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Resolution of Inventive Problems: Different Kind of Mechanisms

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ABSTRACT

The difference between inventive problems and optimization ones is defined in this article. There exist among the engineering practices different kind of tools and methods aiming at designing, but which are not specified for the same nature of problem. It is thus relevant to be able to recognize the two kinds of problems: optimization ones, for which a solution can be found by adjustment of the value of problem parameters; and inventive problems, for which no solution is known. If no solution is known, either a solution exists and has to be found, it means that it has not been formulated the right way; either no solution exists and it is required to use a method to invent a solution. For these two cases, the matter is the problem, as it is modeled has to be reformulated, the model has to be changed, in order to build a representation enabling the resolution of the problem. The article will be focused on the question of problem model change and will compare the mechanisms to change this model for inventive problems from two problem solving theories: dialectical methods and models, on the one hand; and constraint satisfaction problem (CSP), on the other hand.

Keywords: Dialectical methods, Optimization, Over-constrained problems, Problem model.

1. Introduction

The objective of our research work is to find a solution to design problems by browsing a design problem space. This problem space is defined in (Goel and Pirolli, 1992) in terms of states of problem solving, operators that move the problem solving from one state to another, and evaluation functions. We try to analyze how different solving methods explore the problem space, which operators are used for and where an adequate solution to the design problem appears in the problem space. Two kinds of design problems are suggested. The first one can be solved by optimization solving methods when adjustment of values of problem parameters gives an optimal solution (non-creative design). The second one requires some creativity for its solution. The optimization algorithms browse a space of potential solutions which is nevertheless limited by the stated problem space. If no solution is found the classical optimization algorithms are not able to explore the solution space behind. In this case inventive solving theory TRIZ proposes methods to change the stated problem model and therefore to define a new problem space.

The creative design problems were identified as ill-defined or ill-structured by (Reitman, 1964). It means that the start state of presented for both methods. In the previous work (Dubois et al., 2008), a comparatory analysis of Constraint Satisfaction Problem (CSP) issued from optimization methods and dialectical methods and tools issued from inventive solving theory TRIZ were presented. Our goal is to find a new unified solving approach based on matching of both solving methods. This unified approach will permit to overcome limits of each individual method and to benefit from their advantages. Using the optimization methods or even evolutionary computation in design domain is not a new practice. An extensive state of the art of evolutionary computation and optimization methods used in structural design is presented in (Kicinger et al., 2005).

TRIZ (Altshuller, 1988) is a theory for inventive problem resolution based on dialectical representation of problems. One among the main approaches of TRIZ for problem resolution is to use contradictions as a way to formulate problems and analyze this contradiction in order to solve the problem. A Generalized model of Contradiction has been proposed (Dubois et al., 2009a) to state inventive problems, whatever the domain of problem could be. A problem, in accordance with the generalized contradiction model, will be characterized by:

problem solving is not completely specified, the goal state could be changed or reformulated in time and the transformation function is completely unspecified. In general, there is often very little information about design problem which means problem solving requires a lot of structuring (Restrepo and Christiaans, 2003). Problem structuring is a process of drawing external information to compensate for missing information and using it to construct the problem space (Simon, 1973). It begins with an interpretation of the problem situation – definition of problem parameters and functions. Then it follows with generation of design requirements and constraints. These are used to specify the design assignment (defining the problem space) and to describe and explore aspects of the desired solution (exploring the solution space).

The goal of the present study is to compare two solving principles – optimization and inventive one – from the design problem resolution's point of view. Definition of problem space and browsing of the solution space is

- a set of evaluation parameters, which represent the objective of the problem resolution;
- a set of action parameters, which are the resources to resolve the problem, i.e. to satisfy the evaluation parameters;
- a set of relations between the evaluation parameters and the action parameters.

One of the main interests of TRIZ is to propose principles to separate the contradictory properties of a situation, and thus to solve problems.
Constraint satisfaction problem is defined as (Freuder and Wallace, 1992):

- a set of variables;
- for each variable, a finite set of possible values (its domain);
- and a set of constraints restricting the values that the variables can simultaneously take.

