relevant examples are provided in several papers and organized in a more extensive but comprehensive manner in Lin (2016). TRIZ, developed by Altshuller (1985), is a set of methods and tools organized into one system to facilitate the invention of physical objects. The underlying principle behind the combination of methods that constitute TRIZ is based on a set of

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fundamental assumptions derived from dialectics and analysis concerning the evolution of technical systems. As a significant portion of innovative research carried out in this field is of increasing order, it aims to improve different components of existing approaches. Some foundations of TRIZ, such as dialectical thinking, are very generic. Several studies have attempted to take an approach analogous to Altshuller's work for other application domains, such as management, advertising, and logistics. If these research works had achieved some success, recurrent difficulties in the implementation of the problem formulation through their underlying contradiction could be solved by the same approach. This was also one of the problems when the laboratory initiated research work on the identification of contradictions that underlie simulator system limits by developing numerical models of system behavior. To accomplish this, the definition of the concept of contradiction, as defined by TRIZ, was too vague to use with computer tools. This definition could be the origin of difficulties for human users when attempting to define and understand contradictions. Because of these practical and theoretical reasons, the definition of contradiction has been revised, and a generalized contradiction model has been proposed in Dubois et al. (2009a). This new contradiction model is even more difficult to identify and understand by humans; however, it is sufficiently precise to be processed by a computer, assuming that enough data regarding the system behavior is available.

The first objective of our research work is to propose the methodology, tools, and algorithms to identify these contradictions, from experimental data or system simulation data, and to understand and formulate system problems and search for their solutions. The second objective is to use these new tools to analyze and explain certain practical difficulties that humans encounter when identifying contradictions. Finally, research on the formalization of generalized contradictions has reinforced our idea that there is a link between optimization theory and inventive problem solving through the concept of contradiction. Furthermore, the tools developed in this work aim to explore the link between optimization theory and inventive problem resolution by using the concept of generalized contradictions and the Pareto line.

The following section discusses the background of our research work, especially the concept of contradiction in TRIZ. The specific model used in our research is the generalized system of contradictions (GSC) involving generalized technical and physical contradictions. We use the formalism of the experimental design as the common model permitting support for optimization and inventive methods used to illustrate, identify, and extract generalized contradictions. Our problem is presented through several questions, and to answer these questions, a research method is proposed; questions are answered completely or partially through the utilization of the proposed algorithms. The general framework of the inventive design problem-solving process is proposed, and the results and prospective for future research are discussed.

7.2 Background

7.2.1 From Optimization to Invention

Problem solving is a common activity in a number of domains, and its crucial role in design is particularly recognized in Bonnardel (2000) and Gano (2001). Different methods and tools are available to formulate and solve design problems. Two types of design problems are identified. Once modeled, the optimization design problem entails searching for values for a fixed set of variables. This approach prompts the objectives to arrive at an optimal value without changing the model or without creative design. Optimization methods have been proven to be effective in many situations but not for inventive design problems that require the improvement of a system by adding new variables or new relationships between variables. Optimization algorithms cover a search space of potential solutions, which is limited by the stated problem space. If no solution is found, the classical optimization algorithms are unable to continue exploring the solution space. For such cases, the inventive solving theory TRIZ proposes methods to change the stated problem model, thereby defining a new problem space. Our approach of model change is based on the best results developed from the optimization methods and represented by the Pareto front (Collette and Siarry 2004). By considering an arbitrary optimization problem with k objectives, where all objectives should be minimized and equally important, i.e., no additional knowledge about the problem is available, we can assume that a solution to this problem can be described in terms of a decision vector in the decision space X. Subsequently, a function can be developed that evaluates the quality of a specific solution by assigning it an objective vector in the objective space Y (Fig. 7.1).

Following the well-known concept of Pareto dominance, an objective vector Y is said to dominate other objective vectors if all components of the considered vector are as good as the components of other objective vectors and at least one component of Y is better. Accordingly, we can say that one solution is better than another, i.e., x_1 dominates x_2, if $f(x_1)$ dominates $f(x_2)$. Here, optimal solutions, as defined by solutions not dominated by any other solution, may be mapped to different objective vectors. In other words, there may exist several optimal objective vectors representing different trade-offs between the objectives.

Our goal is to go beyond this limit represented by the Pareto front and obtain results from the desired objective space. For this purpose, we use the best solutions obtained by the optimization methods and issued from the Pareto front representing a conflict of performance. As an example (Fig. 7.2), for solution 1, the evaluation parameter EP1 is better than that for solution 2; however, the evaluation parameter EP2 is worse and vice versa. This conflict in the evaluation (objective) space is a limit expressed by technical contradiction. This conflict also represents an entry point to use the dialectical approach with the view of contradiction corresponding to this conflict, as shown in Fig. 7.2. The subsequent task is to determine how to

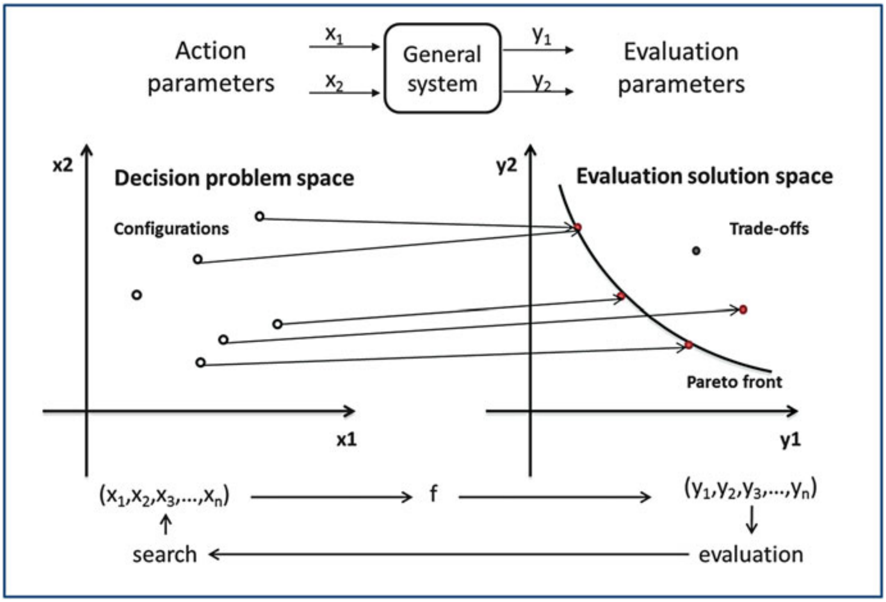

Fig. 7.1 Illustration of a general multi-objective optimization problem

translate this conflict via the search space system parameters, which correspond to the physical contradiction within the TRIZ theory.

7.2.2 The Dialectical Approach and Contradiction

The inventive design is based on specific principles of problem solving to offer new, creative solutions that meet the specifications. TRIZ is based on the dialectical approach to problems. One of the axioms of TRIZ states that the evolution of technical systems requires identifying and resolving contradictions. These contradictions emanate from the apparent impossibility of meeting the changing requirements in a specific context; they manifest a conflict of values between the parameters of technical systems. TRIZ formulation offers different levels of contradictions, of which only two are relevant to the resolution of the problem: technical contradiction and physical contradiction. OTSM-TRIZ (Khomenko and De Guio 2007), which was developed to apply the axioms of TRIZ to build methods of resolution of invention problems for nontechnical systems, further provides a system of contradictions that binds the two previous levels of contradiction. A technical contradiction expresses the opposition between two parameters of a system and that the improvement of one of the parameters causes the degradation of the second. Physical contradiction defines two contradictory statements required for a single parameter. The system of contradictions connects a physical

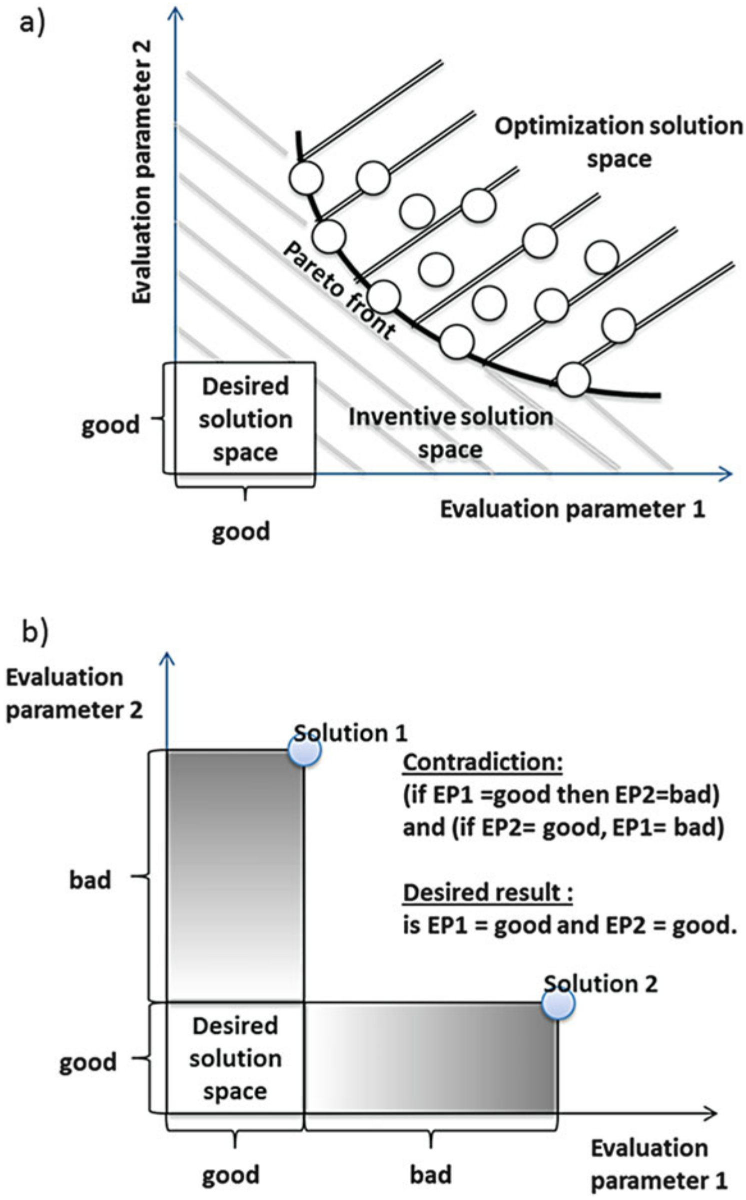

Fig. 7.2 From optimization to invention through a contradiction

contradiction to two technical contradictions that express why the two contradictory statements are required. Both technical contradictions are complementary and correspond to the improvement of the first parameter, which causes the degradation of the second, and vice versa (improving the second parameter causes the degradation of the first). In Eltzer and DeGuio (2007), the two parameters involved in the technical contradictions were named evaluation parameters as they participate in the definition of the objective of the problem, while the parameter characterizing the physical contradiction defines a way to act on the situation, which was named the action parameter (AP). Note that, in the evolution of the TRIZ technical contradiction, suitable resolution methods came first, and more than a dozen years after it appeared, the concept of physical contradiction was accompanied by a new family of methods. Altshuller reflected a deeper contradiction for physical contradiction (in the sense of dialectics). Readers interested in the philosophical groundings and methodologies consistent with the TRIZ approach of contradiction can refer to Sève and Guespin-Michel (2005), Sève (1998), and Brohm (2003). The assumption was that, behind any technical contradiction, a more fundamental contradiction, physical contradiction, was hiding. The interesting point of this TRIZ model is that it highlights the link between the design space and the evaluation space. Figure 7.3 shows the model of contradiction of OTSM-TRIZ and provides an example of the mapping between the evaluation space and the design decision space. Indeed, let us consider, for instance, point solution 1 in Fig. 7.3. This point fits only the objective for y_1, not the y_2 evaluation parameter. The Pareto front expresses the fact that it is not possible to simultaneously reach the objective for both the y_1 and y_2 evaluation parameters with the actual known model of solutions. Thus, solution 1 of the Pareto front expresses TRIZ technical contradiction 1 (TC1). Similarly, solution 2 of Fig. 7.3 and Pareto knowledge express technical contradiction 2 (TC2). The physical contradiction linked to the previous technical contradictions is obtained in the decision space. To get solution 1 (reach the objective for y_1), it is required that our actual systems have x_1 at value 1, but unfortunately, in this case, the objective for y_2 is not reached. Alternatively, to reach solution 2 (reach the objective for y_2), it is required to

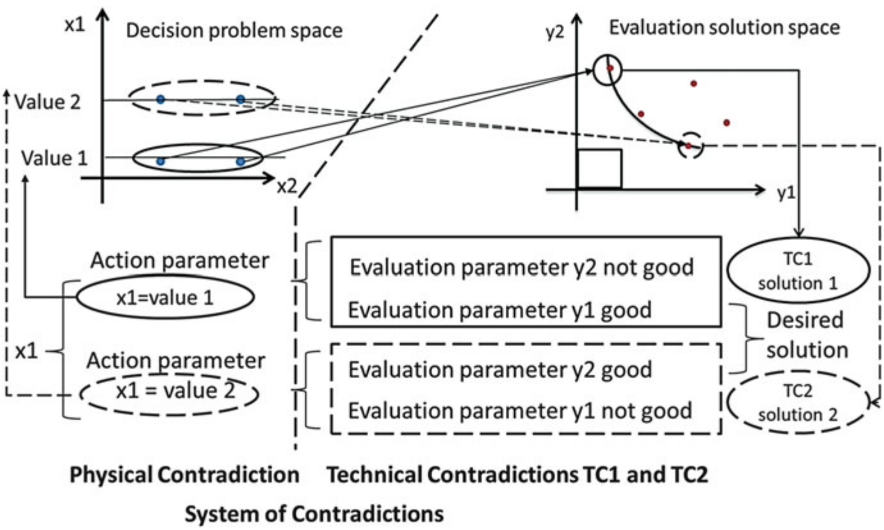

Fig. 7.3 OTSM-TRIZ system of contradictions and analogy in the problem space

have x_1 at value 2, but the objective for y_1 is not reached. To summarize, to reach the objectives for y_1 and y_2 simultaneously, it would be necessary to have x_1 at value 1 and value 2 simultaneously, which is a physical contradiction.

In this example, the physical contradiction in the decision space provides a picture of the Pareto trade-off in the evaluation space. Let us be precise from the point of view adopted in this chapter concerning Pareto points. Pareto points in mathematics represent the optimal solutions of the Pareto dominance relation. The concept of compromise only appears when none of them is satisfying for the decision maker. In this case, the problem of the decision maker (not the designer) is to choose among these points and not to propose new solutions as in inventive design. In our case and in TRIZ, the designer wants to get a new solution beyond the Pareto points toward the ideal because they are not satisfied with the solutions of the Pareto set (i.e., with our model, going beyond Pareto is contradictory to our goal). Nevertheless, comparing the points of the Pareto set allows the conflicts among evaluation parameters to be expressed when aiming to improve a solution toward the ideal point.[1] Indeed, points of the Pareto set express that, in existing models of our system, we cannot improve any evaluation parameter without worsening at least one of the others, which is contradictory to our goal of improving at least one parameter without worsening any other.

The motivations to use the dialectical approach are twofold. On one side, contradictions permit a better understanding and formulation of the problems regarding inventive design. Alternately, the problem-solving procedure can be perceived strictly as a procedure for solving contradictions. Another argument to use the dialectical approach is the possibility of coupling the optimization and inventive solving principles to improve the performance of the design problem-solving process. The contradictions must be clear and understandable in the early stage of the resolution process in order to choose one contradiction to resolve. A bad choice of contradiction can lead to a decrease in the effectiveness of the problem-solving process. Hence, the extraction and the interpretation of contradictions play an essential role in the dialectical approach. TRIZ does not resolve the question of the appropriate choice of contradiction. Our hypothesis, explaining this particular practical problem of choice of contradiction, is that the concept of contradiction within TRIZ should be reworked and clarified.

As far as classical TRIZ contradictions are concerned, there are several limitations and gaps in their definition and utilization. We note in certain situations the proven absence of contradictions, appearing from the available relations between the variables of a system, which corresponds to the definition of contradiction provided by the classical TRIZ approach (Dubois et al. 2009a). A sample of the absence of physical contradiction described with only one parameter of the model is given in Fig. 7.4, where the conflict between the two points of the Pareto in the

[1]The ideal point is the same as defined in optimization (i.e., the point with the best value for each parameter). It is not necessarily the ideal final result of TRIZ.

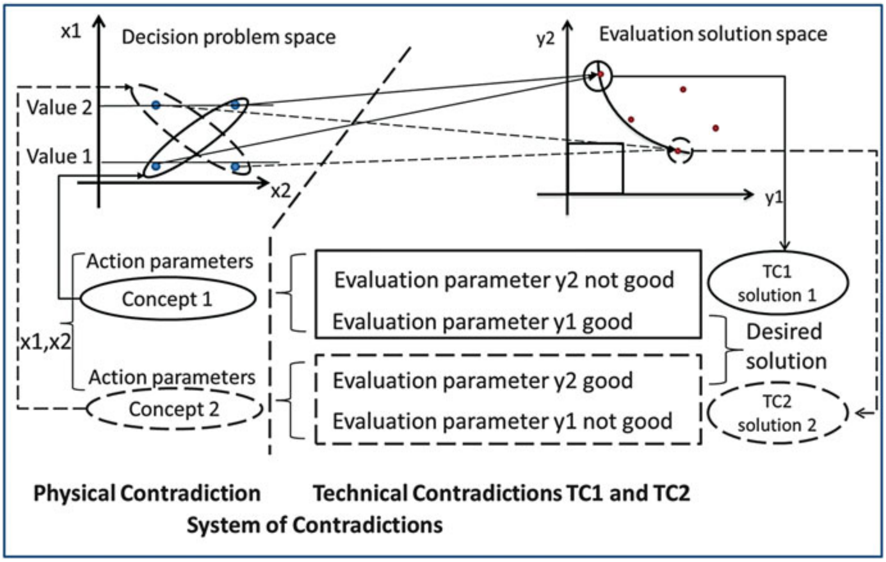

Fig. 7.4 Limit of a classical TRIZ system of contradictions

evaluation space cannot be described in the design space with only one parameter of the model. The limitation of the classical TRIZ model of technical contradiction is easy to highlight when there are at least three evaluation parameters: it is possible to find systems that meet the requirements for each pair of evaluation parameters but never for the three of them, and thus this type of system has no technical TRIZ contradiction.

The observed general trend can be summarized as follows: the more the experiments and knowledge regarding a system that exists, the lower the chances of finding a technical contradiction (i.e., an input for inventive problem-solving methods). Another inconvenience is that the classical technical contradiction considers only two evaluation parameters. Supposing that there exists a technical contradiction that can be solved, nothing can be said about the satisfaction of the other evaluation parameters. Moreover, there is a lack of explicit definition of the context required to validate the contradictions for the problem-solving method.

To address these limitations, the concept of a GSC involving generalized technical contradictions (GTC) and generalized physical contradictions (GPC) was proposed in the previous work (Dubois et al. 2009a) as an enhanced equivalent to the classical TRIZ contradictions. These generalized concepts avoid situations where no classical TRIZ technical and physical contradictions exist, as was mentioned before. The GTC model in Fig. 7.5 replaces two evaluation parameters defined in a classical technical contradiction with two concepts of evaluation parameters. A concept consists of an evaluation parameter or a logical disjunction of several evaluation parameters. One parameter can only participate in one of the two concepts involved in a GTC. The desired result is the simultaneous satisfaction

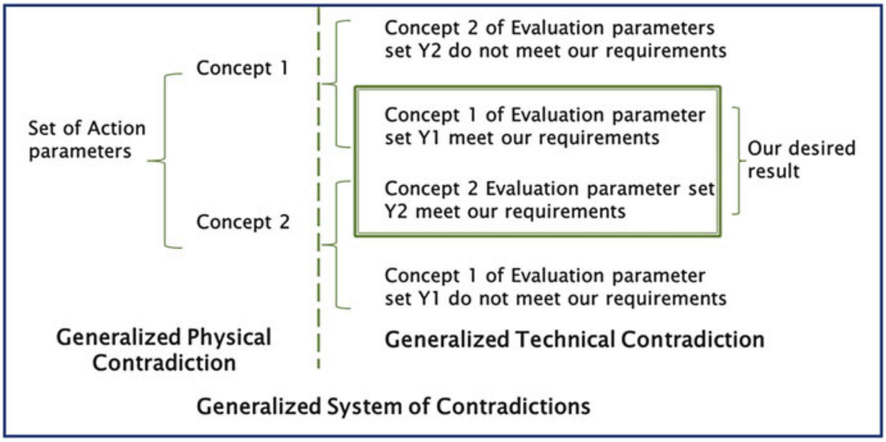

Fig. 7.5 Generalized system of contradictions

of the two concepts. In each concept, there are at least one or more evaluation parameters where the solution of each generalized technical contradiction should satisfy all the evaluation parameters associated with the two concepts. Thus, the result will be improved over the case of classical technical contradictions. Note that the classical TRIZ contradiction is a special case of generalized contradictions.

7.2.3 The Representation Model of Contradiction for Optimization and Invention

A common representation model of a design problem is necessary to enable shifting from optimization representation models to inventive models. The representation model should support the simulation-optimization-invention loop and should enable the simultaneous use of both optimization and inventive solving strategies. To extract the generalized contradictions, information regarding the technical system is required. The use of the experimental design is a good starting point as it involves a strategy for gathering empirical knowledge on the studied technical system. In other words, the gathering of knowledge is based on an analysis of the experimental data and expressed in a rectangular experiment table (Table 7.1), not in theoretical models. In general, we generate the experiments in the table with raw data. If it is possible, we develop a complete design of experience, or if this is not possible because of too many variables, we will then randomize according to uniform law among all possible experiments from the research space.

The rows of Table 7.1 represent the experiments, and each column corresponds to different process variables expressing one system parameter. In each experiment, as noted by *e*, one or more process variables or factors are changed to observe the effects these changes have on one or more response variables or outputs. The

Table 7.1 A table of experiments

	x_1	...	x_l	y_1	...	y_i	...	y_r
e_1	v_{11}		v_{1l}	y_{11}		y_{1i}		y_{1r}
e_2	v_{21}		v_{2l}	y_{21}		y_{2i}		y_{2r}
...								
e_{k-1}	v_{k-11}		v_{k-1l}	y_{k-11}		y_{k-1i}		y_{k-1r}
e_k	v_{k1}		v_{kl}	y_{k1}		y_{ki}		y_{kr}

factors are the controlled parameters, usually noted as x, and correspond to the action parameters in the GSC model. The outputs are the measured parameters, usually noted by y, and correspond to the evaluation parameters in the GSC model.

Once the experiments are complete, we can begin to organize and interpret the data. First, to simplify the extraction problem, the response variables are transformed into a binary system: each y_{ij} value of Table 7.1 is replaced by z_{ij}, where $z_{ij} = 1$ when y_{ij} satisfies the objective for the evaluation parameter y_j; $z_{ij} = 0$ otherwise. The obtained table is denoted as the "binary experiment table" (see also the example in Fig. 7.6a and b).

Second, the EP part of the binary table of experiments is analyzed to get a GTC, which provides a definition of the GSC linked to this GTC thanks to the AP. Indeed, the properties of a GSC can be characterized by the set of definitions that enables the extraction of the GSC from the binary experimentation table. A binary experimentation table can be characterized by the following:

- A set of action parameters $X = (x_0, x_1, \ldots, x_n)$ and a set of domains $D = (D_0, D_1, \ldots, D_l)$, where D_i defines the possible range of values for x_i.
- A set of evaluation parameters $Y = (y_0, y_1, \ldots, y_r)$ for evaluating the performance of the system for different combinations of action parameter values.
- A set of experiments $E = (e_0, e_1, \ldots, e_k)$. An experiment e_i is a particular instantiation of the action parameters $(v_{i1}, v_{i2}, \ldots, v_{il})$ such that v_{ij} belongs to D_j combined with the induced values of evaluation parameters $(z_{i1}, z_{i2}, \ldots, z_{ir})$, resulting in the binary values of $z_{ij} = 1$ if the y_j value is satisfied by experiment e_i or $z_{ij} = 0$ if y_j is not satisfied by experiment e_i.

The goal is to satisfy all the evaluation parameters for at least one experiment. However, the situation should be considered where such a solution does not exist in the considered table above, i.e., no experiment enables the satisfaction of all the evaluation parameters.

A GSC seeks to identify the following clustering of the table of experiments and results:

Three sets of evaluation parameters Y_0, Y_1, and Y_2, such that $Y_0 \cap Y_1 = \varnothing$, $Y_1 \cap Y_2 = \varnothing$, $Y_0 \cap Y_2 = \varnothing$, $Y_0 \cup Y_1 \cup Y_2 = Y$, $Y_1 \neq \emptyset$, and $Y_2 \neq \emptyset$.

Three sets of experiments E_0, E_1, and E_2 such that $E_0 \cap E_1 = \varnothing$, $E_1 \cap E_2 = \varnothing$, $E_0 \cap E_2 = \varnothing$, $E_0 \cup E_1 \cup E_2 = E$, $E_1 \neq \emptyset$, and $E_2 \neq \emptyset$.

Moreover,

(a)

	AP					EP					
	x_1	x_2	x_3	x_4	x_5	y_1	y_2	y_3	y_4	y_5	y_6
e_1	1	1	0	0	1	8.6	0.4	1090	1.3	4.59	-10
e_2	0	1	1	1	1	5.2	0.6	202	0.1	2.10	-8
e_3	1	0	1	0	0	9.1	0.5	999	0.3	8.65	4
e_4	1	1	0	0	0	9.5	0.7	1070	1.4	8.45	5
e_5	1	0	1	0	1	8.9	0.1	997	0.2	2.12	-7
e_6	0	1	0	1	2	3	0.7	500	1.5	3.09	-9
e_7	1	0	1	1	0	8.8	0.1	1010	0.6	5.94	4
e_8	1	0	0	0	1	9.6	0.2	300	1.1	4.16	-6
e_9	0	1	0	0	2	2.4	0.7	100	1.2	0.11	-3

(b)

	AP					EP					
	x_1	x_2	x_3	x_4	x_5	y_1	y_2	y_3	y_4	y_5	y_6
e_1	1	1	0	0	1	1	0	1	1	1	1
e_2	0	1	1	1	1	0	1	0	0	1	1
e_3	1	0	1	0	0	1	0	1	0	0	0
e_4	1	1	0	0	0	1	1	1	1	0	0
e_5	1	0	1	0	1	1	0	1	0	1	1
e_6	0	1	0	1	2	0	1	0	1	1	1
e_7	1	0	1	1	0	1	0	1	0	0	0
e_8	1	0	0	0	1	1	0	0	1	1	1
e_9	0	1	0	0	2	0	1	0	1	1	1

Fig. 7.6 Experimental data (**a**) and binarized EP (**b**)

E_1 is a set of experiments for which all the evaluation parameters of Y_1 are satisfied.

E_2 is a set of experiments for which all the evaluation parameters of Y_2 are satisfied.

Such a definition provides a path for reorganizing the experimentation table by permutations of the rows and of the columns to group the previously defined E_i and Y_i (Rasovska et al. 2010) (Table 7.2).

The extraction of the GSC in the experimentation table is described as a set of equations characterizing the blocks of the matrix (Dubois et al. 2009b):

Table 7.2 GSC representation in experimentation output

X	Y_1	Y_2	Y_0
E_1	$E_1 \times Y_1$: $z_{ij} = 1$	$\forall e_i \in E_1, e_i \times Y_2$: $\exists\, j/z_{ij} = 0$	$E_1 \times Y_0$
E_2	$\forall e_i \in E_2, e_i \times Y_1$: $\exists\, j/z_{ij} = 0$	$E_2 \times Y_2$: $z_{ij} = 1$	$E_2 \times Y_0$
E_0	$E_0 \times Y_1$	$E_0 \times Y_2$	$E_0 \times Y_0$

$$z_{ij} = 1 \text{ or } 0$$

$$\sum_{i/e_i \in E_k; j/y_j \notin Y_k} \left(1 - z_{ij}\right) \geq 1$$

$$\forall \left(e_i, y_j\right) \in E_{k \neq 0} \times Y_{k \neq 0}; z_{ij} = 1$$

$$\forall \left(e_i, y_j\right) \in E_0 \times Y_{k \neq 0} : \sum_{j/y_j \in Y_k} \left(1 - z_{ij}\right) \geq 1$$

$$\forall \left(e_i, y_j\right) \in E_{k \neq 0} \times Y_0 : \sum_{i/e_i \in E_k} \left(1 - z_{ij}\right) \geq 1$$

The matrix is divided into nine blocks, and in Table 7.2, we have formulated the features into blocks. In the blocks where $E_1 \times Y_1$ and $E_2 \times Y_2$, all of the elements are equal to 1. In the remaining four blocks associated with Y_1 and Y_2, there must be at least one element equal to zero in each row.

Figure 7.7 provides an example of GSC characterization for the example of Fig. 7.6b. Different methods of data analysis can be used to identify the blocks in the matrix: principal component analysis (PCA) (Shlens 2014), seriation methods (Liiv 2010), clustering (Jain et al. 1999), and blockmodeling (Doreian 1999; Rasovska et al. 2010; Lin et al. 2013; Dubois et al. 2011). Once the blocks are identified, the GSC is defined. Nevertheless, it would be more convenient to be able to describe the GPC part of the GSC by a simple concept than by the set of experiments E_1, E_2, and E_0. This question is part of the issues discussed in the next section.

7.3 Research Issues and Research Method

7.3.1 Research Problem

In the current practice, the system of contradictions is identified by interviewing human experts. In our previous research, we have shown that there are some cases in which no classical TRIZ contradiction exists, and the problems still cannot be solved by optimization. Therefore, the concept of a GSC was proposed. These generalized contradictions are typically not searched by human experts as their expression is too difficult to interpret for the human mind. For a human expert, it is simpler to validate a generalized contradiction, although it is much more difficult to

Fig. 7.7 Reorganization of Fig. 7.6b highlighting conflicting sets of experiments (decisions) when trying to reach the objectives of Y_1 and Y_2

							EP					
		AP					Y1		Y2			Y0
		x_1	x_2	x_3	x_4	x_5	y_1	y_3	y_2	y_5	y_6	y_4
E1	e_1	1	1	0	0	1	1	1	0	1	1	1
	e_3	1	0	1	0	0	1	1	0	0	0	0
	e_4	1	1	0	0	0	1	1	1	0	0	1
	e_5	1	0	1	0	1	1	1	0	1	1	0
	e_7	1	0	1	1	0	1	1	0	0	0	0
E2	e_2	0	1	1	1	1	0	0	1	1	1	0
	e_6	0	1	0	1	2	0	0	1	1	1	1
	e_9	0	1	0	0	2	0	0	1	1	1	1
E0	e_8	1	0	0	0	1	1	0	0	1	1	1

define it. Moreover, looking for simple technical or physical contradictions as represented by the classical TRIZ model of contradictions, the human practitioner could be faced with reaching their own expertise limits when the system is too complex or when they have no relevant knowledge about the system.

Our work contributes to addressing the problematic concerns as situated in three different levels. The following discussion specifies the three levels and related questions.

The first level of questions regarding the design theory is concerned with the concept of contradiction, which is one of the foundations of TRIZ:

Question 1 When no classical technical or physical contradiction exists, do the generalized technical and/or physical contradictions exist, and are there a significant number of those contradictions? Can we always extract the generalized contradictions intrinsically the same way as Pareto, for example, from the behavioral representation and the objectives of the system? If so, what are the consequences?

Question 2 How can the generalized contradictions be exhaustively identified and extracted?

Question 3 Once all generalized contradictions are known, how can the relevant contradictions be chosen or defined? Alternately, how can a relevant contradiction be defined in a straightforward manner?

The second level of questions regarding the methodology concerns the practical consequences of the new definition of contradictions for inventive problem solving:

Question 4 Once the contradictions have been identified and extracted, how can we use them in the inventive problem-solving process?

Question 5 How can we extract the relevant contradictions without exhaustive research, which is often too expensive and time consuming despite a posteriori filtering?

Question 6 Can we use the concept of a generalized contradiction to express the implicit knowledge from a system expert?

Finally, the third level of questions discusses the exploration of the relationship between optimization methods and TRIZ to develop cross-fertilization from a theoretical and/or a practical point of view:

Question 7 Can we use methods and concepts from the optimization to facilitate the identification of generalized contradictions?

Question 8 Is there a relationship between the Pareto concepts and the generalized contradictions?

Question 9 If this link exists, could it be used to identify the generalized contradictions?

Question 10 Alternately, if this link exists, could it be exploited to facilitate the optimization process?

One of the objectives of our work is to answer all these questions. The research strategy adopted to address these questions is described in the next section.

7.3.2 Research Method

To answer the questions proposed in the previous section, it is necessary to build an exhaustive extraction tool to identify and extract the generalized technical and physical contradictions from system data. To do this, the problems of identifying generalized technical and physical contradictions are modeled in the form of combinatorial optimization problems along with solving the algorithms, which are proposed for each case. Once these algorithms have been realized, they can be used for empirical studies that are necessary to answer questions Q1 and Q2. Furthermore, they also help us to develop hypotheses required to answer questions Q4 and Q6. We answered the question Q7 in a preceding section.

The exhaustive methods have their limitations. The methods can be implemented for a system with a limited number of variables because of the time complexity of calculation. Alternately, the number of generalized contradictions is significant as indicated by the answers to Q1 and Q2. This limit is reflected in the number of action parameters. To reduce the limitations related to the number of variables, our strategy is to analyze the data to identify the action parameters and their values involved in the concepts of GPC before determining these concepts. This can simplify the system by reducing the number of action parameters by only considering the influencing parameters. The exhaustive algorithm can then be used for the simplified system with a reduced number of variables.

This approach of data preprocessing permits the reduction of the number of action parameters and their values. Then, identifying the contradictions is realized by providing answers to questions Q8 and Q9. An alternative solution to this sequence, which is not developed in this chapter, is to design a heuristic-based research algorithm of relevant contradictions by using the data without including the exhaustive research of contradictions. The development of these algorithms requires the identification of specific properties of the relevant contradictions. The search for these properties can be performed by experimentation, using real cases involving human inventive design experts, coupled with the analysis of the exhaustive search results. In this chapter, we used an academic school example from the logistics domain as a test case to answer question Q5. In the context of this chapter, we do not expect to provide a complete answer to question Q4; however, we believe a contribution to the answer of Q4 can be accomplished by testing the previous heuristics on the real or academic examples with the appropriate number of variables. Question Q10 is discussed based on the synthesized results developed for questions Q8 and Q9.

