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FROM SIMULATION TO INVENTION, BEYOND THE PARETO-FRONTIER

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Abstract

In this article, the authors will present a general approach to build a continuum between optimization and dialectic based invention (problem solving) methods. The building of this continuum is mainly based on the consideration of the Pareto-frontier as a link between both approaches. The authors considered TRIZ contradiction models as the entry point of the inventive methods. As this Pareto-frontier is recognized as the limits of the optimal solutions for the optimization approaches, a link between this frontier and the contradiction model is described in this article. Then the general approach is described, and illustrated through the resolution of a supply chain problem.

Keywords: Design methods, Design theory, Innovation, Dialectic models

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1 INTRODUCTION

Industries are becoming more concerned with the necessity to propose novelty and with the importance of managing their inventive processes. The general tendency is to consider the innovative process as one particular process, such as a production process, a logistic one, or even processes different from traditional design process, in companies. This tendency even requires a need for norms, as defined by the European Project (CEN, 2014). Considering traditional design approaches separately from inventive (or innovative) ones is also due to the fact that both approaches imply different problem solving methods. In the work of Rosenman and Gero (1993), three different design approaches are defined based on the browsed problem space when searching for a solution. A routine design proceeds within a totally defined state space, an innovative design extends this space by enlarging the domain of values of existing design variables, and a creative design extends the state space by adding new dimensions or totally re-defining the state space. In this article, the authors distinguish optimization problems for situations when a solution exists in the research space and when it is possible to find this solution with at least one optimization method; i.e., it can be solved by optimization methods. The nature of the optimization or inventive problem is not known a priori. Therefore, it is necessary to choose a method to tackle new problems. Two main solutions have been developed. The first solution is to develop specific tools and methods in order to enlarge the domain space based on optimization approaches, mainly based on the use of genetic algorithms (Cagan et al., 1997, Gero and Kazakov, 2000) or by identifying specific mechanisms to create new dimensions (Cagan and Agogino, 1991, Zavbi and Rihtarsic, 2010). Another solution, which is the one considered by the authors of this paper, is to build a continuum between the two approaches by considering optimization and inventive methods as complementary methods, thus defining relations and interfaces between them.

For many years, TRIZ-based methods (Altshuller, 1988) have been used to consider and solve inventive problems. TRIZ is a theory for inventive problem resolution based on a dialectical representation of problems. Among the main approaches of TRIZ for problem resolution is to use contradictions as a way to formulate problems (Dubois et al., 2009) and analyse this contradiction in order to solve the problem. The roles of the contradiction model in this approach are to identify the limits of the system as it is first considered and to enable the solver to overcome these limits. Thus, the contradiction model could be recognized as the starting point for inventive processes, and if building a continuum, a contradiction has to be the output of the optimization process. In the work of Burgard et al. (2011), such a continuum has been proposed based on the use of sequential experimentation.

In this article, the authors will first present the TRIZ model of contradictions, its benefits for problem resolution and the requirements for good contradiction formulation. Second, the benefits of optimization approaches and how they could help in building contradictions through the definition of the Pareto frontier will be introduced. Third, a general methodology to build this continuum will be described. Then, the authors will conclude and propose future works

2 TRIZ CONTRADICTIONS, A MEANS TO OVERCOME SYSTEM LIMITATIONS

TRIZ is a theory to develop methods of problem resolution in the design of technical systems. It is centred on formulating and solving problems. In TRIZ, several models of the problems' formulation are proposed. Each of these models corresponds to a different level of abstraction. Some of the models are used to enable resolution by the use of shaped databases of generic solutions; some of the models are only intermediary steps in the problem formulation process. The objective of the different models is to enable a progressive understanding of the limits of the considered system and how it is possible to act on it in order to make it evolve. Among these different models, there are two models of contradictions. The first model of contradiction, called "technical contradiction", is the understanding of two requirements on the system that cannot both be satisfied and thus are in conflict. The satisfaction of the two requirements, or the two parameters, could be recognized as being two states of the same system. Khomenko, in (Khomenko et al., 2009), proposed a more precise definition of the problem, describing these parameters as evaluation parameters. Evaluation parameters are used to check if the problem is solved or not, but they are not used as parameters that can be directly acted on in order to solve the problem.