The solution of a constraint satisfaction problem is an assignment of a value from its domain to every variable, in such a way that all constraints are satisfied. Such systems, where it is not possible to find valuation satisfying all the constraints, are called over-constrained. There exist different algorithms to look for a solution for CSP and over-constrained CSP.

The objective of this article is to define the kind of model change that is operated by CSP resolution mechanism and also that the TRIZ principles lead to the building of a model that cannot be obtained with CSP algorithms. When a contradiction occurs in a problem, it means that two properties that cannot be satisfied simultaneously in the initial model of problem are identified. To be able to solve such a problem a new model of the problem has to be built in which the two properties can be both satisfied. What kinds of model changes are operated by the TRIZ principles to build such a model? In the article (Rasovska *et al.*, 2009a) the different spaces browsed by the mechanisms of model change have been defined. In the present article the mechanisms to define and to browse these spaces will be illustrated. Different spaces defined in (Rasovska *et al.*, 2009b) to illustrate the way problem solving principles enable to look for new solutions. These spaces (specific problem space, problem space and solution space) will also be reminded in the article.

2. What is a problem

In this part, the nature of problem will be defined in order to be able to distinguish different kind of situations and to recognize the ones tackled in this article.

Problem solving is a common activity for a lot of domains, and its crucial role in design is particularly recognized (Simon, 1987). Problem solving cannot be distinguished from problem formulation. Indeed a good formulation of a problem nearly means solving it. But what does it mean "a well formulated problem"? This supposes that some problems are not well formulated or are not real problems, so what is a real problem? The different kind of answers to this questions arise heterogeneous ways to tackle the concept of problem, of its formulation and thus of the way to manage its resolution process (Dorst, 1997). The concept of problem is directly linked to the nature of the considered knowledge. Thus, in the domain of problem solving for technical systems design, it is important to clarify the kind of knowledge relevant for the resolution.

Several dimensions characterize the resolution of problem in technical systems design. (Bonnardel, 2000) presents the design problems as being open-ended and ill-defined. Design problems are considered open-ended as they do not have one single solution but a set of possible ones. The solution synthesis is thus the result of the choice of one solution among several ones. Moreover the problem is considered ill-defined as the initial formulation of the problem is not exhaustive and do not enable the direct synthesis of a solution. The information bordering the problem to be solved is collected throughout the trials to solve it. These notions of open-ended and ill-defined problems can be matched with the one of structured problem as defined in (Simon, 1973). Indeed, the whole set of solutions being unknown a priori, and the desired solution being defined step by step justifies to consider design problems as ill-structured ones.

As the problem resolution aims at well formulating the problem, it means that it is necessary to make evolve the first understanding of the problem, the first model of the problem. In the next part a problematic situation will be described, this problem will be used to illustrate the way an initial model of problem could be changed in order to go to its resolution.

2.1 Synthesis of problem models

The problem representation model of CSP is based on a set of variables that can represent physical parameters of the system and on the variables domains defining the possible values of the variables. Further more the CSP representation model introduces a set of constraints restricting the values that variables can take simultaneously. The constraints describe relations between the variables of the system; i.e. these relations can illustrate conditions in which the system can operate, given objectives of system functions or

relations between physical parameters. A solution in CSP is an assignment of a value from its domain to every variable such that all the constraints are satisfied all together. In the case of inventive problems where no solution is found and which are called over-constrained problems in CSP, solving methods try to minimize the number of not satisfied constraints. The research space of solving methods in CSP is characterized by a set of assignments of all problem variables without verification of constraints satisfaction. The solution space of CSP is then a set of assignments of all variables which satisfy all constraints or in the case of over-constrained problems which satisfy a maximum of constraints (one speaks about constraints relaxing).

In TRIZ representation model two kinds of parameters are defined (action parameters and evaluation ones) with their respective values to satisfy. The action parameters with their required values describe different possible configurations of the system (physical parameters...) on which one can operate. While the evaluation parameters with their required parameters describe solution objectives (desired results...) and their satisfaction is fully required. TRIZ methods are looking for a contradiction inside the system model inherent to a problematic situation. A system of contradictions based on linking between a physical contradiction and two technical contradictions is proposed in (Khomenko, 2007). The physical contradiction reflects the impossible nature of the problem by identifying one action parameter of the system that has to be in two different states. The technical contradiction expresses the opposition between two evaluation parameters of the system. To solve the inventive problem means to eliminate these contradictions and for this the TRIZ methodology proposes different principles.