7.4 Results

To recap the previous research method and the answers to the above questions, this paragraph presents the respective identification and extraction of generalized technical and physical contradictions. The identification problem is formulated as an optimization problem, specifically a binary programming problem that can be organized into subproblems based on the original problem properties. This subproblem is proven to be NP-hard (nondeterministic polynomial-time hard). The combinations of subproblem solutions provide the GTC. We can relate several GPCs to one chosen generalized technical contradiction to form a GSC. Thus, an algorithm to search all the GPCs related to one chosen generalized technical contradiction was proposed. The limitations in terms of number of variables and their possible values to be processed are discussed, as are the contributions to our problematic concerns and potential applications. The use of exhaustive search algorithms has limitations related to the number of possible variables that can be processed because of the computation time, which increases exponentially with the number of parameters. For the GTC research, the algorithm can only evaluate 15 evaluation parameters, while for the GPC research, the algorithm can only evaluate 12 action parameters with binary values. Nevertheless, the use of the existing algorithms provides practical evidence that only a few action parameters within the model are involved in the description of the physical contradictions. The purpose is then to define reduced sets of action parameters that are relevant candidates for GPCs or eliminate those that are not defined beforehand. This may allow the use of exhaustive physical contradiction search algorithms for systems described by more than 12 action parameters including two values or facilitate a human search of the physical contradictions. To accomplish this task, a search of the parameters is stated as a set of classification problems where an adaptation of a support vector machine (SVM) feature selection algorithm was proposed to address the problems. The limitations of this algorithm are also discussed. Finally, strategies for using the proposed SVM algorithm within the GPC extraction context are suggested. A synthesis on how to combine the algorithms within the inventive solving process is illustrated in the general inventive design problem-solving process.

7.4.1 Extraction of Generalized Technical Contradiction

We proposed a GTC identification and extraction model in the form of optimization programs and two solution strategies. The first solution strategy is an exhaustive search algorithm that can identify and extract all GTCs from an experimental table when the number of evaluation parameters is fewer than 15. The second extracts one GTC by an existing binary programming algorithm as a supplementary strategy. However, to the best of our knowledge, there is no powerful tool that can effectively solve the binary integer programming problem for the second strategy.

The exhaustive algorithm for GTC extraction presented in Lin et al. (2013) makes it possible to answer Q2. With this algorithm, we can also consider answering Q1 for a technical contradiction by performing appropriate experiments. From these experiments, we made the following observations:

- The more available solutions there are that meet multiple evaluation objectives, the smaller the possibility of obtaining a classical technical contradiction. When over 50% of the targets in the experiment table are satisfied, there is virtually no possibility of obtaining a classical technical contradiction. This point explains the difficulties encountered by human experts to formulate contradictions based on the classical model of the TRIZ contradiction in some situations.
- The number of GTCs seems to increase until the disappearance of the classical technical contradictions; however, it also gradually decreases as we increase the number of satisfied targets. There is always at least one generalized contradiction in the data, unless the problem is completely solved (i.e., all targets are satisfied and there is no Pareto).

The number of contradictions of each type from the real case data (i.e., the number of typical TRIZ contradictions or generalized contradictions) belongs to the main part of the distribution of the random data having the same percentage of one value in the binary matrix. This result contributes to validate the hypothesis that the percentage of "one" value of the evaluation parameter matrix (i.e., the ratio of satisfied evaluation parameter values/the potential number of satisfied evaluation parameters) explains the existence or nonexistence of classical TRIZ contradictions. Indeed, the higher this ratio, the lower the probability of not having at least one experiment satisfying each pair of evaluation parameters. Similarly, this ratio also seems to explain the number of GTCs. More details about the shape of the distribution of the number of technical contradictions are given in Lin et al. (2013) and Lin (2016). Thus, it seems that we can use randomly generated data to construct and validate the heuristic identification of technical contradictions.

The application of the results also provides partial answers to Q4 and Q6. A case study was processed by GTC extraction, and the results were validated by experts. Among more than one hundred GTCs, four were found and interpreted by experts; such interpretation essentially helps experts to express implicit knowledge of the system, and we define GTC as our objective for future investigation.

7.4.2 Extraction of Generalized Physical Contradiction

We proposed a GPC identification and extraction algorithm through the extraction of two GPC concepts, each of which involves many system states (Lin et al. 2015). The classical physical contradiction with context was proposed by comparing the two states in each concept. The concept extraction was initially transformed into a binary integer programming problem, and then because its constraint is a logical equation, we proposed a filter method for filtering all possible concept states.

A possible use for this algorithm, which was not expected at the beginning of the study, is the possibility of identifying the classical or generalized physical contradictions in the context of setting action parameters. This allows us to consider more applications as part of the inventive design and assistance in understanding the contradictions. Indeed, in the classical approach, the contradictions provided by experts never explicitly provide the context of validity of contradiction (the values of those variables not involved in the contradiction). For example, the contradictions found by experts could be understood or completed by defining the limits of their validity, or, vice versa, the simple GTC contradictions close to the TRIZ classical contradictions could be proposed to the experts by adding the limits of their validity.

Sometimes, searching for a sample of contradictions helps identify the solutions of the optimization problem. Indeed, it is possible that, in the set of experiments, searching concepts 1 and 2 are separate, and two unconflicting states could appear in each concept. In this case, the combination of the two concepts could be a potential solution for the original problem, but this part needs further statistical study; we do not further discuss this situation.

Here, Q2 is addressed by the GPC extraction algorithm. The case study for the electrical circuit breaker presented in Lin et al. (2013) has no TC but does have a GTC; we performed GPC extraction for a given GTC, two concepts were obtained that could create numerous physical contradictions with context, and thus the result of the case study partially answers Q1. For the case study of a simple Kanban presented in Lin (2016), we extracted GPC for two conflict evaluation parameters (Service Breakdown and Average Stock). There are 12.768 physical contradictions with context; we selected one and formulated the system of contradictions. The situation of the contradiction was analyzed by experts, and thus the system of contradictions organized the knowledge of experts for the system and positively answered Q6.

7.4.3 Identification of Parameters Involved in Physical Contradictions

The aim was to propose heuristics for selecting relevant parameters and their values for searching relevant generalized contradictions. To do so, the identification of parameters, which is to classify discriminative parameters for two separate sets related to concepts 1 and 2 of the generalized system of contradictions, was addressed in terms of machine learning methods as in artificial intelligence. We first showed that the identification of parameters and values used in the concept of the generalized physical contradiction is similar to a series of problems known as the “feature selection problem” in some areas of research.

Feature selection techniques receive a great deal of attention in the areas of pattern recognition and bioinformatics. Specifically, with the development of text categorization in Lewis and Ringuette (1994) and Yang and Pedersen (1997) and gene expression in Guyon et al. (2002) and Saeys et al. (2007) whose data size and dimension are dramatically increasing followed by explosive growth of computational complexity, feature selection has become an inevitable preprocessing step in text analysis and gene analysis. As the name suggests, the feature selection task consists of selecting an optimal subset of features according to a certain criterion to improve the accuracy of the classification problem. The task also ensures that the data mining algorithms work faster on larger size data, thereby providing a better understanding of the mined results (Liu and Motoda 1998; Guyon 2003). The entire process of feature selection depicted in Fig. 7.8 mainly includes three steps: generation procedure, evaluation function, and stopping criterion. The generation procedure generates a subset of features for evaluation. The evaluation function evaluates the adequacy of a feature subset produced by the generation procedure.

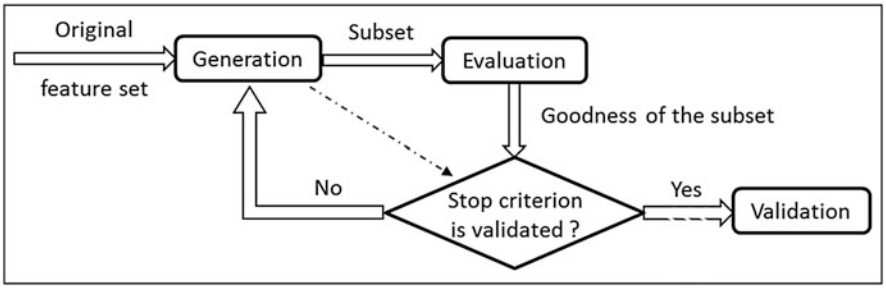

Fig. 7.8 Feature selection process with validation (Dash and Liu 1997)

The stop criterion decides when to stop using the result from the evaluation function and avoids exhaustively searching the entire subset space. The last step, validation, is not a part of the feature selection process itself; its objective is to test the validity of the subset selected by the feature selection algorithm.

Among the methods of "feature selection," those that are "signed feature selection" seem to best suit our case. We developed an SVM-based methodology customized to our problems, which allows for a definition of the action parameters and their values involved in the concepts of the GPC associated with a generalized technical contradiction. Let us recall that a classical TRIZ contradiction is a particular case of generalized contradictions. For details about the algorithm, see, for instance, Lin (2016). In addition, the feature selection-based action parameter provided a partial solution for Q5 because the selection process removed many irrelevant parameters that did not participate in the contradiction formulation. In Q5, we want to select the relevant contradictions from numerous contradictions, but thus far, we have not found criteria that define the relevant contradictions. The proposed selection method helps us conduct data preprocessing to filter a large amount of irrelevant contradictions and reduce contradiction size, which indirectly contributes to the relevant contradiction extraction.

There are two proposed meta-strategies for extracting the APs: one is called evaluation parameter-based extraction, and the other is GTC-based extraction. Both are based on the basic AP extraction process summarized in Fig. 7.9. Let us consider the "binarized" table of experiments (i.e., the table of experiments where the evaluation parameter values of the experiments are equal to 1 when the objective is reached for the evaluation parameter in the experiment and 0 otherwise). In this table, a given y_i splits the experiments in two sets: E_1, the set of experiments e_j, such as $z_{ji} = 1$, and the set of experiments E_0, such as $z_{ij} = 0$. In step 1, these two sets are the learning set for the SVM algorithm, which provides weights for each action parameter, allowing for separation of the parameters influencing the evaluation parameter y_i toward the objective in step 2. This operation can be repeated for each evaluation parameter providing a set of influencing parameters for each y_i; the union of these sets is the set of action parameters positively influencing the entire set of evaluation parameters. Then, when the number of parameters of this set can be treated by the exact GPC extraction algorithm, it can even be possible to extract the GPC (Lin et al. 2015). The previous strategy is called the evaluation parameter-based strategy, which holds for almost all the GTC of the system.

The next proposed strategy is called GTC-based action parameter extraction. When searching for the evaluation parameters more specifically involved in a given GTC, the process described in Fig. 7.9 can also be used by changing the inputs of the process. We now consider the two subsets Y_1 and Y_2 of Y, the set of evaluation parameters. We build Y'_1 as the evaluation parameter where y'_{j1} equals 1 for experiment e_j when all the evaluation parameters of Y_1 equal 1 for e_j and 0 otherwise. In the same manner, $Y'2$ is the evaluation parameter where y'_{j2} equals 1 for experiment e_j when all the evaluation parameters of Y_2 equal 1 for e_j and 0 otherwise. Actually applying the process of Fig. 7.9 to the table of experiment consisting

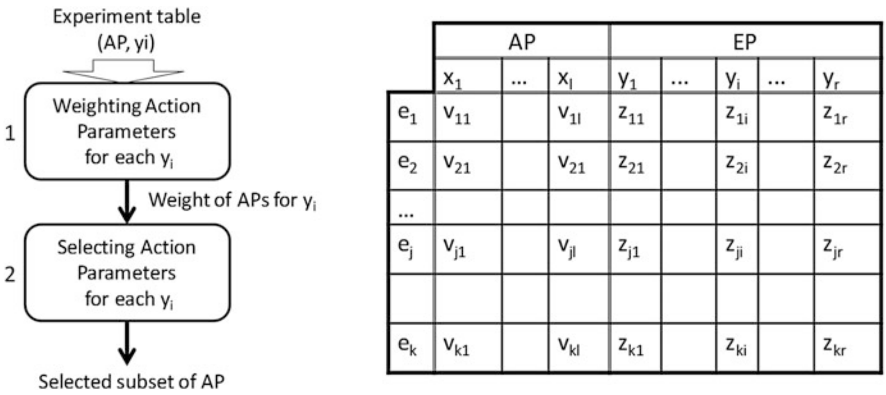

Fig. 7.9 Process of AP extraction

of AP and $Y'1$ (resp. $Y'2$) provides the subsets of action parameters involved in concept 1 (concept 2) of the GPC.

7.4.4 Process of Model Change Using Three Algorithms

We used the dialectical approach from the TRIZ theory to solve inventive design problems that cannot be solved solely by optimization methods. Practical evidence has shown that it may sometimes be less expensive to use an inventive problem-solving method even if the problem can be solved by optimization. However, in many situations, both approaches are required to provide satisfactory solutions and are used in sequence. A theoretical or general framework for the design problem-solving process based on the simulation-optimization-invention loops when simulation or experimental means are available is proposed and shown in Fig. 7.10. The solving process involves five functions (as represented by boxes in Fig. 7.10). The functions can be performed independently by using different methods and tools, such as the design of problem models (quality function deployment, design of experience, etc.), simulator models (CAD, Witness), simulation algorithms (stochastic optimization, genetic algorithms), multi-criteria decision analysis, and changing model methods, such as TRIZ. The first function represents the problem formulation and definition through the requirements and the dissatisfaction of the customer. The evaluation parameters (EPi) are used to describe the objectives and are measured to check whether the customer's requirements are satisfied. The action parameters (APi) with their possible values represent the system variables on which one can act. Some relations (Ri) between system variables and parameters are described through the system constraints.

The second function generates the experiments with the valuation of possible solutions, which are obtained with the aid of a simulator or by physical experimentation. Sometimes a large number of action parameters and their values are

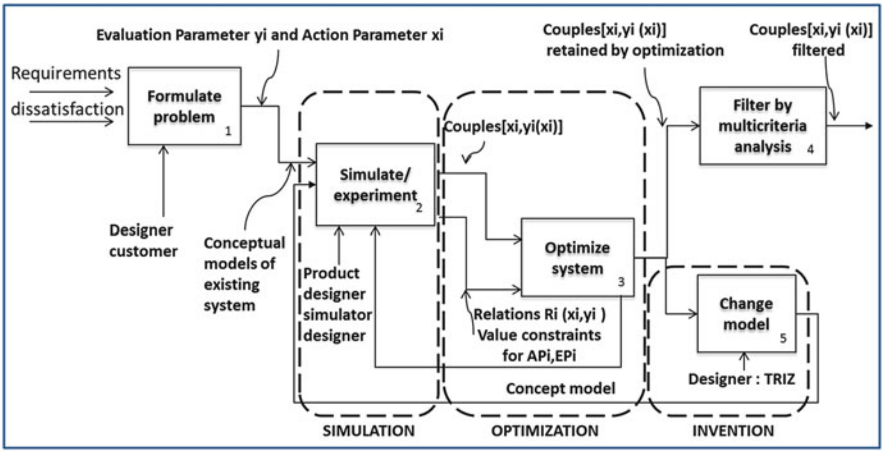

Fig. 7.10 General inventive design problem-solving framework

accessible, making it impossible to process all data. Thus, the third function should choose the relevant action parameters for the valuated experiments with possible solutions (i.e., design of the experiment or optimization algorithms). When satisfactory couples (APi, EPi(APi)) are obtained (i.e., their evaluation parameters achieve the expected values) or when the time allowed for the experiment is over, the results are filtered, for example, by a multi-criteria analysis, which is the fourth function. When the evaluation parameters do not achieve the expected values after the time allowed for the experiment or because of proven limitations of the system as noted by the experiments, it is necessary to change the conceptual model to reach the requirements, which is the fifth function. This process proposes the use of the dialectical inventive solving approach. Then, the loop starts again with a new model by performing Step 2.

Our contribution is focused on function 5, called model change. In Fig. 7.11, a process of function 5 is proposed, where inputs are experiments or simulation results. This process combines the GTC extraction algorithm, GPC extraction algorithm, and parameter selection strategy. The GTC can be extracted by experts or by the GTC extraction algorithm referred to in Sect. 7.4.1. For Step 2, the target GTC can be selected by experts, or we select GTC based on the number of evaluation parameters. If we completely solve the generalized contradiction involving more evaluation parameters, then there will be a higher level of satisfaction based on the achievement of evaluation parameters. Once the target GTC is determined, we need to select the GPC. If the time complexity is suitable for GPC algorithm extraction, we can directly extract the GPC or let the experts extract it. Otherwise, we perform the feature selection before GPC extraction. When we obtain the GTC and corresponding GPC, the generalized system of contradictions is formed. Among these GPCs, we propose to select a physical contradiction in which only one action parameter has a conflict because this type of contradiction can be directly addressed by classical TRIZ tools. Additionally, the context that develops

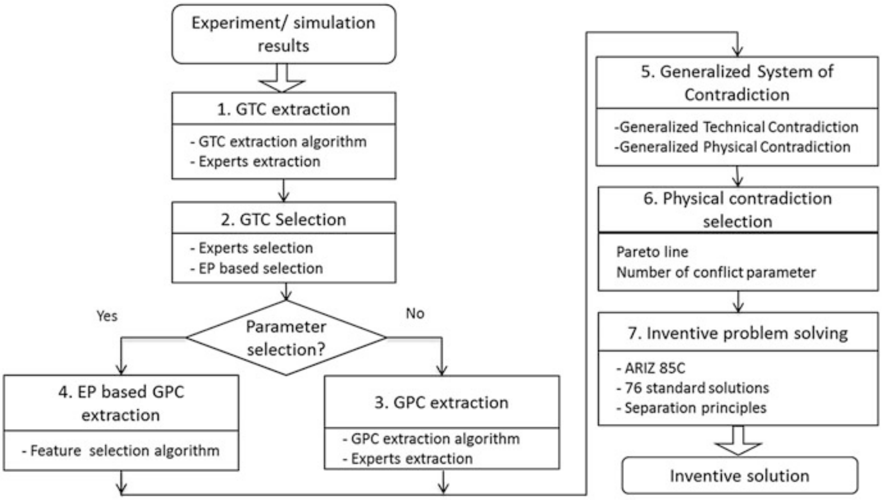

Fig. 7.11 Process of model change

the conflicting state located within the Pareto line should be selected for the physical contradiction. The last step is to solve this physical contradiction by TRIZ methodology when the system of contradictions allows it.

7.5 Illustration

In this section, the study case is presented to illustrate the use of the proposed model change process with the tools introduced in previous sections. This example was first developed in Lin (2016).

7.5.1 *Problem Formulation and Simulation*

This case involves a simple manufacturing system managed by Kanban cards simulated with the aid of the flow simulation software Witness 14, and the simulation layout is shown in Fig. 7.12.

The system is composed of one manufacturing machine producing two different items stored in two independent inventories and delivered to two types of customers, customer_1 and customer_2. The interval times of customers' arrival times follow a uniform random distribution, i.e., the interval of customer_1's arrival time follows a uniform distribution (0.18, 0.22), and the interval of customer_2's arrival time follows a uniform distribution (0.9; 1.1). It is a simple pull system where Kanban cards are sent back to the manufacturing machine when the container is

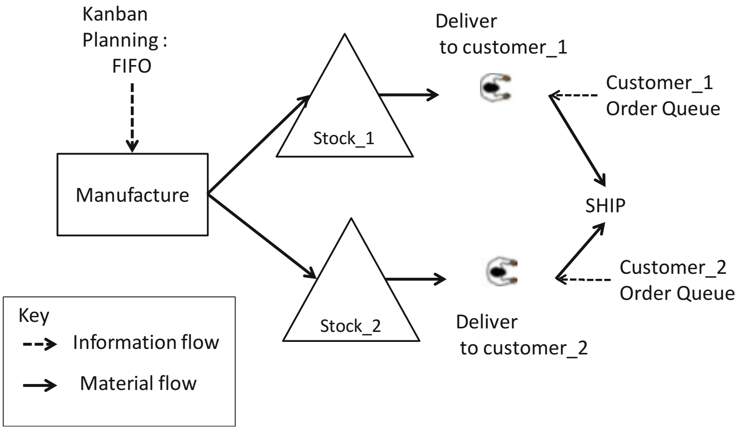

Fig. 7.12 Double Kanban system

empty. The Kanban card provides the quantity to be put into a container. The manufacturing machine has two different setup times for each item (i.e., 1 time unit for the first item and 2 time units for the second item); the operation time is 0.1 time units for both items, and the transportation time from the manufacturing machine to the inventories is neglected. The transportation Kanban size from the machine to the customers' inventories is one Kanban. The scheduling rule for the machine is first in first out (FIFO) according to the arriving Kanban cards. Thus, a setup is performed any time the type of item (Kanban) changes in the Kanban waiting line. The total running time of one simulation is 1000 time units (1 time unit corresponds to 1 h), with 10 time units required for warm-up. During the warm-up time, all the Kanban cards come into the model and go to the manufacturing machine, and thus the initial stock of the two inventories is from the manufacture of the warm-up time.

This study is modeled as follows: the Kanban size (quantity of items corresponding to one Kanban card) and the number of Kanban cards are the action parameters of the system on which we can act. To evaluate the performance of this system, the average stock in the inventories and the average waiting time for customers for both items are defined as the evaluation parameters. In summary, four action parameters are defined: number of Kanban for item 1 (NK1), number of Kanban for item 2 (NK2), Kanban size for item 1 (KS1), and Kanban size for item 2 (KS2). In addition, the four evaluation parameters are average stock in stock 1 (AS1), average stock in stock 2 (AS2), service breakdown for item 1 (SB1) corresponding to the average lateness of the delivery to customer 1, and service breakdown for item 2 (SB2). The definition of the range of action parameters for optimization should be defined by engineers first and then examined to see if there is a good solution out of the defined range through a statistical analysis of generated solutions. For our case, the range is defined from 1 to 10 for each action parameter.

7.5.2 Optimization and Solution Filter

Once the action parameters (NK1, NK2, KS1, KS2) and evaluation parameters (AS1, SB1, AS2, SB2) are determined, the experiments are performed. The Witness software provides tools for random experiments. We used a random experiment as an optimization, and 1039 experiments were performed.

In our problem, the goal is to have a situation with no lateness and no stock, which means that the value of each evaluation parameter is ideally targeted to be 0. However, this goal is impossible to achieve by the system described above. The best values that we did obtain separately by optimization means for each evaluation parameter of this system were SB1 = 0, AS1 = 0, SB2 = 0, and AS2 = 0. No experiments provided a solution where all the evaluation parameters were simultaneously within the interval [0; 0.1]. This solution could not be reached by the above-described system. Thus, our objective was then to modify the model of the existing system as little as possible such that a solution where each evaluation parameter stands within the range [0, 0.1] existed. Such a solution should outperform any solution of the actual system.

7.5.3 Model Change

7.5.3.1 GTC Extraction and Selection

The results of experiments are transformed into a binary matrix. The transformation rule is illustrated in Table 7.3.

The GTC extraction algorithm proposed in Lin et al. (2013) and Lin (2016) was performed on the Pareto of the binarized matrix. As a result, several pairs of GTCs were found where only two of them included all the evaluation parameters, as shown in Fig. 7.13. This indicates that, if any of the two GTCs were overcome, all the objectives would be achieved.

From a problem-solving point of view, we should choose one of the GTCs in Fig. 7.13 because, if we solve one of them completely, we can obtain our final ideal solution. Thus, in the next step, we choose the GTC in Fig. 7.13a as the target GTC for searching a solution. As the experiments are not full factorial, and performing

Table 7.3 Binarization principle of the evaluation parameters

Action parameters				Evaluation parameters Experimental values				Evaluation parameters binarized from objectives point of view (in the range [0, 0.1])			
KS1	KS2	NK1	NK2	SB1	AS1	SB2	AS2	SB1	AS1	SB2	AS2
2	8	1	1	1.67	0.05	0.11	2.76	0	**1**	0	0
7	9	1	1	1.50	0.26	0.13	3.07	0	0	0	0

Bold: the expected values of all evaluation parameters are within the interval [0; 0.1] than evaluation parameter is satisfied and equal to 1, otherwise it is equal to zero

Fig. 7.13 GTCs involving all the evaluation parameters. (**a**) GTC: SB1 and SB2 VS AS1 and AS2. (**b**) GTC: SB1 and AS2 VS AS1 and SB2

Table 7.4 Relevant values of the action parameters

Action parameters (AP)	KS 1	KS 2	KB 1	KB 2
Relevant values for GTC extraction	1, 2, 8, 10	1, 2, 8, 9	1, 2, 7, 10	1, 3, 8, 10

full factorial experiments and using the GPC extraction algorithm consume a large amount of time, we use parameter selection to reduce the number of action parameters and values.

7.5.3.2 EP-Based GPC Extraction

Then, we performed the EP-based GPC extraction process. The first result of this process was that all the APs were found to be relevant candidates for GTC identification. The second result was that the set of relevant values of these parameters when seeking the GTC (Table 7.4) was obtained. Readers interested in the details of this part of the example can refer to Chap. 5 of Lin (2016).

To evaluate the validity of the new model, a full factorial experimental design was performed based on the selected value, and it was verified that the Pareto of the experimental results fits the Pareto of the random 1039 experiments.

GTC Extraction and GPC Extraction

The GTC extraction algorithm was performed on the 256 full factorial experiments. Twelve GTCs were extracted, and they are the same as the 12 GTCs of the original

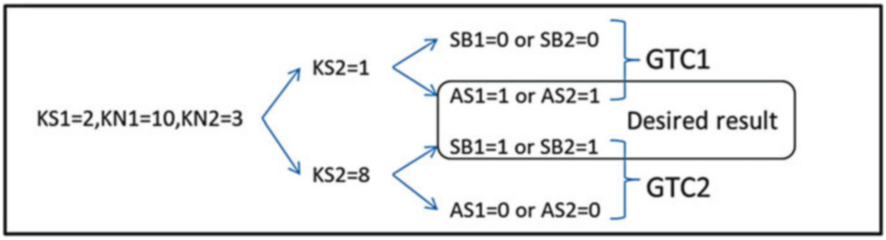

Fig. 7.14 Physical contradiction with context

system. This indicates that both of them are acceptable models with regard to GTC extraction and that we can use the algorithms developed in Lin (2016) and Lin et al. (2015) for GTC extraction.

Based on the results of the GTC extraction on the reduced system, GPC extraction was performed for the target GTC in Fig. 7.13a. Once we had the GPC, the GSC model was formulated as an initial point of the TRIZ analysis. As a result, 68 basic concepts held GTC1, and 30 basic concepts held GTC2. These basic concepts allow all the GPCs related to our contradiction to be built. In the next section, we will select a physical contradiction with context from the generalized system of contradictions and attempt to solve it.

Through the comparison of two concepts, 2040 physical contradictions with context were obtained. The selected physical contradiction should have one conflict action parameter, and there were 16 contradictions with one conflict action parameter. However, the conflict action parameter was just one action parameter KS2 with different values (Kanban size of Kanban 2); thus, KS2 was selected as the physical contradiction parameter. We choose the context that ensures two conflict states around the Pareto line. Therefore, we choose the contradiction state $KS1 = 2$, $KS2 = 1$, $KN1 = 10$, and $KN2 = 3$ versus state $KS1 = 2$, $KS2 = 8$, $KN1 = 10$, and $KN2 = 3$, as shown in Fig. 7.14. This conflict provides us a physical contradiction $KS2 = 1$ versus $KS2 = 8$ with the context $KS1 = 2$, $KN1 = 10$, and $KN2 = 3$.

7.5.3.3 Inventive Problem Solving by Using TRIZ

In this section, we formulate the TRIZ model for solutions and then list the TRIZ solutions. First, we formulate the two GTCs shown in Fig. 7.15. Since the service breakdown was of priority, GTC 2 in Fig. 7.15b was chosen as our initial technical contradiction. In GTC 2, concept 2 satisfied the service breakdown ($SB1 = 0$ and $SB2 = 0$). However, it had a harmful effect on the two stocks.

ARIZ85C (Altshuller 1985; Cameron 2015) was performed, and some details are described below:

- Operation zone: Stock and machine.

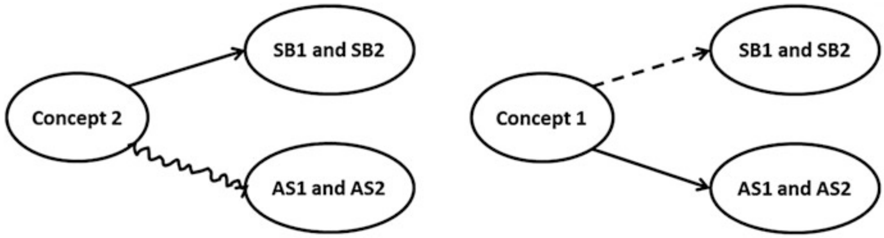

Fig. 7.15 Two sides of the target GTC: (**a**) GTC 1, (**b**) GTC 2

- Operation time: When producing the items for Kanban 2 and when Kanban 2 is in the Kanban stock.
- Ideal final result: The *X*-element, without any complication of the system and without harmful side effects, eliminates <Average stock> during the <period when producing the items for Kanban and when Kanban is in the Kanban stock> inside the <machine and stock> and ensures consistency in the tool's ability to provide <items to customer requirements in time>.

Several partial solutions were obtained, which are summarized below:

- Solution indicated by 76 inventive standards (3.1.1, Formation of bi- or poly-systems): Indicated to use two machines to produce items. Although this solution can technically solve our problem, bringing another machine is a big change that does not follow the principle of minimal change in TRIZ and could be considered as too expensive. Thus, it could only be an alternative solution in the case when no satisfying solution is obtained.
- Partial solution from ideal final result 1 (IFR1): Kanban for item 2, without any complication of the system and without harmful side effects, eliminates <average stock> during the <time when producing the items for Kanban 2 or when Kanban 2 is in the Kanban stock> inside the <machine and stock> and ensures consistency in the ability to provide <items to customer requirements in time>. On the analysis of this partial solution, if we want to remove the average stock by Kanban during <time when producing the items for Kanban 2 and when Kanban 2 is in the Kanban stock>, we should decrease the Kanban size when producing items for Kanban 2 or reduce the items when Kanban is at customer stock.
- Ideal final result 2 (IFR2): The machine has to <provide item> when there is <customer requirement>, and the machine has to <provide no item itself> <when there is no customer requirement>.

Synthesizing of partial solutions:

Through the analysis of IFR2, the hidden reason why the machine cannot directly manufacture the item when the customer is coming is that the setup time and cycle time prevent the machine from providing the item immediately when the customer comes. The double-machine solution is just an approach for the removal of the setup time (except the initial one).

Table 7.5 The result of state (KS1 = 2) (KS2 = 8) (KN1 = 10) (KN2 = 3)

KS1	KS2	KN1	KN2	AS1	AS2	SB1	SB2
2	8	10	3	9.71	18.65	0	0

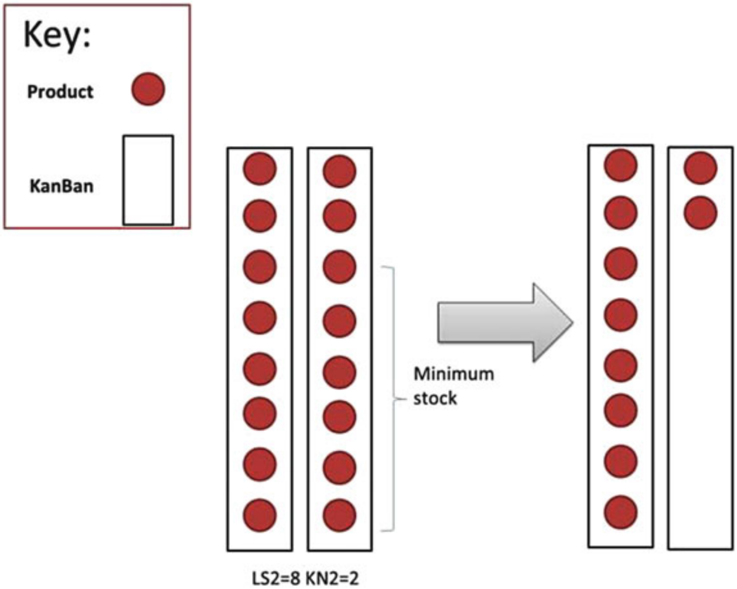

Fig. 7.16 Illustration of the supplying strategy

The solution synthesized from the partial solution Kanban_2: if we keep the context KS1 = 2, KN1 = 10, and KS2 = 8 and define KN2 = 3, the result is shown in Table 7.5. We can also find that after 1000 time units of operation, the minimum stock in stock_2 is 14, which means that there are 14 items in the stock for all 1000 time units. Thus, we can make KN2 = 2 to remove eight items, and the minimum stock in stock_2 becomes six. The following problem is how to use Kanban_2 to remove the minimum stock. If we make KN2 = 1, although the minimum stock becomes 0, SB2 increases.

The strategy for addressing this problem is to keep the supplement as two Kanban_2 but keep the stock as one Kanban_2 and two items, as shown in Fig. 7.16.

To realize the solution and keep the context, we made ten items for stock_2 during the warm-up time and defined Kanban_2 = 1. To keep the supplementary rhythm, which is to send Kanban to the machine after delivering eight items, we let the Kanban go to the machine after delivering each eight items and keep two items in stock during the supplementary time of production for Kanban_2. Thus, the mechanism is to make Kanban Size_2 = 8, and there is security stock = 2 when the Kanban_2 with items returns to stock_2. Kanban_2 must supplement the security stock if its items are less than two in number. With this approach, the simulation result obtained was SQ1 = 0, SQ2 = 0, AS1 = 9.71, and AS2 = 4.65, whereas the best simulation solution of the original model that made SQ1 = 0 and SQ2 = 0 had a result of AS1 = 11.7 and AS2 = 10.65.

7.5.3.4 System Evolution from a Partial Solution

Inspired by the partial solution of Kanban in the previous section, the simulation model is evolved by adding two parameters: Security_Stock_1 and Security_Stock_2. The purpose of the security stock (Security_Stock) is to keep delivering items to the customer even when all the Kanban are sent to the machine. However, when the items of the Kanban arrive in stock, it must fulfill the security stock first.

In contrast to the original simulation model, an obvious conclusion that can be drawn is that, if the security stock is equal to 0, the evolved model is equal to the original model. This means that the Pareto front of the original model must be dominated by the evolved model. To show the optimal Pareto front of the original model, we define the range of four action parameters from 1 to 15 and perform all combination of experiments (50,625 combinations). In regard to the experiments of the evolved model, simulated annealing was performed on the minimization problem SB1 + SB2 + AS1 + AS2. In Fig. 7.17, we only removed the results in region [0, 1] × [0, 17]. However, the Pareto known from simulated annealing was covered and went beyond the optimal Pareto front of the original model. Therefore, the improvement on this model pushed the system evolution and overcame the Pareto front of the initial model. Unfortunately, there was no solution to arrive at for our final goal, as each EP was below 0.1.