A technical contradiction exists when a solution is known to reach the satisfaction of evaluation parameter 1 but the application of this solution disables the satisfaction of evaluation parameter 2.
For example, a technical contradiction exists in belt-pinion systems when higher rigidity of the belt enables a better transmission but then disables the ability of the belt to turn around the pinion.
A second model of contradiction is proposed in TRIZ for problem representation and is called the "physical contradiction". This model focuses the problem on one single element of the system, which is defined as the core of the problem. According to TRIZ, a problem can always be formulated as a physical contradiction. Such a contradiction is defined as the requirement for one element to be in two contradictory states. A physical contradiction exists when one element of a system has to be in two contradictory states. For example, a physical contradiction exists in belt-pinion systems as the belt has to be both rigid to transmit energy efficiently and flexible to turn around the pinions.
In the work of Khomenko et al. (2007), a relationship between the models of contradiction has been clarified and a system of contradictions has been presented, as illustrated in Figure 1. This system of contradictions well clarifies the role of each contradiction. As the physical contradiction indicates a mean to act on the system, it is formulated based on a parameter, which is classified as an action parameter (Dubois et al., 2009); the technical contradiction identifies two contradictory parameters that have to be satisfied, in other words, two parameters of the specs, thus called the evaluation parameters. The value of the action parameter has to be Value 1 (thus defining the first state of the system) in order to satisfy the first evaluation parameter, but the value of this action parameter has to be Value 2 (defining the second state of the system) to satisfy the second evaluation parameter. The desired result is, of course, to satisfy the objective with the two evaluation parameters.

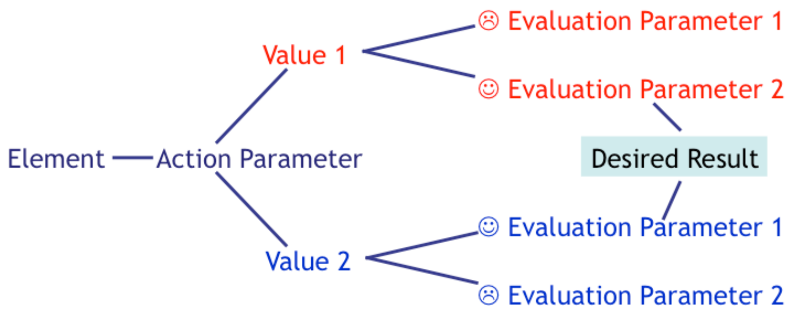

Figure 1. System of contradictions

This system of contradictions is the representation of two known states or classes of states and are denoted S1 and S2, where the solutions of the first state S1 satisfies the objectives for the first evaluation parameter EP1 only and the second state S2 satisfies the objectives for the second evaluation parameter EP2 only. Thus, the conditions for the existence of such a system of contradictions are as follows:

- At least two evaluation parameters for describing the objectives,
- A given desired result (an objective defined with two sets of acceptable values for EP1 and EP2)
- At least two known states, S1 and S2, such that when the EP1 value satisfies the objectives, the EP2 value does not and vice versa

This definition implies that no solution satisfying both objectives is known and that there is no dominant relationship between the two states S1 and S2 of the system. Indeed, the values of the first state S1 are better for EP1 and worse for EP2 compared to those of S2, whereas the values of the second state S2 are better for EP2 and worse for EP1 compared to those of S1. Consider the evaluation space as a two-dimensional space defined by the two evaluation parameters EP1 and EP2. Define the objective as (EP1<V1), (EP2<V2), and $Z(EPi)_{i \in (1,2)}$, the zones of the space where EPi is satisfied. Then, any pair of points A and B, where $A \in Z(EP1)$ and $B \in Z(EP2)$, will define a technical contradiction (cf. Figure 2).

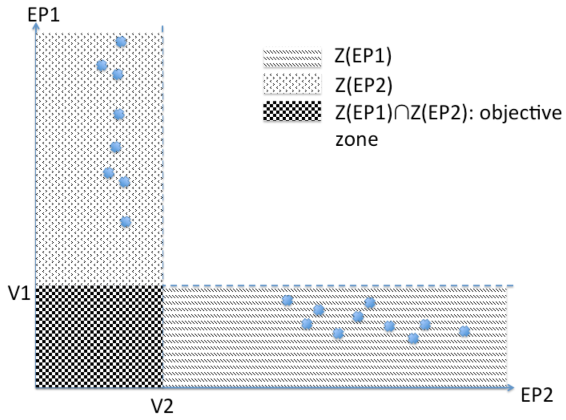

Figure 2. Evaluation space and technical contradiction

Therefore, in order to define a technical contradiction, it is necessary and sufficient to identify such a pair of points. Then, the inherent physical contradiction will be defined by considering the two states of the system relative to these points and identifying a third parameter (apart from the two evaluation parameters) that changes its value between these two states.

