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## Abstract

During the development of a product, several steps and iterations are necessary for meeting specifications and optimizing performance criteria. This article address machining problem, that are faced to increasing constraints and performance criteria. A multi-objective optimization approach is a common approach for determining a solution that meets all these constraints. The Design of Experiments (DoE) is used for modeling and understanding of the process with a minimum of experiences. When the multi-objective optimization approach demonstrates that, for a given design, no single solution exists that optimizes all objectives, the best partial solutions belong to the set of Pareto optimal solutions. In this study, a global approach for determining the optimal solution from a DoE and overcoming this optimum by the complementary use of TRIZ-based methods is proposed. In the proposed approach, optimization and inventive methods are linked. The proposed approach aims to exploit the data from multi-objective optimization and the concept of Pareto optimums to identify ways of modifying a system to respond to more objectives. A new definition of the system of generalized contradictions, which is more complete than previous definitions, is used in the proposed method. This proposal is an illustration of a global research project that aims at linking optimization and inventive methods. An application of this method is proposed for the design of a new cutting tool for the machining of composite materials. Furthermore, the limitations of the method, which proves to be satisfactory in comparison with previously proposed methods, are discussed.

*Keywords:* Optimization and Inventive Design, Generalized System of Contradictions, TRIZ, Machining of Composite Materials.

# 1. Introduction

The new advances in technology and aeronautic industry increase the requirement level of the quality and productivity of the machining process. The specifications of products have increased in terms of quality, productivity, cost, and also to propose eco-friendly products. In this article, authors will focus on the machining of composite materials used in the aeronautical industry. Today, in order to respond to this problem, the multi-criteria optimization of cutting parameters remains the most efficient way to achieve the objectives initially desired during the manufacture of machined parts. But optimization approaches are ways to find the most relevant solution in a solution search space defined a priori by the considered parameters, and the article will propose a way to overcome these limitations.

Several studies have been developed in order to choose the optimal cutting parameters during the machining of composite materials. (Ahmad, 2009) concluded that cutting conditions are an important factor in determining the reliability of the machining of composite materials. In (Durão et al., 2010) a comparative study on different drill point geometries and feed rate, for composite laminates drilling, is presented. For this goal, thrust force monitoring during drilling, hole wall roughness measurement and delamination extension assessment after drilling were accomplished. Several studies highlight the fact that choice of cutting conditions could not only affect surface integrity and productivity, but also cause severe damage to the workpiece. The common defects encountered during composite machining are delamination, fiber pullout, and resin overheat. (J. Paulo Davim & Reis, 2005) proposes a study that evaluates the cutting parameters under the surface roughness, and damage in milling laminate plates of carbon fiber-reinforced plastics (CFRPs). The objective was to establish a model using multiple regression analysis between cutting speed and feed rate with the surface roughness and damage in a CFRP composite material. (Marques, Durão, Magalhães, Silva, & Tavares, 2009) proposes a study of delamination in Drilling of carbon fiber/epoxy laminates. In (Khashaba, 2004), the influence of drilling and material variables on thrust force, torque and delamination of CFRP composites are presented.

To assess the efficiency of the machining operations, several methods such as multi-criteria optimization and experimental modeling was studied. (Chibane, Morandea, Serra, Bouchou, & Leroy, 2013; Chibane, Serra, & Leroy, 2017) propose new technique to help the operator to select the optimum cutting conditions such as cutting speed and feed rate (chip thickness) in order to avoid damage to the carbon/epoxy composite material T800S/M21 and increase machining productivity using multiple analysis regression MSR methodology. In another study (Morandea et al., 2013), the same authors provide a comparative study in terms of cutting force, workpiece temperature, and tool wear for different configurations of the tool. (Serra, Chibane, & Duchosal, 2018) presents a multi-objective optimization study of cutting parameters during turning process of AISI 52100 hardened steel, using genetic algorithm (GA) optimization. Finally, in (J. Paulo Davim & Mata, 2004; J. P. Davim, Mata, Gaitonde, & Karnik, 2010), the machinability of composite material polyetheretherketone and fiber-reinforced plastics using response surface models and analysis of variance (ANOVA) are studied.

The previously described studies have been performed with multi-criteria optimization methods. The results obtained are not satisfactory, as they do not fit all the defined specifications. Thus, the

authors aimed to design with minimal change a new system that could meet all the specifications. ARIZ 85C, which is a TRIZ method, was proposed by G. Altshuller (Altshuller, 1985) to facilitate this model change. However, to use ARIZ, a so-called “TRIZ contradiction” as input is required. Several attempts to link the partial results of optimization methods to the input of ARIZ or another TRIZ method using the concept of contradiction have been proposed; however, for all the attempts, the problem of choosing among the numerous contradictions persists. The findings described in this paper reveal that this problem could be addressed by analyzing the achievement of the objectives (specifications) with the concept of Pareto optimization and expressing technical contradictions by systematically including all objectives. The result is an inventive design method linking optimization methods and TRIZ-based inventive design methods.

The organization of the paper is as follows. Section 2 presents a review of previous studies, whose findings will be used to develop the method proposed in this paper. It also highlights the limitations of these studies and the practical problem of identifying contradictions in the case of non-trivial multi-objective optimization problems. Section 3 presents a proposal for defining the contradictions and linking multi-objective optimization and TRIZ-based inventive design methods. In section 4 the steps of the proposed method are illustrated using a case study. Section 5 discusses the results from the case study and concludes the paper.

## **2. Background**

The utilized optimization and invention methods are presented in this section. First, an overview of the design of experiments (DoE) will be given; then, the classical TRIZ model of the system of contradictions will be introduced, and its limits will be illustrated. To overcome these limitations, the generalized system of contradictions will be presented.

### **2.1 Design of Experiments**

The method presented in this article exploits the DoE in one of its steps. Here, we describe some of its foundations. DoE is a powerful data analysis tool that allows the understanding and study of different complex processes; the use of a DoE also makes it possible to reduce the number of experiments necessary for understanding the process. It is generally used to determine the effect of several inputs (action parameters) on desired outputs (evaluation parameters). There are several types of DoE depending on the desired results (complete factorial, reduced and composite DoE) (Montgomery, 2004). The central composite design (CCD) is an alternative to the complete factorial DoE; the advantage of this type of DoE is that it ensures the model of the nonlinear process. When analyzing a process using DoE, statistical methods such as response surface methodology RSM (Box & Draper, 2007) and linear regression methodology (LRM) (Cohen, Cohen, West, & Aiken, 2002) are used to model the output parameters as a mathematical equation, i.e. as a function of the input parameters. RSM uses a DoE sequence to obtain an optimal response. (Box & Hunter, 1957; Box & Wilson, 1951) suggests to use a second degree polynomial model. They recognize that this model is only an approximation, but they use it because such a model can be used to express linear or nonlinear processes in opposition to the LRM which is used only for a linear modeling.