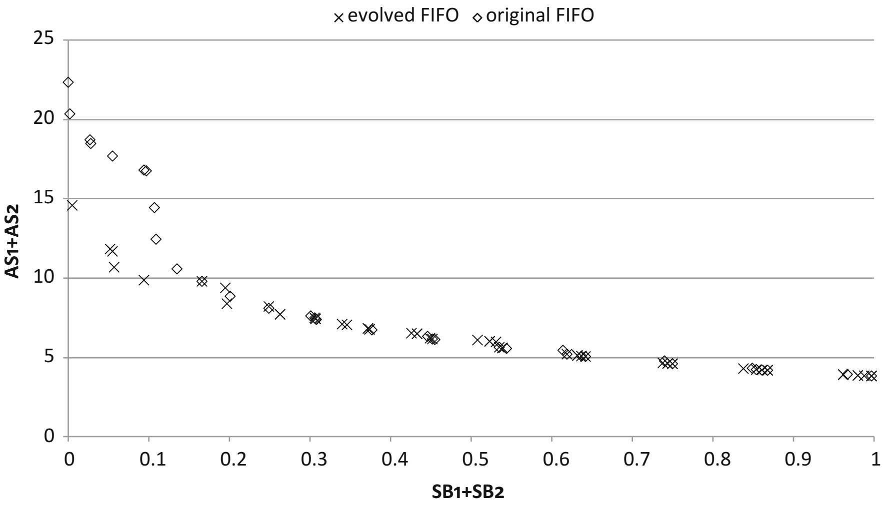

Fig. 7.17 Comparison of the partial Pareto front of the evolved and original models

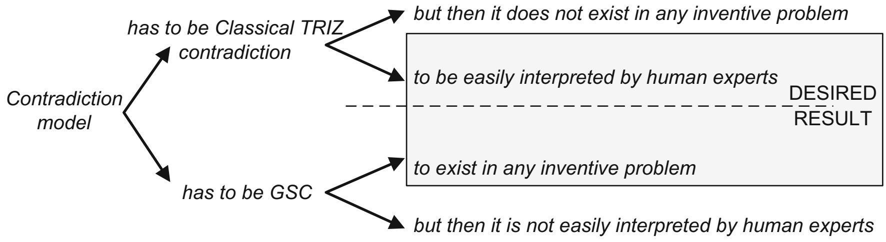

Fig. 7.18 Contradiction of the model to be used for inventive problems

7.6 Discussion and Prospective

In this part, we summarize the extent to which we answered the ten questions and discuss what we should do to attempt to completely answer all ten questions in the future. Q1 is partially answered by the experiments conducted thanks to the algorithms referred to in Sects. 7.4.1 and 7.4.2. In the future, we would like to develop a multi-objective optimization algorithm that can approach Pareto while facilitating GTC extraction.

The classical TRIZ model of contradiction is easier to solve because it is easier to interpret for a human expert of the domain: it is more significant. Alternately, GSC is more difficult to interpret, and thus to solve, but it exists in any problematic situation for which no solution is known. This contradiction is illustrated in Fig. 7.18.

As mentioned previously, we answered Q2 by the GTC and the GPC extraction algorithms when the number of evaluation parameters were fewer than 15 and the binary action parameters were fewer than 12. For other situations, because of computational limitations, we could not search through the contradictions exhaustively, but we did propose strategies to obtain at least some generalized contradictions.

To answer Q3, we need to define the relevant contradiction. The concept of "relevant" may differ with the specific problem. To become aware of the different situations and interesting selection criteria, several practical experiments should be performed. Working with the actual software could facilitate this new knowledge in the future. As a starting point, we propose the following options for analyzing the set of contradictions:

- Filtering (variables involved in GTC or GPC), which is the goal of the methodology referred to in Sect. 7.4.3. Some action parameters do not always have an effect on the evaluation parameter involved in GTC. After removing these action parameters, we can remove several physical contradictions.
- Selecting contradictions with specific characteristics (an EP set and experiment sizes). There are two key characteristics that are important for describing contradictions: experiment and evaluation parameter sizes for GSC, i.e., the size of the experiments involved in contradictions and that of the set of

evaluation parameters involved in the GTC. The GSC experiment size indicates the amount of knowledge regarding the problematic situation, and thus we propose choosing the GSC associated with the largest experiment size. Alternately, solving a contradiction also means satisfying all the evaluation parameters implied in the contradiction. Therefore, the other factor we need to consider is the size of the GSC evaluation parameter. We propose choosing the GSC with the largest size.

- Selecting a GPC where only one parameter is variable but which holds for a given combination of the other action parameter. Such a combination has been named "context."

With time, if some specific outputs appear to be interesting, heuristics could be built to address more variables or provide the selected set directly without explanation of all generalized contradictions.

For Q4, we conducted two trials on the resolution of a simple Kanban and double Kanban. For the simple Kanban, the resolution we obtained from ARIZ85C was to change the single Kanban to several Kanban running in the model; subsequently, Pareto goes beyond the original Pareto of the simple Kanban. However, this proposed solution only reinvented the existing simple Kanban system. Nevertheless, the solution might be cheaper because it takes from the existing solutions only that which is required for the specific situation. To advance and test the practical problem of Q4, more case studies have to be performed. At the same time, to answer Q6, we need to ask the experts and determine whether they can validate the obtained contradictions or learn about the system's behavior.

For Q5, we proposed a binary programming model for single GTC extraction; if we were to transform our requirements into a constraint for the binary program model, we would change our relevant GTC extraction problem into a binary programming problem, which would provide us with the opportunity to solve such a problem via the binary programming algorithm, which is similar to the branch and cut method. In addition, we want to develop a heuristic algorithm that directly searches for GTC in the experimental results. For GPC filtering, we will progressively develop a utilization of the feature selection algorithm in GTC-based GPC extraction; the ideal situation is to directly use the results to formulate a generalized physical contradiction without performing new experiments.

For Q7, the answer is obvious: GTC or GPC extraction is a search problem; we proposed using the optimization model to find GTC and GPC and proposed an SVM model (where the learning process is an optimization process) for action parameter selection, which is to facilitate GPC extraction.

To investigate Q8, if we were to define an acceptable range, the real Pareto could be changed into a "binary" Pareto. The relationship between the concept of Pareto and the generalized contradiction could be connected by the binary Pareto. From the GTC perspective, the binary Pareto involves the entire GTC set. From the GPC perspective, with the approach of SVM, we can extract some values of action parameters to help us locate the Pareto points. In the future, we will attempt to further investigate the relationship between the Pareto and the binary Pareto.

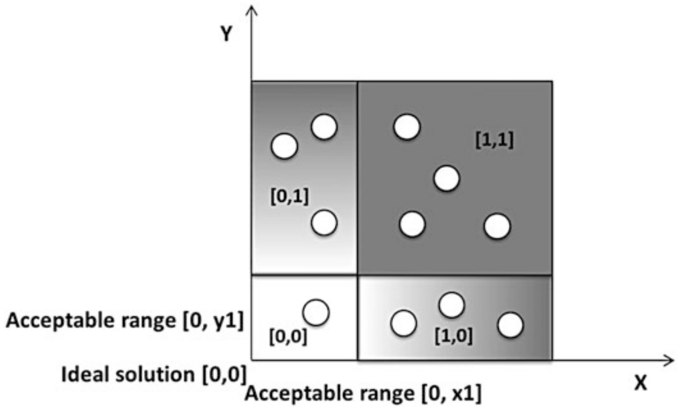

Fig. 7.19 Binary output for multi-objective optimization

Q9 could be partially answered by the binary Pareto because the latter involves all GTCs. Thus, in the future, we will attempt to use a multi-objective optimization algorithm to maximize the evaluation parameters of our system and output the binary value, similar to the two-objective problem shown in Fig. 7.19. Unlike the real-valued output, the solution falls in the same area with the same binary outputs. This way, we can determine whether the optimization algorithm can help us to effectively and efficiently obtain the binary Pareto, which facilitates GTC extraction. From this figure, we also know that, after binarization of the evaluation parameters, GTC extraction is in the binary result of experiments, but the binary result (binary Pareto) cannot be the points on the Pareto. Therefore, GTC extraction, after defining the acceptable range, does not truly need the real Pareto.

With regard to Q10, the EP-based GPC extraction strategy showed that it intensifies the extreme points for any combination of those evaluation parameters not obtained by the optimization process. Thus, we suppose that the GTC-based GPC extraction strategy with SVM-based algorithms can also help us reveal the extreme point for Y_1 and Y_2 (the two sides of GTC) as well as $Y_1 + Y_2$ (candidate solution). Therefore, this strategy could assist the multi-objective optimization in the search for objective $Y_1 + Y_2$. This means that, after optimization, we could use the action parameter with values from the EP-based GPC extraction to overcome the Pareto of optimization.

7.7 Conclusion

Our research approach led us to gradually develop tools/algorithms/experiments to respond to issues classified at different levels of our problematic problem solving in the inventive design. To meet the first level of questions regarding the concept of contradiction in TRIZ, we proposed comprehensive extraction algorithms and generalized contradictions based on combinatorial optimization problems (how to extract generalized contradictions exhaustively, Q2), and we have conducted empirical studies. The results show that, if the case where no technical contradictions or classical physics are available is quite common and increases with the number of available solutions, at least widespread contradictions still exist, and in most cases, they are extremely numerous [answer to question Q1]. In this case, the question of how to select/define relevant contradictions arises (Q3). We try to respond by exploiting and using the links between methods, optimization concepts, and TRIZ, such as the concept of Pareto. At the same time, the fact of generating a large amount of results limits the exhaustive extraction methods, and there are contradictions in terms of the number of parameters that can be factored into the algorithms. To address the limitations of comprehensive methodologies, our strategy has been to develop heuristics that are designed to solve the same problem for systems containing a large number of variables. One possible operation of the algorithm is the ability to identify conventional or generalized physical contradictions in the context of setting action parameters. This allows for the consideration of multiple applications as part of the inventive design and assistance in understanding the contradictions. For example, the contradictions found by experts could be understood or completed by defining the limits of their validity, or, vice versa, the simple GTC contradictions close to the TRIZ classical contradictions could be proposed to the expert by adding the limits of their validity. Following the successive establishment of algorithms and heuristics, we addressed issues concerning the practical implications of new contradictions for solving inventive problems (Q4). The algorithm was also used to provide a partial answer to question Q6 by comparing the contradictions made by independent experts and those defined by previous algorithms. Based on our research, we are increasingly encouraged to think about how to combine algorithms and heuristics in a previously general approach to extract relevant generalized contradictions effectively and efficiently without exhaustive research (Q5).

We analyze data to identify the action variables and their values involved in the concepts of GPC without having to determine the concepts themselves and then use the comprehensive algorithm on the system to reduce the identified variables. The process for the pretreatment and reduction of action variables for the identification of relevant contradictions is achieved by exploring the relationship between optimization methods and TRIZ, thereby providing answers to questions Q7, Q8, and Q9. The identification of variables and values involved in contradictions helps to provide a better understanding or identification of elements (variables) and keys to find the Pareto (Q10).

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Chapter 8
Contribution to Formalizing Links Between Invention and Optimization in the Inventive Design Method

Thongchai Chinkatham, Dominique Knittel, and Denis Cavallucci

Abstract A link between invention and optimization applied to the inventive design method (IDM) framework is presented in this chapter. Optimization is considered here to be a step in the simulation-based design approach, and it is applied to enhance the problem formulation in the IDM framework. A set of contradictions are identified from the explored characteristics of the system. Thus, design concepts are generated after a model of solutions from a TRIZ knowledge base is applied. Furthermore, the role of design parameters (action parameter or evaluation parameters) are discussed. Two case studies are presented to demonstrate the proposed approach. This chapter closes with a discussion, conclusion, and indications of future research work.

8.1 Introduction

In today's competitive market, one task of innovation is to improve or find new ways to solve emerging problems in the new-product design process (NPDP). Various effective methodologies (e.g., brainstorming, morphological charts) are available to assist the designer in solving design problems and generating a set of design concepts. These methods are limited by the need to fit requirements to existing solutions. As a result, forcing creativity to both address requirements and pursue innovative solutions is a major source of pressure.

TRIZ (the Russian acronym for theory of inventive problem solving) (Altshuller 1984, 2000) makes a difference. Based on a set of postulates and axioms, TRIZ

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considers that technical systems evolve in similar ways according to the objective laws of evolution, thus reducing any situation and its associated problems to an abstract level independent of the domain of the technical system, namely, the *contradiction*. Standard solutions and problem-solving techniques can generally be applied from hundreds of thousands of patents in various fields of technology. In this way, a rich set of concepts is generated with the aid of TRIZ. It increases the range of design freedom and extends the solution space into different domains of knowledge. During two decades of existence in highly industrialized countries, TRIZ has led to impressive successes and is considered an important tool in innovation.

From prior work (Rousselot et al. 2012), one of the authors (Cavallucci) has been working to formalize the central notions used in TRIZ and has conceived an extension of the method, called the *inventive design method (IDM)*. IDM was developed to solve classical TRIZ limits (Cavallucci 2011) and consequently to address wider and more complex problematic situations specifically in the concept generation stage. The four major steps of the IDM are (1) analysis of the initial situation, (2) contradiction formulation, (3) synthesis of solution concepts, and (4) choice of solution concepts to develop. We note that the design concepts developed with the help of IDM in this chapter are called s*olution concepts*.

During the past decade, research has been conducted to increase the performance of IDM. For example, the use of patent-mining techniques to analyze the initial situation of a technical system being designed (Souili and Cavallucci 2013), the application of artificial intelligence in automatically mapping a model of a problem to the model of solutions from a TRIZ knowledge base (Yan et al. 2014), and the use of optimization as a tool to assist designers in augmenting confidence in a solution concept by providing a rapid estimate and/or exploring the feasibility of a tested solution concept (Chinkatham and Cavallucci 2015). An overview of the latter, the link between invention and optimization, is presented in Fig. 8.1. It is positioned between steps 3 and 4 of the IDM framework. This link has been formulated by introducing the Screening, Modeling, Exploring approach. Furthermore, a supporting software tool (CSC-Modeler) has been developed to support this proposed approach.

In this chapter, another viewpoint on the link between invention and optimization will be specified. Optimization in this chapter is considered a step in the simulation-based design approach. It has been used to explore the characteristics of a system being designed. The simulation-based design is applied between steps

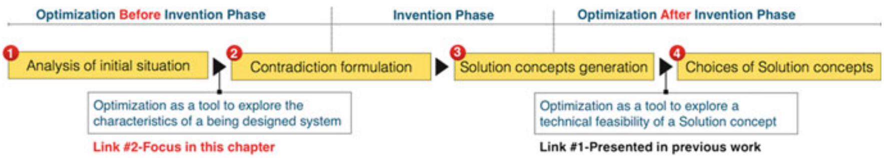

Fig. 8.1 The positioning of links between invention and optimization in the inventive design method

1 and 2 of the IDM (depicted in Fig. 8.1). The objective of this application is to assist the designer in identifying a possible set of contradictions by considering the correlation of design parameters from known characteristics of the system. In addition, the role of design parameters (action parameter or evaluation parameters) is observed, as will be discussed in this chapter.

The remainder of this chapter is organized as follows: Section 8.2 presents the technical background and discusses the motivation of this research. In Sect. 8.3, we introduce an approach to apply optimization in the IDM framework as a tool to enhance problem formulation. We illustrate the proposed approach with two case studies in Sects. 8.4 and 8.5. Finally, in Sect. 8.6, we conclude and discuss future work.

8.2 Technical Background

In this section, we review the synergy of TRIZ with other design methods/tools. We then detail certain works related to the proposed methodology.

8.2.1 Synergy of TRIZ with Other Design Methods/Tools

TRIZ has been applied and integrated in several design frameworks. For example, in the early design stage, TRIZ is applied with quality function deployment (QFD) (Yamashina et al. 2002; Su and Lin 2008; Yeh et al. 2011; Vinodh et al. 2014). Hu et al. (2000) proposed using TRIZ as a tool to identify the output parameters for the Taguchi design method. Several authors (Kim and Cochran 2000; Duflou and Dewulf 2011; Ogot 2011; Kremer et al. 2012; Borgianni and Matt 2015) applied TRIZ for decoupling a design matrix in axiomatic-based design. A few authors applied TRIZ in the area of computer-aided design (CAD)/computer-aided engineering (CAE) (Chang and Chen 2004). TRIZ also has been used in nontechnical domains. Smith (2001) presents an overall view of the synergy of TRIZ with others design methods/tools.

8.2.2 Initial Situation Analysis and Contradiction Formulation in Inventive Design

Initial situation analysis is the first step in using IDM. It relies on two parts (Fig. 8.2): one is brainstorming by actors (engineers and experts) inside the company; the other is the collection of current knowledge from patents or any published sources that relate to the technical system under consideration.

Overall information in this early analysis is used to initiate the problem graph. A *problem (PB)* in the problem graph could be solved by one or more *partial solutions (PS)*, and the PS may induce new PBs. Each PB or PS has one or more parameters that characterize its context. A parameter is one of the key elements used to define a proper contradiction from the TRIZ viewpoint.

The definition of the parameter should be made carefully in order to avoid fuzziness in the problem. There are several attributes to each parameter:

1. Typology (action or evaluation parameter)
2. Unit (how its evolution of states is measured)
3. Opposite states related to it (only concerning action parameter).

An action parameter (AP) is defined as a parameter whose states the designer has the ability to modify. This type of formulation has generally two directions, which can potentially result in positive impacts on the object or its supersystem.

Evaluation parameters (EP) can be observed in their ability to evaluate both positive and negative results. This type of parameter often has one logical direction of progress (its positive direction seems obvious), while the other seems absurd.

Within the problem graph viewpoint, the requirements, expectations, and customer preferences are viewed as problems that may be satisfied by one or more partial solutions, or it can be a source of a new problem. The notion of problem graph allows designers to observe the overall context of the design project. Thus, the direction to be solved is identified by counting the greatest number of problems that one problem generated or with which it is associated. Consequently, by solving this main or core problem, a new solution will have a significant impact to the future technical system.

After the problem graph has been filled, the *evolution hypotheses* (Cavallucci and Rousselot 2011) of the new system will be specified with the aid of methods and tools from the TRIZ knowledge base, specifically, multiscreen, system completeness, and objective laws. Here the evolution hypothesis is the logical interpretation of observed facts from the current system to portray the specific characteristics of the future system. A set of parameters identified in the previous steps (Fig. 8.2) has been formulated into a system of contradictions. One of the advancements that the

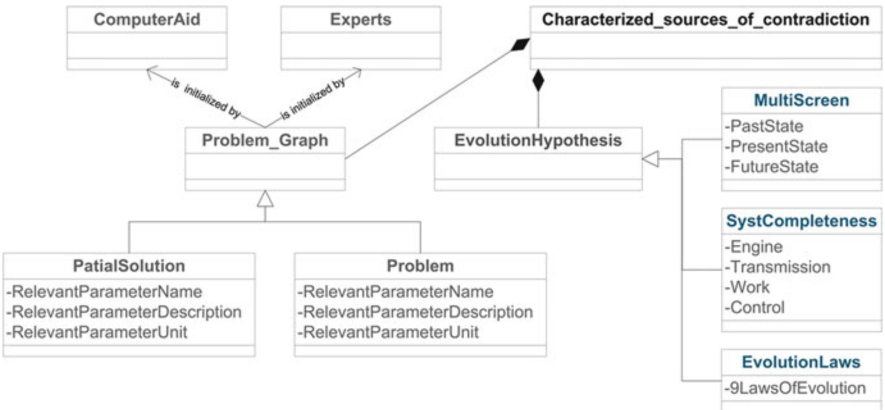

Fig. 8.2 A model to characterize the sources of the problem: contradiction

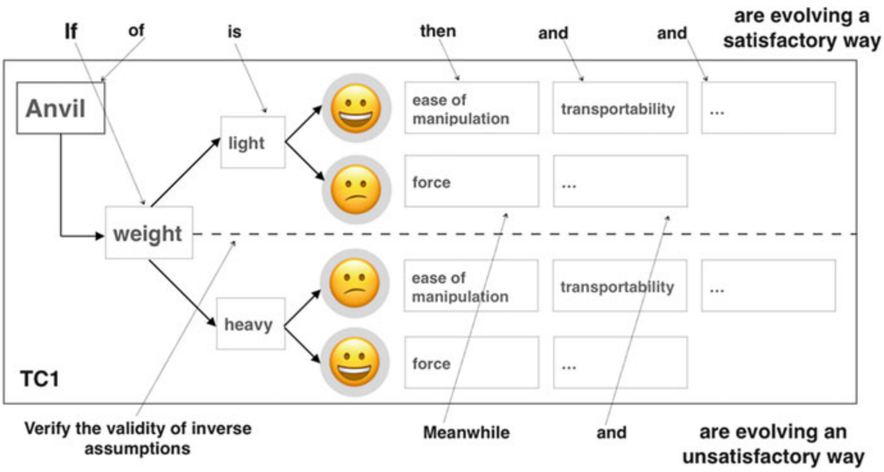

Fig. 8.3 An example of poly-contradiction of a system

IDM stated is *poly-contradiction*. Currently, a technical system is represented as a very complex system. It is interconnected in many layers and is combined with many sophisticated elements. The relation of a pair of evaluation parameters is not sufficient to characterize the actual situation of the system.

The notion of *poly-contradiction* presented in Fig. 8.3 is based on the *ENV model* (element, parameter name, and values) (Rousselot et al. 2012). An element (identified in the system completeness model that may be considered a resource) may have several APs that have two opposite state values (or directions, described by adjectives). Each state of an AP affects many EPs. Moreover, an EP may appear and be related to other APs. A mono-contradiction is interpreted from this poly-contradiction representation.

The representation of the populations of contradictions is made by considering the importance, universality, and amplitude of parameters (AP and EP) that are evaluated by actors in the design team. The most effective contradictions will be selected and resolved in the synthesis of a solution concept step. More details of this contradiction representation and how to evaluate the most effective contradiction are presented in (Cavallucci et al. 2011).

8.2.3 Discussion and Motivation

An engineering design method should integrate several design techniques or tools in order to bring a significant result in the design of a technical system. In the early phase of design, an open session for conducting creative or inventive activities must be taken into account. In the latter phases of design, several CAD/CAE tools will be used to evaluate, estimate, analyze, and improve the performance of the design concept.

According to the literature surveys mentioned in Sect. 8.2.1, the synergy achieved in the use of TRIZ comes from different domains (customer, function, parameter). This synergy is used with many design methods and tools, especially with axiomatic design. The application of TRIZ to axiomatic design is usually used for resolving a conflict of parameters in the design matrix. The application of TRIZ in the area of CAD/CAE is still limited. There are a few research works that apply TRIZ to solving problems using CAD tools. There are a few research works that have applied optimization during the invention phase, for example, the use of optimization and binary integer programming (BIP) techniques to extract a set of technical and physical contradictions (Lin et al. 2015).

Presently, many good achievements of design engineering have come from the advancement of CAD/CAE tools, more specifically, the multidisciplinary design-analysis and optimization (MDAO) framework. These tools allow the designer to integrate a number of perspectives in design (structure, the dynamic behavior of the system, etc.). The framework assists the designer to evaluate, analyze, and optimize the overall design results. The time span in the design cycle is reduced, and the ability to integrate the overall design is ensured due to the aid of MDAO. In addition, many statistical tools and decision-making aids are also provided in MDAO frameworks (i.e., ModeFrontier). We note that the design methods that use MDAO tools are simply referred to as *simulation-based design*.

TRIZ-based design, more precisely, the inventive design method, IDM, provides effective steps in analyzing the initial situation and proposing steps to solve an inventive problem systematically. It overcomes the limits of routine design. Nevertheless, IDM is still based on the expertise of designers in exploring, evaluating, and identifying the most relevant problems in observing a technical system. On the other hand, simulation-based design provides many tools and shows many advantages in design engineering, as mentioned above. The use of simulation-based design assists the designer in optimizing design characteristics through the virtual design environment and with traceability in the design processes.

The use of simulation-based design requires sufficient information such as approximate configuration, dimensions of geometry, and behavior to initiate the simulation. But none of this information is available in the early state of NPDP. The use of simulation-based design in the early state is possible while one is working on the redesign of a technical system for which the physical objects or simulation models exist and are accessible. Nevertheless, the final results of redesign based on existing models may not provide novel solutions.

The motivation of this chapter relies on the scenario of redesigning a technical system. The main assumption is the integration of simulation-based design to assist the designer in formulating the problems (contradictions) in the IDM framework. The most influential design parameters will be explored through the aid of simulation-based design, based not only on the expertise of the designers but also on the technical system itself.

Figure 8.4 presents an overview of the proposed approach to applying simulation-based design in the IDM framework. The overall content of this chapter will detail only the steps used to enhance the problem formulation (from step 1 to

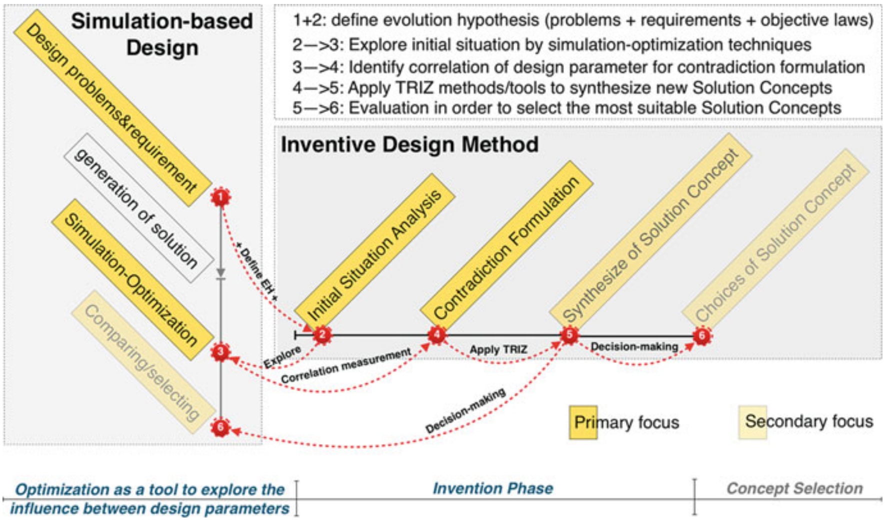

Fig. 8.4 Overview of the integration between the simulation-based design approach in the IDM perspective

step 4 in Fig. 8.4). The result of this development is presented in the following sections.

8.3 Enhancement of the Problem Formulation in the IDM Perspective

In this section, we review the concept of system completeness of TRIZ. We propose a model for observing the relationships of design parameters generalized from characteristics of the technical system. At the end of this section, we introduce an approach to enhance the problem formulation applied to the IDM framework.

8.3.1 System Completeness of TRIZ from the Viewpoint of the Simulation-Based Design Approach

System completeness is one of the objective laws of technical system evolution. Every technical system is the result of a synthesis of several parts into a single whole. In order for such a system to be viable, its main components have to present and perform a minimal level of working efficiency. The main components of the system completeness model are (1) engine, (2) transmission, (3) work (tool), and

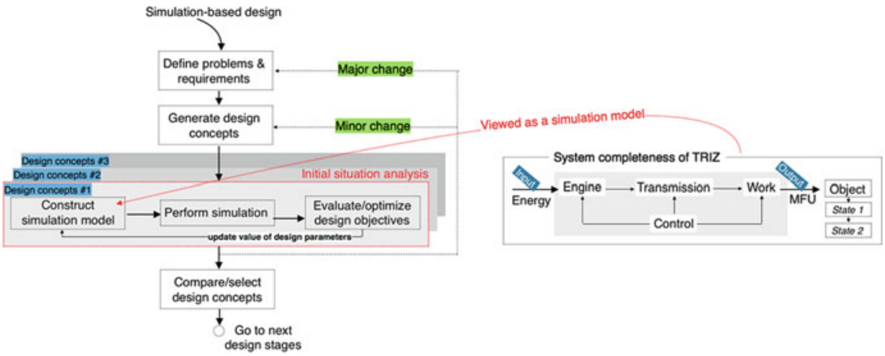

Fig. 8.5 System completeness of TRIZ from the point of view of the simulation-based design approach

(4) control, as depicted in Fig. 8.5. It should be noted that to make a technical system controllable, at least one of its components must be controlled.

In the simulation-based design approach (Fig. 8.5), the designer states the design problems and requirements, then generates design concepts with the aid of routine design approaches (e.g., brainstorming, morphological chart, design matrix). Afterward, a simulation model of each design concept (solution) will be constructed. We note that the method to construct a simulation model includes several modeling techniques, for example, model-based design tools (e.g., OpenModelica and SimulationX), and experimental approaches (i.e., DOE).

With the constructed simulation model, the designer performs the simulation and optimization to evaluate and optimize the design objectives. Simulation-optimization steps are resumed with other design concepts. In the following stage, the most suitable design concepts will be selected and further developed in the next design phases. One of the advantages of simulation-based design is avoiding infeasible design concepts passing through the selection stage. Furthermore, it provides a quantitative evaluation-selection, since design concepts have a parametric model that is optimized to satisfy the common objectives. These common objectives are referred to the objectives in optimization problems that appear in each design concept. We note here that the quantitative evaluation-selection is possible only if there is a common objective between design concepts, which means that there is a slight difference in the set of design concepts.

According to Fig. 8.5, in the redesign project of a technical system, the designer can access the simulation model (CAD or CAE model) of the technical system. This model may be viewed as a system completeness model of TRIZ. Consequently, the problem formulation stage can be made simpler with the aid of simulation-optimization. This model can be used to explore the overall characteristics of the technical system being designed. In this way, the design team can avoid mistakes in identifying and observing the design parameters of the overall system.

8.3.2 Development of the Sim-TRIZ Contradiction System Model

In Fig. 8.6, the system completeness model has been represented as a system, a subsystem, or a component in the system architecture model. This architecture model has been derived from (Fenves et al. 2008; Derelöv 2008). Here each element in the system completeness model is integrated by at least one relation. The *relation* refers to the physical conjunction or integration that can send or receive data and/or actions between components. The product of this relation provides an effect. The *effect* is defined as an outcome of an action in a system or mechanism that is based on a natural (physical) phenomenon.

Furthermore, in Fig. 8.6, a system completeness model could be viewed as a simulation model. The system of contradictions is generalized using the collected information from the exploration stage. Each element of the system completeness model (engine, transmission, work, and control) is simply called a *module*. A module consists of elements and has an annotation; for example, the element of the Control Module is annotated as E-Cx. Each element has been characterized by

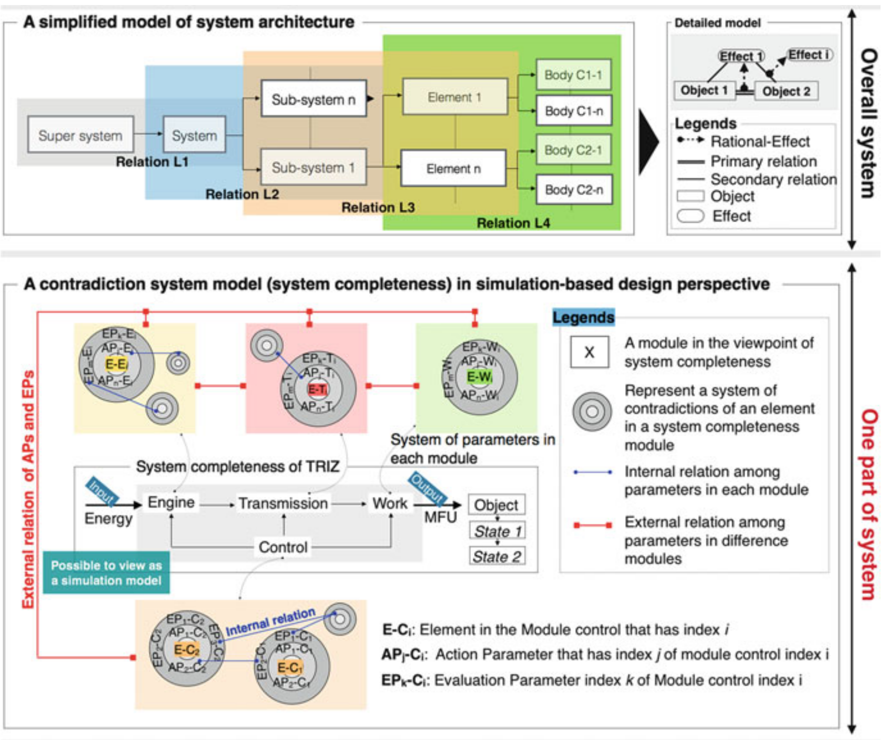

Fig. 8.6 The Sim-TRIZ contradiction system model (grounded from the system completeness viewpoint)

two typologies of the parameter. A parameter can be an Action Parameter (APx-Cx), or an Evaluation Parameter (EPx-Cx). The relations among design parameters can come from inside or outside the module (internal or external relationship).

In the IDM framework, during problem formulation, the roles of the parameters (action or evaluation) have been specified at the outset. The importance of parameters is defined by the design team depending on the specific scenario or strategy. In addition, the interaction of elements in the system is viewed via the problem graph. *The context of problem formulation in IDM is grounded on the observation and expertise of the design team.* In contrast to the model proposed in Fig. 8.6, the roles and relations of parameters are specified based on the correlations among design parameters that are characteristic of the system. The assumptions that we have made according to this difference include:

1. The importance of parameters should be specified according to the impact of the interaction of elements on the entire system architecture.
2. The roles of the parameters are changeable (from action to evaluation parameter and/or conversely). This change may lead to a new set of contradictions and may offer a new solution.

In regard to these two assumptions, we have proposed an approach to enhance the problem formulation for the IDM framework. Our result is presented in the following section.

8.3.3 Development of the Approach

The proposed approach has been intentionally used as an additional tool to analyze the initial situation. It provides steps to explore the design parameters of a technical system. Thus, the relationships among the design parameters will be identified by measuring the correlation of the design parameters and will be used to formulate a system of contradictions. In the following, techniques and tools of TRIZ will be used to resolve selected contradictions and to synthesize the new solutions. We base our approach on the following considerations:

1. The technical system under observation has a simulation model or it is possible to perform an experiment on the physical object.
2. Requirements, needs, or customer preferences are modeled as problems used for specifying the *evolution hypothesis* of the technical system being designed.