3 THE PARETO FRONTIER, THE LIMITS OF OPTIMIZATION

In the work of Burgard et al. (2011), a method to extract technical contradictions based on the use of sequential experimentations was presented. The approach was based on the use of the following elements:

- Principal component analysis and factor analysis, which belong to the family of multivariate analysis (Rencher and Christensen, 2012). Multivariate analysis aims to reduce the data into a smaller number of components (few underlying factors). The main idea of principal component analysis is to choose the axes maximizing the variance of the values representing the system (Amato et al., 2010). Principal component analysis is commonly used as one step in a series of analyses when there are too many predictors relative to the number of observations. By analysing the data covariance structure, the data dimension can be greatly reduced.
- Factor analysis (Harman, 1976) is very similar to principal component analysis but is designed for a different purpose. The purpose of factor analysis is to reduce the dimensionality of a problem by exploring the correlation among its variables (Machado et al., 1999). Factor analysis (Mooi and Sarstedt, 2011) identifies unobserved variables that explain patterns of correlations within a set of observed variables. It is often used to identify a small number of factors that explain most of the variance embedded in a larger number of variables. Factor analysis is used to understand what constructs underlie the data. The two analyses, factor analysis and principal component analysis, are often performed on the same data. For example, one can conduct a principal components analysis to determine the number of factors to extract in a factor analytic study.
- Factorial designs allow for the simultaneous study of the effects that several factors may have on a process. When performing an experiment, varying the levels of the factors simultaneously rather than one at a time is efficient in terms of time and cost and also allows for the study of interactions between the factors. Interactions are the driving force in many processes. Without the use of factorial experiments, important interactions may remain undetected. Design of experiments (Montgomery, 2004) is an organized method for determining the relationship between factors (process variables Xi) affecting a process and the output of that process (response variables Yi). One of the objectives of DoE is to obtain the most robust model with the minimum number of experiments, which can be reached by the use of Taguchi's methods (Roy, 2001). The factorial design method estimates both the main effect and the interaction effects. The main effect refers to the effect caused by that changed factor, while the interaction effect refers to when the effect of one factor is dependent on the value of another factor.
- In a factorial experiment, the responses are measured at all combinations of the factor levels, which may result in a prohibitive number of runs. For example, a two-level full factorial design with six factors requires 64 runs, and a design with nine factors requires 512 runs. To minimize

time and cost, one can use factorial designs that exclude some of the factor level combinations. Factorial designs in which one or more level combinations are excluded are called fractional factorial designs. Fractional factorial designs are useful in factor screening as they reduce the number of runs to a manageable size. The runs that are performed are a selected subset or fraction of the full factorial design. The fractional factorial design methodology originates from the planning and performance of experiments and is a subtype of factorial designs (Montgomery, 2004).

- Response surface methods (Box and Draper, 1986) are used to examine the relationship between a response and a set of quantitative experimental variables or factors. Response surface methods (Lizotte et al., 2012) belong to a class of global optimization algorithms that retain all accumulated data about the objective function and use all of it to determine where next to evaluate the objective. They are particularly appropriate for problems where the objective is multimodal and expensive to evaluate, which is common in engineering applications; response surface methods are thus extremely important in the development and analysis of complex, real-world, deployed systems. These methods are often employed after identifying "vital few" controllable factors when finding factor settings that optimize the response. Designs of this type are usually chosen when the curvature in the response surface is suspected. A response surface design helps to model the "Pareto frontier" of a set of parameters.

When considering the Pareto frontier related to previously introduced system of contradiction, as illustrated in Figure 3, the points that are above the Pareto frontier are points that are at least dominated by one point, which means that at least one point has better values for the two evaluation parameters. The points that are on the Pareto frontier are points that are dominated by no other reachable points. It means that if a point is better on one of the two evaluation parameters, this second point will be worse for the second evaluation parameter. The desired result is any point that will satisfy both parameters, so any solution will be in the zone Z(EP1)∩Z(EP2). Thus, any solution will be part of a new Pareto frontier, and it will dominate some points of the initial Pareto-frontier but not necessarily all of the points of the initial Pareto frontier.