## **2.2 Classical TRIZ Systems of Contradictions**

G. Altshuller analyzed thousands of patents to elicit the principles used in these discoveries and to understand how problems are solved. The result of this analysis is the formalization of problem models and their inherent solving principles (Madara, 2015). To invent a new system, Altshuller stated that problems have to be formulated as contradictions. He proposed two kinds of models of contradictions (Altshuller, 1988): the technical and the physical models. The first understanding of a problem relies on the impossibility to satisfy together two requirements of the specifications, the so-called Evaluation Parameters (EP). Then, the analysis of the root cause of this technical contradiction, i.e., why the specs cannot be both satisfied, highlights the physical contradiction, “when one element of the considered system has to be in two different states to satisfy each EP of the technical contradiction” (Altshuller, 1999). These two states of the element are thus two different values of a parameter of this element, the so-called Action Parameter (AP).

These models, defined by Altshuller for engineering problems, and that one can call “classical TRIZ” models of contradictions were extended to non-technical problems by N. Khomenko. Khomenko also linked the models of physical and technical contradictions, and stated that “many physical contradictions may be linked to a given pair of technical contradictions” (Khomenko, De Guio, Lelait, & Kaikov, 2007). Thus, this link between physical and technical models highlights a system of contradictions, which aims to explain how the physical contradiction is the root reason for the existence of the technical contradictions.

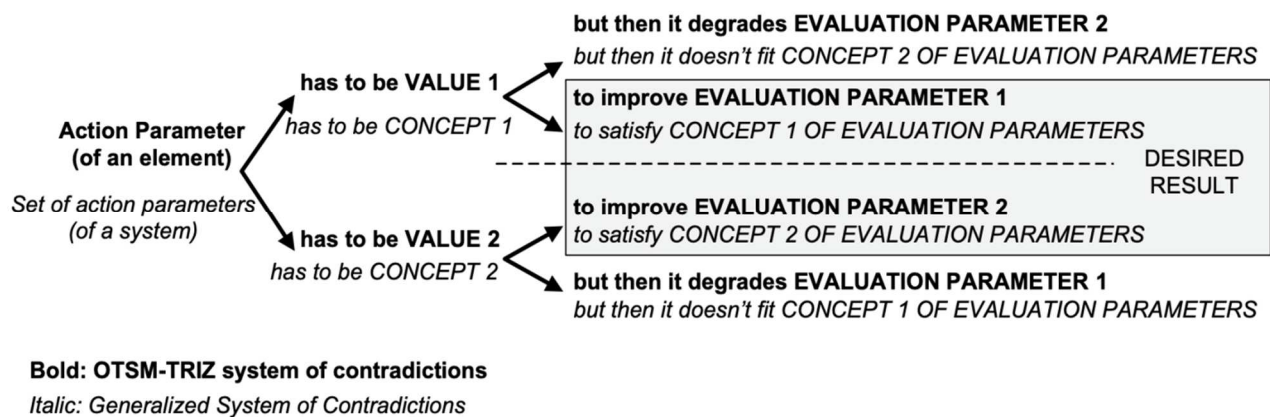
These models of contradictions point out one of the main hypotheses of TRIZ. It underlies that, having a problem means not being able to satisfy simultaneously several specs for a given system. Then if a problem occurs, a contradiction could be formulated. However, the classical TRIZ system of contradictions does not systematically fit this hypothesis, as demonstrated in (S. Dubois, Eltzer, & De Guio, 2009). The authors have given examples where all the specs of a situation cannot be satisfied by a known system, but for which no system of contradictions could be formulated. A classical TRIZ model of contradiction has been effective in solving problems and helping human solvers to think about new solutions. Nevertheless, this model considers at best a pair of evaluation parameters for the expression of technical contradictions and a single action parameter for the physical contradiction. This can lead to the expression of many contradictions and systems of contradictions. As these contradictions are too numerous to be all treated with TRIZ, the choice of the contradictions to be treated is left to the user and is a matter of expertise. Moreover, this type of contradiction analysis does not provide a holistic view of the conflicts as they do not include all the EPs simultaneously in the statement of the problem for defining the physical contradiction. A method for partially addressing these questions is provided in the next section.

## **2.3 Generalized System of Contradictions (GSC)**

To synthesize the contradictions of the classical TRIZ, (Cavallucci, Rousselot, & Zanni, 2008) proposed gathering the evaluation parameters that share the same physical contradiction. This model of a contradiction system does not allow for the expression of the causes of technical contradictions whose expression would combine several action parameters.

In (Cascini, Rissone, & Rotini, 2011), mono-variable optimization methods are used to search for contradictions. Furthermore, the authors propose looking for contradictions of the classical TRIZ among the solutions obtained by the mono-criteria optimization of each evaluation parameter. This approach proposes a criterion for the selection of solutions but does not integrate a multi-objective view of the solutions. Similar to previous studies, it does not deal with the expression of physical contradictions integrating several action parameters.

The concept of generalized contradiction initially proposed in (S. Dubois et al., 2009; Sébastien Dubois, Rasovska, & De Guio, 2009) is based on the automated search for contradictions from digital data. This research has highlighted multiple informal hypotheses related to the notion of contradiction in the classical TRIZ. The concept of generalized contradiction results from the extension of the OTSM-TRIZ concepts of technical and physical contradictions. When the problem involves more than two evaluation parameters, the Generalized Technical Contradiction (GTC) makes it possible to express conflicts of objectives between subsets of EPs comprising several evaluation parameters. In the same way, the Generalized Physical Contradiction (GPC) allows for the expression of conflicts of action parameters at the origin of a pair of Generalized Technical Contradictions by expressing it, if necessary, with several pairs (parameters and values) of action parameters. The combination of two Generalized Technical Contradictions (GTCs) and one GPC constitutes a Generalized System of Contradictions (GSC), as illustrated on figure 1.