Figure 8.7 presents the proposed approach. It consists of five steps, and the details of each major step are described below:

Step 1: Define the Evolution Hypothesis
Customer preferences, technical specifications, and any requirements are combined and used to identify the evolution hypothesis of the future technical system. In this

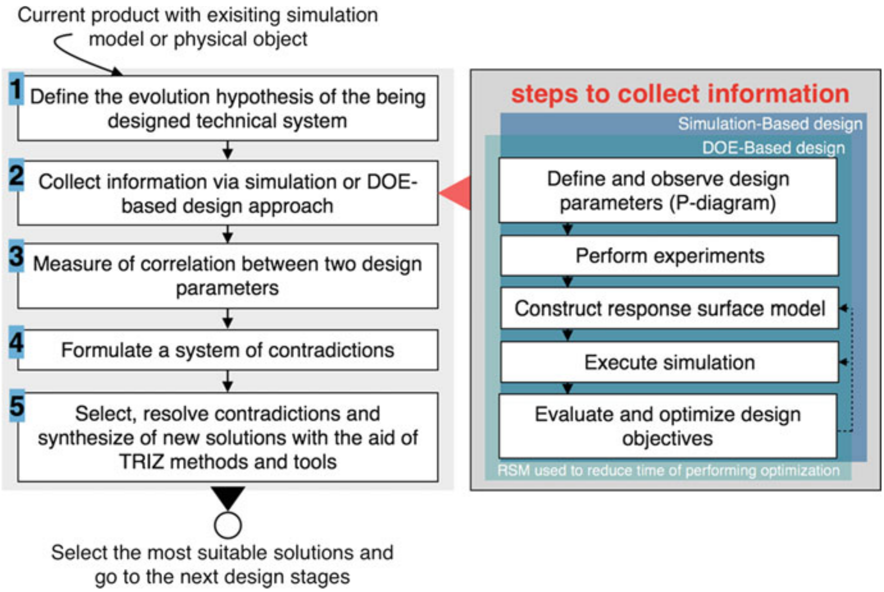

Fig. 8.7 Design steps to enhance the problem formulation in the Inventive Design Method framework with the aid of simulation-based design

step, TRIZ multi-screen analysis can be used as a tool to analyze the list of design parameters involved in changing from the past to the future. Consequently, the list of design parameters will be mapped with the objective laws of evolution in order to identify the current trends of the technical system. Thus, the evolution hypothesis will be defined according to these trends. Designers evaluate the importance of each evolution hypothesis and select one that is adequate. The selected evolution hypothesis is the one most relevant to the requirements of the overall design project. Thereafter, designers go to Step 2.

Step 2: Collect Information

In this step, the overall characteristics of the technical system are explored and observed. There are two directions to performing this exploration, and they are classified by scenarios like the following:

Experiment-Based Scenario

In this scenario, the designer is able to access the physical object (technical system), and an experimental technique will be applied to analyze and collect information. The designer specifies the scope of observation by identifying the set of input/output parameters and control/uncontrolled parameters of the system. This list of parameters is represented by the parameter diagram (Jugulum and Frey 2007). Then the designer associates the parameters with the evolution hypothesis identified in Step 1.

The designer performs experiments to collect information. We note that the number of experiments depends on techniques used (e.g., full-factorial, half-factorial, random). If the cost and time to perform an experiment are limited, then *surrogate modeling techniques* will be used to construct the simulation model (i.e., response surface model: RSM). Lastly, the designer performs simulation optimization to explore the overall characteristics of the system.

Model-Based Scenario

In this scenario, the designer has a simulation model in hand; simulation optimization is performed and information collected. On the other hand, in the new design project, the designer constructs the simulation model with the aid of CAD/CAE tools and performs the simulation afterward. The methods to construct the simulation model are various, and which are used depends on the characteristics of the system under observation (dynamic problem, structural, magnetic properties, etc.).

In both scenarios, the formulation of an optimization problem is roughly defined. The boundary of the design variables is approximately expressed. The constraints are stated as soft constraints.

Step 3: Correlation Measurement

From the information collected in Step 2, the designer analyzes the correlation between design parameters. Classical statistic tools (i.e., correlation matrix, *t*-student) have been used in this step. The selection of a set of parameters to analyze is associated with the evolution hypothesis in Step 1. The correlation matrix is an useful classical statistical tool, which evaluates the correlation coefficient between a pair of variables. The range of correlation is from +1 to -1, which reveals the strength of correlation. A zero value means lack of correlation.

Step 4: Formulate Contradictions

With the aid of correlation matrix analysis in the previous step, designers identify the possible set of contradictions related to the model in Fig. 8.6. The parameters that have a strong correlation will be considered first. A number of contradictions are formulated in this step.

Step 5: Synthesize New Solution Concepts

The designer selects the appropriate contradictions to resolve with the aid of TRIZ techniques (i.e., contradiction matrix and inventive principles). The appropriate contradiction may be considered from the viewpoint of evolution hypothesis as defined in Step 1. We note that the contradiction that was formulated from a set of highest-correlation parameters is not the high-impact choice in all cases, since that depends on the scenarios or objectives of the design project.

The synthesis of Solution Concepts depends on the number of contradictions selected. After a set of Solution Concepts has been generated, designers evaluate and select the most suitable ones to study in detail and move to the next design stage (embodiment, detailed design).

In order to demonstrate the overall design approach, two case studies are provided in the next sections. The redesign of a Mini-USB fridge in Sect. 8.4 will be used for demonstrating the viability of the proposed approach in the experiment-based scenario. Section 8.5, the case of a solenoid actuator, will be used to illustrate the proposed approach in the model-based scenario.

8.4 Case Example 1: Redesign of a Mini USB-Fridge

In this section, the ***experiment-based scenario*** will be illustrated by the redesign of a mini USB-fridge. The general context of this redesign project and the application of proposed approach are as follows.

8.4.1 General Context of Mini USB-Fridge

The overall view of the mini USB-fridge is shown in Fig. 8.8. The thermoelectric (TEC1-1270240) module is a core component. This module is attached to a heat sink and a cooling plate. A simple control board is supplied by a DC current source. An LED connected to this board is used to show the status of the fridge. A fan will operate when the temperature reaches its threshold. According to the datasheet of the thermoelectric module, the maximum cooling capacity is obtained by

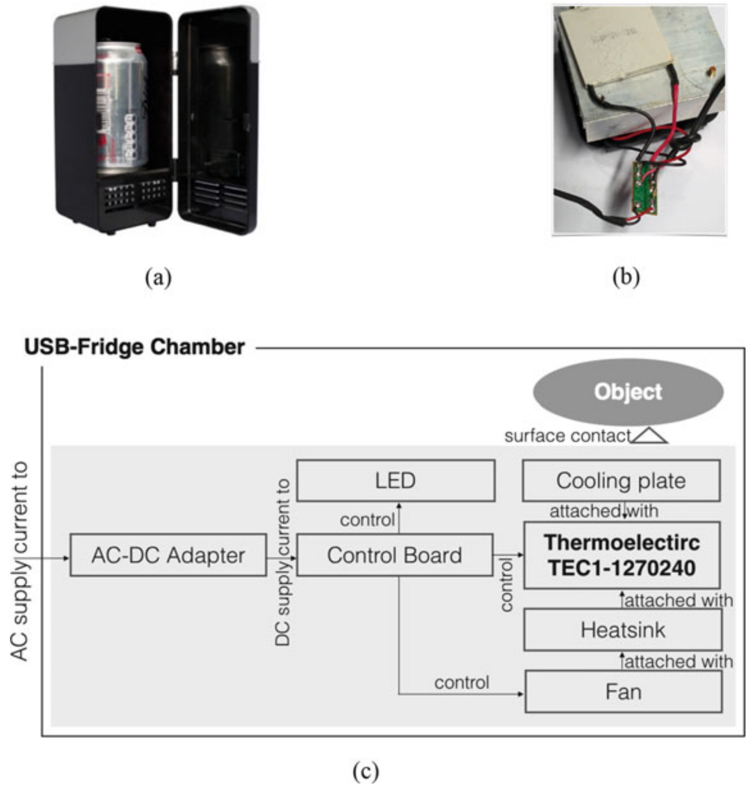

Fig. 8.8 Mini USB-fridge (**a**) current product, (**b**) a simple control board, and (**c**) a simplified system architecture model

controlling the difference in temperature between the hot and cool sides. Unfortunately, the current mini USB-fridge seems to be deficient in controllability (Fig. 8.8b). The sensor and control loop are not integrated into this current product.

The product description is:

1. Easy installation, no driver required, plug and play. Powered by USB cable, no batteries required, and internal LED light.
2. Compatible with all platforms. Dimensions: 19 × 58 × 39.4 cm.

8.4.2 Application of Proposed Approach

The evolving of information according to each step of the proposed approach is described in this section:

Step 1: Define Evolution Hypothesis

The evolution hypothesizes of this redesign project are combined from two viewpoints:

1. Requirements in changes:
   a. No change in the external dimension (keep current external structure)
   b. Making a small change in term of elements added to the new system, for example using a single thermoelectric or the old control part
2. Requirements from the user/customer:
   c. Energy efficiency (well-organized flow of energy)
   d. Speed in cooling
   e. Extending temperature range for cooling.

   In considering the requirements of the laws of evolution of the technical system, we note that the evolution hypothesizes rely on system completeness, energy conductivity, and harmonization. These hypotheses are related to several design parameters, such as input current supplied to the thermoelectric module, the on/off status of the cooling fan, and the insulation between the fridge's chamber and the environment.

Several solutions can be applied directly. For example, one could add some insulation into the fridge's chamber and change the control board within a temperature sensor to measure the actual temperature and regulate the input current of the thermoelectric module. However, those solutions have already been applied to the higher grade of mini USB-fridge.

Step 2: Collect Information

Figure 8.9 shows the P-diagram of the mini USB-fridge under observation. Thus, a number of experiments will be performed.

A can of Coca Cola of size 330 ml is used as the object to be cooled. A snippet of data collected is presented in Fig. 8.10. The data collected in the previous step are

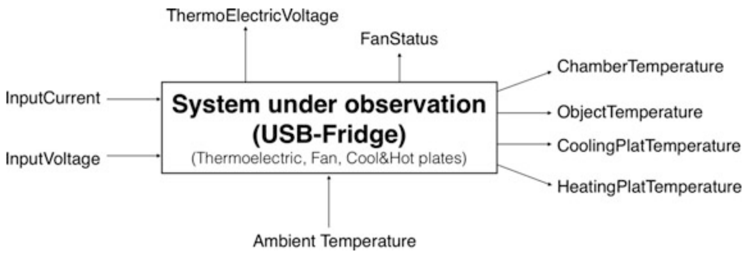

Fig. 8.9 System under tested and collected of information

Ambiient Temperature (°C)	Hotside temperature (°C)	Input Current (A)	Dif of Temperature (hot-cool) (°C)	Input Voltage (V)	Cooling capacity	Chamber Temperature (°C)	Object Temperature (°C)
30	27	2	0	7.8	25.5	13	7
30	27	2	10	8.2	21.5	14	7.5
30	27	2	20	9	16.8	16	8.2
30	50	2	0	8	28	12.5	7.2
30	50	2	10	8.5	24	13	8
30	50	2	20	9	20	13.6	8.2

Fig. 8.10 A snippet of data collected from performing the experiment

Object_Temp	0.860					
Colling_Capacity	-0.929	-0.876				
Ambient_Temperature	N/A	N/A	N/A			
Input_Voltage	0.178	0.078	-0.336	N/A		
Dif_Temperature(hot-cool)	0.833	0.826	-0.948	N/A	0.568	
Input_Current	-0.313	-0.426	-0.196	N/A	0.851	0.055
	Chamber_Temperature	Object_Temperature	Colling_Capacity	Ambient_Temperature	Input_voltage	Dif_Temperature (hot-cool)

Fig. 8.11 Correlation between design parameters of Mini USB-Fridge

used to construct the surrogate model. The objective of this surrogate model is to minimize time and resources needed to perform the experiment and to explore the large design space of the mini USB-fridge.

We note that details on surrogate modeling are not provided in this chapter. A comprehensive reference on the application of surrogate modeling in engineering design is provided by Forrester et al. (2008).

Step 3: Measure the Correlation of Design Parameters

The correlation between design parameter collected from the previous step is presented in Fig. 8.11. This measurement was made with the Pearson correlation.

From the correlation matrix in Fig. 8.11, the temperature of object is seen to be positively correlated with the temperature of the chamber. On the other hand, the cooling capacity has a negative correlation with the temperature difference between the hot and cool sides of the thermoelectric module. The designer can use this correlation as a guideline to formulate a contradiction that relates to the real behavior of the system under observation.

Step 4–5: Formulate the Contradictions and Synthesis of New Solution Concepts

According to Fig. 8.11, the temperature of the object is positively correlated with the temperature of the chamber, which in turn is related to the structure of the mini USB-fridge. The possible contradiction may be formulated by the pair of Evaluation Parameters *"Chamber's temperature—shape of chamber,"* which is related to the action parameter *surface area of cooling plate* (Fig. 8.12). The contradiction matrix between temperature and shape suggests that one apply *inventive principle #14: Spheroidality—curvature,* which suggests using curvilinear parts instead of rectilinear ones. With this suggestion, we can think about a form of insulation to put inside the chamber that is more specific than the aforementioned classical solutions.

It is seen from the proposed approach and results obtained in Fig. 8.11 that there are several viewpoints from which to formulate contradictions, such as focusing on the cooling capacity, which is positively correlated with the temperature difference between the hot and cool sides of the thermoelectric module, and the relationship between input voltage and current of the thermoelectric module. Regarding the proposed approach, the problem formulation is more flexible and broader than the classical TRIZ-based approach. An example of the system of contradictions represented as the model developed in Sect. 8.3.2 is presented in Fig. 8.12.

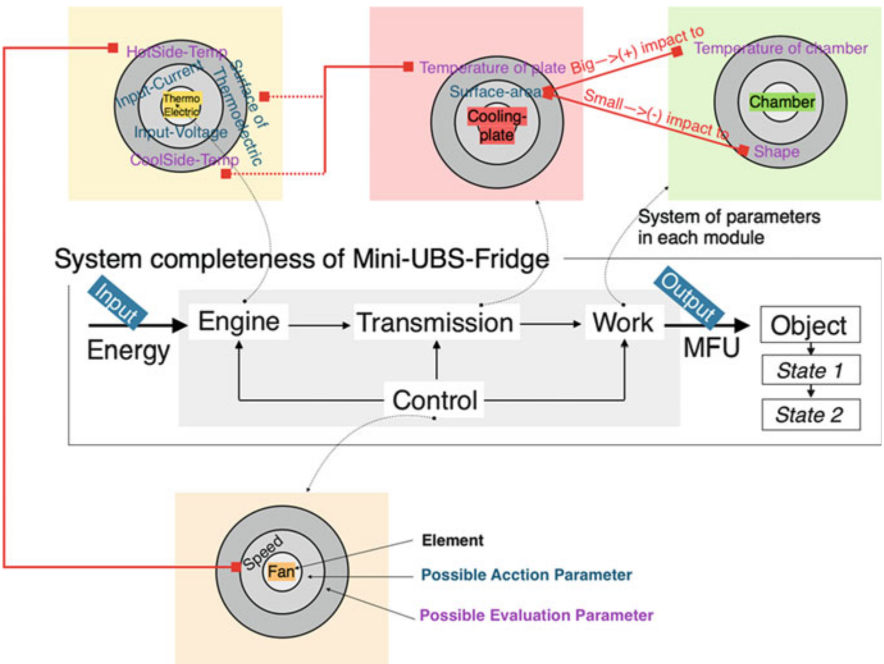

Fig. 8.12 System of contradictions of the Mini USB-Fridge viewed as the model proposed in Sect. 8.3.2

The role of the parameters is flexible, as illustrated in Fig. 8.12. For example, the surface of the thermoelectric module could be an Action Parameter that relates to the temperature of the cooling plate. This change leads to a new problem model. Consequently, in order to resolve this problem, another solution model will be applied. In this way, the design freedom is increased and extended to another knowledge domain.

8.5 Case Example 2: Redesign of a Solenoid Actuator

In this section, a ***simulation-based scenario*** will be illustrated by the redesign of a solenoid actuator. The general context of this redesign project and the application of proposed approach are as follows.

8.5.1 Context of the Design Project

Linear solenoids are electromechanical devices that convert electrical energy into a linear mechanical motion used to move an external load a specified distance. Current flow through the solenoid coil winding creates a magnetic field that produces an attraction between a movable plunger and a fixed stop. When electrical power is applied, the solenoid's plunger and its external load accelerate and move toward the solenoid's stop until impact occurs. The plunger moves inside the core of the coil assembly. This core may be either a plastic bobbin or a nonmagnetic metallic guide.

Removal of power from the solenoid eliminates the current flow through the coil. The plunger, with its external load, returns to the rest position, aided by a return spring, gravity, or the load itself, which could also be spring loaded. In some cases, when the solenoid is energized and in the seated position, the only load might be that of the plunger plus the opposing force of the compressed spring.

Some criteria in selecting a solenoid include the following:

1. Minimum force required at a specified maximum stroke
2. Available electrical input power, duty cycle
3. Maximum solenoid envelope dimensions.

Figure 8.13a shows an open-frame solenoid actuator that will be used as the case study in the model-based scenario.

8.5.2 Application of Proposed Approach

The evolution of information according to each step of the proposed approach is described in this section.

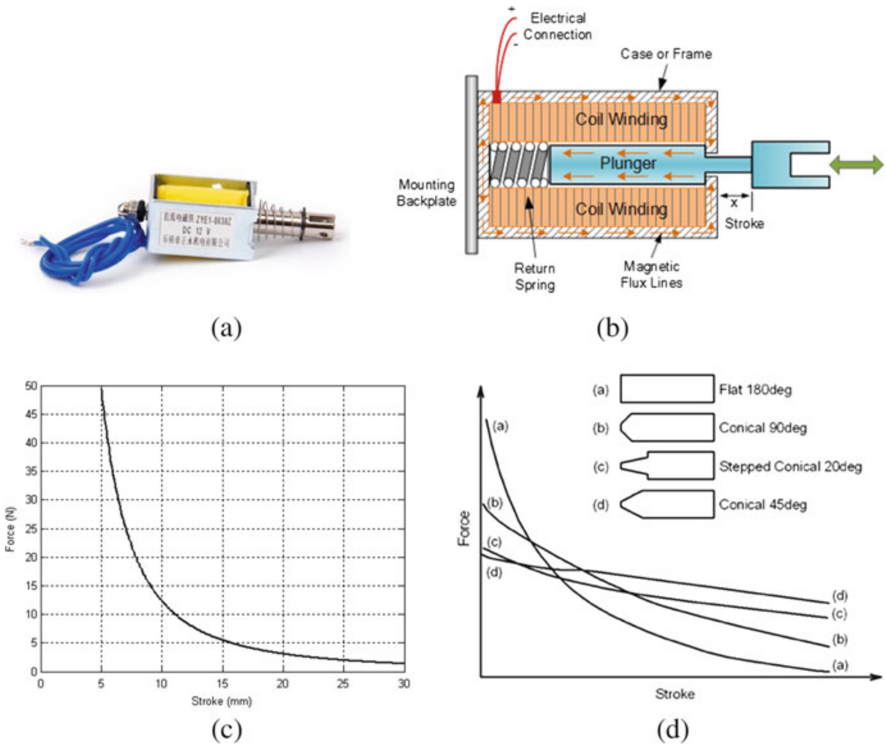

Fig. 8.13 A simple solenoid: (**a**) actual product, (**b**) cross-sectional diagram, (**c**) force-displacement characteristic, (**d**) example of plunger shape

Step 1: Define the Evolution Hypothesis

The main objective of this redesign project is to improve the overall performance of a solenoid. The construction, magnetic efficiency, and other criteria to select the solenoid have been taken into account. Therefore, energy conductivity is the evolution hypothesis that we used to define other design requirements. The improvement of energy conductivity will affect several characteristics of the solenoid, such as reducing leakage energy in the magnetic circuit, minimizing the force required at maximum stroke, and minimizing the response time of the solenoid.

The mechanical force generated from magnetic energy is described by the following equation:

$$F = \frac{dW_{\text{mag}}}{dl_{\text{g}}} = \frac{\mu_{\text{o}} N^2 I^2 A_{\text{g}}}{2l_{\text{g}}^2} \tag{8.1}$$

In order to maximize the force, the gap length (l_g) is minimized, while the turn number, cross-sectional area of the coil, and input current are maximized.

Unfortunately, maximizing these variables is limited by the dimensions of the solenoid. The relationship between force and displacement of the solenoid is highly nonlinear. The first-order approximation is similar to an exponential decay, as illustrated in Fig. 8.13c.

As minimizing force required at the maximum stroke is one of the desired solenoid. Several shapes of plunger can be used; such a form of the plunger is shown in Fig. 8.13d.

If we applied TRIZ-based design directly here, with the aid of Eq. (8.1), a contradiction could be formulated by considering the number of turns of the winding coil (N), which has a positive impact on the mechanical force (F). But the implementation of a huge number of windings in the solenoid frame is limited by its frame dimension. From this simple analysis, a contradiction can be formulated, as presented in Fig. 8.14.

The existence of parametric model can assist the designer in scoping down the research space and formulating problems, but it may force the designer to stick to the old solutions.

Step 2: Collect Information

A simulation model in this case study is presented in Fig. 8.15a. This model is an example from the OpenModelica platform. It was constructed in Modelica language. The system of equations for this simulation model consists of 194 equations in 194 variables. The simplified model of the solenoid actuator is presented in Fig. 8.15b.

At this point, the evolution hypothesis will be used to specify a set of design parameters. Subsequently, simulation–optimization will be performed to explore the behavior of the solenoid actuator. Figure 8.16 shows a snippet of some interesting variables that will be used to formulate the optimization problem. In this

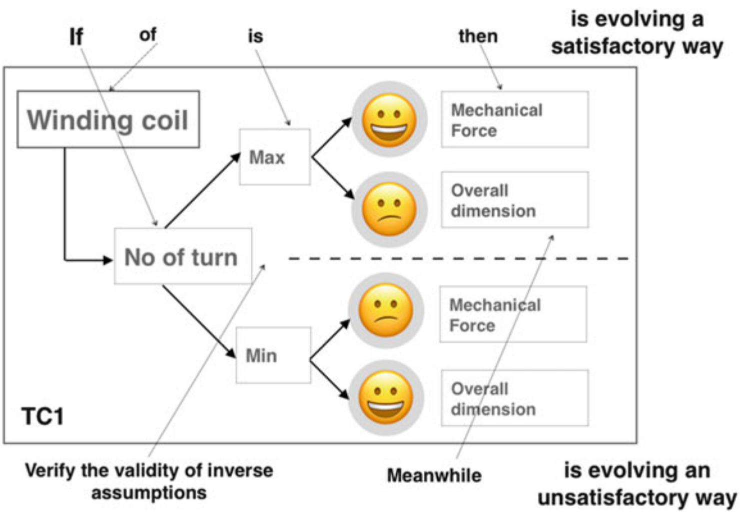

Fig. 8.14 A contradiction of a solenoid actuator generalized from Eq. (8.1)

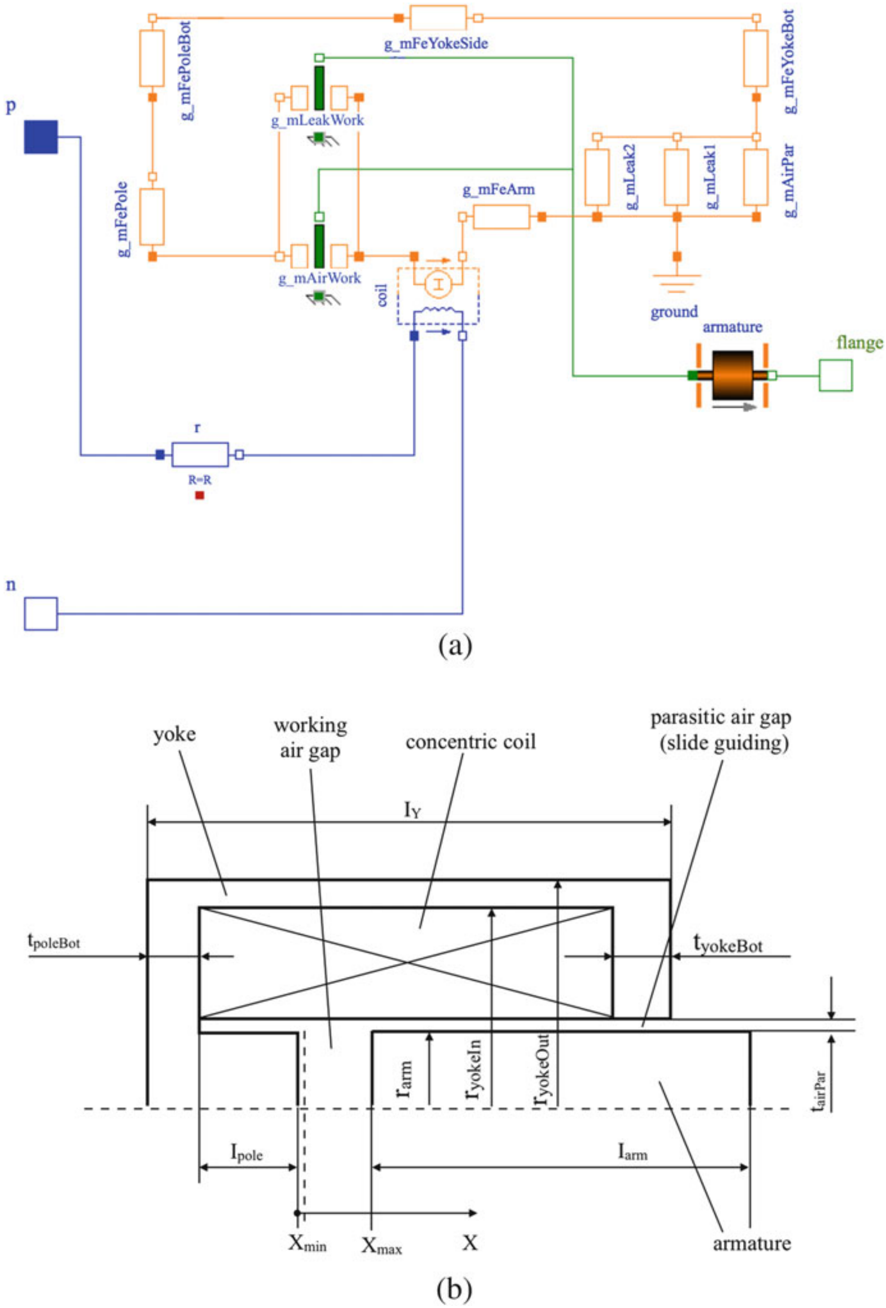

Fig. 8.15 (**a**) Simulation model and (**b**) Simplified model of a solenoid actuator in the OpenModelica environment

<table>
<tr><td>mass1.L</td><td>0.1</td><td>Length of component, from left flange to right flange (= flange_b.s - flange_a.s)</td><td>Real</td><td>Input</td></tr>
<tr><td>mass1.m</td><td>0.01</td><td>Mass of the sliding mass</td><td>Real</td><td>Input</td></tr>
<tr><td>mass1.stateSelect</td><td>3</td><td>Priority to use s and v as states</td><td>Integer</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.N</td><td>957</td><td>Number of turns</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.R</td><td>10</td><td>Armature coil resistance</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.g_mAirWork.A</td><td>7.85398163397448e-05</td><td>Cross-sectional area orthogonal to direction of flux</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.g_mLeakWork.r</td><td>0.003</td><td>Radius of leakage field</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.r_arm</td><td>0.005</td><td>Armature radius = pole radius</td><td>Real</td><td>Input</td></tr>
<tr><td>stepVoltage1.V</td><td>10</td><td>Height of step</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.mass.m</td><td>1</td><td>Mass of the sliding mass</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.material.n</td><td>12.5</td><td>Exponent of approximation function</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.g_mAirPar.B</td><td>0</td><td>Magnetic flux density</td><td>Real</td><td>Output</td></tr>
<tr><td>simpleSolenoid1.g_mAirPar.H</td><td>0</td><td>Magnetic field strength</td><td>Real</td><td>Output</td></tr>
<tr><td>simpleSolenoid1.r.LossPower</td><td>0</td><td>Loss power leaving component via HeatPort</td><td>Real</td><td>Output</td></tr>
<tr><td>simpleSolenoid1.armature.L</td><td>0</td><td>Length of component from left flange to right flange (= flange_b.s - flange_a.s)</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.c</td><td>100000000000</td><td>Spring stiffness between impact partners</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.d</td><td>20000000</td><td>Damping coefficient between impact partners</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.m</td><td>1</td><td>Armature mass</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.mass.L</td><td>0</td><td>Length of component, from left flange to right flange (= flange_b.s - flange_a.s)</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.mass.stateSelect</td><td>3</td><td>Priority to use s and v as states</td><td>Integer</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.n</td><td>2</td><td>Exponent of spring forces (f_c = c*|s_rel|^n)</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.stopper_xMax.c</td><td>1</td><td>Spring constant</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.stopper_xMax.d</td><td>1</td><td>Damping constant</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.stopper_xMax.n</td><td>2</td><td>Exponent of spring force (f_c = -c*|s_rel-s_rel0|^n)</td><td>Real</td><td>Input</td></tr>
<tr><td>simpleSolenoid1.armature.stopper_xMax.s_nominal</td><td>0.0001</td><td>Nominal value of s_rel (used for scaling)</td><td>Real</td><td>Input</td></tr>
</table>

Fig. 8.16 Snippet of the parameter list used in performing the exploration

case, we would like to minimize the cutoff force and to maximize the flux density. The overall dimension of the solenoid actuator (Fig. 8.15b) is defined as a soft constraint. The simulation–optimization was performed afterward, followed by the next step.

Step 3: Measure the Correlation of Design Parameters
The correlation of design parameters (input/output) is measured using the Pearson correlation. The flux density is positively correlated with the coil resistance. This result confirms the relationship between the mechanical force and the turn number of the winding coil, as observed in Eq. (8.1). Furthermore, the power loss of the solenoid actuator has a negative correlation with the flux density.

Steps 4 and 5: Formulate the Contradictions and Synthesis of New Solutions
According to the correlation of the design parameters, resistance of the winding coil is considered an action parameter that has a positive impact on flux density. Moreover, it poses a negative impact to the structure (limited in structure) of the solenoid actuator. Decreasing resistance means to increase the diameter of the winding coil. A pair of evaluation parameters in this case is *"productivity–volume of the stationary object."* With the contradiction matrix, the designer can apply inventive principle #35, *change of physical and chemical parameters,* to resolve this contradiction and to generate new solutions for this problem.

8.6 Conclusion and Future Work

The main objective of this chapter was to propose steps to assist the designer in preventing human error in exploring and identifying design parameters of a technical system. The use of simulation-based design to assist the problem formulation stage of IDM was presented. This approach can be used in redesign projects.

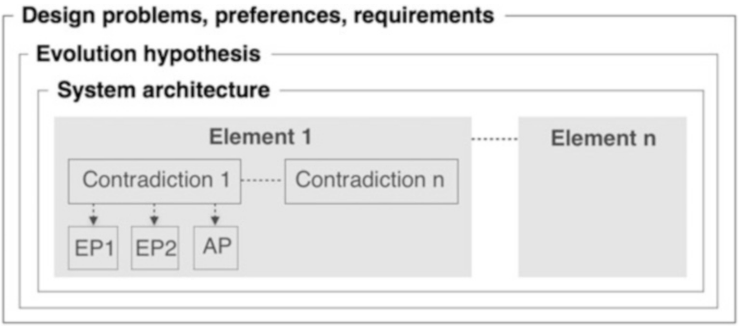

Fig. 8.17 Difference scopes of information evolving from the proposed approach

As presented in the case studies, the interaction of design parameters explored with the aid of simulation-based design can lead to another viewpoint in formulating contradictions.

Moreover, the existence of a parametric model of a technical system can be used as a guideline to establish the scope of the research space. The different scopes of information that evolve in each step of the proposed approach are presented in Fig. 8.17. The solution (design concept) is under the scope of design problems, preferences, and requirements.

The proposed approach is combined with the open session in specifying the evolution hypothesis and also in keeping to the actual facts of the technical system. The use of simulation-based design is made design traceable. In order to evaluate and validate this proposed approach, a more complex case study is needed. Furthermore, the automatic association of design preferences and requirements with laws of technical system evolution is one of our future research directions.

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Chapter 9
Collaboration Framework for TRIZ-Based Open Computer-Aided Innovation

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Abstract In the current industrial context, there is an increasing interest in the collective resolution of creative problems during the conceptual design phase. With collaboration, companies can expect to facilitate aggregation of multi-intelligence and knowledge for the proposal of new inventive solutions. Recent advances in theoretical approaches to innovation management as well as in information and communication technologies provide a more structured knowledge-driven environment for inventors, designers, and engineers. As a result, a new category of tools known as computer-aided innovation (CAI) is emerging, with the goal of assisting designers in their creative performance and of effectively implementing a complete innovation process. This chapter proposes a next evolutionary step for CAI, arising from two major recent developments: one coming from the advances in information and communication technology possibilities commonly referred to as "Web 2.0" and the other coming from a strategic paradigm shift from closed to open innovation. To go further, in this work we introduce an information-based software framework to collaborate for inventive problem solving. This framework proposes the implementation of techniques from the collective intelligence research field in combination with the systematic methods provided by the TRIZ theory. While collective intelligence focuses on the intelligent behavior that emerges in collaborative work, the TRIZ theory concentrates its attention in the individual capacity to solve problems systematically. The framework's objective is to improve the individual creativity provided by the TRIZ methods and tools, with the value created by the collective contributions. This contribution highlights the importance of knowledge acquisition, capitalization, and reuse as well as the problem formulation and resolution in collaboration.

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9.1 Introduction

One core challenge in the strategic management of technological innovation is the diverse nature and location of sources for innovation. As Schilling (2012) argues, innovation can originate from different sources: individuals, universities, firms, and nonprofit or government-funded entities. However, according to the last author, the most important source for innovation arises from the linkages between these different sources. Consequently, enterprises require strategies and tools to explore the different sources and their linkages to improve their innovation capacities and capabilities.

Currently, advances in theoretical approaches to innovation as well as in information and communication technologies (ICTs) provide a more structured knowledge-driven environment for inventors, designers, and engineers. As a result, a scientific research field known as computer-aided innovation (CAI) is emerging, with the goal of assisting designers in their creative performance and of effectively implementing a complete innovation process throughout the whole product or process life cycle. Within the front end of the innovation process, this chapter proposes an evolutionary step of CAI toward the concept of Open CAI 2.0 previously defined by Hüsig and Kohn (2011). Open CAI 2.0 arises from recent developments on two drivers: (1) one coming from the advances in technological possibilities in the software field commonly referred to as "Web 2.0" and (2) the other coming from a strategic paradigm shift from closed to open innovation. Therefore, this work proposes an Open CAI 2.0 framework which relies on the coupling between the innovation TRIZ theory and case-based reasoning. This CAI tool aims to support the generation of inventive technological solutions through a problem-solving process that needs a reformulation of the initial problem to build an abstract model of the problem. This work also highlights the importance of knowledge acquisition, capitalization, and reuse as well as the problem formulation and resolution in collaboration.