The final comparison of CSP and TRIZ model is illustrated on the Table 1. The parameters in contradictions and the variables in CSP can be matched. The main difference between CSP and TRIZ is that TRIZ differentiates evaluation and action parameters and does not permit to operate on the evaluation ones. This can be translated as a required unary constraint in CSP which has to be satisfied. The notion of binary constraint as a relation between two variables in CSP is close to the notion of technical contradiction in TRIZ. On the contrary the two strategies are different from the problem solving point of view; this will be shown in the next section.

If comparing the representation models of the different problem solving methods, one can notice that:

To model the system, TRIZ uses a set of action parameters and the possible values of these parameters, whereas CSP uses variables and the domain of these variables (unary constraints)

The links between the physical contradiction and the technical ones in TRIZ could also be match with the binary constraints in CSP model of the system.

At last, the way the objective of resolution is represented in TRIZ is based on a set of evaluation parameters and their required values, whereas in CSP it is one more time variables and the domain of these variables (unary constraints) that is used, without any differentiation between the model of the system and the model of the problem.

2.2 Synthesis of solving methods

In order to compare different solving modes and different principles of model changes in CSP and TRIZ methods, we have proposed in (Rasovska et al., 2009) the definition of problem space browsed by both methods. See Figure 1. The previous analysis of the browsed space involved definition of three distinct spaces:

- Specific Problem Space (SPS) is defined by variables (parameters) of the problem which are limited by the Domains of these variables (Di). The dimension of this space is equal to the number of variables defined by the inventive problem.
- Problem Space (PSp) is also defined by variables (parameters) of the problem but these are not limited by their domains. The dimension of this space is equal to the number of variables too.
- Solution Space (SSp) is defined by all possible variables concerning the system the inventive problem concerns. The dimension of this solution space is so infinite.

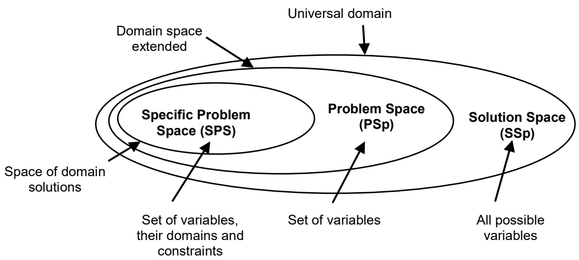

Figure 1. Definition of Knowledge Spaces.

These spaces could be compared with the ones define to make the difference between routine, innovative and creative design in (Rosenman and Gero, 1993):

- Routine design proceeds within a well-defined state space, all the design variables and their possible range being known and the problem being one of instantiation.
- Innovative design refers to situations where the space of known solutions is extended by making variations or adaptations to existing designs. The range of values of existing design variables being thus extended.
- Creative design implies the formulation of the state space.

Thus the Specific Problem Space (SPS) is equivalent to the space of domain solutions, the Problem Space (PSp) is equivalent to the extended domain space and the Solution Space (SSp) is equivalent to the universal domain.

3. Problem statement

Let us consider an electrical circuit breaker. When an overload occurs, the overload creates a force (due to magnets and electrical field) which operates a piece called firing pin. The firing pin opens the circuit by pressing the switch, located in the circuit breaker. In case of high overload, the firing pin, this is a plastic stem, breaks without opening the switch. Components are presented on Figure 2.

Figure 2. Components of Electrical Circuit Breaker.

The problem has been studied and the main system parameters and their domains have been defined as: x1: firing pin material (plastic – 1, metal – 0) ; x2: core internal diameter (high – 1, low – 0) ; x3: core external diameter (high – 1, low – 0) ; x4: firing pin diameter (high – 1, low –0) ; x5: spring straightness (high – 2, medium – 1, low – 0) ; y1: circuit breaker disrepair (satisfied – 1, unsatisfied –

0) ; y2: circuit breaker reusability (satisfied – 1, unsatisfied – 0) ; y3: spring core mounting (satisfied – 1, unsatisfied – 0) ; y4: firing pin bobbin mounting (satisfied – 1, unsatisfied –; y5: normal mode release (satisfied – 1, unsatisfied – 0) ; y6: firing pin initial position return (satisfied – 1, unsatisfied – 0). In this definition of the problem the xi are the action parameters whereas the yi are the evaluation ones. The system behavior was modeled by Design of Experiments and it is shown in Table 1. The objectives that have been established to build the DoE are:

- the satisfaction of at least one evaluation parameter in each experiment;
- each of the action parameters has at least one time each of its possible values;
- to minimize the number of experiments.