**Figure 1. OTSM-TRIZ system of contradictions and Generalized System of Contradictions**

As these models have been created for numerical data processing, algorithms for the automated extraction of these concepts from data have been proposed. The algorithm for automatically extracting the complete set of GTCs from experiments is presented in (Lin, Rasovska, De Guio, & Dubois, 2013). The search for Generalized Physical Contradiction (GPC) is described with two binary integer programming problems in (Lin, Dubois, De Guio, & Rasovska, 2014) where two heuristics are proposed to solve them and provide the complete set of Generalized Physical Contradictions. The following conclusions can be drawn from the use of the algorithms: (1) The search of GTCs reveals that the number of GTCs is too important to enable a human to treat all of them. The necessity to provide a structure and rules that allows choosing among the GTCs has thus been highlighted; (2) in (Lin et al., 2014), a similar conclusion formulated related to the physical and generalized physical contradictions was formulated. It has been illustrated, with a case study, that for

one selected Generalized Technical Contradiction, more than 3.000 Generalized Physical Contradictions could be extracted; and (3) in (Sébastien Dubois, Lin, De Guio, & Rasovska, 2015), the authors pointed out that particular Generalized Physical Contradictions could be recognized. These GPCs could be considered classical-TRIZ physical contradictions under some conditions that are called the context. This context is a set of instantiated Action Parameters.

Please note that, in (Ben Moussa, De Guio, Dubois, Rasovska, & Benmoussa, 2019), an logistics case study was used to show that the ARIZ 85C problem solving method was easily adaptable to the use of GTCs and the Generalized Physical Contradictions under context mentioned above.

## **2.4 Pareto optimization**

In the field of multi-objective optimization, when no single solution exists that simultaneously optimizes each objective, the notion of goal conflicts is addressed using the concepts of dominance and Pareto optimality: “A solution is called non-dominated or Pareto optimal, if none of the objective functions can be improved in value without degrading some of the other objective values”.

The concept of Pareto optimums was first proposed to identify GTCs (Bach, De Guio, & Gartiser, 2017) in an example of logistics (Bach et al., 2017). Compared to the case presented in (Bach et al., 2017), our case study addresses product design, it is more complex, and only few data are available owing to the cost of one experiment. Thus, this work also proposes a method (1) to test this approach for obtaining GTCs with only few data resulting from an “economical” design of experiment and (2) to test, explore, and expand this approach in the area of product design. Moreover, the methodology proposed in section 3.1 below proposes an alternative definition of the GSC.

## **2.5 Synthesis**

The previous brief state of the art reveals that there is a theoretical link between the results of multi-criteria optimization and model transformation methods via the notion of generalized contradiction. To be easily operational in practice, the number of contradictions proposed by automatic contradiction identification algorithms should be reduced in a significant and relevant manner. In the following section, we present a method that utilizes the Pareto optimization to reduce the number of contradictions.

# **3. Linking optimization results and TRIZ-based inventive design inputs**

In this section, we first present the principles of our method for finding a few relevant contradictions and then present a design approach based on these principles dedicated to the type of problem described in the introduction.

## **3.1 Bridging optimization and model change methods**

Let us explain the method with the didactic example below.



Figure 2 represents the available experimental data, i.e., nine experiments denoted e1 to e9, which are characterized by the inputs  $x_i$  and outputs  $y_i$ . The  $y_i$  values that meet the specifications of the problem are highlighted. Figure 3 is obtained from Figure 2 by substituting the output values with the value “1” when the output meets the specifications and “0” otherwise.

The methods outlined in section 2 use all the data in Figure 3 to extract technical and associated physical contradictions. In this example, the number of technical contradictions exceeds 100, and there are several generalized physical contradictions linked to each of them.

The method proposed here keeps only the values in this table corresponding to the Pareto optimums of Figure 3. To define the Pareto optimums, a dominance relationship between the solutions must first be defined. In our case, we will state that a solution  $e_i$  dominates a solution  $e_j$  if  $e_i$  achieves all the objectives of  $e_j$  plus at least one additional objective. Thus, in our example e9 dominates e2 (cf. Figure 3) because e9 meets all the objectives reached by e2 ( $y_2, y_5, y_6$ ), but it also meets the objective  $y_4$ .

The non-dominated solutions are the Pareto optimums. In our example, the Pareto optimums are the solutions e1, e4, e6, and e9. The GTCs can then be identified either by applying the methods mentioned in section 2 to the part of Figure 3 corresponding to the Pareto optimums, or in simple cases such as this one, directly by manipulating the matrix as illustrated in the next paragraph. A row of the Pareto set in Figure 4 defines a GTC. Furthermore, each pair of different rows in terms of objectives defines a pair of GTCs involved in a system of contradictions. Thus, the objectives are achieved in the same way by e6 and e9, and, therefore, there is no conflict between these two solutions. Moreover, the conflicts of the objectives of e6 with any other solution will be similar for e9.

Let us now consider for example the solutions e4 on the one hand, and e6 and e9 on the other hand. Note that the  $y_2$  and  $y_4$  objectives are achieved for both groups. These objectives are thus not in opposition between these groups of solutions. In contrast, in these three experiments, when objectives  $y_1$  and  $y_3$  are reached, they are not reached for e6 and e9 and vice versa. Thus, objectives  $y_1$  and  $y_3$ , and  $y_5$  and  $y_6$  are in conflict: they express the conflictual part of the pair GTC1 and GTC2 in Figure 5. The objectives  $y_2$  and  $y_4$  are the non-conflictual objectives of the pair GTC1 and GTC2. The non-conflicting objectives are not explicitly stated in the models of the contradiction system of previous studies. In this paper, we propose to make them explicit as shown in Figure 5, as this clarifies the objectives and keeps all the information necessary for the evaluation of a solution. Omitting them can lead to solutions that are already present or that can be obtained by optimization. Thus, in our example, if one omits e1 to include  $y_2$  and  $y_4$  in the expressions GTC1 and GTC2, e1 would constitute a solution to the resolution of the GTC1 and GTC2 contradictions. Unfortunately, e1 is not a solution to our problem because e1 does not meet the objective  $y_2$ . The experiment e1 resolves the conflict between the sets of EPs ( $y_1, y_3$ ) and ( $y_5, y_6$ ); but then  $y_2$  is no longer satisfied, and a new conflict appears. The purpose of model transformation with TRIZ-based method is to resolve the contradiction of Figure 5 while maintaining the satisfaction of the objectives of  $y_2$  and  $y_4$ . The definition of the generalized contradiction proposed in this article ensures that the solution will dominate the experiments involved in GTC1 and GTC2, will be a Pareto optimum of the binary matrix and will achieve more objectives.