9.1.1 Industrial Context

In the scope of the knowledge-based economy, the management of technological innovation is a critical aspect toward the success of the modern industry. As Laperche et al. (2011) argue, the capacity to innovate has evolved to become the engine of competition and industry competitiveness. Therefore, the design and industrialization of new and more complex products in a shorter time is a challenge for industrialized countries. To cope with this pressure, industries depend on information, knowledge, and highly specialized skills in various domains. Companies are aware of the importance of collaborations with other organizations as the source of specialized knowledge. Such companies consider innovation as an interactive process capable of creating and exchanging knowledge within and outside the firm's boundaries. Within this scenario, the methods and computational tools that must face industrial challenges in innovation demand the ability to mobilize individual tacit knowledge toward a more interactive strategy. Such a strategy should also encourage staff skills to develop innovative products in a shorter time, to increase the level of inventiveness of products, and to lower development costs.

9.1.2 From Closed to Open Innovation

Some authors (Hüsig and Kohn 2011; Chiaroni et al. 2011) agree that open innovation shows its efficiency by changing the way in which the enterprises interact with customers and other external actors (suppliers or universities). The interaction is practiced in a more open way to improve their innovative capabilities and to accelerate internal innovation. The scope of open innovation has progressively evolved to lead to the definition of Chesbrough and Bogers (2014): "Open innovation is defined as a distributed innovation process based on purposively managed knowledge flows across organizational boundaries, using pecuniary and non-pecuniary mechanisms in line with organization's business model." This is contrasted with the "closed" model of innovation, where firms typically generate and develop their own ideas and innovation in isolation. To detail the open innovation concept, Table 9.1 makes a comparison between closed innovation and open innovation. In their contribution to the debate on open innovation, Trott and Hartmann (2009) explain that the dichotomy between closed and open innovation may be true in theory but does not really exist in industry. They have examined the six principles of closed innovation (and by consequence those of open innovation), and they have concluded that the open innovation paradigm has created a partial perception by describing something which is true (limitations of closed innovation), but false in propagating the idea that firms follow these principles.

Table 9.1 Closed innovation versus open innovation (Chesbrough 2003)

Closed innovation	Open innovation
The smart people in the field work for us	Not all the smart people work for us
To profit from R&D, we must discover, develop, and ship it ourselves	External R&D can create value; internal R&D is needed to claim a portion of that value
If we discover it ourselves, we go to market first	We don't have to originate the research to profit from it
If we are the first to commercialize an innovation, we will win	Building a better business model is better than getting to market first
If we create the most and best ideas in the industry, we will win	If we make the best use of both internal and external ideas, we will win
We should control our intellectual property so that our competitors don't profit from our ideas	We should profit from others' use of our intellectual property and vice versa

In the industry, open innovation represents the antithesis of the traditional vertical model in the new product development process, and it is a solution to problems and drawbacks for the design process in traditional hierarchical organizations (Sorli and Stokic 2009). The open innovation paradigm focuses on the use of explicit internal as well as external knowledge to accelerate internal innovation, in opposition to the "not invented here" syndrome.

As a process, open innovation demands a massive effort of knowledge management. It uses the principle that valuable ideas can come from inside or outside the company, but also can go to market inside or outside the company as well; this knowledge flow is often represented by the classical funnel illustrated in Fig. 9.1. However, useful knowledge is widely distributed, a condition that represents a challenge to identify, interact, and take advantage of external knowledge sources and then to integrate it at the core of the innovation process.

9.2 Computer-Aided Innovation and TRIZ

The use of computer-aided technologies facilitates the transition from a closed model to drive the innovation process to a more open approach which includes actors and knowledge beyond the enterprise boundaries. In this scenario, CAI tools are useful to promote collaborative work, to implement knowledge management systems, to perform routine and time-consuming activities (e.g., patents search), and to access external sources of information. CAI is a software-based solution assisting participants in the different stages of the innovation process. In the beginnings, CAI software was mainly inspired by TRIZ methods and tools. However, CAI solutions are progressively evolving and adapting to enterprises' requirements.

In the last years, the development of CAI tools has given birth to different commercial software applications. Some of them are focused on specialized tasks of the innovation process, while others try to cover the whole innovation process. An area of opportunity arises because most of the CAI products concentrate on specific tasks like idea management or patent search and only a few of them consider the whole innovation process. Concerning CAI tools, this work covers only developments oriented to the new product development. Specifically, it includes some TRIZ tools for improving creativity in the resolution of inventive problems.

For Nattrass and Okita (1983), humans and computers form a symbiotic relationship in product design. In this relationship, human beings outperform computers in thinking spontaneously and relating disjointed facts and are creative by association. On the other hand, computers are faster, more accurate, and tireless, and they are more efficient in processing huge quantities of engineering data at a time. In the experience of Pollack et al. (2003), humans should be engaged in higher-level forms of creativity, while computers are suitable for lower-level details of design. Since the front end of innovation requires developing a solution with a

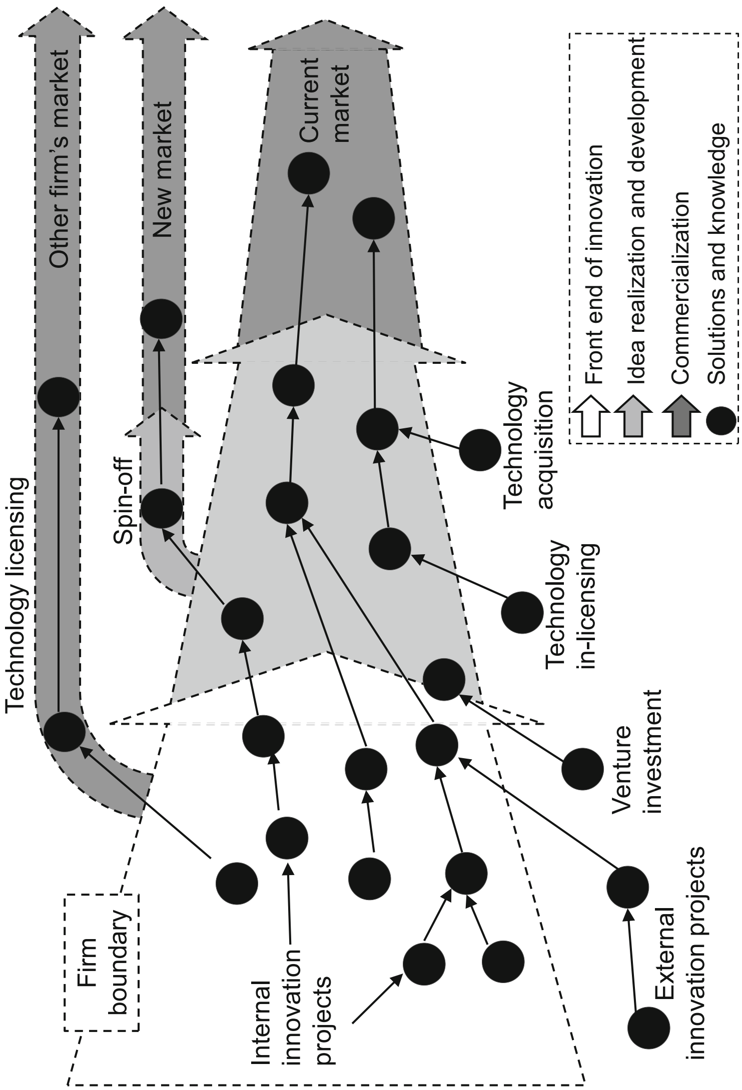

Fig. 9.1 Open innovation model (Herzog and Leker 2011). (C) 2010 Springer, reprinted with permission

high degree of inventiveness and creativity, it is reasonable to expect that humans are the most qualified for this task.

Furthermore, as Giachetti et al. (1997) highlight, engineering design is characterized by a high level of imprecision, fuzzy parameters, and ill-defined relationships. Therefore, the principles of the innovation process need to take into account these imprecisions in design. As observed in Fig. 9.2, imprecision is more important in the early stages of design, because they typically begin with a description

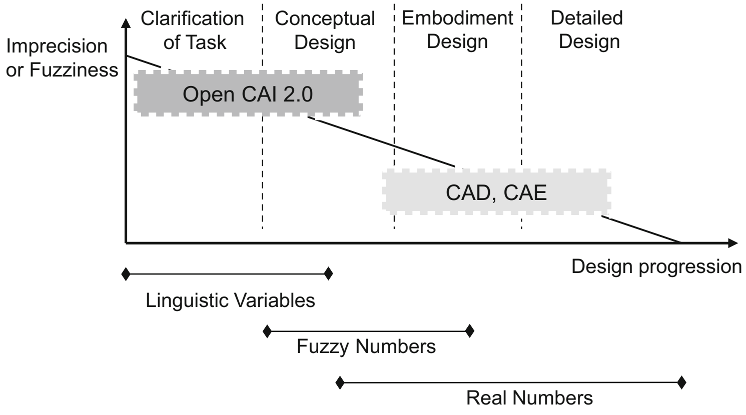

Fig. 9.2 Imprecision level in Open CAI 2.0 (Giachetti et al. 1997)

regarding the natural language statements. At this level, linguistic imprecision arises from the qualitative descriptions of goals, constraints, and preferences made by humans (Giachetti et al. 1997).

To deal with the previous requirements, ICTs supporting innovation processes are evolving simultaneously as are the methods for managing innovation. There is a real interest for ICTs as new ones are continually emerging (Sorli and Stokic 2009). Specifically, the Web technologies are transforming all human activities dependent on information, including social interactions.

9.2.1 Web 2.0 as a Platform for Collaboration

Web 2.0 as a technological driver leads to implement and to take advantage of collaborative workspaces. Indeed, the Web 2.0 technology supports an emerging form of collaboration that can be beneficial for open innovation, based on the many-to-many form of communication. But before understanding collaboration within Web 2.0, it is necessary to make a semantic distinction between cooperation and collaboration. According to Caseau (2011), the main difference between both terms is the degree of organization of the activities between actors. Indeed, collaboration is a fuzzier concept, and the participants do not have a hierarchical organization. Instead, the work is guided by a common objective which is shared by all the members. Both cases require an orchestration of activities, which justifies the definition and the formalization of a model.

For Campos et al. (2006) and Sorli and Stokic (2009), situations of collaboration in the industry seek to facilitate the participation of different actors in activities related to reach a common objective (e.g., solving a problem, designing a new product). Figure 9.3 shows a generic framework with the main activities to consider in collaboration whatever the situation and the collaboration purpose.

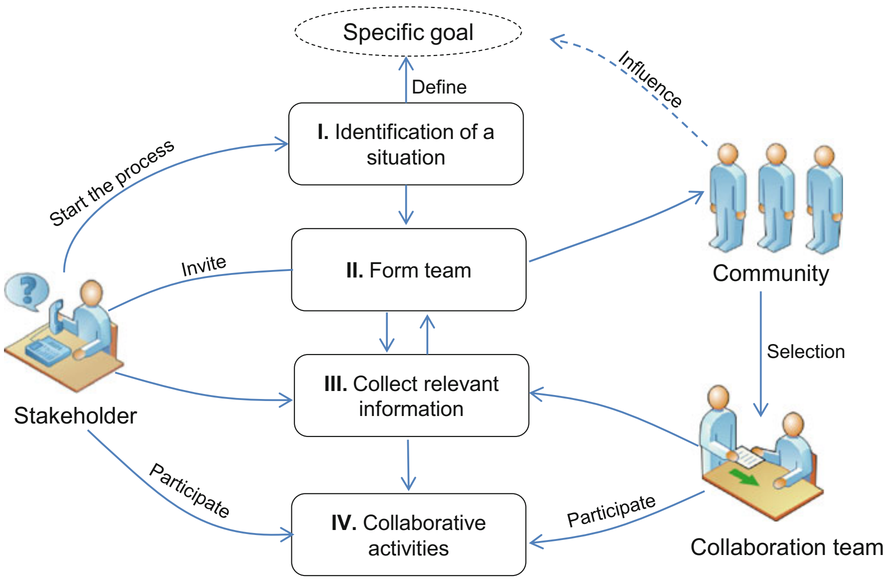

Fig. 9.3 Generic model for industrial collaboration. Adapted from Campos et al. (2006)

For implementing such a framework, Web technologies offer new possible ways to communicate and share information, from the use of the e-mail up to the incorporation of the "architecture of participation" relying on Web 2.0. Building on the Web 2.0 technologies, social network services create new forms of communication, interaction, information sharing, and collaboration. Social networks base their operation in the creation of relationships between participating members (e.g., social or family ties), through the use of ICTs. For Caseau (2011), there is an emerging way to organize collaborative work in the industry, leading to what is known as "Enterprise 2.0."

Profile diversity in collaboration environments is another element to take into account in the creativity driver. Indeed, to have an efficient collaboration, the community must gather members with various domains of expertise. Consequently, it is important to have a shared technical language which enables participants to bridge the gap between their backgrounds and problem abstractions to exchange information and knowledge. Moreover, the complexity of inventive problems requires a clearly defined language and a step-by-step procedure to transform the initial problematic situation into a solution. The TRIZ theory is probably the most appropriate tool for reconciling concrete and abstract visions of the problem and to facilitate the knowledge exchange between different scientific domains.

9.2.2 TRIZ-Based Inventive Problem Resolution

The evolution of CAI-based solutions also depends on the expansion of the methodologies to assist the creative process of idea generation and problem resolution. According to Ilevbare et al. (2013), different visions exist about TRIZ, either as a methodology, a toolkit, or as a science. Consequently, the multiple approaches lead to confusion on its definition. Moreover, in practice, TRIZ is particularly challenging because the engineering nature of the methodology makes it difficult to adapt for application in a wide range of situations. The lack of standardization in the application also makes the practice of TRIZ difficult. The Algorithm for Inventive Problem Solving (ARIZ) is considered as one of the most powerful algorithms of TRIZ to guide the problem-solving process. Ilevbare et al. (2013) explain that ARIZ is a sequence of logical steps to analyze an ill-defined initial problem and leads to the formulation of a solution by using TRIZ concepts and tools.

Although ARIZ brings together most of the fundamental concepts and methods of TRIZ, it does not have a broad application due to the following reasons:

- It is a long step-by-step guide.
- It is considered as an analytical approach rather than a problem-solving process.
- It is exhausting, especially when the user does not have much time for solving a problem.
- It is required for $<1\%$ of all technical problems.

Due to the previous drawbacks, this work studies alternatives to ARIZ. The use of TRIZICS seems feasible as a roadmap to organize the process of problem resolution. In practice, TRIZ tools are organized depending on the problem situation. In this case, it is particularly challenging for inexperienced users to select and apply the appropriate TRIZ tools. Cameron (2010) proposes a standard process, named TRIZICS, to guide the user from the beginning of a problem-solving process to the end. The TRIZICS roadmap is composed of six sequential steps which structure a systematic problem-solving process: (1) identifying the problem, (2) selecting the problem type, (3) applying analytical tools, (4) defining the specific problem, (5) applying TRIZ solution tools, and (6) solutions and implementation. Each of these six steps provides a formal model to define the problem, specifies the limitations, establishes deadlines for a solution, reviews assumptions, and defines the cost, resources, and the implementation plan. TRIZICS offers a basis to integrate classical TRIZ methods and tools in a framework for the development of CAI.

9.2.3 Academic Developments

TRIZ methodology provides the concepts and tools to enhance creativity while providing a logical framework for problem resolution. However, commercial tools

Table 9.2 Academic development analysis

Work	Objective	Advantages	Disadvantages
TREFLE-ENSAM (2003)	To adapt TRIZ tools with functional analysis and to introduce ecological concerns in the earlier steps of the design	– Adapted to preliminary design – To develop innovative concepts from existing products	– Brainstorming organization for interpretation and the choice of concept
Cavallucci and Leon (2004)	To establish the theoretical basis to build a CAI tool by interacting with a computer-aided design (CAD)	– Formulating theoretical bases to build CAI systems – Defining a generic model adopting a guided design approach	– The proposition to design up a contradiction network is complicated
Cugini et al. (2009)	To improve the product development cycle integrating CAI tools with optimization and product life cycle management	– A design tool integrating optimization techniques – Interoperability with CAD environments	– Oriented to incremental innovation – Limited to the use of contradictions
Chen et al. (2009)	To involve nontechnical staff in the innovation process	– Highlighting the importance to involve nontechnical department staff – A well-structured process analysis problem can solve the problem and has an action plan	– The interaction between nontechnical and TRIZ practitioners is not defined
Li et al. (2009)	To set up a process of technology innovation based on TRIZ and CAIs according to the characteristics and the existing problem of the manufacturing enterprises	– Combination of a classical innovation process with TRIZ tools and CAI technology	– Interested only in product innovation – The problem solving strategy is not detailed
Zhang (2011)	To simulate the thinking process of the human in the innovation to shorten the innovating time	– Incorporation of a knowledge discovery system – Proposition of an expert system to accelerate the process of invention	– The process workflow is not clear
Tan (2011)	To apply computer-aided innovation (CAI) systems based on TRIZ to solve some ill-structured problems that appear in an innovation pipeline	– An application to solve ill-structured problems in an innovation pipeline – Applying TRIZ in two sub-processes, the input design and the conceptual design separately	– Limited to a two-stage analogy process model
Li et al. (2012)	To classify patents according to the level of inventiveness as defined in the theory of inventive problem solving (TRIZ)	– Detailed workflow for a conceptual design activity – Incorporating data mining of patents, natural	– Drawbacks for scaling up the work or putting the proposed method into practice – Increasing the

(continued)

Table 9.2 (continued)

Work	Objective	Advantages	Disadvantages
		language processing, and machine learning	computational burden for processing newly published patents
Hu et al. (2013)	To combine the case-based decision theory approach (to store and reuse knowledge) with TRIZ	– Supporting decision making during the design process – Incorporating knowledge management	– Limited to formulate the problem as a contradiction – The process is not organized in phases
Lopez Flores et al. (2015a, b, c)	To explore the use of collective intelligence within the TRIZ deployment	– Regarding the collaborative aspect to deploy TRIZ – The use of experience capitalization	– The lack of semantic analysis – It requires tools to facilitate problem modeling

implementing TRIZ are limited to the classic methodology. Therefore, the development of integrated CAI products based on TRIZ tools and modifications to TRIZ are still areas of opportunities that the academic world has taken to propose new evolutions of TRIZ and the development of CAI, as demonstrated in the special issue of the *Computers in Industry* journal in 2011. Table 9.2 presents an analysis of advantages and disadvantages of academic developments; the analysis gives a perspective about CAI looking to propose more global and inclusive solutions. Thus, it is possible to identify two principal evolutions: to advance the methodology and to advance the theoretical foundations of the CAI field.

Table 9.2 documents the interest in the academic community for complementing TRIZ with other approaches. The first case (TREFLE-ENSAM 2003) proposes a tool to integrate TRIZ creativity tools with other approaches such as functional analysis. In other proposals, Cavallucci and Leon (2004) and Cugini et al. (2009) try to have a more inclusive process and interoperable tools covering all the phases of product life cycle management. Regarding knowledge capitalization, Hu et al. (2013) propose to combine TRIZ with case-based decision theory, and Li et al. (2012) incorporate data mining of patents. Finally, as an effort to simplify the use of TRIZ, Chen et al. (2009) propose the involvement of nontechnical employees, and Zhang (2011) tries to simulate the thinking process of humans. As observed, the interest to advance TRIZ and the CAI tools associated is different: from covering the whole product life cycle and the incorporation of knowledge capitalization approaches to trying to make easy the practice of TRIZ for nontechnical employees. However, few academic developments address the collaborative dimension**.**

9.3 Architecture for TRIZ-Based Collaborative Open CAI

9.3.1 Overview

The description of the functionalities of our proposed collaborative Open CAI 2.0 starts with the presentation of the general usage of operation in Fig. 9.4. The logical basis of the collaborative resolution process consists of orienting the interactions of the involved participants in such a process with a common language, specifically the problem formulation tools provided by the systematic approach of the TRIZ methodology.

The main operations of the general use case are as follows:

I. The first activity, identification of a situation, corresponds to the description of the problematic situation. The basic information to describe and analyze the problem is as follows:

   a. Project name and general description
   b. Clear problem statement
   c. Images and documents related

II. The second activity is the composition of the collaboration team. This situation requires identifying specific experts for the problem faced. Two types of search are possible:

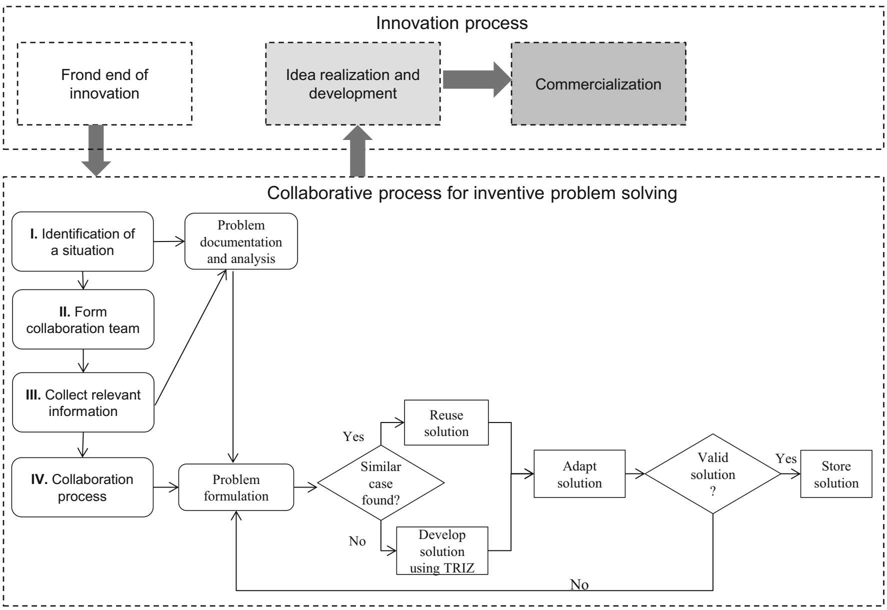

Fig. 9.4 General usage of the collaboration process for problem solving (Lopez Flores et al. 2015a)

a. Among the group of registered users
b. Outside the platform, looking in other sources for the required expertise

III. Collecting relevant information helps to provide details to make clear the problematic situation. Once the collaboration team is complete, the participants have the option to review and complete the information about the problematic situation.
IV. The collaboration process uses an asynchronous pattern to coordinate the participations to ensure information integrity. In this phase, it is the hybrid TRIZ-CBR model (our synergy previously developed in Cortes 2006) which drives the collaboration activities.

In this combined approach, TRIZ provides the generic knowledge and the initial structure to generate case indexation. CBR brings techniques to compare and search for a previously solved problem. Thus, this coupling is a way to add memory to TRIZ for the capitalization of new solved cases in inventive design. This synergy combines two types of knowledge: generic from various fields using TRIZ and domain specific through capitalization. Built with the aim to accelerate the design, implementation of such a synergy brings several questions. Indeed, it is neither the use of CBR in inventive design nor the original logic of TRIZ. But the proposed approach offers the possibility to create new knowledge with a limited scope but useful for the generation of a concept with a medium level of inventiveness. This coupling also facilitates the transfer of technological solutions avoiding some pitfalls, thanks to information on the implemented solution. The tool built on this approach facilitates the handling of TRIZ methods and tools. Another advantage is that the knowledge stored in the system could be useful in two ways: in the early design stages (preliminary design) and as a criterion for evaluating the pertinence of proposed concepts or ideas.

Concerning collaboration, the advantage of using the TRIZ-CBR model is that the TRIZ theory is an approach that provides a common language to communicate the problem formulation (Ilevbare et al. 2013). For instance, contradiction and Su-field model are very well-defined patterns with a high level of abstraction. Consequently, they facilitate the creation of problem models which are independent of a specific technical domain. Moreover, the proposed collaboration model aims at facilitating the interaction between TRIZ beginners and experienced TRIZ users.

The software-based architecture is a socio-technical system capable of linking together people having inventive problems (stakeholder) with a community of solution providers. Figure 9.5 provides a description of the proposed service for an Open CAI framework.

(1) "Stakeholder"—includes, but not limited to, the individual or group of individuals having inventive problems. The stakeholder is responsible to start the collaboration process by sharing an idea or an inventive problem.
(2) "Inventive problem"—refers to the need or idea imagined by the stakeholder and which is formulated as an inventive problem. An inventive problem is a complex situation that required the transformation of existing technical knowledge for the formulation of new concepts.

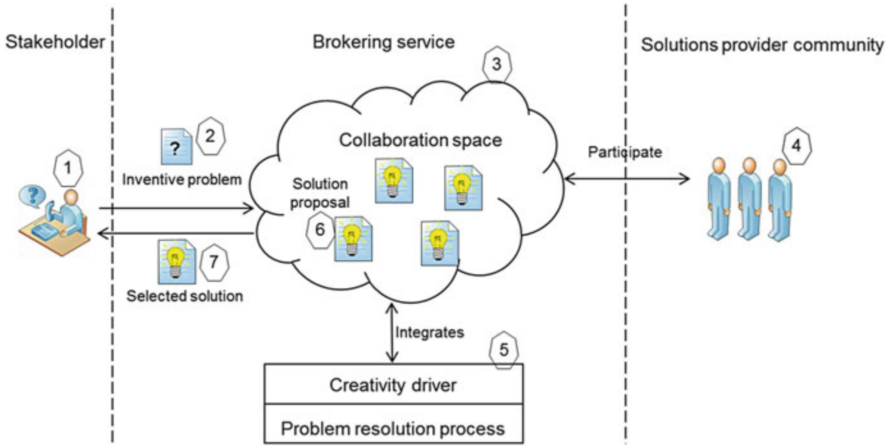

Fig. 9.5 Elements of the crowdsourcing service

(3) “Collaboration workspace”—is the virtual workspace that relates the stakeholder with a community of solution providers. This workspace includes the workflow to formulate the problem and to develop one or multiple solution proposals following the problem resolution process. It takes into account the collaboration aspects previously addressed in Sect. 9.2.1. Also, the collaborative workspace implements the mechanism to communicate, coordinate, and control the contributions from the involved participants.

(4) “Solutions provider community”—includes, but not limited to, the group of individuals with the potential to participate in the workflow of the problem resolution process. The community is composed of members having different technical profiles, like TRIZ practitioners.

(5) “Problem resolution process”—is the sequence of steps that coordinates the search for a solution to a problematic situation. In this work, the process is organized following the principles of the tools proposed in the TRIZ theory and the model TRIZ-CBR.

(6) “Solution proposal”—is the formulation of a possible solution for a specific inventive problem. They are formulated through the different phases of the resolution process. To promote participation, the collaborative workspace allows for one inventive problem to have multiple solution proposals.

(7) “Selected solution”—is the creation of new concepts or new relationships between existing concepts to propose a new conceptual design of a product, a process, or services. It is the stakeholder who takes a decision about the solution that best fits the requirements for his specific inventive problem. Currently, the selection of conceptual solutions is subject to the stakeholder criteria and expertise. However, it is feasible to improve the evaluation with a method that highlights the areas of conflict in the initial decisions, and use the Pareto front to make a more objective selection (Chinkatham and Cavallucci 2015).

9.3.2 Framework Architecture

To organize the different elements of the proposed framework, Fig. 9.6 introduces a three-level structure. During operation, the different process stages are executed following an asynchronous pattern, namely, each user works on the sub-activities in the problem formulation activity separately in time within a shared resolution space, and the activities assigned to different members are achieved at distinct times. In the following, we provide a description of the operations of each level.

9.3.2.1 Innovation Process

In this work, we use some of the elements of the TRIZICS roadmap to propose a simplified version to organize the classical and modified TRIZ tools into two phases: problem description and analysis and problem formulation and solution. The application has two phases. This segmentation consents some benefits: it allows the participation of TRIZ inexperienced users as well as TRIZ experts in the same roadmap. As illustrated in Fig. 9.7, problem description and problem analysis include the use of classical tools oriented to a broader audience of

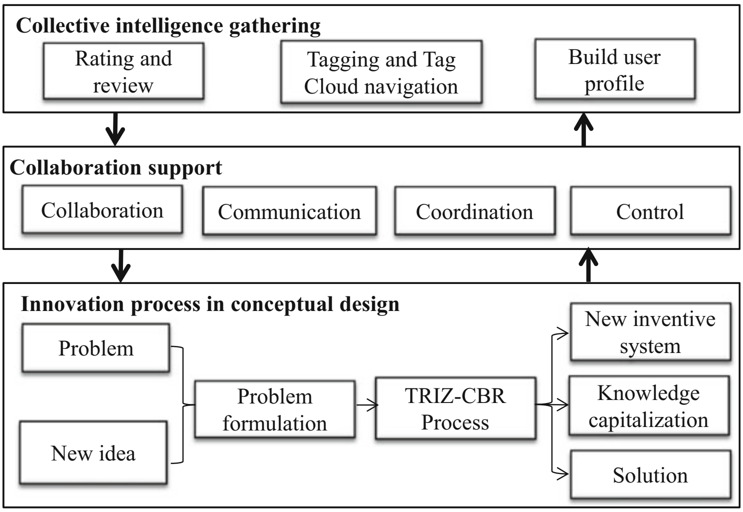

Fig. 9.6 Organization of theoretical elements in our Open CAI solution (Lopez Flores et al. 2015b)

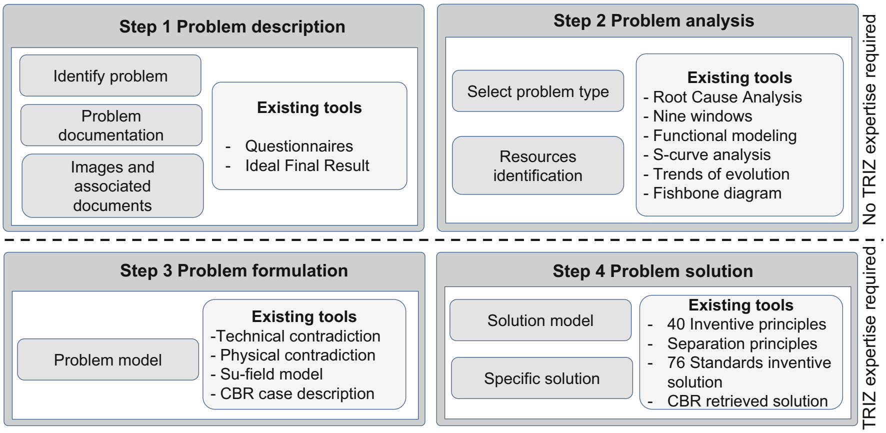

Fig. 9.7 Problem resolution roadmap

non-TRIZ practitioners. Problem formulation and problem solution are tools that require expertise in the use of TRIZ. This versatility in the roadmap aims to create the conditions to promote an active participation of the two types of users. Additionally, the workflow is affected by the CBR cycle, as it was previously described in Cortes (2006) about the interest and strengths of the hybrid model TRIZ-CBR.

9.3.2.2 Collaborative Resolution Process

Figure 9.8 describes the operation of the collaborative workspace, using BPMN notation. The actors involved in the process are the stakeholder (project creator), the solution provider(s), and the control system. After the project creation, the stakeholder is responsible for sharing the project, either to all the community or a collaboration team. Then, the mechanism to share the project is realized through an invitation generated by the stakeholder. The operation of the collaborative workspace presented in Fig. 9.8 aims to maintain information integrity when different participants collaborate on the same project. The mutual exclusion finishes when the user ends the edition or by the mutual exclusion control when the timer is over. Consequently, it takes into account the following aspects:

- To coordinate the activities performed by users
- To allow users to create, edit, and share projects
- To allow the creation of collaboration groups
- To ensure information integrity and to keep tracking the progress

The project is a structure that contains all the information related to a problem. Once a project is created, the owner describes the problem situation, adds relevant

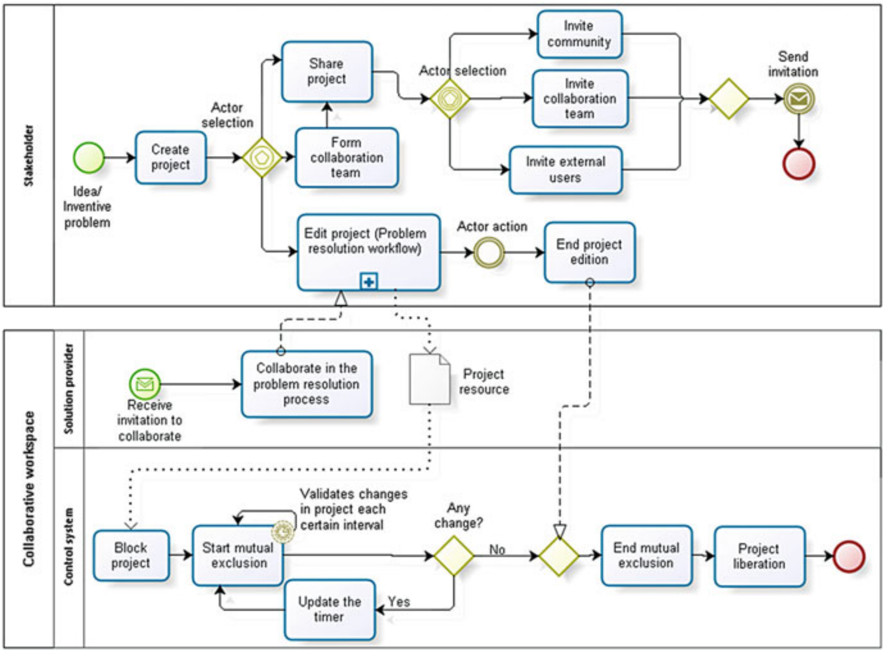

Fig. 9.8 Workflow of the collaboration service (Lopez Flores et al. 2015c)

documents, and specifies the problem background. The objective of this first step is to provide as much information as possible to describe and analyze the problematic situation. In the following steps, the stakeholder and solution providers deploy the problem resolution process as explained in the innovation process. It is worth mentioning that the way users declare all the information is via dialog forms, most of the theme composed of free-text inputs. Free-text dialogs are a common way to communicate with social network services, since they give users the means to express in the imprecise first stage of conceptual design.

9.3.2.3 Implications of Collective Intelligence

The evolution of innovation, from an idea to production and marketing, requires the participation of different intelligences. Around an idea that seems innovative, it requires an organization to aggregate collective intelligence to complete, improve, and implement such an idea (Christofol et al. 2004). Collective intelligence has existed since humans started to bring together intellectual efforts to fulfill specific tasks. Nowadays, industries have begun to focus on immaterial elements to define the firm value (i.e., brand portfolio, collective intelligence). Collective intelligence is a kind of intelligence that emerges from the synergy of individual creative efforts when a cognitive task (e.g., collaborative innovation) takes place. The purpose of collective intelligence is not only to store and share the specific knowledge of team members but especially to bring new knowledge from the collaboration between different fields of expertise. Collective intelligence is not limited to sharing knowledge; it seeks to create new ones which are more demanding. This synergy is important in new product development to reduce the time to market and to improve the possibilities of a product's success.