Even if the assumption is not totally consistent, the action parameters have been considered independent in the limits of their defined domains.

Table 1. DoE for the Circuit Breaker.

	x1	x2	x3	x4	x5	y1	y2	y3	y4	y5	y6
e1	1	1	0	0	1	1	0	1	1	1	1
e2	0	1	1	1	1	0	1	0	0	1	1
e3	1	0	1	0	0	1	0	1	0	0	0
e4	1	1	0	0	0	1	1	1	1	0	0
e5	1	0	1	0	1	1	0	1	0	1	1
e6	0	1	0	1	2	0	1	0	1	1	1
e7	1	0	1	1	0	1	0	1	0	0	0
e8	1	0	0	0	1	1	0	0	1	1	1
e9	0	1	0	0	2	0	1	0	1	1	1

First evidence is that no solution can be found in the defined DoE, as no experiment enables the satisfaction of all the evaluation parameters. This problem can be recognised as an inventive one, or an over-constrained one.

4. Resolution by means of over-constrained CSP

4.1 Application of the resolution mechanisms

One can consider each experiment of the previously defined DoE as a constraint, for example:

$$C_1: [1, 1, 0, 0, 1] \qquad [1, 0, 1, 1, 1, 1] \quad (1)$$

This leads the definition of nine constraints. Then the search for a solution is defined by an optimization function (Barták, 1999), defined in Equation (2).

$$\text{Max} \quad y_i \ \text{Optimal Solution} = [1, 1, 1, 1, 1, 1] \ (2)$$

The solution to Equation (2) cannot be found in the initial Specific Problem Space, it is thus necessary to refer to methods for over-constrained problems. One of the well-known methods is the hierarchy of constraints (Borning *et al.*, 1992). It means that the satisfaction of the evaluation parameters will be relaxed according to a defined hierarchy of importance. For example, one can define that the satisfaction of the parameters y_1, y_5 and y_6 are required, the satisfaction of the parameters y_3 and y_4 are strong constraints and that the satisfaction of y_2 is a weak constraint. Then the solution will be searched by satisfying first the required constraints, then the strong ones and at least, if possible the weak ones.

The experiments e_1, e_5 and e_8 satisfy the required constraints, the experiment e_1 satisfies also the strong constraints, but no solution can be found to satisfy all the constraints. Then, according to this algorithm, and to this hierarchy, the solution is the experiment e_1 (see algorithm on Figure 3).

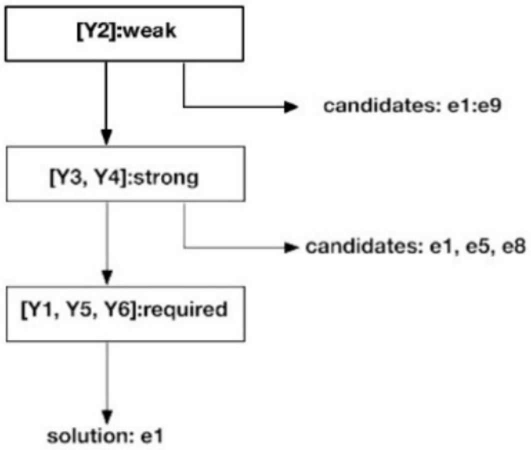

Figure 3. Over-Constrained Algorithm Resolution.

4.2 Analysis of the resolution impact on the solution space

The comparison of initial domain and domain of solution leads to the following conclusions:

- The set of parameters remains the same.
- The considered constraints are different, as the constraint y2=1 is not considered anymore.