The analysis of the values of the APs corresponding to these GTCs allows for the expression of a contextual physical contradiction. Thus, one can observe that the expression  $(x_2 = 1).(x_3 = 0)$  characterizes the Pareto solutions. In this context,  $x_1$  must be 1 and  $x_5$  must be 0 to meet objectives  $y_1$  and  $y_3$ , but  $x_1$  must be 0 and  $x_5$  must be 2 to meet objectives  $y_5$  and  $y_6$ . Figure 5 summarizes the generalized system of contradiction (GSC) under the context that has just been described.

|    | AP    |       |       |       |       | EP    |       |       |       |       |       |
|----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|    | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $y_1$ | $y_2$ | $y_3$ | $y_4$ | $y_5$ | $y_6$ |
| e1 | 1     | 1     | 0     | 0     | 1     | 8.6   | 0.4   | 1090  | 1.3   | 4.59  | -10   |
| e2 | 0     | 1     | 1     | 1     | 1     | 5.2   | 0.6   | 202   | 0.1   | 2.1   | -8    |
| e3 | 1     | 0     | 1     | 0     | 0     | 9.1   | 0.5   | 999   | 0.3   | 8.65  | 4     |
| e4 | 1     | 1     | 0     | 0     | 0     | 9.5   | 0.65  | 1070  | 1.4   | 8.45  | 5     |
| e5 | 1     | 0     | 1     | 0     | 1     | 8.9   | 0.1   | 997   | 0.2   | 2.12  | -7    |
| e6 | 0     | 1     | 0     | 1     | 2     | 3     | 0.68  | 500   | 1.5   | 3.09  | -9    |
| e7 | 1     | 0     | 1     | 1     | 0     | 8.8   | 0.1   | 1010  | 0.6   | 5.94  | 4     |
| e8 | 1     | 0     | 0     | 0     | 1     | 9.6   | 0.2   | 300   | 1.1   | 4.16  | -6    |
| e9 | 0     | 1     | 0     | 0     | 2     | 2.4   | 0.65  | 100   | 1.2   | 0.11  | -3    |

Figure 2. Initial experiments

|    | AP    |       |       |       |       | EP    |       |       |       |       |       |
|----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|    | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $y_1$ | $y_2$ | $y_3$ | $y_4$ | $y_5$ | $y_6$ |
| 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     |

Figure 3. EP binarization with specs

|    | AP    |       |       |       |       | EP    |       |       |       |       |       |
|----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|    | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $y_1$ | $y_3$ | $y_5$ | $y_6$ | $y_2$ | $y_4$ |
| e1 | 1     | 1     | 0     | 0     | 1     | 1     | 1     | 1     | 1     | 0     | 1     |
| e4 | 1     | 1     | 0     | 0     | 0     | 1     | 1     | 0     | 0     | 1     | 1     |
| e6 | 0     | 1     | 0     | 1     | 2     | 0     | 0     | 1     | 1     | 1     | 1     |
| e9 | 0     | 1     | 0     | 0     | 2     | 0     | 0     | 1     | 1     | 1     | 1     |
| e2 | 0     | 1     | 1     | 1     | 1     | 0     | 0     | 1     | 1     | 1     | 0     |
| e3 | 1     | 0     | 1     | 0     | 0     | 1     | 1     | 0     | 0     | 0     | 0     |
| e5 | 1     | 0     | 1     | 0     | 1     | 1     | 1     | 1     | 1     | 0     | 0     |
| e7 | 1     | 0     | 1     | 1     | 0     | 1     | 1     | 0     | 0     | 0     | 0     |
| e8 | 1     | 0     | 0     | 0     | 1     | 1     | 0     | 1     | 1     | 0     | 1     |

Figure 4. Experiment Pareto set

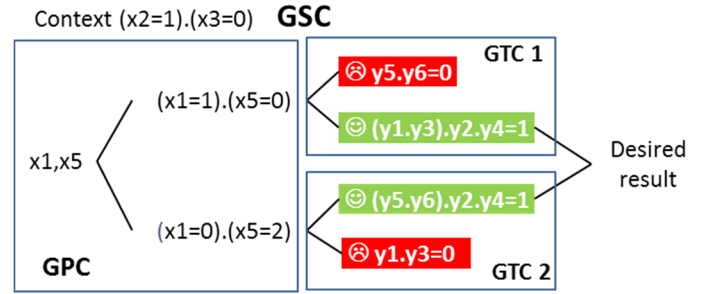
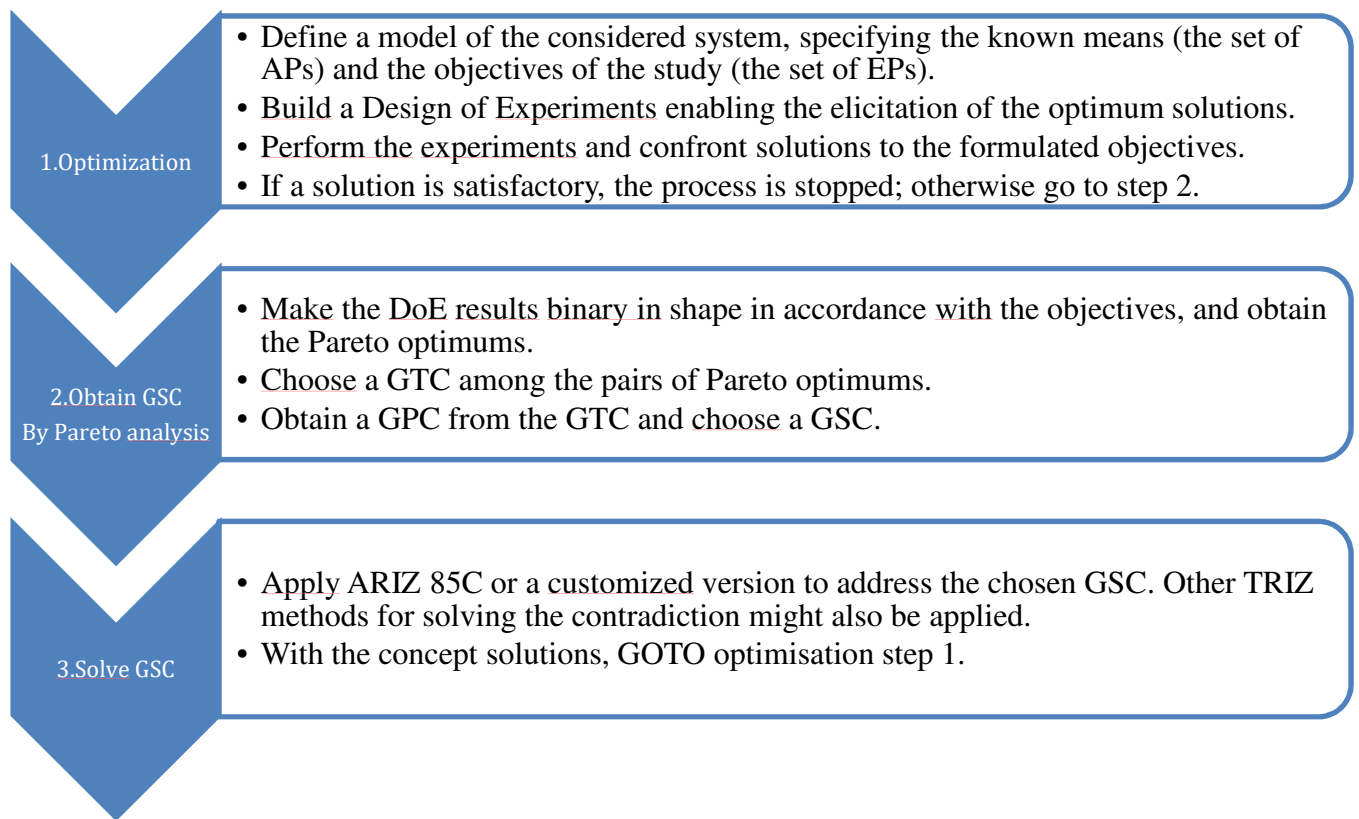