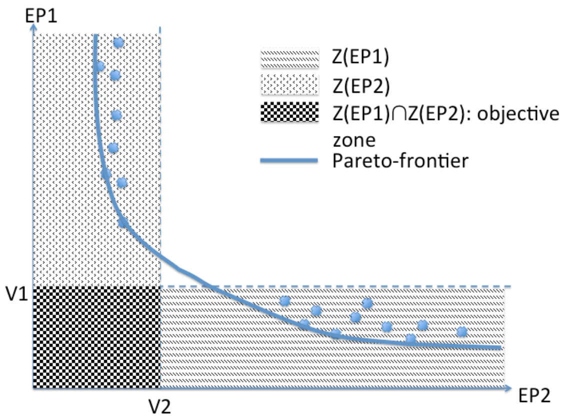

Figure 3. The Pareto Frontier

Based on these definitions, one can recognize that considering two points of the Pareto frontier, one in Z(EP1) and the second in Z(EP2) directly enables the formulation of the previous technical contradiction.

4 GENERAL APPROACH TO BUILD A CONTINUUM

4.1 Multi-dimensional problems

The discussion in this article up to this point has been presented from a two-dimensional objectives problem point of view. There are two reasons for this: it is simpler to understand and to illustrate for a pedagogical perspective, but moreover, the contradiction model in TRIZ is built with this limitation. The TRIZ technical contradiction model is only built by considering two evaluation parameters. This limitation has been recognized as a limit of the TRIZ model, as real problems are generally multi-dimensional problems. In the work of Cavallucci et al. (2010), a model of the technical contradiction for multi-dimensional problems is proposed by grouping together parameters that are positively correlated. In the work of Dubois et al. (2009), a generalized model of the system of contradictions is defined to tackle multi-dimensional problems regardless of the correlations between the parameters. In this generalized system of contradictions, the action parameter and evaluation parameters are replaced by sets of parameters, as illustrated in Figure 4.

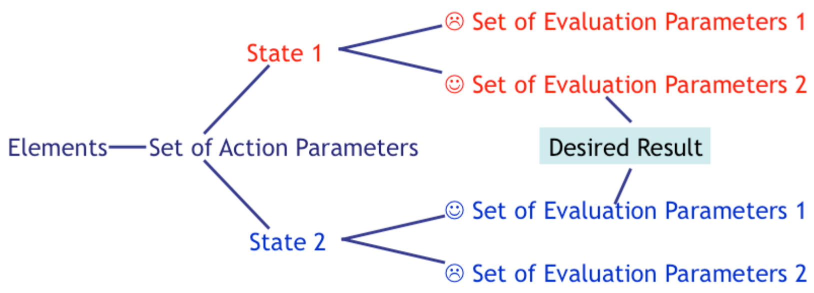

Figure 4. Generalized System of Contradictions

This new definition of the generalized system of contradictions thus defines a generalized physical contradiction (GPC) and also generalized technical contradiction (GTC). The link between this new GTC and the Pareto frontier is a research question. Is it possible to build a GTC by considering points of the Pareto frontier as it is possible for two-dimensional problems? As the topic of this article is not to answer this question, which, however, remains interesting, the developments of the article will remain focused on two-dimensional problems.

4.2 General description

Based on the previously defined link between the TRIZ contradiction model and the Pareto frontier, Lin et al. (2013) proposed an algorithm to automatically extract generalized technical contradictions from any design of experiment. This enabled the authors to propose a general approach that makes a continuum between the optimization approaches, the one described in part 3, and the inventive approaches, based on TRIZ, by the formulation and resolution of a system of contradictions. This general approach is presented in Figure 5.