The intensification of this mechanism leads to a space defined by the initial set of parameters without any constraints. This means that solving principles of constraint hierarchies – or Partial Constraint Satisfaction Problems (PCSP) as presented in (Freuder and Wallace, 1992) – start from initial problem defined by the specific problem space 1 (SPS1) and extend this space by relaxing certain constraints and variables in order to define a new specific problem space SPS2. This space is larger than SPS1 but always covered by respective Problem Space characterized by the set of variables describing the initial problem (see Figure 4).

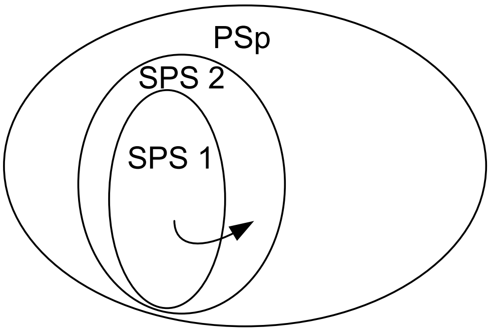

Figure 4. Model Change Mechanism of Optimization Methods.

But this solution can easily be recognized as a compromise and from an ideal point of view, i.e. if all the constraints are considered as required ones, the experiment C1 could not be recognized as a solution. And then other approaches have to be considered to find a solution.

5. Resolution by means of dialectical approach

To solve an inventive problem with TRIZ-based methods, it is first necessary to formulate the problem in an adequate form, i.e. to identify the contradictions. Then, the application of resolution mechanisms could be applied.

5.1 1 Identification of contradictions

In classical TRIZ approach (Altshuller, 1988), there exist different kinds of contradictions (administrative, technical and physical ones). Only the technical and physical contradictions are helpful as they propose the formulation of the problem enabling the application of resolution mechanisms. In (Khomenko et al., 2007) a system of contradiction has been proposed to clarify the role of each element of the contradiction and also to clarify the link between technical and physical contradictions. In (Dubois et al., 2009b) a generalization of this concept of system of contradiction is defined as Generalized System of Contradiction and is presented on Figure 5.

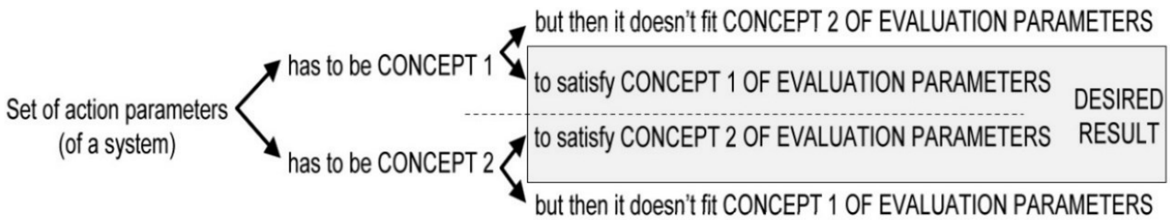

Figure 5. Generalized System of Contradictions.

The analysis of Table 1 enables the identification of several Generalized Systems of Contradictions; one of these GSC is presented on Figure 6.

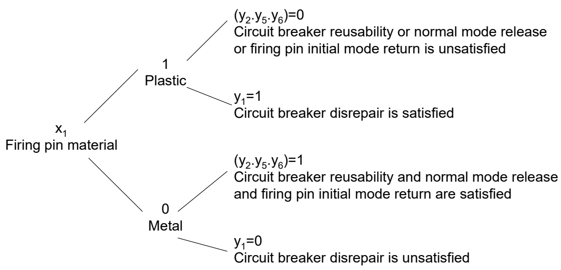

Figure 6. Generalized System of Contradictions for the Example.

The elicited contradiction can be reformulated this way: the firing pin material has to be plastic in order disable the disrepair of the circuit breaker; but the firing pin diameter has to be metallic in order to satisfy simultaneously the reusability of the circuit breaker, the normal mode release and the return in initial position of the firing pin.