Figure 5. Generalized System of Contradictions

In the example in Figure 2, we can see that there is at least one highlighted cell per column of objectives, which means that there is at least one experiment meeting each objective individually. Situations may arise where there is no experiment that meets a given objective. This situation has two possible interpretations. The first interpretation is that action parameters do not influence this evaluation parameter and that an evaluation parameter was forgotten in the model during the DoE. This indicates a gap in the knowledge of the model; and the DoE and the optimization process should be reworked. In the design method described further in section 3.2, this situation is addressed prior to the contraction search. The second interpretation is complementary to the previous one: the action parameters influence the evaluation parameters, but there is no satisfactory solution for this objective. In this case, to identify the contradictions, we propose to highlight some of the best optimization solutions obtained for this evaluation parameter before proceeding with the binarization as indicated above. This remark suggests that this method can be applied when there is no fixed numerical limit for certain objectives, but only qualitative objectives such as maximizing or minimizing the value of the evaluation parameters.

### 3.2 Integrated methodology

Based on previous considerations, the process described in Figure 6 is evaluated on the type of problem described in the introduction.



**Figure 6. Proposed integrated method**

## **4. Case study**

### **4.1 Preliminary study**

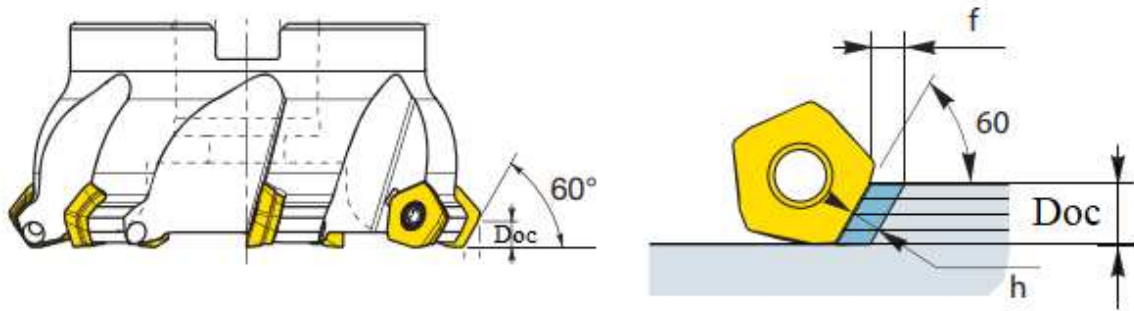
The study was conducted as a collaboration between the Center for Studies and Research on Cutting Tools (CEROC) and the Laboratory of Mechanics and Rheology (LMR). Aspects of the study were also the topics of two PhD theses (Chibane et al., 2013; Chibane et al., 2017). A response surface methodology was applied, and is presented in (Morandea et al., 2013) for the optimization of milling T800 M21 carbon/epoxy composite material. It has enabled the clarification of the impact of the cutting behavior of 19° and 60° lead angle tool on specification criteria, such as cutting force, material temperature, milled surface roughness, delamination, and tool wear. The results of the studies pointed out that a lead angle of 19° is favorable for cutting force reduction, less wear, and also less delamination.

The multi-objective approach enabled the authors to clarify the optimal solutions that can be reached, based on initial hypotheses of the study. However, these optimal solutions are compromises, as none of them satisfy all the defined specs. Thus, one aim of this study is to check and illustrate how inventive based methods can help us to have a better understanding of the model of the problem and how to propose concepts enabling overcome the Pareto optimal solutions obtained with the optimization process.

## 4.2 Optimization step

### 4.2.1 Presentation of the case

The experiment involves performing milling tests on a horizontal high-speed milling machine. An aeronautic composite material (carbon/epoxy T800S/M21) was machined with a diamond like carbon (DLC) coating cutting tool provided by Safety Cutting Tool (Safety, 2007) as shown in Figure 7.



**Figure 7. Cutting tool and parameters.**

The fixed machining parameters are presented in Table 1.

**Table 1. Fixed machining parameters.**

| <i>Parameters</i>                  | <i>Values</i>            | <i>Specificity</i>                            |
|------------------------------------|--------------------------|---|
| Axial depth of cut DOC             | 1.04 mm                  | 4 layers of carbon fabric ( $4 \times 0.26$ ) |
| Radial engagement                  | $a_e = 36.4$ mm          | 50% of the tool diameter (110 mm)             |
| The cut length $L_c$ is            | $L_c = 55$ mm            | 1/5 of the total part length (275 mm)         |
| Orientation of the composite plies | $[(45/90/135/0)_{16}]_s$ | Carbon / epoxy T800S/M21                      |

### 4.2.2 Design of Experiments and Action Parameters

Central composite designs (CCD) are the most frequently applied response surface designs. A CCD is the combination of a two-levels full factorial design ( $2^f$  experiments for  $f$  parameters), a star design ( $2f$  experiments) and a center point. Thus, a CCD requires  $N = 2^f + 2f + 1$  experiments to examine  $f$  parameters. The full factorial design analyzes the parameters at levels  $-1$  and  $+1$ , the star design at levels  $-\alpha$  or  $+\alpha$  for one parameter and the center point at level 0. To obtain a so-called rotatable CCD, the extreme levels of the star design ( $-\alpha$ ,  $+\alpha$ ) should fulfil the requirement  $|\alpha| = (2f)^{1/4}$ . Therefore,  $|\alpha|$  is equal to 1.41 in the case of two parameters.