9.3.3 Techniques for User-Generated Content

The emergence of the Web 2.0 platform allows studying the intelligence derived from groups of individuals doing things together through Web applications (Leimeister 2010). It is acknowledged that relying on the sharing and cooperation architecture provided by the Web 2.0 technologies, it is feasible to deploy applications using collective intelligence capabilities. In the architecture of participation of social network services, it is possible to combine the user-generated content with sophisticated algorithms to exploit explicit and implicit information in Web-based applications. By combining user-generated content with such algorithms, the applications improve their performance as more users take part. The techniques included to enhance these applications taking benefit from the collective contribution are tag integration, user profile, harness external content, and review.

9.4 Application Scenario

The application scenario deals with a case study focused on the conversion of biomass into energy through thermochemical processes, particularly the gasification process. The description of the problem and the constitution of the community of experts are depicted in Lopez Flores et al. (2015a). This section analyzes the problem formulation and the solution selection.

9.4.1 Problem Analysis and Formulation

After the composition of the community, the next step is to deploy the resolution process. In this part, the process is detailed, presenting the crucial phases and subphases. The attention is focused on the input data necessary for the resolution and the description of the retained idea.

The methods and tools developed in Sect. 9.3 about the innovation process afford to have a deeper and detailed analysis of the problematic situation. For the implementation, problem features are necessary as input information for the problem resolution; such features are classified as project details, problem description,

Table 9.3 Project details

Project name	Conceptual design for a fluidized bed gasifier
Nature of the problem	This project is about the conceptual design of a circulating fluidized bed process to improve heat recovery and to facilitate the operation with biomass moisture >20%
User-generated tags	Fluidized bed, gasifier, heat recovery, moisture, and biomass
System-generated tags	Fluidized bed, fluidized bed process, combustion chamber, gasification chamber, and biomass gasification

Table 9.4 Problem description

Problem statement	The circulating fluidized bed process is composed of a gasification chamber, a combustion chamber, an upper and lower stream between both chambers, an outlet stream in the combustion chamber to withdraw the combustion gases, and an outlet stream in the gasification chamber for the produced syngas. The dried biomass is fed in the lower part of the gasification chamber and then flows to the combustion chamber. In the combustion chamber, gases produced by pyrolysis react with oxygen to produce CO_2 and H_2O with an exothermic reaction. This energy is transferred (through the upper stream) in the gasification chamber where the biomass is converted into solid residues (char), and the previous compounds react to produce syngas and tars with an endothermic reaction The three major drawbacks of circulating fluidized bed reactors for biomass gasification are: (i) the production of ashes and tars in the outflow syngas, (ii) low heat recovery, and (iii) difficulty to operate with different biomass moistures
What is the name of the technical system in which the problem resides?	Circulating fluidized bed process
Describe the main useful function of the technical system	Biomass gasification
What is the impact or cost of not solving the problem?	Low energy efficiency
What are the success criteria to consider the problem is solved?	A gasifier increasing energy efficiency and using the same device to a wide range of biomass without increasing the energy consumption (in the pretreatment stage)
What are the limitations and the requirement?	Temperature in the combustion chamber cannot be more than 1000 °C Drying chamber operation does not exceed 150 °C to avoid the risk of ignition of the biomass

problem type, resources analysis, and problem formulation. To illustrate the input information, the following tables (Tables 9.3, 9.4, 9.5, 9.6, and 9.7) present the information related to the application scenario.

Table 9.5 Problem type

Failure mode common to	Machine
Specific failure mode	Fluidized bed gasifier
Problem type	Improvement

Table 9.6 Resources analysis

Resources	• Material – Gas, etc. • Energy – Translational energy – Heat rate – Temperature, etc.

Table 9.7 Problem formulation

Positive characteristic	Negative characteristic	Associated parameters
17 Temperature	39 Productivity	15 Dynamics 28 Mechanics substitution 35 Parameter changes
20 Use of energy by stationary object	39 Productivity	1 Segmentation 6 Universality
22 Loss of energy	17 Temperature	19 Periodic action 38 Strong oxidants 7 Nested doll
39 Productivity	33 Ease of operation	1 Segmentation 28 Mechanics substitution 7 Nested doll 10 Preliminary action
22 Loss of energy	36 Device complexity	7 Nested doll 23 Feedback

Through the process, details about problem description, analysis, problem formulation, and solution documentation are documented in graphic user interfaces (GUIs) as shown in Fig. 9.9.

9.4.2 Solution Selection

Several ideas were generated, but only the one which was selected is presented here. This concept was chosen with the opinion that the community members expressed in a numerical way, i.e., rating, which is also useful as an input to the algorithms for a recommendation system. A collective restitution of the assessment with a ranking is made by the community members. Obviously, the potential flaw is the self-judgment bias, i.e., an individual can be inclined to give a higher score to their idea during the evaluation stage.

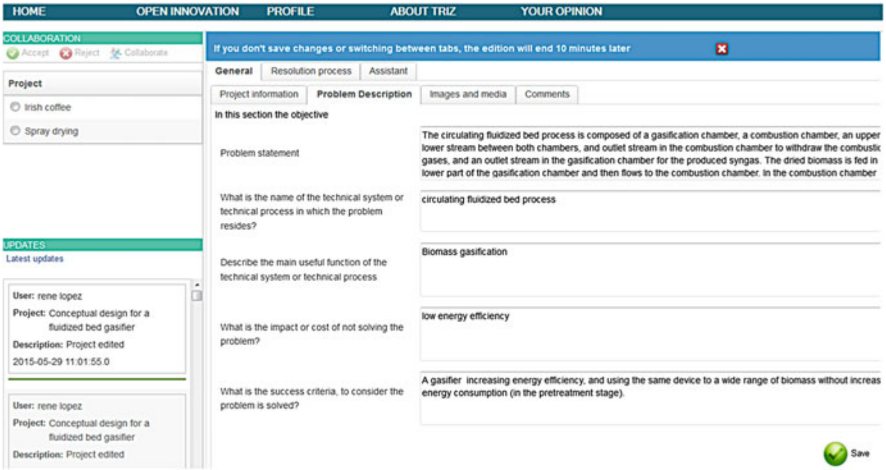

Fig. 9.9 Problem description GUI

Regarding the case study, a two-round process was used to extract the most promising idea, with a cross-evaluation for each round. After the first round, the first three ideas were retained and were studied in more detail by the community members to ensure their pertinence and feasibility. With this additional information for each idea, the second cross-evaluation provides the second ranking, and this is the first idea that was chosen and is detailed below.

When the resolution process was deployed, the TRIZ principle number 7, "nested doll," which is based on the geometrical effect "put a system inside another," is one of the preferential solutions to explore for transforming it into a concrete concept. The first direction explored was to increase heat exchange by increasing the gas residence time in the combustion chamber. However, this leads to an increase in the size of the apparatus, which is not in line with the current trend of process intensification. Furthermore, this configuration has two major drawbacks: the enhancement of the size of the combustion chamber increased thermal losses, and the more the residence time is increased, the more the energy flux toward the gasification chamber is reduced.

To proceed further with the research of the solution, the TRIZ-CBR tool is used. After the retrieving step and relying on the previous problem description (objectives, contradictions, and resources), the case-based reasoning system extracts several devices from the knowledge base with the recommended order of use: heat exchanger coil, dividing wall column (classic, extractive, or reactive column), and heat exchanger. The common denominator between all these devices is that they are all feasible technological ways for saving energy with a reduced capital investment. The exchanger coil is not a relevant solution as a similar system is already implemented with the solid grain media for heat recovery. Concerning the dividing wall column, it is a concrete application of process intensification for a better heat integration. It is a special column obtained by including a vertical wall inside the column shell.

Based on the combination of the TRIZ principle 7 and the concept of the dividing wall column, the following solution can be proposed: the combustion chamber could be inside the gasification chamber to reach a high exchange surface and thus increase the thermal transfer. Always with the purpose of heat integration, the gasification chamber could be situated within the storage enclosure to value the external thermal loses and to dry the biomass before to gasification to reach the 20% moisture content. However, we must account for the temperature constraint of 150 °C. Due to the high temperature of the gasification chamber compared to the desired temperature, an insulation layer should be applied to it. As a result, the proposed device is similar to nested dolls, with successive overlapping of the different chambers. Figure 9.10 presents the elements related to the conceptual solution for a new fluidized bed gasifier.

Nevertheless, in a traditional gasifier, the hydrodynamic and thermal behaviors and the produced gas are closely related to the first reaction that occurs when the biomass is fed into the fluidized bed: devolatilization. Consequently, for the proposed device, a detailed design must be done to characterize the new hydrodynamic and thermal conditions and their consequences on the transfer coefficients and thus on the conversion. It is crucial as the devolatilization phenomenon has a strong influence on the local hydrodynamics of the fluidized bed.

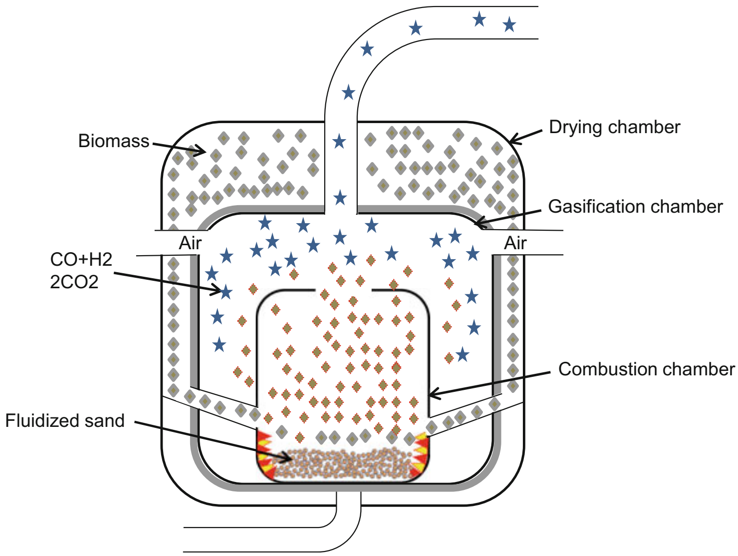

Fig. 9.10 Nested doll gasifier

9.5 Trends and Future Research

Although there are different opinions about the diversification and the future of CAI tools, they all converge in the idea that these kinds of tools are evolving through the adoption of newer technologies and techniques in the information technology field like Web technologies, virtualization, and knowledge representation, among others. These new trends are explored in this section.

9.5.1 Ontology-Based CAI

Knowledge extraction and representation, in the context of TRIZ, are explored to improve the capacities of CAI tools to assist in the process of innovative design. Souili et al. (2015) state that knowledge extraction from technological knowledge documents (e.g., patents) is important to boost innovation performance, while Yan et al. (2014) discuss the usefulness of ontologies for the development of TRIZ-based tools. The ontology presented by the previous authors aims to be a domain ontology of TRIZ, in specifying its basic notions for operating inventive design. Their ontology also aims to ensure that experts have a common understanding of those notions. Despite the fact that the authors try to formalize the theory's main concepts and compile partially the vocabulary that is used by TRIZ experts, the ontology is anchored to a specific resolution methodology OTSM-TRIZ (Khomenko et al. 2007). This is an inconvenience because the ontology should remain as abstract as possible to be used in different contexts.

Li et al. (2015) argue that the indexation of different knowledge sources to solve inventive problems is promoting the development of CAI systems including ontology-based models; these types of systems combine TRIZ with various computer technologies such as text mining or natural language processing. For example, Prickett and Aparicio (2012) propose the design and development of a TRIZ technical system ontology for indexing knowledge contained within available resources (e.g., patent database). The objective of the proposed ontology is to incorporate a Web-based information retrieval system in the problem-solving process. For these authors, the development of ontologies integrated with natural language processing and artificial intelligence allows having Web agents with an analysis capacity close to humans.

On the other hand, the use of semantic technologies is explored in Yan et al. (2014) to formalize the main concepts in the TRIZ knowledge sources through an ontology. The previous authors intend to build an "intelligent manager" system based on short-text semantic similarity and ontologies. Short-text semantic similarity defines missing links among TRIZ knowledge sources, and the solutions are obtained through ontology reasoning. The objective of the proposed systems is to reach more accurately defined solution models.

9.5.2 Avatar-Based Innovation

Traditionally in the market-pull strategy for innovation, manufacturers start exploring user needs and then develop products to fulfill the requirements; nevertheless, this activity is complex, time consuming, and expensive. Moreover, the approach shows its limitations when the user needs change rapidly. Von Hippel and Katz (2002) propose the use of toolkits as an emerging alternative to understand user needs in detail. As a design tool, toolkits transfer *need-related* aspects of new products or services to users. On the other hand, a more interactive approach to address this problem is found in the emerging technology of virtual worlds.

Virtual worlds offer new possibilities for enhancing innovation activities through virtual customer integration. The use of virtual worlds for real-world innovation is explored in Kohler et al. (2011) with the concept of avatar-based innovation. Avatar-based innovation provides a digital environment conducive to develop open innovation and creative tasks. The authors demonstrated how virtual worlds deploy an open innovation platform, which allows producers and customers to swarm together with like-minded individuals not only to create new products but also to find an audience to test, use, and provide feedback about those creations. The previous authors formulated two questions in order to understand the potential of virtual worlds for real-life innovation:

- How are virtual worlds different from the two-dimensional Web and the real world?
- What opportunities arise from this difference?

Avatar-based innovation offers a new medium to understand the user needs through virtual customer integration in an open innovation process. Using this approach, companies can enhance their innovation efforts by learning how to engage and co-create with avatars (the latest visual representation of their potential customers).

9.6 Conclusion

The initial motivation for this research work is to contribute to the evolution of CAI tools to the next evolutionary step named Open CAI 2.0. We studied recent advances on innovation management paradigms as well as the implication of Web 2.0 as a technological driver for collaboration. Also, we addressed some problems related to the systematizing of creativity in inventive problem solving. The use of collective intelligence in combination with the TRIZ-CBR model was proposed to improve the capacity of a community to develop, evaluate, and select a solution for inventive problems.

The first contribution of this work was to understand the mechanism related to the innovation process, specifically when it happens in collaboration. The research approached to the open innovation paradigm, which is a model that promotes the active participation of internal as well as external actors to the enterprise boundaries. Moreover, it valorizes internally generated knowledge through different channels, and it promotes the integration of external knowledge sources in the innovation process.

With the increasing amount of information and the challenge to coordinate participants located in different geographical areas, it becomes necessary to have adapted computational tools to assist the different activities. One technology widely implemented and widely accepted in the industry is the Web platform. Specifically, Web 2.0 as a platform for collaboration has multiple advantages, such as the following:

- Not an expensive technology.
- Supporting different collaboration patterns.
- Accessible from different locations and different devices.
- Employees are familiarized.

After the study of the innovation mechanism and collaboration technologies, the second contribution was to analyze existing tools related to the field of CAI. It was observed that current trends in the CAI field are related to the use of collective intelligence (i.e., crowdsourcing services) for the implementation of open innovation practices.

The third contribution was to propose a collaboration architecture for TRIZ-based Open CAI 2.0. The functional aspects were introduced. The framework is organized according to three core levels. The lower one concerns the Innovation process and it is mainly focused on ideas generation and selection. To manage the large amount of knowledge deployed in open innovation while continuing to generate rapidly innovative ideas we have developed a dedicated methodology based on TRIZ and Case Based Reasoning. The intermediary level is focused on the collaboration and the way to create a collaborative environment to facilitate knowledge exchange. This is done by taking advantage of the benefits of on line Social Network. Finally the last level is dedicated to the Collective intelligence, i.e. human creative effort in community in combination with the power of computer algorithms.

Finally, our findings suggest that it is necessary to overcome several barriers to achieving a real collaborative innovation in an open context. In this chapter, some of them have been tackled: social interaction, knowledge management, and the definition of an innovation process based on problem resolution. A solution that integrates these elements using the Web 2.0 platform was described. The concepts from collective intelligence expose the possibilities to improve participant's creativity in the innovation process.

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Chapter 10
System Dynamics Modeling and TRIZ: A Practical Approach for Inventive Problem Solving

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Abstract The application of the theory of inventive problem solving (TRIZ) to face complex problems in the current scientific and industrial environment is an active research field. The TRIZ capacity to produce valuable technological solutions is an attractive resource to impel the innovation process and technical performance. The intensification of the research effort has unveiled new paths for proposing more efficient problem-solving tools and techniques. Among these opportunities, two are crucial in this chapter: the TRIZ limitation to observe the progression of an inventive problem in time and the difficulty that any solver faces when the system under analysis contains several interrelated problems. Nonetheless, there is an approach that analyzes a system through time and that offers some tools for modeling and simulating the different system states: system dynamics modeling. The system dynamics (SD) approach analyzes the nonlinear behavior of complex systems over time. SD is a computer-aided approach with a large extent of application domains, practically in any complex system—social, managerial, economic, or natural—defined by a set of interdependence relationships, a flow of information, and effects of causality. Hence, SD can produce useful information

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within a problem network and create, in combination with TRIZ, a synergy to solve inventive problems.

10.1 Introduction

The theory of inventive problem solving (TRIZ) as an approach to assist the innovation process and as a problem-solving tool has successfully permeated the industrial environment and the scientific community. Several important enterprises, such as Samsung, Volkswagen, and the Ford Motor Company among many others, have assimilated TRIZ and have adapted it to their internal processes (Wang 2015). Many universities are also teaching TRIZ in their undergraduate and postgraduate courses (ETRIA 2016). The effort to adapt and apply TRIZ in very different contexts has impelled its transformation and the incorporation of other tools to the TRIZ key solving processes. Concurrently, the assimilation of the TRIZ tools has revealed new research opportunities and drawbacks. One of the most significant TRIZ limitations a rises in the modeling stage. Frequently, there are several conflicts in a system creating a problem network. When this condition occurs, typically these conflicts have strong relationships. Thus, before moving to the next stage of the solving process, the solver should take into account the existing links inside the network. The information about the most significant relations within a problem demands a tool to model and evaluate the impact that any given solution could have on the system. Thus, the information extracted in the modeling stage enables the conception of the problem network that presents several advantages: (1) The problem network has new resources that discover new problem-solving paths. (2) The new information is useful in ranking problems according to their expected impact and in organizing the solving process. (3) The valuable information enables new problem-solving strategies and is an advantage for creating practical solutions. Despite the importance of the information extracted in the modeling stage, the TRIZ theory does not have a particular tool to deal with the lack of information about the relation among different conflicts and their dynamic feedbacks.

Another significant problem of the TRIZ modeling process is that TRIZ does not have a means to explore how an adverse situation changes in time (or their most important relations). Consequently, TRIZ can model a system or a problem from a static point of view, although some TRIZ tools take the time and space where the conflict exists into account (Altshuller 1999). For example, the nine-screen tool is useful to observe the most relevant transformation that a system has endured. The Algorithm of Inventive Problem Solving (ARIZ) delimitates the time where the conflict occurs and the space where the problem exists. However, the insights produced by these tools do not change in time and are not useful to predict or explain the impact of a possible solving path.

The information extracted from the dynamic behavior of the system is useful to formulate a set of restrictions, some key performance indicators, or those used just as input data for other stages of the solving process. Consequently, the information and knowledge about the dynamic relations within a problem are critical in the solving process. However, there is not a particular TRIZ tool for exploring the evolution of the system in time from a dynamic point of view.

There is an approach that analyzes a system through time and that offers some tools for modeling and simulating the different system states: the system dynamics modeling. The system dynamics (SD) analyzes the nonlinear behavior of complex systems over time. SD is a computer-aided approach with a large extent of application domains, practically in any complex system—social, managerial, economic, or natural system—defined by a set of interdependence relationships, a flow of information, and effects of causality. Hence, SD can produce useful information within a problem network and create, in this combination, a synergy with some TRIZ tools to solve inventive problems efficiently.

This chapter proposes a framework that combines the process of solving inventive problems with the modeling procedure of the system dynamics simulation. The chapter is divided into four sections. The first section explores the TRIZ opportunities for improvement. The second section describes the system dynamics approach. The third section offers a methodology to model inventive problems and depicts a case study. The last section discusses the advantages and limitations of the combined approach.

10.2 The Theory of Inventive Problem Solving: Opportunities and Advantages

In contrast to the typical trial and error solving methods (i.e., brainstorming, synectics, and lateral thinking, among other psychological approaches), technical and scientific knowledge are the foundations of TRIZ. The particular knowledge capitalization process behind TRIZ is probably the most significant difference with other tools or techniques: a transversal problem-solving knowledge base. The roots of this knowledge base and the source of the mechanisms to reuse this knowledge that guide the innovation process are as follows (Altshuller 1999; Savransky 2000):

(1) The synthesis of valuable information about the work of great inventors
(2) An analysis of several methods for problem solving
(3) The history of technical systems evolution
(4) An extensive patent review
(5) The scientific literature

Therefore, the unique process behind the TRIZ approach for problem solving produced several advantages that have permeated the industrial and academic world. Nevertheless, it is also the cause of some drawbacks that drives the effort for creating a more performant inventive problem-solving approach.

The assimilation and application of the TRIZ to deal with the challenges that innovation problems impose have considerably evolved in the last decade.

Enterprises like the Ford Motor Company, Samsung, and Volkswagen among many others reported the use of TRIZ for solving an extent of different problems (Wang 2015). The use of TRIZ in the academic world has also increased its activity. The number of published articles has augmented at a regular pace. The reasons behind the interest that TRIZ unveils repose on its advantages and among the most relevant are as follows:

(1) TRIZ facilitates the connection between the problem requirements with a set of scientific effects that can produce the desired result. Hence, scientific knowledge is a crucial component in the solving process (Fey and Rivin 2005).
(2) The TRIZ solving process creates a synergy where the individual psychology patterns become more flexible while simultaneously enables knowledge creation via analogical thinking (Altshuller 1984).
(3) The TRIZ tools create a context where the frontiers among domains become fuzzy. Thus, the successful solutions available in a particular area could then be transferred and reused in a different problem (Savransky 2000).

Like any other approach for problem solving, TRIZ has several limitations:

(a) The dependency on the user's experience to determine the right problem to solve and the subjective selection of the plausible solving path. The efficiency of the solving process depends on the solver's ability to identify the root conflict within a system, and frequently, complex problems contain more than one problem. Thus, it is necessary to explore the relations among these conflicts to determine which one has the stronger priority. Subsequently, when there are several potential solutions, again the solver's experience plays a critical role to select the most promising one. Hence, an evaluation process or technique is a crucial requirement. The concept of ideality is particularly useful in this stage of the solving process. However, there is no accurate methodology available to deploy this concept (Savransky 2000; Ilevbare et al. 2013).
(b) A considerable abstraction effort to apply the TRIZ tools in the service design field. Most of the TRIZ tools were conceived to deal with problems related to physical parameters in different domains, through models with a high level of abstraction. Thus, the application of a TRIZ tool in the service area involves an adaptation process, which demands to increase the degree of abstraction (Orloff 2016). The application of TRIZ in the service domains is a key scientific challenge due to the positive correlation between economic wealth and services (OECD 2016; Jiang et al. 2011).
(c) Collaboration and collective intelligence are necessary to solve inventive problems. Frequently, an inventive problem demands knowledge outside the frontiers where it lies, creating a multidisciplinary context which mobilizes different competencies. Hence, solving complex problems calls for a collaborative process. The open computer-aided innovation (open CAI) is the discipline dealing with this challenge (Lopez et al. 2015a, b).
(d) The appropriation of the theory is a complex task. The exigency to assimilate all the TRIZ tools is one of the most explored drawbacks. The comprehension and

deployment of the TRIZ toolbox ask for a considerable effort and time for training. The variety of offers makes even more difficult the selection of a suitable training program. Subsequently, the new TRIZ practitioners must face the challenge to find problems in a clear context to increase their performance and control over the recently acquired abilities, and this is neither a simple task.

(e) The necessity to solve simultaneous conflicts. The formulation of an inventive problem produces, in many cases, a situation where the solver recognizes the existence of more than one crucial conflict. Under such a condition, each conflict should be solved separately, ignoring the effect that each solution will have on the system. The TRIZ does not offer a tool to deal with this level of complexity and solely recommends to establish a solving sequence, based on the solver's experience (Barragan et al. 2012).

(f) A learning mechanism is necessary to avoid reinventing the wheel. The methodology of some TRIZ tool (i.e., the Algorithm of Inventive Problem Solving) suggests storing the experience acquired during the solving process as a means to improve the tool. However, even if knowledge is at the core of the TRIZ solving process, there is not an explicit feedback loop to assure long-term learning (Cortes et al. 2009).

(g) The lack of a tool to dynamically model the essential relations within a problem. The internal and external environment of a system is changing continually. Consequently, the analysis of any conflict must take into account the most relevant variations that the system endures in time. The observation of the system produces new information and knowledge that are useful to predict the effect of a potential solution. Also, it is possible to explore how the components of the system will evolve to improve the comprehension of the conflict.

In the context of this chapter, three drawbacks are of particular importance:

1. The need for a tool to evaluate the effects produced by the interaction of several problems in a system. If TRIZ develops the capacity to perceive the repercussions of overcoming entirely or partially a conflict in a system, then the decision of how to design the solving strategy will not ultimately depend on the solver's experience. Hence, the solver will only face the most relevant interconnected problems.
2. The necessity to observe the system behavior in a given period to predict some future state. In fact, the TRIZ trends of evolution propose some general guidelines to accomplish this objective. However, the application of these patterns uses the information from patent databases, which implies to observe only the result but not the process. Besides, many technical solutions are protected as industrial secrets or not patented at all and then not available for a solver. If TRIZ assimilates the capacity to detect how the system behavior changes in time, then it will be possible to anticipate a conflict.
3. To explore the possibility to solve simultaneous conflicts. The TRIZ solving process can only deal with one conflict at a time, and frequently, once one problem is solved, the expert finds that the conflict "moves" to another

component (subsystem) or affects another useful function. The knowledge about the system states and how they change enables the possibility to intervene in coexisting problems.

The central hypothesis of this chapter states that a synergy between some TRIZ tools with the system dynamics modeling can surmount these limitations. The next section describes the system dynamics approach as part of the logic to demonstrate the feasibility of a synergy.

10.3 The System Dynamics Modeling and Simulation

System dynamics (SD), initially called industrial dynamics, was proposed by J. Forrester in the 1960s. SD is a method for studying and managing complex systems, which combines a conceptual framework, some methods, and philosophy to analyze the complex relations within a system and understand how the system changes over time (Forrester 1988; Sterman 2000). Three essential elements are necessary to build a dynamic model: (1) state variables, (2) flow elements, and (3) auxiliary variables and constants. The logic structure of these elements makes it possible to simulate changes over time and allows the creation of a feedback mechanism. The application of the SD approach demands a different perspective to model a problem. A complete model requires at least five activities:

(1) The construction of some graphs that explain how the system changes over time
(2) To conceive the minimal logic operations that describe the system behavior
(3) To observe the problem as interconnected feedback loops and internal causality and also as variations of stocks or levels and the conditions that increase or decrease flow
(4) To express the most important relations within the system through nonlinear equations
(5) To extract knowledge from the mathematical model and understand its natural states to propose potential solutions and evaluate their impact

To cope with these challenges, SD uses some flexible tools: the causal loop diagram (CLD) and the stock and flow diagram. Both diagrams are critical in a dynamic model, and then, the next section briefly describes both graphical tools (Forrester 1963, 1988).

10.3.1 The Causal Loop Diagram and the Flow and Stock Diagram

The objective of the CLD is to represent the feedback interactions in a system graphically and the variables that get involved. Conventionally, a CLD uses two

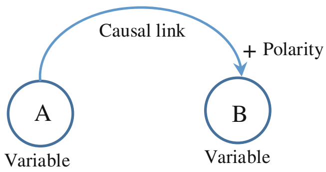


Fig. 10.1 A causal relationship in system dynamics modeling (Sterman 2000)

types of variables: exogenous and endogenous. Endogenous variables are those which participate in the feedback loops of the system. These variables change with the system and are controllable via other endogenous variables or even exogenous. Exogenous variables are those whose value is not directly affected by the system and are not controllable.

Essentially, a CLD is an oriented graph where arcs represent the causal link between variables. An arc has a polarity determined by its positive or negative influence (anything about SD). Figure 10.1 depicts that there is a causal relationship between variables A and B.

A causal link from one variable A to another variable B is positive if two possible actions occur: (1) A increases the value of B or (2) any variation in A produces a modification in B in the same direction. On the opposite side, a causal link from one variable A to another variable B is negative if (1) A reduces the value of B or (b) any variation in A produces a modification in B but in the opposite direction.

The relations among several variables and causal links create an oriented graph, which usually contains a closed path between at least two variables. Any closed path or circuit in a CLD produces a feedback loop. Loops transmit information continually that is useful to analyze the system, but they are also the source of complex behavior. In other words, feedback loops are responsible for the causes that move the system to a particular pattern or behavior (Sterman 2000).

A feedback loop could be positive or negative (Fig. 10.2).

– A feedback loop is positive (+) if there is an even number of negative causal links. Frequently, this kind of loop is called a reinforcing loop and is denoted with the capital letter R. Positive loops are unstable and move the system to chaotic situations or even to collapse.
– A feedback loop is negative (−) if it has an odd number of negative causal links. A negative loop is also known as a balancing loop, and it is denoted with capital letter B. Negative loops move the system toward a stable state. Consequently, the sign of a loop results from the algebraic product of all the links involved. Figure 10.2 depicts an example of a feedback loop.

Despite the usefulness of this visual tool to model a system, it does not have a way to represent the changes that the system endures in time. Thus, the system dynamics approach has another tool: the stock and flow diagram. This diagram shows the relations among the variables that evolve in time and then define a state in the system. As the name of the tool underlines, there are two different variables. The stock uses a rectangle that means something is accumulated, that reach a level

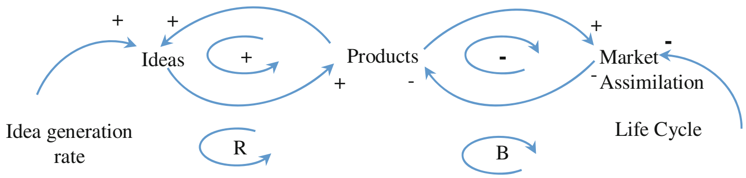


Fig. 10.2 Reinforcing and balancing loops

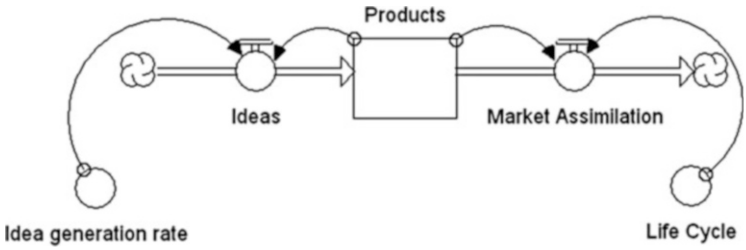


Fig. 10.3 The stock and flow diagram

or produces a stock. It is something that can be measured and observed, such as the global automotive production, but also something intangible, such as the market trust or the seller reputation.

The second type of variables uses the symbol of a valve and represents something that moves from one stock to another or something provided or consumed with a particular rhythm or rate. Flow is then the changes in stocks and usually is evaluated in units of stock over a period (e.g., the car shipping rate of a country) (Sterman 2000; Forrester 1963).

The last element in a stock and flow diagram is information, which uses an oriented arc to explain the influence of one variable over another. Figure 10.3 shows the building blocks of the stock and flow diagram.

The next section describes the methodology to build dynamic models with the goal to define the opportunities for linking the TRIZ solving process and the SD approach.

10.3.2 The System Dynamics Methodology

The versatility of the SD modeling and simulation approach asks for a methodology equally flexible and with a broad range of applications. The simplest methodology encompasses four stages (Forrester 1963):

(1) The conceptualization process involves four activities: to define the objective of the model, to describe the model boundary and isolate the key variables, to characterize the system behavior of the key variables, and finally to schematize the feedback loops of the system.

(2) The formulation stage calls for two activities: to transform the feedback diagram to level and rate equations and to estimate the value of critical parameters.
(3) The testing process asks for three steps: to formulate at least one dynamic hypothesis and simulate it in the model to observe its effect, to test the model's assumptions, and finally, to check the model under the influence of perturbations.
(4) The implementation step encloses two activities: to verify the model response to different scenarios and, finally, to synthesize knowledge and express it in a usable or accessible form.

Yeo et al. (2013) consider that the SD modeling process needs only three logical stages: logical modeling, model quantification, and model application for a total of eight activities:

– The logical modeling stage involves the problem definition, the CLD, and the conceptual model design.
– The model quantification stage also involves three activities: the stock and flow diagram, data acquisition, and model validation.
– The model application stage considers only two events: the model test and the model application.

The methodology used in this chapter combines both sequences in a more detailed framework.

10.3.3 SD Advantages/Benefits and Limitations

Following are some of the advantages/benefits of system dynamics.

(1) System dynamics is a method to enhance learning in complex systems. Frequently, SD models are interpreted as predictive models. However, like other modeling approaches, uncertainty is an intrinsic component of any model. Hence, it is worthwhile to increase the general understanding of a problem to guide future research or verify the impact of a certain hypothesis. The mathematical foundation of SD deals well with uncertainty (Forrester 1963; Townsend and Busenitz 2015).
(2) Similar to TRIZ, SD has a multidisciplinary background: it has its roots in the theory of nonlinear dynamics and feedback control, differential equations, and some analogies from physics and engineering. Also, due to its nature, SD also uses some principles from cognitive, economic, and social sciences (Sterman 2000; Forrester 1963).
(3) Another SD advantage it is their flexible application. There are documented cases of application in social, biological, physical, and technical systems.
(4) The simulation approach of SD empowers the creation of different scenarios, an activity that calls for the solver's creativity to conceive an improvement path or a failure mechanism.

(5) SD reveals unexpected effects in complex systems that very often challenge or contradict the common sense of a solver, creating knowledge or exposing new solving paths.
(6) SD has a simulation tool to explore the global effect that results from the modification of critical variables and causal links. SD isolates the causal relationship that has the greater impact on the system, and then it guides thinking to the right problem to solve.

SD also has some limitations, and the below points describe the foremost in the context of this chapter:

(1) Despite the capacity of SD to deal with complex systems, the intuitive modeling approach depends on the solver's experience, knowledge, and common sense. Consequently, the comprehension of the model for a different person is not an easy task, a condition that makes challenging the knowledge transfer to other domains and the reuse of past solutions in a similar context (Sterman 2000).
(2) As any other modeling approach, it lacks specific problem-solving tools, particularly when any essay to improve one variable produces an undesirable effect in a second one.
(3) The generality of the causal relation in SD does not facilitate the problem-solving process. A causal link has only a bipolar nature: its effect is positive or negative. A more detailed classification will be useful to propose a solving strategy or a pattern to modify an effect.