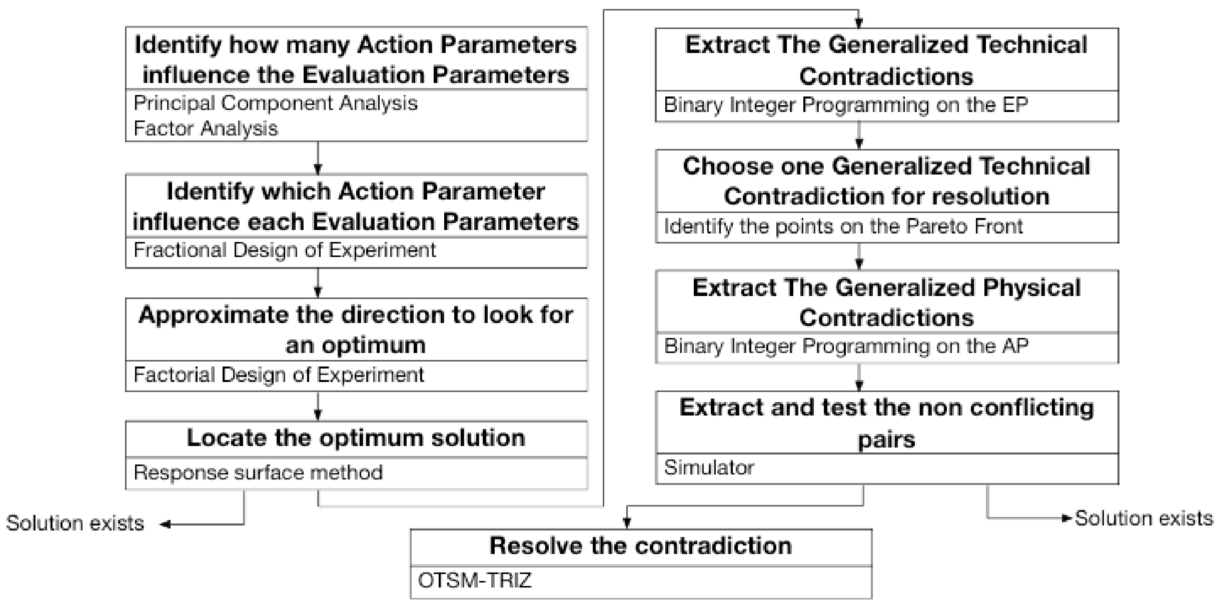

Figure 5. General approach

The objective of the general approach is first to search for optimal solutions using traditional optimization methods by analysing the minimal set of parameters to consider for problem modelling and thus browsing the reachable solutions through the factorial design of experiments. The response surface method helps determine whether a satisfactory solution exists or not. If no solution is found, then the Pareto frontier will be built, and the algorithm presented in the work of Lin et al. (2013) will extract the generalized technical contradictions. Previously (Lin et al., 2013, Lin et al., 2014), it has been shown that the number of GTC that can be found is huge, and thus, the question of choice of the GTC to consider is crucial. The authors propose considering in prior the GTC that are built with points that are on the Pareto frontier. For example, when considering our two-dimensional problem, many technical contradictions could be built considering many points of the zones Z(EP1) and Z(EP2), but if considering a point of Z(EP1), which is not on the Pareto frontier, it is possible to find a second point in this zone that is on the Pareto-frontier and thus dominates the first point. Therefore, the authors consider that the more robust formulation of problems is the one built with two points that are not dominated, i.e., points on the Pareto frontier. When a technical contradiction is chosen and identified to build the system of contradictions, the physical contradiction related to the considered technical contradiction has to be elicited. A second algorithm has been defined and is presented in the work of Lin et al. (2014). One of the results of the application of this algorithm is that potential solution concepts will be proposed, which are combinations of action parameters instantiation, that were not considered throughout the application of that optimization methods and could be tested to check if they are real solutions or not, as will be illustrated with the design of experiments in the next part. A second interesting result of the application of this algorithm is the elicitation of "contextual" classical TRIZ physical contradictions, i.e., GPC were found with only one conflicting parameter. This means that they are equivalent to classical TRIZ contradiction but, under some conditions, are defined by fixed values for the others action parameters. Therefore, if no solution is found by the test of non-conflicting pairs, then a classical TRIZ-method, for example, ARIZ (Altshuller, 1999), could be applied to solve the contextual physical contradiction. Notice that TRIZ methods do not precisely define the domain where a contradiction holds.

4.3 Illustration

In this section, the authors illustrate how to use a design of experiments result in order to identify a contradiction and how the TRIZ solving principle could be used on this contradiction. The proposed case is a case that has been built out of an industrial supply chain problem, but only an excerpt of the problem is presented in this article. The problem is the following one: let us consider an inventory of products that has interaction with a supplier (which has a delay of 8 time units to deliver the product) and a customer (which has exclusive demands of one unit, the average period between two demands being one, but with no regular period between two demands). The process has been modelled on Witness[1], as illustrated in Figure 6. The inventory is controlled by a Kanban system, based on a type of reorder point system. The value of the reorder point is written on the Kanban card. The order quantity is also written on the Kanban card. When the inventory level is lower than the reorder point, the Kanban card is sent to the supplier. Goods are delivered with the Kanban card and left together on the inventory shelf until the inventory level crosses under the reorder point[2].