Taking into account the high cost of a machining test (cost of tool, material and operation) and, the non-linearity of the evaluation parameters observed, a CCD with 9 experiments for each set of

quantitative parameters (Cutting speed ( $V_c$ ) and chip thickness ( $h$ )) has been carried out. The same CCD was repeated for each qualitative parameter (angle of attack  $K_r$  and coating of the cutting tool) which brings the total number of experiments to 54. To measure the repeatability of the process, the central test was repeated 3 times. The cutting parameters levels were chosen in accordance with the recommendations of cutting tool manufacturer (Safety, 2007) as shown in Table 2.

**Table 2. Machining parameters**

|                | <b>Cutting speed<br/>(m/min)</b> | <b>Chip thickness <math>h</math><br/>(mm)</b> | <b>Lead angle<br/><math>K_r</math> (°)</b> | <b>Cutting insert<br/>Coating</b> |
|----------------|----------------------------------|---|--|-----------------------------------|
| Min (-1.41)    | 96.5                             | 0.06  |  |                                   |
| Min (-1)       | 200                              | 0.1   | 19   | DLC                               |
| Mean (0)       | 450                              | 0.2   |  | M-CVD                             |
| Max (+1)       | 700                              | 0.3   | 60   | N-CVD                             |
| Max<br>(+1.41) | 803.5                            | 0.34  |  |                                   |

#### 4.2.3 Output parameters (Evaluation Parameters)

Several evaluation parameters related to machining process and the quality of machining parts were measured.

1. The quality of machining part: Surface roughness
2. The machining process: Vibration levels, Cutting forces, Material removal rate MRR
3. Defects: Delamination, Fiber flaking FF and Temperature of the work part

The objective was to minimize the set of these parameters except productivity (MRR) where we seek to maximize.

#### 4.2.4 Results of the optimization

The objective of this study was to determine an optimal configuration of machining of composite materials which favors two objectives, maximum production and better quality of machining parts. The values of the evaluation parameters were set according to the need sought, as shown in Table 3.

**Table 3. Design of Experiment Objectives**

| Evaluation parameters                                 | Targeted objectives |      | Optimization Target |
|---|---------------------|------|---------------------|
|   | Min                 | Max  |                     |
| Surface roughness Ra (um)                             | 0                   | 3    | Minimize            |
| Fiber flaking FF (mm)                                 | 0                   | 0.1  | Minimize            |
| Delamination length DL (mm)                           | 0                   | 0.1  | Minimize            |
| Workpiece temperature T (°)                           | 0                   | 80   | Minimize            |
| Cutting forces F (N)                                  | 0                   | 200  | Minimize            |
| Vibration levels Arms (m <sup>2</sup> /s).            | 0                   | 80   | Minimize            |
| <b>Material removal rate MRR (cm<sup>3</sup>/min)</b> | 1200                | 2000 | Maximize            |

The experiments were conducted, and a part of this DoE is presented in Table 4, where the satisfactory results of the experiments are highlighted in green.

**Table 4. DoE inputs / outputs.**

| Test | Action Parameters         |        |            |        | Evaluation Parameters |         |         |        |        |                            |                          |
|------|---------------------------|--------|------------|--------|-----------------------|---------|---------|--------|--------|----------------------------|--------------------------|
|      | Coating                   | Kr (°) | Vc (m/min) | h (mm) | Ra (μm)               | FF (mm) | Ld (mm) | T (°)  | F (N)  | MRR (cm <sup>3</sup> /min) | Arms (m <sup>2</sup> /s) |
| e 1  | DB3                       | 19     | 96.5       | 0.2    | 11.26                 | 3.30    | 0.00    | 56.00  | 164.41 | 754.56                     | 61.94                    |
| e 2  | DB3                       | 19     | 200        | 0.1    | 4.20                  | 2.10    | 0.00    | 95.00  | 302.78 | 1532.43                    | 73.88                    |
| e 3  | DB3                       | 19     | 200        | 0.3    | 11.12                 | 3.70    | 0.00    | 67.00  | 129.14 | 464.42                     | 160.15                   |
| e 4  | DB3                       | 19     | 450        | 0.06   | 2.35                  | 0.00    | 0.00    | 122.00 | 461.22 | 933.05                     | 85.30                    |
| e 5  | DB3                       | 19     | 450        | 0.2    | 19.00                 | 2.40    | 0.00    | 101.33 | 207.28 | 493.50                     | 141.60                   |
| e 6  | DB3                       | 19     | 450        | 0.34   | 9.44                  | 0.00    | 0.00    | 62.00  | 112.99 | 147.54                     | 203.46                   |
| e 7  | DB3                       | 19     | 700        | 0.1    | 3.92                  | 0.86    | 0.00    | 282.50 | 874.15 | 448.15                     | 190.26                   |
| ...  | Tests 8 to 49 are skipped |        |            |        |                       |         |         |        |        |                            |                          |
| e 50 | DSP3N                     | 60     | 450        | 0.2    | 1.51                  | 1.10    | 2.80    | 118.00 | 411.36 | 19.84                      | 93.18                    |
| e 51 | DSP3N                     | 60     | 450        | 0.34   | 2.59                  | 2.00    | 6.10    | 98.00  | 285.28 | 12.86                      | 113.78                   |
| e 52 | DSP3N                     | 60     | 700        | 0.1    | 0.90                  | 0.00    | 0.52    | 159.00 | 580.24 | 32.71                      | 79.24                    |
| e 53 | DSP3N                     | 60     | 700        | 0.3    | 1.68                  | 0.00    | 3.67    | 121.00 | 314.66 | 12.35                      | 124.50                   |
| e 54 | DSP3N                     | 60     | 803,5      | 0.2    | 2.11                  | 0.00    | 3.20    | 134.00 | 381.05 | 13.17                      | 128.74                   |

Table 4 shows some of the results obtained by the optimization approaches in the study. These results illustrate that designers could find satisfying the specifications challenging, as no experiment satisfies all the EPs. This is typically the kind of situation that one can recognize as an inventive

problem. Thus, the next step of the method is to identify contradictions so that TRIZ- based methods can be applied as described in section 3.

### **4.3 GSC step**

The Pareto frontier is a representation of the best solutions that can be reached, given the model of a system. The concept of dominance defines the relationships between two points of the design space (two experiments in a DoE), with regard to the satisfaction of the EPs. We suggest using the real values when dealing with optimization and to understand the border limits of our model. However, in our case, we want to extract the contradictions. Thus, we use the binarization of the DoE results, which acts as a relevant filter of the data, for identifying contradictions related to the Pareto of the real data. The EPs for each experiment will be fixed at 1 if the experiment satisfies the specs for the considered EP, and 0 otherwise.