The arguments of preceding sections support the hypothesis that the complementarity between the TRIZ theory and the system dynamics modeling approach could produce a useful problem-solving framework. The next section describes the initial strategy to combine TRIZ with SD.

10.4 A Combined Solving Process: TRIZ + SD

The program to create a synergy between TRIZ and SD could follow several directions:

– To maintain independence between both approaches. Thus, each tool is deployed separately but developing an efficient execution plan. The originality of this alternative lies in the design of a well-planned methodology.
– To propose a synthesis of both approaches. This possibility encloses at least three options:
  - To model a problem with TRIZ and then simulate the solving strategy with SD
  - To create a model with SD to identify the conflicts and then translate them to the TRIZ language

- To transform the TRIZ tools in such a way that they operate inside the SD simulation environment

– To design an entirely new simulation tool where TRIZ and SD get combined.

Due to the complexity and the recent effort of this research opportunity, the first alternative seems adequate; this means to preserve the orientation of each tool and only to organize a logical and useful progression of steps to model an inventive problem. This primary process will produce a return of experience to provide a new perspective about the feasibility of combining TRIZ and SD.

The next section describes some related works about the use of SD to impel innovation and about the application of TRIZ in a more dynamic environment.

10.4.1 Related Work

Ash et al. (2015) apply SD to the beef cattle enterprises in northern Australia with the purpose to observe if the future productivity of the company will sustain the market share and competitiveness. Authors propose several scenarios including a genetic gain, the use of alimentary additives, the introduction of new pastures and forage crops, and the adoption of new technologies. The conception of a complex scenario where different alternatives get involved produced a feasible solving alternative to maintaining the beef enterprises competitive in northern Australia.

Wu et al. (2010) propose a dynamic model to evaluate the decision-making risk in the context of technological innovation. Authors explain that the simulation model generates information congruent with the current practices of the market. The analysis of different scenarios brings to light some mechanisms to achieve decisive projects.

Timma et al. (2015) combine an empirical study with system dynamics modeling to conceive a model of innovation diffusion in the field of energy efficiency solutions. The case study focuses on light-emitting diodes (LEDs). The model explains well the relationship between product development and market absorption.

Samara et al. (2012) analyze the effect of innovation policies on the national innovation system. SD is the testing tool of several scenarios with the goal to evaluate the impact of alternative innovation policies. The usefulness of each policy is evaluated via the dynamic behavior of product and process innovation with a simulation model.

Kreng and Wang (2013) develop an SD model that explains the innovation diffusion of successive product generations. The model considers three decisive factors: the dynamic market potential, the competitive relationship among generation products, and the price. Results show that the model explains the causes of the industry dynamics. The work of Martins et al. (2009) has a similar orientation.

Zhou et al. (2016) present an SD model that evaluates the environmental and socioeconomic benefits of putting into practice strict environmental greenhouse gas emission regulations, while simultaneously the Chinese government promotes technological innovations for power generation. The model explains that the implementation of strict directives without adequate incentives for technological innovation affects economic growth. This work makes clear the relationship between the innovation in the energy sector and the reduction of air pollutants.

The use of the SD model to analyze the effect of different factors on the innovation process is the central subject of a vast number of articles (Dawid et al. 2015). Nevertheless, the application of the SD modeling is not yet reported in the inventive problem-solving domain or vice versa. For example, Pokhrel et al. (2015) adapt the contradiction matrix to the field of process engineering. Authors added new inventive parameters and principles for the TRIZ contradiction matrix to expand its flexibility to deal with problems encountered in the chemical process industry. In this case, there is no simulation or modeling approach associated to the contradiction matrix.

Becattini et al. (2012) develop a dialogue-based software that guides a solver during the analysis of inventive problems. This piece of software uses part of the logic of the Algorithm of Inventive Problem Solving (ARIZ) and some models from the General Theory of Powerful Thinking (OTSM-TRIZ). The dynamic modeling is not a software attribute. Hence, the simulation or testing of different scenarios is not possible.

Chechurin et al. (2015) propose a piece of software that helps the user in the invention process. The problem statement uses the function and mathematical modeling to obtain a quantitative analysis and assure a high level of abstraction. The software consents several benefits in the conceptual design stage. Authors underline that the solving process includes a dynamic function analysis. However, the system causality and feedback are not explicitly considered in the software; neither is possible to simulate scenarios.

Zeng and Yao (2009) describe a computer simulation software that provides a process to model design activities and test design theories. Three elements are the basis for the simulation model: a mathematical model, a simulation model, and a statistical analysis. Authors state that a computer simulation environment is useful to study design activities, and the results show that incorporating a computer simulation model is a practical approach to studying design activities.

Li et al. (2009) underline some of the challenges that the computer-aided innovation field is facing: the establishment of the technology innovation organization network, the implementation of new processes based on TRIZ and CAI, the need for a more flexible approach, and the participation of other relevant actors. However, a more detailed model is not proposed.

Lopez et al. (2015a, b) suggest that the open innovation paradigm must evolve to a collaborative open computer-aided innovation approach. Authors developed a piece of software where a knowledge base assists a person for solving inventive problems. This software combines the case-based reasoning (CBR) process with collective intelligence in a collaborative web. Nevertheless, this software does not offer a tool to model simultaneous contradictions or a mechanism to observe the system behavior in a period.

Table 10.1 State of the art about inventive dynamic problem solving

Author	Modeling approach	Solving tools	Multiple domain application	System dynamic	TRIZ	Simulation tools
Ash et al. (2015)	√	∅	∅	√	∅	√
Wu et al. (2010)	√	∅	√	√	∅	√
Samara et al. (2012)	√	∅	√	√	∅	√
Kreng and Wang (2013)	√	∅	√	√	∅	√
Pokhrel et al. (2015)	√	√	∅	∅	√	∅
Becattini et al. (2012)	√	√	√	∅	√	∅
Lopez et al. (2015a, b)	√	√	√	∅	√	∅
TRIZ-SD	√	√	√	√	√	√

Other authors have combined TRIZ with other techniques to develop software applications: Yang and Chen (2012) use the CBR process, Yoon and Kim (2011) employ patent data mining, Lopez et al. (2015a, b) propose the use of collective intelligence, and Borgianni et al. (2015) introduce a Monte Carlo simulation to deal with uncertainty. However, a search in databases does not report a combination of TRIZ with the system dynamics simulation. Table 10.1 summarizes some pertinent findings.

10.4.2 Methodological Approach

This section describes the simplest process to connect the system dynamics modeling with inventive problem solving. It is necessary to specify that this primary process is only applicable to problems modeled as contradictions (physical or technical). The methodology has four stages: conceptualization, formulation, testing, and application proposed by Forrester (1988) and Sterman (2000) and complemented with the contradiction modeling described in Altshuller (1999).

Conceptualization

1. Describe the objective of the model: to define the primary useful function
2. Describe the model boundary and isolate the key variables
3. Build the feedback loop diagram
4. Set dynamic hypothesis
5. Identify the most significant conflict among feedback loops

Formulation

- Build the stock and flow diagram
- Deploy the data acquisition process
- Validate the model

Testing

- Transform the conflict into physical or technical contradiction
- Select the right tool: separation principles or the contradiction matrix
- Define the ideal result and available resources in the system
- Combine one or more principles with the system resources to propose at least one strategy to transform the system
- Formulate at least one dynamic hypothesis and simulate it in the model to observe its effect
- Introduce perturbations or change the operative conditions in the model

Application

- Verify the model response to different scenarios
- Synthesize knowledge and express results

The specific steps to model a physical or technical contradiction are implicitly considered in each activity. Similarly, the identification of the separation principles and the use of the contradiction matrix are not detailed in the methodology. The next section presents a case study that focuses on the most time-demanding stage: the conceptualization phase.

10.5 Case Study

The following sections describe the activities that give shape to the conceptualization stage.

Describe the Objective of the Model To define the primary useful function. The system under study is a recuperative glass furnace that is melting raw materials in its chamber. Once the mix has the right temperature and homogeneity, carefully conduct it to a set of molds. In this stage of the process, the mix takes the shape of a bottle. Later, each bottle goes to another furnace where its temperature reduces in a controlled environment to assure the right crystalline structure and strength. The more expensive and complicated operation is the control of temperature. The furnace produces 360 t/day. The extraction level is the amount of tons produced per day. Thus, if the extraction changes, then the furnace temperatures must also follow this modification. The temperature depends on two variables: the calorific value of the fuel and the fuel volume that feeds the melting chamber. The following points offer a more detailed description of essential variables.

Describe the Model Boundary and Isolate the Key Variables

– Extraction: this variable refers to the increase or reduction of the raw material that gets into the melting chamber. Any change of matter is measured in a ton of melting glass. Three more variables are necessary to calculate the extraction:

  • The bottle weight (in the causal diagram as *Weight*)
  • The production rate in each production lane (in the causal diagram as *Speed*)
  • The number of melting glass drops per minute consumed in the manufacturing process including all production lanes (in the causal diagram as *Drip*)

– Energy: the production of glass objects is essentially an energy-based process. The selection of the correct power source and the heat recovery mechanisms determines the most significant production cost. Decisions about the settings of each section in the melting chamber impact the efficiency of the fusion process and the environment. The primary energy source is fossil fuels, in this case, natural gas. To calculate the potential calorific value and its consumption, it is necessary to obtain the following information:

  • The particular calorific value of natural gas (heating value)
  • The addition of energy according to the furnace operation time (the furnace age determines this variable)
  • The tolerance of the expected energy consumption
  • The percentage of recycled material called glass cullet

Build the Feedback Loop Diagram Hence, the quantity of ton per day defines the energy requirements. This assumption is the first dynamic hypothesis. The extraction and the energy give form to the first feedback loops (Fig. 10.4).

Set Dynamic Hypothesis The causal diagram in Fig. 10.4 explains that if the speed (production rate) increases, the weight (the bottle weight) increases, and the

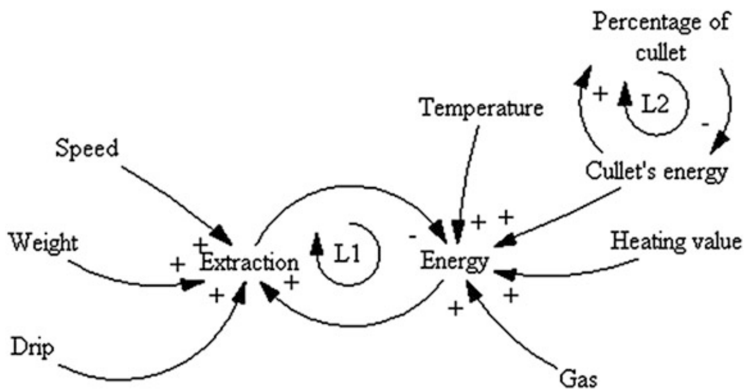


Fig. 10.4 The causal relationship between the extraction and the energy in the melting chamber

drip (total drops of melting glass) rises, then the extraction will increase. Similarly, if the temperature in any section of the melting chamber rises, the volume of natural gas increases and consequently the energy also increases. The heating value is a constant value used to calculate the amount of energy consumed (natural gas produces 8700 kcal/m^3). Figure 10.4 has two feedback loops. In this case, it is important to underline the effect of the second feedback loop: if the percentage of cullet increases, then the energy requirements will reduce. The observation of the melting chamber reveals that if the percentage of cullet increases in 10%, then energy volume reduces by 2%. Both feedback loops belong to the balancing loop class; then they move the system to its equilibrium.

Figure 10.5 illustrates the reference mode of both variables. The graph shows that if the extraction augments, the energy consumption reduces. This statement defies the common sense; however, this apparent contradiction is explained with more information: the melting chamber reaches its maximal performance when the extraction arrives at its maximal value. Under these conditions, the distribution of the inner heat is homogeneous, and, consequently, less heat is necessary to melt the same amount of matter.

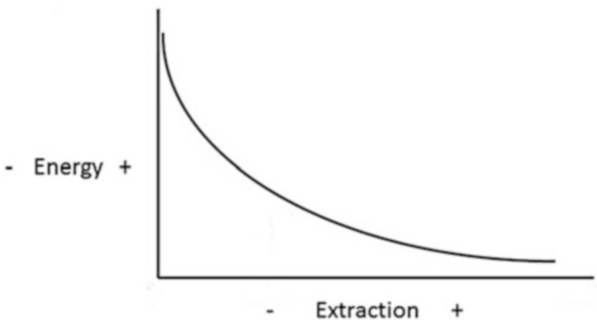
The software Stella® includes the tools for the model and tests the dynamic hypothesis. The model encompasses all the variables to represent the extraction and the energy for melting. Figure 10.6 exposes the stock and flow diagram.

The software uses a differential equation to model the system behavior. The equation that represents the melting glass extraction is crucial. It puts into relation all the system variables.

$$\text{Extraction}(t) = \text{Extraction}(t_0) + \int_{250}^{t} (\text{Flow 1} - \text{Flow 2})\,dt \tag{10.1}$$

In Eq. (10.1), the values of Flow 1 and Flow 2 represent the input flow and the output flow from the melting chamber. These values comprise the secondary variables depicted in the causal diagram. Equation (10.1) starts with a value of 250 t of extraction. The simulation of the stock and flow diagram for a month generates data to observe the relation between the extraction and the energy (see Table 10.2).

Fig. 10.5 The reference mode between energy and extraction



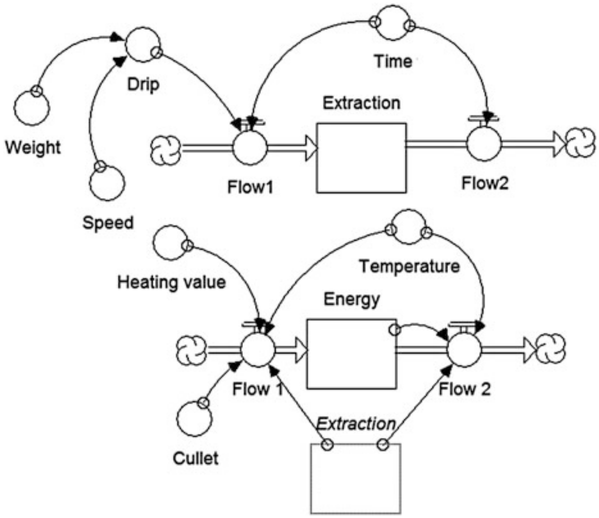


Fig. 10.6 The stock and flow diagram between extraction and energy in the melting chamber

Table 10.2 Data about the relation between extraction and energy

n	Extraction (tn)	Energy (kcal)	*n*	Extraction (tn)	Energy (kcal)
1	142.51	46,759,412.15	16	206.54	38,265,766.37
2	156.79	44,263,666.79	17	206.64	38,257,369.92
3	173.77	41,829,985.56	18	212.63	37,725,029.14
4	182.15	40,796,653.21	19	221.26	37,008,844.07
5	183.40	40,650,921.38	20	223.75	36,812,226.92
6	184.74	40,497,081.80	21	225.00	36,715,327.72
7	187.67	40,166,208.47	22	230.88	36,273,503.94
8	189.67	39,947,112.10	23	233.57	36,078,484.88
9	190.29	39,880,303.19	24	238.95	35,702,721.60
10	193.58	39,531,676.15	25	240.49	35,597,625.87
11	196.22	39,259,770.70	26	242.04	35,494,124.16
12	196.84	39,197,341.97	27	258.21	34,483,843.08
13	197.33	39,148,709.16	28	264.77	34,109,072.46
14	199.01	38,981,339.76	29	276.52	33,482,600.00
15	202.80	38,614,939.74	30	278.92	33,361,128.80

Figure 10.7 confirms the behavior of the furnace: if the melting chamber operates at its maximum extraction level, it demands less energy.

Identify the Most Significant Conflict Among Feedback Loops The causal diagram and the stock and flow scheme expose the next conflicts:

(1) The melting chamber must operate at its maximal extraction capacity to reduce the consumption of energy. However, the extraction should be adjusted to

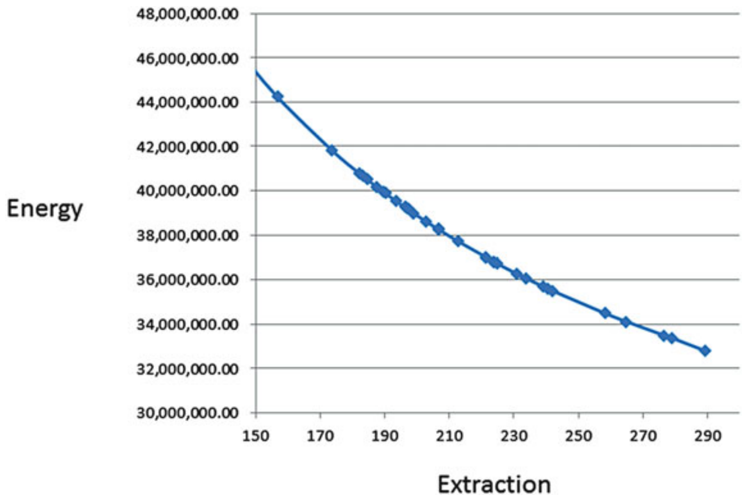


Fig. 10.7 The relation between energy and extraction

match the market demand. Thus, this conflict could be stated as a physical contradiction: the extraction must be fixed at its maximal level to reduce the consumption of energy but also should be flexible to answer the market demands.

(2) The glass cullet contains another conflict in the system. If the percentage of the glass cullet increases, then the energy consumption reduces, but the raw material cost increases are unacceptable. This problem is a technical contradiction between the use of energy by moving objects and productivity/manufacturing cost. Figure 10.8 depicts this conflict.

The application of the TRIZ tools in the above problems will generate some potential solving paths that can be simulated in the stock and flow diagram. A group of experts are dealing with these problems to improve the furnace performance. The purpose of this chapter is to create a feasible framework to combine TRIZ with the system dynamics modeling. The next section analyzes the feasibility of combining the TRIZ theory with the system dynamics modeling.

10.6 Discussion

As stated in Sect. 10.4.2, the methodological approach is the simplest process. This simplification is necessary to observe the challenges that unveil the creation of a synergy between TRIZ and SD with the goal to implement a learning feedback mechanism. From this initial case, it is possible to observe some advantages and limitations:

Extraction	Energy (Mcal)	Cost ($)
250	35679.86917	334042.37
255	35367.55639	340723.21
260	35067.25564	347404.06
265	34778.28701	354084.91
270	34500.02089	360765.76
275	34231.87356	367446.61
280	33973.30292	374127.45
285	33518.63915	380808.31
290	33238.03757	387489.14
295	32966.94792	394169.99
300	31832.75146	401799.63

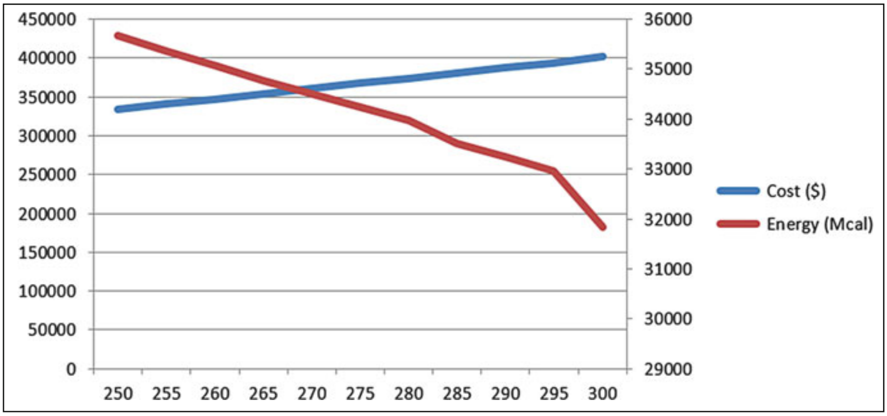
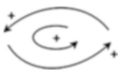
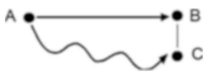
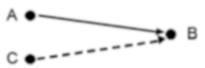


Fig. 10.8 The relation between energy and cost

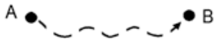
- The modeling process is not able to classify problems. This initial observation has its origin in the dichotomy used to classify feedback loops in SD. The construction of the CLD recognizes only two different feedback loops: reinforcing and balancing loops. The nature of a loop stimulates chaos or equilibrium in a system. Nevertheless, this scarce classification does not facilitate the problem formulation. In TRIZ, the problem formulation determines the selection of the tool. Hence, the modeling approach needs a more detailed classification scheme to improve the problem-solving performance (Table 10.3).

Table 10.3 Comparison of different causal relations (Sterman 2000; Forrester 1963; Salamatov 1999)

Causal relations in SD		Causal relations in TRIZ	
	Positive relation		*A* produces the desired effect on *B* (solid arrow), but there is a partial or continual negative reaction of *B* (wave arrow). Thus, it is necessary to maintain or increase the positive effect on *B* without the adverse effect
	Negative relation		The useful effect of *A* on *B* produces a simultaneous negative effect on *B*. The conflict appears when it is necessary to increase or maintain the positive effect, but the negative effect should be eliminated
			This causal relation is similar to the preceding one. The effect of *A* on *B* is useful for one part or component of *B* but harmful for another part or component of *B*. Some actions must be in place to eliminate the negative effect on B_2, while the positive effect on B_1 remains the same or improves
			In a system involving several components, *A* has a positive effect on *B* but produces a simultaneous negative effect on *C*. It is necessary to eliminate or reduce the negative effect and preserve or improve the useful effect without damaging the system
			The useful effect of *A* on *B* produces a harmful effect on *A*. Thus, it is necessary to eliminate the negative effect but maintain or increase the useful effect
			The useful effect of *A* on *B* is excluding the useful effect of *C* on *B*. It is necessary to provide the effect of *C* on *B* without changing the effect of *A* on *B*. A mutually exclusive relation could also be present in the system
			This relation has several interpretations. The first one is that *A* has a single effect on *B*. Nevertheless, two different effects are demanded. The second interpretation explains that *A* has no desired effect on *B*, or that it is necessary to change *B*, but the mechanism to execute the transformation is not known. Finally, the relation exposes that it is a need to provide the effect of *B*, but the complexity of *A* should not increase

(continued)

Table 10.3 (continued)

Causal relations in SD		Causal relations in TRIZ	
			The information or interaction between *A* and *B* does not exist. A mechanism to collect information or to implement a useful action is necessary. Essentially, the conception of this interaction is a creative process
			The effect of *A* on *B* is not controllable; the control process is unknown or the mechanism to make the effect controllable is not known

The available software for system dynamics modeling cannot model a conflict following the TRIZ causal relationships. Consequently, a textual description should be part of the modeling process. The lack of more versatile modeling tools raises several questions:

How should the graphical tools in SD be applied to model any inventive problem?

How to adapt the resulting model to apply a TRIZ tool?

If there are more than one TRIZ tools to solve the problem, how to assist the solver to select the right tool?

- Modeling contradictions: the causal diagram makes evident some crucial problems in the system that could be formulated as contradictions. However, the translation of these problems into contradiction is not an easy task. In the first place, the user should decide if the problem is directly stated as a physical contradiction or if it is surrounded by a technical one. A solver without the basic TRIZ knowledge will find this task as time and effort demanding. The SD modeling does not propose any guide to identify a conflict, but it offers the graphical resources to observe the evolution of a conflict in time. Finally, like any other simulation tool, it does not provide a potential solving path but proposes the technical tools to evaluate the impact of a possible solution.
- The TRIZ tools cannot model an inventive problem dynamically. The Algorithm of Inventive Problem Solving considers time and space in its second section (Part 2. Analyzing the Problem Model), and more specifically in two points: (2.1) Define the operational zone (OZ) and (2.2) Define the operational time (OT). The operational zone is the space where the conflict appears. On the other hand, the operational time has two conditions: the time when the conflict occurs (T1) and the time before the conflict (T2). ARIZ does not contain any other recommendation or tool to deal with the operational time/zone (Altshuller 1984, 1999; Savransky 2000; Salamatov 1999). However, this condition does not forbid the use or introduction of other tools. To face this limitation, the stock and flow diagram is particularly useful. The simulation software asks for a

description of the causal relationships and assists the user to model the differential equations that define the system behavior, reducing the mathematical modeling effort.

- The application of TRIZ in different domains also faces many challenges, especially when intangible variables are part of the system. The central TRIZ concepts should increase their abstraction level, and not all users deal well with high-level abstractions. The application of TRIZ in the service domain is one example of this difficulty (Jiang et al. 2011). Likewise, the field of processes is a source of complex problems. The nature of the variables required to model a process is changing in time, which means variables that have a dynamic behavior are needed (Barragan et al. 2012). Despite this dynamic requirement, there are several applications of TRIZ in the process domain. Nonetheless, the combination of TRIZ with the SD modeling approach has the potential for improving performance in this domain. On the other hand, in the system dynamics modeling, it is not easy to represent a physical product, although the object operation is less complicated than TRIZ.

10.7 Conclusion and Future Work

The purpose of this chapter is to explore the feasibility of combining TRIZ with the system dynamics modeling based on their complementarity. The analysis of the TRIZ drawbacks revealed that the solving process needs an approach useful to observe how the variables in conflict evolve in time. Simultaneously, it is possible to state that the system dynamics modeling needs some technical tools to represent and solve a conflict and, particularly, problems that are in fact contradictions. Thus, a synergy is possible, which indicates the conception of a new problem-solving process where the advantages of both approaches are deployed systematically while their intrinsic limitation is surmounted.

Any effort in this direction is future work. Nonetheless, the research team considers the following points as a priority:

- The transformation of the TRIZ tool to operate inside the simulation environment of system dynamics
- The evaluation of the methodological approach to assure that any solver can identify, model, and solve a technical or physical contradiction
- The simplification of the TRIZ-SD approach with the goal to facilitate its adoption and application in different domains, specifically in the service and process domains

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Chapter 11
Conceptual Framework of an Intelligent System to Support Creative Workshops

Alex Gabriel, Davy Monticolo, Mauricio Camargo, and Mario Bourgault

Abstract In today's highly competitive economic context, companies are forced to be innovative in order to stay on track. This mandate to innovate requires companies to set up various tools to evaluate the capacity to innovate and implement innovative dynamics. Before purporting to generate innovation, we need ideas. Thus, creativity is in some way the upstream component of innovation. Creativity implies the production of ideas. This production of ideas can be supported by many techniques that can be classified into two categories: systematic and structured methods (TRIZ) and explorative approaches (brainstorming, mind mapping, personas, affinity diagram, etc.). The fact is that these creative techniques can be necessary but are not enough to produce unobvious ideas. The many factors that influence the creation of a creative dynamic lead to a complex situation which is difficult to manage optimally. From among the various ways to establish a creative dynamic in organisations, this work considers the creative workshop, which is a collaborative way of solving problems by maximising the proposition of unusual ideas. In this chapter, we will discuss the need to structure activities before, during and after the workshop itself and how a support system could allow an optimal organisation of the workshop throughout the entire creative process. The components of the creative support system will be described and the potential impacts on the creativity process discussed.

11.1 Introduction

In today's highly competitive economic context, companies are forced to be innovative in order to stay on track. This mandate to innovate requires companies to set up various tools to evaluate the capacity to innovate and implement

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innovative dynamics. Creative abilities are considered to be one of the pillars for developing the firm's innovation capacities (Boly et al. 2014; Chiesa et al. 1996). Creative competences allow firms to explore and develop promising fields, inspire the emergence of new concepts and designs or propose solutions for specific unsolved problems. Consequently, enhancing these competences has become a priority for numerous organisations. Hence, the methodologies and tools for supporting creativity have gained in popularity both for industry and for academia. There are two main creative approaches that can be mentioned: the systematic creativity (SC) approach (Ogot and Okudan 2007) and the creative problem solving (CPS) approach (Treffinger et al. 2008; Osborn 1963). Systematic creativity methodologies such as TRIZ are increasingly being applied due to their ability to take systematic advantage of the available knowledge. It permits intelligent idea generation at condition similar design problems has already been solved. Despite the increasing dissemination of systematic creativity, creative problem solving (CPS) based on techniques such as brainstorming (Osborn 1963) is still by far the most used approach (Paulus et al. 2012). However, implementing and exploiting the results of a creative workshop are time- and resource-intensive activities for an organisation, requiring a huge number of people and effort. Moreover, the results can be disappointing and the workshop perceived as a waste of time if the conditions are not created correctly.

On the other hand, current developments in information and communication technologies (ICT) permitted the emergence of collaborative and cooperative information systems (Boughzala 2007). Functionalities as instant messaging, video calls and file sharing contributed to the increase in virtual team collaboration by enabling communication, coordination and collective problem solving (Boughzala 2007; Nemiro et al. 2008). These developments can potentially help to enrich further the creative process and provide new functionalities in order to apply more systematic approaches (Zanni-Merk et al. 2011).

Despite creativity is individual, collective and organisational (Mumford 2012), the iterative process of a creative workshop is first considered as collective and organisational. Indeed, at each stage of this process, different actors with different roles and knowledge are involved in making decisions and conducting actions that impact the subsequent stages, which could make the entire creative process highly complex. In order to represent this complexity and the flow of information involved, we argue that the multiagent paradigm can properly represent it. The agents were originally designed to model complex systems due to their properties of autonomy, the interaction between them and their environment and the search for a common and individual goals. The idea of applying the agent paradigm to creativity had already been suggested (Boden 1994), but to the best of our knowledge, no application has been implemented in the domain of creative support systems.

Thus, the main focus of this chapter is on improving the organisation and the implementation of a creative workshop and on exploiting its results through a creative support system (CSS) based on the agent paradigm. The systematic perspective of TRIZ somehow inspires this. However, the challenge is to retain the creative character despite the systematic use of information system and digital devices. Consequently, this chapter is organised as follows: the next section aims to give a better understanding of the evolution of innovation and creativity practices. Then, Sect. 11.3 positions the current systems and tools, which support the creativity process, in the creative process and the used technologies. Subsequently, opportunities to improve the software currently available for assisting creativity will be addressed. Finally, in Sect. 11.4, some specifications for designing a CSS will be discussed before concluding on the perspective of a CSS based on a multi-agent system (MAS).

11.2 Evolution of Innovation and Creative Practices

Innovation and design can be considered as problem solving situations which require creativity and flexibility. Flexibility, which can be considered as a characteristic of creativity, means the change of mental process and representation of a situation. Whether it be problem solving, design or innovation, it is a cognitive phenomenon that can be described as a personal and goal-oriented process (Mayer 1999). Problem solving occurs when a person has a goal but does not know how to achieve it (Ward 2012). A solver "engages in some sort of mental computation such as applying a set of operations to knowledge in the cognitive system" (Mayer 1999) in order to find a solution to a problem (reach the goal state). The solving strategy depends on the formalisation of the problem (ill-defined/well-defined) but also on what knowledge the solver uses. If the solver bases his resolution on similar previous problems, the problem can be considered as routine, whereas it is consider as a creative problem if it requires creation of new methods (Ward 2012). Based on these categories, design can be associated to routine problem, which is solving a well-defined problem based on previous experience. Innovation is rather associated to the creation of new methodology and knowledge to solve a problem in ill-defined context (Anderson et al. 2014; Tidd and Bessant 2009). What actually matters in this chapter is innovation and more precisely creativity upstream innovation.

11.2.1 Creativity from Innovation

Innovation is defined as the acceptance and widespread use of a new product, process or service, conveying the notion of success and perceived value from various economic actors (e.g. customers), as well as being different from existing solutions (Tidd and Bessant 2009). The two major activities of the innovation process are idea generation and idea management (Murah et al. 2013). The idea generation activity, also called ideation, is the creative production of ideas individually or collectively (West and Rickards 1999). Idea management is the registering, filtering and evaluation of the ideas in the objective to reuse it. In the perspective to produce ideas, creativity is the ability to look at the problem in a different way and to restructure the wording of the problem in order to make new, unseen possibilities emerge (Linsey et al. 2008). Certainly the most accepted definition of creativity is that of adaptive novelty (Perkins 1994). It means creativity is a balance between concept novelty and usefulness (West and Sacramento 2012; Puccio and Cabra 2012; Lubart 2005) or appropriateness (Zeng et al. 2011; Howard et al. 2008), which is achieved by using existing knowledge (Ogot and Okudan 2007). Creativity can be seen as the synthesis of new ideas and concepts through the radical restructuration of existing ones (Hsiao and Chou 2004).

Whether it be creativity or innovation, it is influenced at different levels of complexity (West and Rickards 1999). Both these concepts can be perceived as a whole of individual attributes (Sternberg 2005). Some authors will defend creativity as a value instead of competences, whereas others will consider the opposite (Perkins 1988). In terms of cognitive sensibility (Lubart 2001) creativity is characterized by problem sensibility, capacity to produce quantity of ideas (fluency), ability to change its mental state (flexibility), ability to reorganise its knowledge, ability to handle competitive context and ability to evaluate. Thus, creativity can be considered as a cognitive competency (processing information), an artefact production or a social production which can be dependent on or independent of the domain (Sternberg 2005). The same author suggests the theory of investment that characterises creativity through six independent aspects: intellectual ability, knowledge, type of thought, personality, motivation and environment. All these characteristics can be perceived through three perspectives: individual, collective (team) and organisational (Mumford 2012):

– The individual perspective gathers some of the already quoted aspects that are expertise, motivations and cognitive abilities (Damanpour and Aravind 2011). This individual aspect can also be decomposed into different systems: the system that triggers creative activity (personality, motivation), the system that conditions creative activity (education, environment) and the resource system of creative activity (knowledge and information related to problem, tools).
– The collective perspective focuses on interaction between individuals who have different characteristic and impact on the team. This perspective deals with cooperation and collaboration. The most well-known phenomena related to the collaboration are the production blocking, the judgement fear and the social loafing (Warr and O'Neill 2005; Ray and Romano 2013).
– The third perspective is organisational. It concerns fostering creativity through management policy of the organisation. It is related to the diversity, the interrelations and the trust among the actors and the governance, the team work, the collaboration, the permeability and the flexibility of the organisation (Hemlin et al. 2008). It implies to manage the processes, the culture, the communications and the knowledge of the organisation (Damanpour and Aravind 2011).