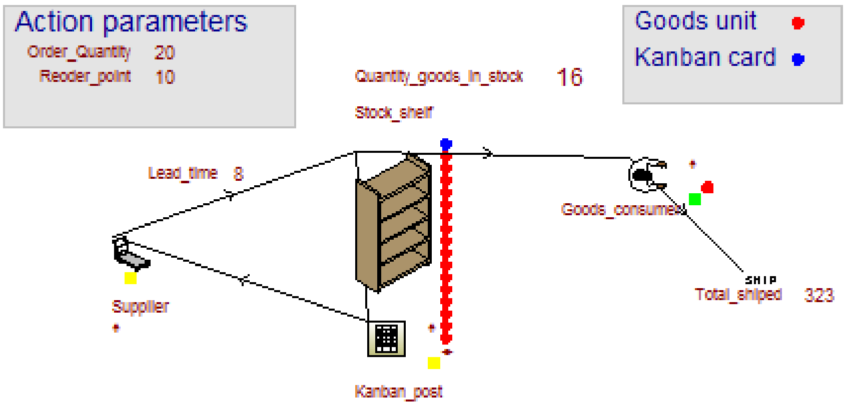

Figure 6. Witness model of the process

[1] http://www.lanner.com/fr/witness/
[2] A system working on this principle is described in https://www.youtube.com/watch?v=tum1lLwy6gE

For this problem, two evaluation parameters have been defined:

- The service breakdown (1-customer level service), which has to be as low as possible, ideally 0
- The average stock, which also has to be as low as possible, ideally 0

Acting on the system due to the perimeter of the system has been defined as follows: there is no possible action on the supplier and no possible action on the customer. Then, the following points are noted:

- The level of the reorder point, which is the level of inventory defining when to order the product, can vary between 1 and 20.
- The lot size (reorder quantity) can vary between 1 and 20.
- The supplier scrap rate, percentage of non-certified raw material. For experiments, four levels have been considered: 0, 1, 6 and 12%.

With these data, 1600 experiments were simulated in Witness, and they defined the reachable solutions (presented in Figure 7).

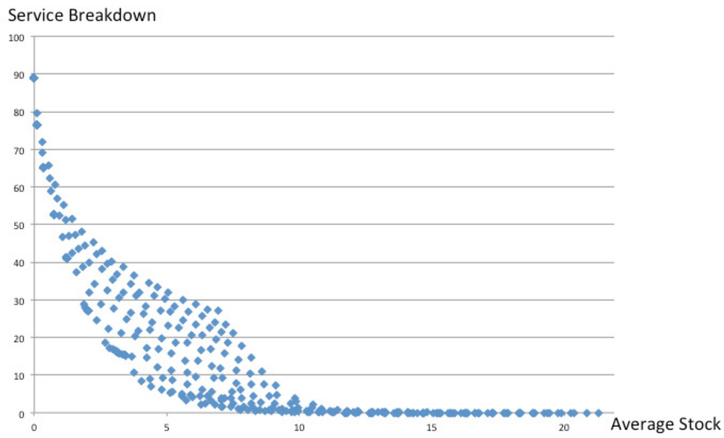

Figure 7. Pareto frontier of the initial simulation

What if the company wants to find a solution better than those proposed by optimization? To tackle such situation, it has been proposed that the contradiction inherent to the model should be formulated and the TRIZ resolution method should be applied to propose a concept solution. To formulate the system of contradictions, the technical contradiction that has been considered is the one considering the two extreme points of the Pareto frontier, i.e., the ones taking separately the best values of each evaluation parameters. The system of contradictions that has been extracted out of the experiments is the one presented in Figure 8.