5.2 Application of the resolution mechanisms

The GSC identified on Figure 6 tackles the problem linked with the firing pin diameter which has to be high and small in the same time. One of the well- known TRIZ mechanisms to solve problems is the separation of contradictory properties in space. Could the contradictory properties be separated in space? Actually the firing pin has to be metallic only from the front of the fixed core, where it begins to deform. And this fixed core is a metallic part. Then a new system of contradictions could be formulated: the fixed core has to become the firing pin as it is a metallic part, but the fixed core cannot be the firing pin as it is fixed. This contradiction can be solved easily through the application of another TRIZ resolution mechanism, the segmentation. One part of the fixed core has to become mobile. The inherent concept of solution is presented on Figure 7. On this figure one can consider that a part of the fixed core became mobile in order to reinforce the firing pin where it is thinner and thus enabling the firing pin to be plastic and metallic in the same time. Another way to present this concept is the resolution of the contradiction about the thickness of the firing pin, which has to be thin to enable its positioning and thick to resist deformation.

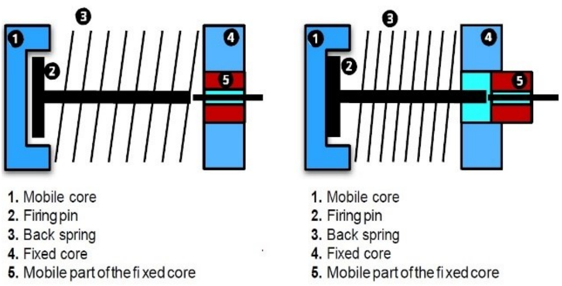

Figure 7. Concept of Solution for the Formulated Problem.

5.3 Analysis of the resolution impact on the solution space

If comparing the final concept of solution with initial model of problem, one can recognized that one parameter has been changed and a new one has been introduced. The parameter x4, firing pin diameter has been splitted into two: the diameter of the upper part of the firing pin and the diameter of the low part of the firing pin. The parameter x6, fixed core segmentation has been introduced. Thus the new solution corresponds to a new set of constraints which enables a new line in the initial DoE, as presented in Table 2.

Table 2. Representation of the Concept of Solution.

x1	x2	x3	x4a	x4b	x5	x6	y1	y2	y3	y4	y5	y6
1	1	0	1	0	2	1	1	1	1	1	1	1

If analyzing the kind of transformation achieved by these resolution mechanisms and the impact on the browsed solution space, one can consider that a new specific problem space is built, with new parameters and new constraints. And for this new SPS, a new Problems Space is defined, as illustrated on Figure 8.

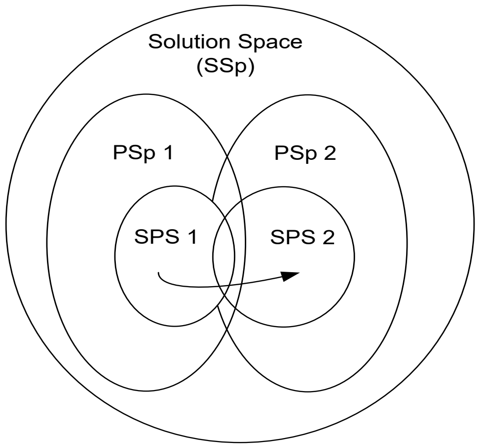

Figure 8. Model change mechanism of inventive methods.

6. Conclusion

In this article the way different kind of spaces are defined by the resolution mechanisms from optimization methods (CSP ones) and inventive methods (TRIZ based ones) is illustrated. Two aspects, the nature of the browsed spaces and the way the model changes are realized, were shown.

The consideration of the complementary aspects of both families of solving principles is of great interest and it puts the emphasis on the necessity to define a unified model that permits to shift easily from an optimization approach to an inventive one.

Each inventive method involves one or more operators of model changes. At the first time, every operator of model change and its using should be described in more details. The mutual enrichment of optimization and inventive methods will support a precise description of the inventive principles involving proposition of algorithms. At the second time, the efficiency of operators should be measured in order to prove a progress in the problem resolution. Later the whole process of inventive problem solving could be described as a succession of single model changes.

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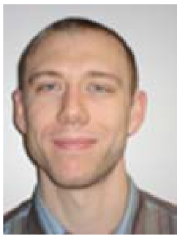

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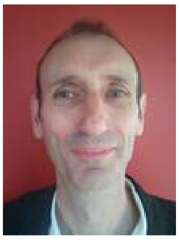

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