All these factors constitute a complex system that have overlaps and correlations that lead to the creative phenomenon in certain configurations. Like most complex systems, creativity has some simplifications to ease its understanding. In order to further understand the phenomenon of creativity, it has been described through steps. These steps are commonly and abusively considered as process. Although it is constituted by activities and results, it does not clarify individuals and equipment involved (Holt and Perry 2008). The perception of the creative phenomenon evolves from an ex nihilo vision (Perkins 1988) to a sequence of thoughts and actions that results in a new and adapted production (Lubart 2001). The first descriptions of creativity through steps are Helmholtz–Poincaré–Getzels model (Lubart 2003) and Wallas model (Ogot and Okudan 2007) which introduce the notion of incubation and insight. This vision of creativity is a more or less conscious knowledge processing that leads to the unexpected emergence of ideas. This vision of creativity evolves from an individual and partly unconscious phenomenon into a collective, active and interactive perspective. It substitutes incubation and insight into a further active step called ideation. Literature abounds with variations of steps that differ according to the number of steps and the degree of details (Salerno et al. 2015; Sawyer 2012; Seidel 2011; Howard et al. 2008; Nemiro 2004). These variations have different origins. The steps of the collective and dynamic vision of creativity arise from six main approaches (Massaro et al. 2012): creative problem solving, lateral thinking, appreciative inquiry, design thinking (re-engineering), synectics and inventive problem solving (TRIZ and similar approaches). Despite the different intents between these approaches and the specific characteristics of each one, these "creative processes" also have much in common. Based on the review on engineering and psychological "creative processes" by Howard et al. (2008), it was highlighted that creative processes can be summarised into four common steps: problem analysis, ideation, idea evaluation and implementation/communication. If the "creative process" is active rather than passive, it requires techniques and tools to guide individuals and team.

11.2.2 Creative Techniques and Tools

Even if some individuals are creative mainly due to their education and/or personality, it is not sufficient. A creative person does not imply a creative team or organisation. In order to facilitate and supervise interaction, communication and exchange of ideas, creative technique can be useful.

11.2.2.1 Creative Techniques

Creative techniques aim to help in the production of ideas and by extension assist in the production of solutions to a problem. One of the most well-known creative techniques is certainly brainstorming, which was invented by Osborn (1963). This is part of a wider approach named creative problem solving (CPS) (Osborn 1963) which provides the framework for the correct application of brainstorming. This framework is a set of rules: deferring judgement, favouring quantity over quality and avoiding any kind of censorship (Osborn 1963). CPS has become a "creative technology" by combining a collection of creative techniques (Magyari-Beck 1999).

For decades, the number of creative techniques and the resulting literature have constantly increased (e.g. Martin et al. 2012; Michalko 2006; VanGundy 2008; Aznar 2005). Despite the large quantity of creative techniques, these are based on more or less strong heuristics that force the use of key processes and mental operations to reshape and reform people's existing knowledge and thus generate ideas (Mumford and Norris 1999). These heuristics have been structured into 17 higher-order rules which represent different styles of processing knowledge to solve problems (Strzalecki 2000). The efficiency of these metaheuristics also depends on the progress in the CPS process (Strzalecki 2000). Since heuristics are the basis for most creative techniques, it means creative strategies and products depend on the creative problem to be solved and the phase in the solving process (Li et al. 2007).

Creative techniques are presented as a way of assisting and supporting the creative process and can appear quite artificial as they force people to have thinking styles. The alternative is to teach creative thinking by experiencing creative problem solving during project-based courses (e.g. Wang 2001; Orono and Ekwaro-Osire 2006; Mingshun 2010) or following a training course (e.g. Higuchi et al. 2012; Basadur et al. 1982). The aim is to automate the cognitive mechanism that leads to creativity for people to whom it does not come naturally. In other words, training makes automatic the application of the cognitive mechanism associated with the creative methods. Similar to the exploration of the "design space" induced by TRIZ that analyses and breaks down the problem and applies solution-orientated rules, the application of creative techniques can also be systematised. At the difference of the systematicity of the TRIZ approach that exploits data of existing innovations and solutions, the CPS and the associated creative technics involve the imagination and the creativity of individuals in the collective creative process. However, the way creative problem solving is implemented evolves.

11.2.2.2 Open Innovation Changes Creative Practices

In practice, innovative and creative activities usually concern an organisation's strategic capabilities, such as the R&D or marketing departments. However, for decades innovation has tended to be broader in the organisation and even open to innovation outside organisations (Getz and Robinson 2003). This is not a new principle, but its theorisation under the term of open innovation (Chesbrough 2004) is recent. The increasing use of ICT in organisations changes the innovation paradigm and creative practices (Adamczyk et al. 2012). A widespread practice permitted by ICT is the innovation contest which is increasingly popular in organisations (Adamczyk et al. 2012). "Innovation contests can generally be described as IT-based and time-limited competitions arranged by an organisation or individual and calling on the general public or a specific target group to make use of their expertise, skills or creativity in order to submit a solution for a particular task previously defined by the organiser who is looking for an innovative solution" (Adamczyk et al. 2012). Such contests can be divided into five categories based on the intention of implementing an innovation contest: economic perspective, management perspective, education focus, innovation focus and sustainability focus

(Adamczyk et al. 2012). Depending on a flat or hierarchical governance and a closed or open participation (Pisano and Verganti 2008), innovation contests are implemented differently. In the case of open participation, innovation contests can also be described as crowdsourcing (Piller and Walcher 2006). The nature of the input required for participation can vary from the idea to the solution, and the nature of the task can vary from open to specific depending on the way the contest is created and on the innovation policy (Elerud-Tryde and Hooge 2014). Various companies from different industrial sectors have experienced innovation contests including Adidas, Salomon, O'Neill, Procter & Gamble, BMW, Volvo, Starbucks, IBM, Dell, Microsoft and Siemens (Piller and Walcher 2006; Adamczyk et al. 2012; Elerud-Tryde and Hooge 2014). Organisations can also subcontract the management of innovation contests to platforms such as InnoCentive,[1] OpenIdeo,[2] Babele,[3] Desall[4] or Atizo.[5] The innovation contests, which are a form of CPS, and their digital tools argue for the non-negligible role of ICT by permitting creative activities and capitalise the results.

Creative practices are tooled in order to simplify their operationalisation and increase their potential results. Since decades, work is being carried out to establish various methods and techniques. The next step, which implies both the increase in digital devices and virtual team collaboration, is to create digital systems adapted to creative practices. Before talking more precisely about CSS, the next section presents in detail the creative workshop, which is one of the creative practices, followed by the issues it implies, and some typologies of the system.

11.3 Current Challenges of Creative Workshops

This section presents an instance of creative workshop and highlights some of the limitations and difficulties when organising and operationalising creativity workshops. The coming statements are not uniquely based on literature but also continuous observation over several years of the "48 h to generate ideas" creative workshop. It is an international contest, organised annually in France by the ENSGSI, an engineering school at the University of Lorraine, since 2001, which proposes simultaneous creativity workshops with participants from different universities in France and overseas.[6] Participants are mainly undergraduate students from different areas of engineering. The workshop deals with subjects provided by

[1]Innocentive: http://www.innocentive.com/

[2]OpenIdeo: https://openideo.com/

[3]Babele: https://babele.co/

[4]Desall: http://www.desall.com/

[5]Atizo: https://www.atizo.com/

[6]In 2015, the number of participants was 1200 students from 20 schools and universities in six countries.

industrialists, whereby a number of teams ideally composed of students from various disciplines work using creativity techniques for 2 days to suggest innovative and original solutions.

The difficulties that have been encountered could be summarised as follows:

– Formalising the problem to be solved
– Selecting creative techniques which are adapted to the problem and the experience of the participants
– Reaching the right balance about the time spent on applying creative techniques to get the richest ideas without leading to frustrations
– Providing the eventually missing information concerning the implementation of the techniques for the facilitator
– Permitting rich exchange between distant teams who work on the same subject.

These difficulties are the on-site observations of organising and managing creative workshops. Firstly, Sect. 11.3.1, we provide more details about what we mean by creative workshop in order to precisely present the challenges of managing a creative workshop in Sect. 11.3.2. Then the prospect of using digital devices will be developed in Sect. 11.3.3.

11.3.1 The Basis of a Creative Workshop

A creative workshop, also known as a creativity session or creative jam, involves bringing together various people (if possible, from different departments or with varying expertise) in order to solve a problem creatively. This creative problem solving consists in applying creative techniques that ease discussion and confrontation of points of view, reduce latent inhibition (Carson et al. 2003) and almost engage people in thinking styles that they would not normally use. A creative workshop can be broken down into the four iterative phases presented previously: problem analysis, idea generation, idea evaluation and implementation/communication (Howard et al. 2008). In accordance with these phases, six different actors take part in the process (Fig. 11.1): facilitator, organiser, "ideator", decision-maker, expert and evaluator.

– The organiser is responsible for providing the facilities for the workshop and communicating with the workshop's different actors. During the problem analysis, the decision-maker discusses the problem to be solved with the organiser and defines the approach to be adopted and the appropriate subject formalisation and the approach for evaluating the product of the creative workshop.
– The decision-maker is the person who has a problem to solve. He is the "project owner" as he provides the problem, the context and the expectation. He is the person who can take decisions to continue the workshop, develop and implement an idea or stop everything.

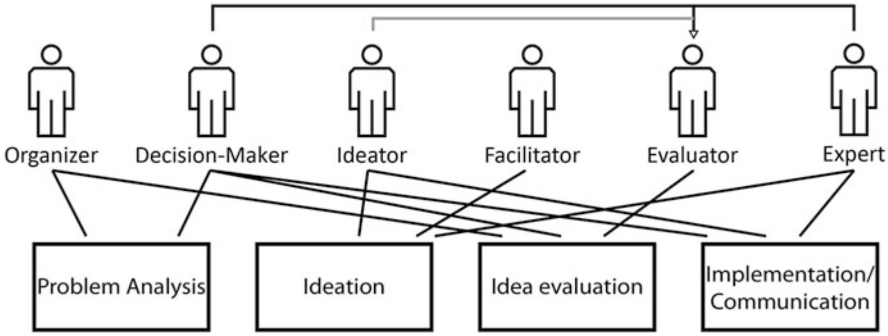

Fig. 11.1 Simplified representation of the roles involved in the creative phases

- The facilitator aims to support the group of "ideators" in the problem solving. This support consists of creating a dynamic and assists the application of creative techniques. He organises the application of creative techniques according to the workshop's objective, the subject, the participants and the facilitator himself. The facilitator preferably has some knowledge about creative practice.
- "Ideators" solve the problem by suggesting ideas through the application of creative techniques. It is suggested "ideators" differ in terms of background and competences in order to have different points of view and thinking styles.
- The evaluators are people who participate in the evaluation of ideas. They can also have another role as facilitator, expert or decision-maker. The role and how the evaluator works differ depending on the strategy initially defined by the decision-maker, but there is at least one evaluator: the decision-maker. The role of evaluator is to apply criteria or provide feedback about the ideas generated according to his expertise and experience. The role of organiser during this phase is to oversee the exchanges and discussions about the idea. Participants who generate ideas can also play the role of evaluator, but the evaluation should be based on the participant's expertise and any conflict of interest should be avoided.
- Experts may be needed during the ideation phase to advise the "ideators" when there is a lack of competences. They can also participate as evaluators in order to judge specific aspects of the ideas.

Finally, the implementation/communication phase depends on the products expected from the workshop. The participants may have to produce some prototypes before the ideas are presented and evaluated. The other aspect of the implementation/communication phase is the transfer of the validated ideas to embodiment design by the decision-maker and the evaluators.

The execution of the creative workshop described above is general enough to be set in an academic or professional context. Different from what happens in an academic context, in companies one person can assume different roles. For example, the same person could be the organiser and the decision-maker simultaneously, or the organiser can also be the facilitator, provided that they have enough experience.

11.3.2 Creative Workshop Issues

Various aspects of the creative workshop can be discussed: the collaboration mode, capitalisation of information, workshop management especially the development of the process and the assistance of the activities specific to each phase.

A creative workshop is collaborative and cooperative by definition since it aims to use collective creativity to solve a problem in a group. A creative workshop usually involves people that are in the same place. This normal co-located configuration entails some difficulties. In general, the application of creative techniques and the creative workshop generate a large amount of information and knowledge in a short time span. The fact that people are all together is positive in terms of knowledge management because it allows informal discussions between participants but makes capitalisation complicated (Gronau et al. 2012). It implies information management challenges. The added value of a creative workshop that matters to be capitalised is the produced number of original ideas. But at the same time, it implies to manage information, such as the problem definition, the context and complementary information to produce it. This information is the first input of the creative process that permits the application of creative techniques and the production of ideas. One practice for the capitalisation of ideas is to complete idea cards in order to keep track of the ideas and their characteristics. This is quite a flexible way to keep track of ideas as it permits annotation, quick changes and the option to draw on it, but the processing of the cards is tedious. In terms of the contextualisation of ideas, it is limited to the title of the subject.

Another challenge concerns the formulation of the subject and the problem to be solved by the "ideators". The subject and the problematic are the prerequisites of the workshop to enable "ideators" to generate ideas in the right way. However, this critical formalisation task is supported by any technique or methodology.

Concerning the organisational aspect, a creative workshop can be resource intensive and inefficient (Mumford and Norris 1999). The aim of the organisational aspect of a creative workshop is to improve the efficiency and overall experience for all those who are participating. However, many factors influence the success of a creative workshop. The creative techniques aim to produce interesting ideas more quickly, but some heuristics inherent in creative techniques are more useful than others depending on the phase in the creative process and the expected creative product (Mumford and Norris 1999). The increase in efficiency and the decrease in eventual frustration affect the organisation of the workshop according to the problem to be solved, the context and the stakeholder's expectation (Herrmann 2009). In order to improve the efficiency of the creative workshop, the way to design it must be explored to improve the consistency between the various activities involved. This construction of consistency is however limited by several things, notably the facilitator's competence in applying creative methods and how he uses the available resources (whiteboard, sticky notes and other supplies). The limiting factors are the knowledge, the experience and the confidence of the facilitator to apply creative techniques, the resources and the tools available and how he uses it to support creative activities and finally its ability to create a creative dynamic in the group.

Some of the main challenges of the usual co-located creative workshop mentioned above are: the limitations of the capitalisation of ideas, almost impossible to reuse, the lack of problem and context capitalisation, the possible lack of consistency between the workshop's activities, the potential optimisation of the creative workshop and high dependency on the facilitator's competence. All these limitations are true when actors are in the same location. In the case of remote collaboration (distributed teams), the issues are slightly different.

The use of ICT cannot be avoided when collaborating remotely. The team is divided into smaller teams or individuals. Some existent innovation contest platforms integrate collaboration into the process, such as the evaluation of the idea by other participants on OpenIdeo, but it is harder to implement the collective aspect of creativity by applying collective creative techniques in a dispersed context. The necessary use of ICT makes it easier to capitalise the information and especially the ideas, but it does not solve the other issue mentioned above. The creative workshop still needs to be designed, and this is even more difficult as activities should be adapted to each actor and permit the creation of a creative dynamic. The organisational aspect remains an issue since it is not a single schedule or environment that has to be managed. Related to the organisational aspect, the operational aspect is also an issue. The application of creative techniques requires a suitable interface since digital devices are less flexible than a whiteboard and sticky notes. Moreover, studies have to be carried out on adapting the creative techniques through a digital interface without inhibiting the creative dynamic.

The management of information (ideas, subject, problem, etc.), the design of the creative workshop and the application of the creative techniques are issues for both co-located and remote collaborations. The challenge is to develop these aspects of the creative workshop. The assumption is to design a digital system that would provide assistance and empowerment during the implementation and processing of a creative workshop. The aim is to gain enough intelligence to ease the creation, formalisation, capture, evaluation and reuse of the ideas during a creative workshop. In order to achieve this sort of intelligence, the adopted approach is applied in the field of knowledge engineering. It consists of modelling human activity and identifying the competences and knowledge involved in order to build the adapted system that would reproduce or assist human activity (Charlet et al. 2000). From a process perspective, the system would aim to nurture creativity during the workshop through the dissemination of adapted knowledge and the use of adapted technology and tools. However, in practical terms, the benefit of digital devices in supporting creativity and its functionalities depends on the collaboration and dispersion settings.

11.3.3 Assisting a Creative Workshop with Digital Systems

The prospect of using digital devices to support creative activities is not original. The idea of computer and artificial intelligence for assisting creativity and creative problem solving has long been present in the field of creativity (Proctor 1999). From the point of view of creativity research, four classes of creativity support systems were suggested (Lubart 2005): coach, penpal, nanny and colleague. The nature of the assistance are, respectively, advising and helping on implementing creative activities, providing support for collaboration and communication, monitoring progress and generating ideas and solutions collaboratively with the humans agents. From the point of view of computer science, another classification of five typologies of computer support programs was suggested (Proctor 1999): (1) creative problem solving programs, (2) outlining and presentation programs, (3) thesaurus programs, (4) incubation programs and (5) groupware programs. In addition to the various systems classifications, a distinction should be made between programs that are designed for individual use and those designed for groups (Proctor 1999). The individual and collective aspect of the system can be linked to the individual and collective aspect of creativity both of which should be considered in terms of support.

From the different approaches of CSS, the assumption is to not prefer one to another. They all provide assistance at different levels of the creative workshop. From the perspective of the creative phases, the CSS would be a combination of the various types of systems adapted at the different phases of creativity as represented in Fig. 11.2. However, even if the intent is to design a system that integrates the different assistance modes presented above, they cannot all be implemented simultaneously. The priority is to cover the management of the creative workshop that implies managing information and knowledge throughout the different phases of the process. From Lubart's classification, it means advice and support to implement a workshop and monitor its progress. The different collaboration modes will be considered and integrated in this research without being the main focus. Concerning the support for the creative activities and tools in general, the operational perspective will not be addressed. In order to defer the integration of functionalities, the system design has to be modular. In other words, it considers the CSS as a platform which provides high-level functionalities like a computer's operating system and

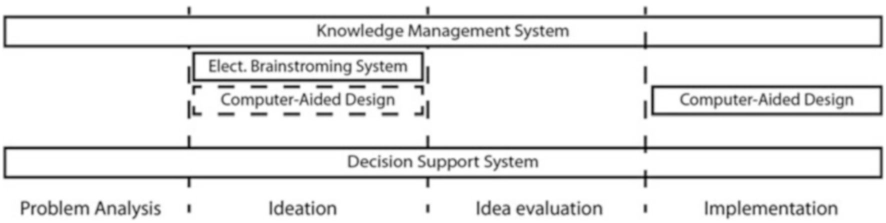

Fig. 11.2 Type of system that a creative support system should combine throughout the creative process to provide extended assistance

modules which provide operational aspects (support for specific techniques) such as computer-aided design software or image-editing software. Based on this position, the next section will present the research done for designing the foundations of the CSS and detail some of its functionalities.

11.4 The Prospect of a Creative Support System for a Creative Workshop

The current application of a creative workshop, regardless of the collaboration mode, has various prospects for improvement through the use of ICT. However, the idea of using it to improve creative activity is not new, and several experiments have been conducted. Despite a significant number of experiments, some avenues remain particularly promising and yet unexplored. Before presenting these promising avenues and the development of some of its functionalities, the previous experiments on CSS have to be reviewed.

11.4.1 A State of the Art of Current Creative Support System

A review of the systems to support creativity (Gabriel et al. 2016) quoted and presented in the scientific literature provided an unexpected number of system examples. From a set of almost 90 systems encountered in the literature, only 49 were considered as having enough documentation to be studied. This review was based on the observation of several criteria: the phases of the creative process supported by the system, the multi-user aspect (individual or collective) of the system, the ability to support remote collaboration (co-located or dispersed) and the technology used. The main results show that half of the 49 systems considered in the study focus mainly on the ideation phase (Fig. 11.3). Regarding collaboration, nearly three-quarters of the systems were designed for collaboration with half of them allowing remote collaboration. In terms of use, half of them were designed for individual use, and only 10% were able to support both individual and collective uses. Concerning the support technology, the observed trend was the use of web-based technology that permits greater flexibility in terms of devices to be used. In other words, the creative technique registered as being most used was unsurprisingly brainstorming.

An additional finding was the lack of flexibility of the system to respond to the variety of contexts for the application of creative techniques. Few of them support individual and collective uses, even less in co-located and remote collaboration, and none of them were able to cover these various collaboration settings throughout the different phases of the creative process. Moreover, in any case, the creative process was described in role- and phase-based knowledge-intensive processes. The

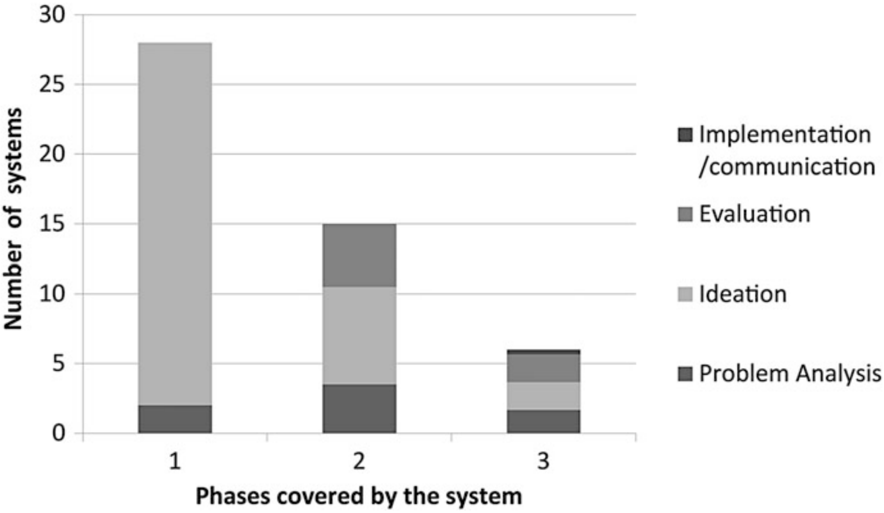

Fig. 11.3 Steps of the creative process supported by systems that support 1, 2 or 3 phases, respectively

systems observed in the literature review were not designed to support the different roles throughout the creative process and provide them with suitable knowledge capture and reuse tools. The aim of this work is then to improve the activities conducted during creative workshops by providing support for decisions made throughout the process. This system needs to support the analysis of the problem to be solved, suggest suitable creative and evaluation techniques, assist in the evaluation of the ideas, provide a suitable interface for applying such techniques and capitalise all the information relating to the problem, the idea generated and the evaluation. In addition, it also needs to individualise this assistance and this knowledge management in every collaboration mode.

In order to respond to these requirements, we decided to explore the field of the MAS. A creative workshop is comprised of iterative steps that nurture each other and should be coordinated by taking into account the needs and the choices of the various actors in the process. A creative workshop, as presented above, is a complex and dynamic process distributed among the various actors. These actors are autonomous but participate in the creative workshop in order to reach a common goal: to solve a problem. These parameters are common points for MAS (Weiß 1999) which are even stronger in the case of remote collaboration. MAS have applications for decision-making support and computer-supported cooperative works which are both aspects of a CSS (Weiß 1999). Despite this potential and a first presentation of the interest of the agent paradigm in creativity (Boden 1994), none of the systems reviewed was presented as multi-agent. In order to enable the agents of the system manipulate the knowledge related to the creative workshop, an ontology of the knowledge related to the management of a creative workshop was created. In the perspective of a MAS dedicated to creativity, ontology is critical to explicit shared knowledge among the agents who have to interact (Ling et al. 2007). It provides a standard vocabulary between the system's agents, which makes communication easier. At the same time, it is also an understandable language between agent and humans. Once again, within the review of the CSS, it was found that only one system uses ontologies but mainly for the description of the ideas. The next subsection details the creation of the MAS model for supporting creative workshop.

11.4.2 Multi-Agent System for Creative Workshops

The agent paradigm applied to support creativity is not new. The idea of applying the agent paradigm was first suggested by Boden (Ferber 1999): it has the ability to interact with the environment and to communicate directly with other agents, has objectives to be satisfied, has its own resources, is able to perceive the environment, represents the environment partially or wholly and has the potential to reproduce itself. Without focusing on properties, an agent can be defined as "a computer system situated in some environment and that is capable of autonomous actions in this environment in order to meet its design objectives" (Jennings and Wooldridge 1998). Based on this definition, a MAS is a set of agents cooperating with each other typically by exchanging messages (Bakar and Ghoul 2011) in order to accomplish a global objective (Isern et al. 2011). "A collaborative design environment can be viewed as a MAS where each agent has knowledge about specific domains and can solve different problems" (Ling et al. 2007). By extension, a creative workshop and its digital support environment can also be considered as a MAS. Using agents can notably provide three possibilities: task assistant for collecting the information and making it easy to achieve the tasks, consultant for providing the knowledge needed to make a decision and global assistant for distributing the information to the organisation. The reactive, proactive and flexible properties of the agents justify their use in this context.

The intention to design a system that would support the process across various agents in organisations is enough to justify the use of the agent paradigm (Wagner 2003). The MAS has two benefits: first, modelling and predicting the development of a system as applied in social and human studies (Amblard and Phan 2006), and second, conceiving a system that addresses and anticipates the needs of agents in organisations. In this context, it is the latter which is being considered. Two different approaches are used to design a MAS (Girodon et al. 2015): agent-based and organisational-based. In order to support the workshop process, the latter is more suitable as it allows both the organisation's activity and the knowledge generated to be represented. In view of an organisational approach, the Design methodology used is based on Organisation, Competence and Knowledge (DOCK) (Girodon et al. 2015). The application of this methodology leads to the formalisation of two types of agents:

- The cognitive agents aim to assist the activities of the humans according to the role they have in the creative process
- The reactive agents who process the information and the data needed by the cognitive agents.

Based on the modelling of the human organisation of a creative workshop, the application of the methodology leads to six cognitive agents who monitor the activities of each role in the creative workshop. In terms of reactive agents, the methodology results in the specification of seven reactive agents focused on processing information in accordance with the missions of the agents inside the agents' organisation that constitute the system. Although it provides the foundations of the MAS by describing the agents that constitute the system through their missions, their competences, their knowledge, their actions and their responsibilities, it is not sufficient in itself to build a system. These agents have to also communicate, share, process and store information, which means a common vocabulary must be defined. This vocabulary would also permit to structure the system's memory. This vocabulary is defined by an ontology that provides a representation of the area of knowledge of the creative workshop.

11.4.3 Creative Workshop Management Ontology

First of all, ontology is "an explicit specification of a conceptualization" which is an abstract, simplified view of the world that we wish to represent for some purpose (Gruber 1993). Although the main objective of ontology is to represent a conceptualisation, this representation can have different uses as it permits interoperability or data integration between humans, between humans and machine or even between machines (Bullinger 2009). In the context of the creative workshops, it would permit the virtual agents to exchange information between each other using a common "language" but also to relate this information process to the virtual agents to those needed by the human agent. It also permits the discovery and the classifications of resources by using ontology as metadata (Héon 2014).

There are various examples of ontologies for creativity and innovation such as OntoGate (Bullinger 2009), the Idea Ontology (Riedl et al. 2009), the Generic Idea and Innovation Management Ontology (Gi2MO) (Westerski 2013), the Brainstorming Ontology (Lorenzo et al. 2011), the Problem Challenge Ontology (Stankovic 2010) or even the Context Awareness Ontology from the European project idSpace (Sielis et al. 2009a, b). However, none of them have an overall point of view of creative workshop. Indeed, some provide a representation of ideas from the perspective of idea management, whereas others describe the concepts of brainstorming. It means some concepts are relevant, but after all, it requires the creation of a new ontology to define specific relations. Since ontology is a partial representation of the reality which is dependent on its purpose, the simple aggregation of the ontologies quoted above is not relevant. Due to the necessity to create a new ontology, we adopted an organisational approach to identify the concept of the ontology. This approach consists in modelling the human activity through their activities, their inputs (resources and knowledge) and their results. This could determine the concepts manipulated throughout the process and know how and when to collect, retrieve and reuse these inputs. Since the ontology's design is combined with the design of a MAS, the organisational modelling can be reused from the MAS design process. The resources, knowledge, artefacts and other objects and concepts illustrated in the creative workshop's organisational modelling can be used to define the vocabulary of the ontology. As the aim of the MAS is to assist the creative workshop, the objective of the ontology is to represent the concepts related to the creative workshop and its management. As a result of its objective, the conceived ontology was called Creative Workshop Management Ontology (CWMO) and developed in Web Ontology Language (OWL) with Protégé (Musen 2015). CWMO will be gradually enriched thanks to its use through the MAS during various creative workshops. However, during the design phase, the ontology creative and evaluation techniques were integrated in order to allow suggestions from the system for the users. The formalisation of the characteristics of the systems' agents, and the formal representation of the area of knowledge of creative workshops, constitutes the foundation of the multi-agent CSS. However, the characteristics of the agents do not specify how the actions should be executed and how the knowledge should be processed. So, each agent can be subject to further study in order to define each one's ability and intelligence. We arbitrarily chose to deepen the ability of the idea evaluation assistant agent. The next subsection will tackle the ability of this agent.

11.4.4 Idea Evaluation Assisted by Agent

Even if the design of the MAS provides specifications for the agents, it does not provide them with the "intelligence" needed to carry out their tasks. The difficulty is to understand the dependencies between agents and their distribution throughout the different phases of the creative process. For example, idea evaluation is distributed through problem analysis, idea evaluation and potentially ideation. The interest in evaluating the idea is manifold: selecting an idea from a pool of suggestions, managing the creative process (Micaëlli and Fougères 2007), defining the next step in the creative process, changing the focus of the creative process (Bonnardel 2006) or even evaluating the performance of the applied creative technique (Oman et al. 2013). The present interest is the selection of ideas from a pool. Choosing one idea from the large number of ideas through creative techniques is a task which implies compromise, judgement and risk (Oman et al. 2013). In order to cope with idea selection, three main techniques are suggested (Westerski 2013): idea assessment, machine-aided preprocessing and data filtering and clustering. Idea assessment is a task performed by evaluators to enhance ideas in line with the organisation's goal and current needs. Filtering and clustering comprises textual and graphical methods during idea selection to enhance browsing and searching the idea pool. Finally, machine-aided data preprocessing is a computational task that generates statistics or recognises patterns and preprocesses an idea prior to human assessment. Both idea assessment and machine-aided preprocessing have been explored.

An overall process for idea assessment was suggested with four main activities, as represented in Fig. 11.4. The aim of this process is to integrate the context definition into idea assessment. Context definition ensures consistency between the organisation's goal and the evaluators' preferences. This context definition involves problem assessment, defining a set of criteria and scales, eliciting a criteria's weight and eventually the assignment of the criteria to the evaluator. Problem assessment aims to clarify constraints, expectations and goals. Next, criteria definition attempts to define the criteria and scale depending on the problem and its context. Special attention should be paid to the balance between the number of criteria and the quality of the evaluation. Using overly simple scales leads to near-random results (Riedl et al. 2010). Then, the weight of the criteria has to be determined. The criteria do not have the same level of relevance from the perspective of the decision-maker and that of the problem. These weights can be either defined expressly by the decision-maker (direct weight elicitation) or elicited from a panel of ideas using the preliminary application of MCDA methods (indirect weight elicitation). Finally, the assignment to evaluators depends on the number of people involved and their competences. Once all tasks in context definition are done, the evaluation can be realised by the evaluators followed by the processing of the evaluation thanks to the MCDA method to produce the final score that will be discussed with the decision-maker. The second contribution concerning idea assessment is the formalisation of a decisional tree to be integrated into idea evaluation to determine the multi-criteria decision analysis used to process the score of the ideas for each criterion.

Regarding machine-aided preprocessing, the use of semantic analysis was also explored in order to preselect the ideas that seem to be the most relevant in responding to the problem without being common ideas. The principle was to extract the main concepts from the subject, thanks to WordNet and WordNet Domain, and do the same for the ideas and compare these concepts. This idea processing should be perceived as a suggestion tool for human evaluation. The semantic analysis as the context definition and the MCDA selection tree constitute the core of the competences that the evaluation possesses to process and generate knowledge. This semantic analysis competence also has some potential for the facilitator and the ideator agents in order to orient the creative workshop process.

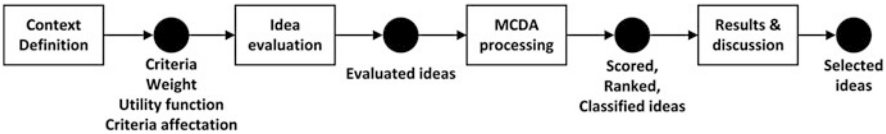

Fig. 11.4 Overall idea assessment process

Several other specifications and functionalities have not been explored, but they remain relevant and useful for the success of future CSS.

11.4.5 Non-Investigated Specifications

As previously introduced, the CSS aims to better address a creative workshop by collecting information concerning the problem that organisations cannot solve and attempt to solve the problem through a creative workshop. It would be interesting to classify the problem into typology in the perspective of a creative workshop. There is already a clue to this typology with the classification suggested by Jonassen (Jonassen 2000), which provides an overall classification of the problem.

Another avenue presented above is the assistance during the application of creative techniques. This avenue implies different perspectives, the adaption of the creative technique to be applied through a digital system for a specific situation, but also the impact of the user interface on the application of techniques. The environment is an influencing factor for creativity, but for remote collaboration, this environment is mainly the interface of the digital devices used between people. The way this interface is designed certainly influences the application of the technique and the productivity.

There is a large amount of creative techniques; each one has to be adapted and experimented to be applied and influenced through a CSS. The best way to deal with the amount of techniques is to consider the CSS as a modular system. This modularity permits to consider creative techniques individually in order to design their digital implementation and their data capitalisation according to the collaborative settings. Even if the idea assessment process was formalised, the evaluation techniques can be redesigned according to the collaborative settings. The different ways of applying and collecting the evaluation were not defined from the user interface point of view.

In the perspective of creating the entire CSS, the development has to be further explored in order to investigate hypotheses. One of the contributions is to provide the specifications of the agents in the perspective of the development of this system. However, technical specifications have been realised as the Creative Workshop Management Ontology which is already developed and some features of the idea evaluation assistant agent.

11.5 Conclusion

Despite the fact that we do not go into detail regarding system design, the results of this research work are mainly represented by the proposal of a conceptual framework for designing a CSS. The specific feature of this framework is the use of the agent paradigm and the creative workshop organisational modelling. The overall requirements concerning the support for the creative workshop can be summarised as follows: improve the creative workshop strategy based on the capitalisation of information about the problem to be solved and on the context; help define the creative strategy, which is composed of the creative techniques used to solve the problem; improve the application of the creative techniques; and assist in sorting and selecting the ideas and the capitalisation and the reuse of the various knowledge generated by the different actors of the workshop. In theory, modelling the creative workshop process to design the CSS is a way of reducing its intrusiveness. However, since the system has not been developed and tested, the issue concerning the systematisation of creative problem solving without affecting the creative ability of individual remains.

The perspective of this research is to deepen the mechanics of the agents that make up the creative support MAS. However, this development could be based on the competences, the knowledge and the interactions determined through the organisational modelling approach applied to design the MAS. The next step in the development of the CSS is to define how the agents that would assist the different actors of a creative workshop would carry out their activities and apply these competences.

This work provides an example of the design of a collaborative system that considers the organisational level for designing the support for creativity. The originality of this work is to consider as much as possible the different aspects of supporting creativity in order to finally fulfil the lack of an overall system as observed in the review of the creative support systems.

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