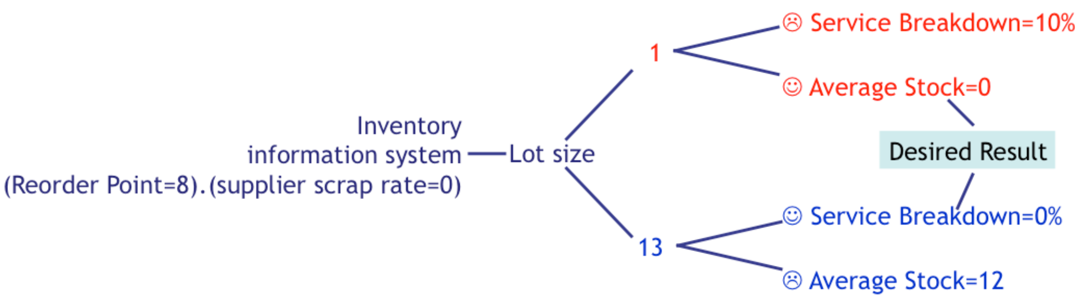

Figure 8. Contradiction related to the initial Kanban system

This contradiction stated that a classical TRIZ physical contradiction exists if the action parameters reorder point and the supplier scrap rate are, respectively, fixed at 8 units and 0%. As a result, the lot size has to be 1 to achieve an average stock of 0 units, but it has to be 13 in order to satisfy a service breakdown of 0%. The first steps of ARIZ-85C have been applied to this system of contradictions, and an ideal final result has been formulated as: "*It is necessary to keep the property of <Lot size=13> to achieve <Service Breakdown=0> in <The Stock> when <Customer is demanding unit> but avoiding <The average Stock=12>"*. One of the considered TRIZ solving principles is separation on the systemic level, which means that it is necessary to have a lot size of 1 at the Kanban level, but it is necessary to have a lot size of 13 at the stock level. The proposed concept solution is to keep a lot size of 1 on the Kanban but to increase the number of Kanbans so that several orders can be sent to the supplier and several deliveries performed during the lead time. This new concept solution has been designed, simulated and optimized. As expected, this solution provides a better result, as illustrated in Figure 9. Some points of the second concept are worse than the Pareto points of the initial system. This result suggests that both systems have to be properly configured before comparison. The comparison of Pareto sets is a good comparison.

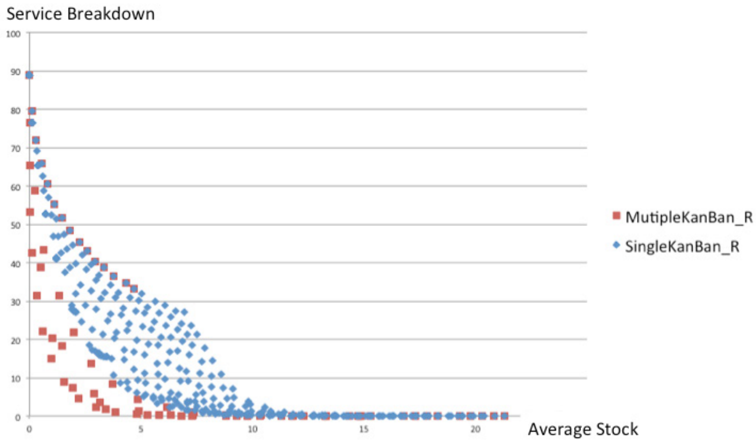

Figure 9. Comparison of the initial system and the implemented proposed concept solution.

5 DISCUSSION AND CONCLUSIONS

The objectives of this article were to present a possible continuum between the optimization and invention approaches, to introduce the link between the Pareto frontier and the TRIZ contradiction model, and to illustrate how this continuum could be used. The given elements and the example illustrated in this article focused on two-dimensional problems. However, there is the issue of using this approach even if the "true" Pareto is not known but only the Pareto obtained by an optimization heuristic or by a large random sample is known; indeed, the Pareto may only be a perceived Pareto and not the true Pareto. Actually, applying the method on the perceived Pareto remains technically possible. Moreover, as illustrated by our example in two dimensions, the perceived Pareto may lead to the same contradictions than the "true" Pareto. Thus, in these cases, which are numerous, the proposed method may also be used for overcoming the Pareto frontier. However, in this case, we are not sure that the new solution really outperforms the true Pareto as it is unknown; nevertheless, the proposed method remains an alternative to improve the solutions obtained by available optimization means.
The authors will now focus their research and propose their results for multi-dimensional (more than two evaluation parameters) problems. One of the interesting elements that the authors have noted and that is described in (Lin et al., 2014) is that even for multi-dimensional problems, it is possible to find physical contradictions that are true under conditions based on one action parameter so that the classical TRIZ resolution methods can be applied. This emphasizes the fact that the problems could be tackled through an optimization approach and that, by eliciting the more relevant parameters to consider and by formulating a system of contradictions, they could be solved through inventive methods when no solution is found by the optimization.

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