In cases where the "targeted objectives (Min, Max)" columns of Table 3 are not available, but the "optimization target" column is, it would be adequate to highlight in the table of the DoE results a set of the best values obtained for each evaluation parameter (e.g. 10%).

#### **4.3.1 Pareto optimum of the binarized results**

When considering the two experiments e1 and e4 in Table 4, which satisfy two different sets of EPs, one can easily recognize a Generalized Technical Contradiction and even a Generalized System of Contradictions. Indeed, the contradiction could be formulated: the system needs to be in the state of experiment e1 to satisfy the first set of EPs (Workpiece temperature, Cutting forces and Vibration levels); however, the system needs to be in the state of experiment e4 to satisfy the second set of EPs (Surface roughness, Fiber flaking and Delamination length). If one tries to build a set of Systems of Contradictions with this rule, the number of contradictions will be huge (that is why algorithms are proposed in (Sébastien Dubois et al., 2015; Lin et al., 2014)), and not relevant. To overcome this limitation and to identify only robust contradictions (those for which no solution is known), it is proposed to only consider the System of Contradictions built with experiments on the binary Pareto optimums. There are only seven experiments belonging to the Pareto set and several experiments provide the same binary output. Thus, finally, there are only four different "binary families" of experimental outputs in the Pareto set: (e1, e19), e6, e11, (e2, e20, e38). The small size of this Pareto set and of the results, showed in Table 5 allows us to identify the contradictions directly from the table.

#### **4.3.2 Choose a GTC**

Any combination of two experiments of two different families could thus be recognized as a robust system of contradictions, the resolution of which will lead to new knowledge beyond the Pareto Frontier. The four families presented on Table 5 lead to the formulation of six robust GTCs.

|             | Action Parameters (AP)    |                   |                          |                       | Evaluation Parameters (EP) |                             |                                     |                             |                              |                       |                      |   |  |
|-------------|---------------------------|-------------------|--------------------------|-----------------------|----------------------------|-----------------------------|-------------------------------------|-----------------------------|------------------------------|-----------------------|----------------------|---|--|
| Test Number | Coating of cutting insert | Lead angle Kr (°) | Cutting speed Vc (m/min) | Chip thickness h (mm) | Surface roughness Ra (μm)  | Workpiece temperature T (°) | Material Removal Rate MRR (cm3/min) | Delamination length Ld (mm) | Vibration levels Arms (m2/s) | Fiber flaking FF (mm) | Cutting forces F (N) |   |  |
| exp. 1      | DB3                       | 19                | 96.5                     | 0.2                   | 0                          | 1                           | 0                                   | 1                           | 1                            | 0                     | 1                    | 1 |  |
| exp. 19     | DB6                       | 19                | 96.45                    | 0.2                   | 0                          | 1                           | 0                                   | 1                           | 1                            | 0                     | 1                    |   |  |
|             |                           |                   |                          |                       |                            |                             |                                     |                             |                              |                       |                      |   |  |
| exp. 6      | DB3                       | 19                | 450                      | 0.34                  | 0                          | 1                           | 0                                   | 1                           | 0                            | 1                     | 1                    | 2 |  |
|             |                           |                   |                          |                       |                            |                             |                                     |                             |                              |                       |                      |   |  |
| exp. 11     | DB3                       | 60                | 200                      | 0.1                   | 1                          | 1                           | 0                                   | 1                           | 1                            | 0                     | 0                    | 3 |  |
|             |                           |                   |                          |                       |                            |                             |                                     |                             |                              |                       |                      |   |  |
| exp. 2      | DB3                       | 19                | 200                      | 0.1                   | 0                          | 0                           | 1                                   | 1                           | 1                            | 0                     | 0                    | 4 |  |
| exp. 20     | DB6                       | 19                | 200                      | 0.1                   | 0                          | 0                           | 1                                   | 1                           | 1                            | 0                     | 0                    |   |  |
| exp. 38     | DSP3N                     | 19                | 200                      | 0.1                   | 0                          | 0                           | 1                                   | 1                           | 1                            | 0                     | 0                    |   |  |
|             |                           |                   |                          |                       |                            |                             |                                     |                             |                              |                       |                      |   |  |
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|             |                           |                   |                          |                       |                            |                             |                                     |                             |                              |                       |                      |   |  |

**Table 5. Families of Pareto optimums and the chosen GTC**

These GTC have been proposed to experts and their conclusion was that the satisfaction of the fiber flaking and cutting forces could be solved easily by the use of lubricant (i.e., use an AP external to the experiment so that the experimental results for the EP are not affected). Thus, the main and remaining conflicting EP are the material removal rate (MRR) and the surface roughness (Ra). This conflict could be expressed considering experiment e11, which satisfies the surface roughness (Ra) and the workpiece temperature (T) requirements, and experiments e2, e20, and e38, which satisfy the material removal rate (MRR). All the considered experiments satisfy also the delamination length (Ld) and the vibration levels (Arms) requirements, which are not conflicting EP in the formulated GTC but are part of the desired result. These objectives have to be maintained to 1 (verify specifications) in the future solutions.

#### 4.4 Choose a GSC

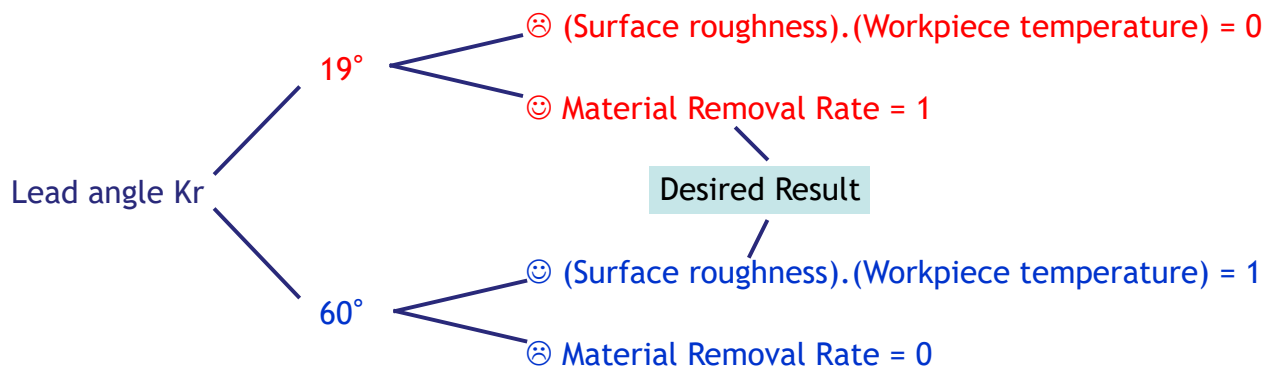
As the GTC offers an initial understanding of the problematic situation, as it allows the situation to evolve and enables the application of TRIZ-based methods, it is necessary to understand the physical contradiction inherent to the chosen GTC. A quick analysis of the four involved experiments pointed out the following:

- the coating of the cutting insert does not explain the GTC, as one common value (DB3) could lead to satisfaction of both the MRR and the Ra.
- the cutting speed and the chip thickness do not explain the GTC, as their values remain the same ( $V_c = 200\text{m/min}$  and  $h = 0.1\text{mm}$ ) in all the considered experiments.
- the lead angle (Kr) could explain the contradiction, as it has to be equal to  $60^\circ$  to satisfy the Ra, and it has to be equal to  $19^\circ$  to satisfy the MRR.
- if considering the entire table of experiments, one can easily find experiments where  $Kr = 60^\circ$  but where the Ra is not satisfied, and where  $Kr = 19^\circ$  but the MRR is not satisfied. Thus, the contradiction on Kr is only true in a certain context, when the cutting speed and the chip thickness values are fixed.

This contextual GSC is illustrated on Figure 8. The delamination length and vibration level are recalled as a reminder for the desired result although they are not at conflict in the actual solutions.



(Cutting Speed=200).(Chip Thickness=0.1)

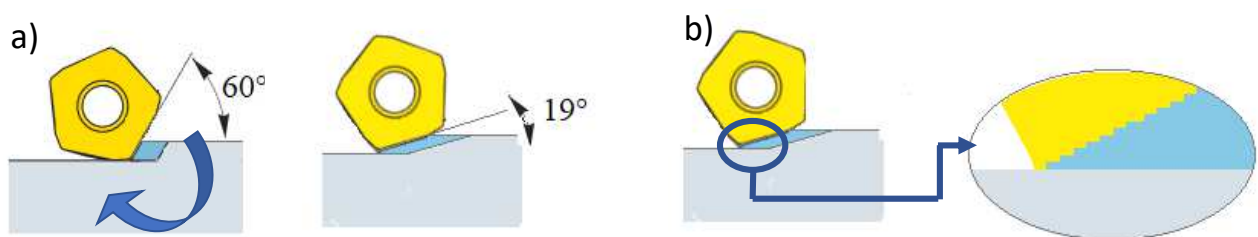


**Figure 8. Contextual Generalized System of Contradiction**

#### 4.5 Resolution of the GSC

Such a contextual GSC is of interest because the GPC can solve with classical TRIZ methods that address physical contradictions without customization for generalized contradictions. For this type of contradiction, several principles called separation principles have been formulated (Savransky, 2000). Three of these separation principles seemed relevant to the formulated problem: the separation in space, the separation in time, and the systemic level separation. If time is dedicated to high speed material removal and time is dedicated to polishing the surface state, it is possible to propose a rotating tool with the two different angles (cf. Figure 9a) so that the properties of the cutting tool can be without changing the tool. Typically, when machining a composite material, the need for a specific surface roughness is expressed for certain defined areas of the part (contact surface, assembly, etc.), otherwise, the maximum productivity is favorite. The solution proposed in this study makes it possible to choose the orientation of the cutting insert between 19 ° and 60 ° depending on the need in terms of surface quality and productivity.

By adding the constraint of time, the systemic level separation principle has been considered. The tackled question was as follows: Is it possible to have a global lead angle of 19° and several elements having a lead angle of 60°? Such a concept has been defined, as illustrated in Figure 9b. The global lead angle (19°) enables realization of the maximum MRR, but locally, the elements have a lead angle of 60° to ensure a good surface roughness. This solution, in terms of performance, seems much more promising than the first one, but its feasibility has to be studied.



**Figure 9. Solution concepts. (a) Rotating tool; (b) Nested geometry**

## 5. Feedback discussion and conclusion

This article described the methodology of bridging optimization methods, which are well known and largely employed in production problem analysis, and TRIZ-based inventive problem approaches. Such a method was reported in the area of logistics and production flow analysis, and has been used in numerous simulations. The research reported in this paper expands, customizes, and evaluates this methodology in the area of multi-objectives product design dealing with more than two objectives and describes the use of DoE optimization methodology. A new definition of the generalized system of contradiction was proposed. The results of this research will now be analyzed by addressing several groups of questions: (1) To what extent do the results of this study confirm or contradict similar approaches previously proposed in theory or on applications in other fields? (2) What positive feedback and practical limitations were observed in the study? (3) What are the potential limitations that have been hypothesized as a result of the application of the method? (4) To what extent did this method provide an innovative solution to the problem of the design of the cutting tool introduced in Section 1?

- (1) The methods described in the article enable us to first model the system through the identification of main action and evaluation parameters, and then to look for optimum solutions. Owing to several presented relevant binarization of the experiment results, the root causes of the problem that prevent realization of the objectives and a generalized system of contradictions can be defined both by highlighting the limits of the system model and enabling us to look for solution concepts. In our case, the proposed solution concepts are two inventive concepts that seem to enable certain benefits, but that also need to be validated, prototyped, and optimized. They could also be integrated into global 4.0. plant processes. Moreover, the contradiction between quality and productivity tackled in the problem is also a recurrent problem in production.
- (2) The benefits of identifying generalized technical contradictions through the use of Pareto optimums of the binary matrix are reinforced by this case study. This method, easy to program in comparison with other methods reported in the literature, was an extremely efficient filter for extracting the few key performance limits of the starting system. This approach for identifying technical contradictions is also original in comparison with other methods as it explicitly and solely recognizes contradictions expressed with all evaluation parameters.

When trying to analyze multi-criteria problems, which the DoE leads to, experts can state the Pareto Frontier (of the real data like those of Figure 1 or Table 4). Initial experiments can be recognized as the quantitative limit of reachable solutions; and if the desired solution is out of this reachable domain, usually experts are choosing a tradeoff among the Pareto optimums. However, the formulation of contradictions, based on the binary transformation proposed in section 3.1, indirectly analyses the Pareto barrier structure, pointing out the

reason why the system (or at least the built model of the system) could not overcome this Pareto Frontier.

Let us recall that it is easier to apply the conventional formulation method of Technical Contradictions when one knows how to satisfy each of the EP (each EP has to be satisfied at least once in the experiments). In our method we have proposed, this problem can be bypassed by selecting the best solutions for each objective before binarization when this information is missing. However, this method raises the question of the choice of threshold values for carrying out the binarization of the experiment results. Further research needs to be conducted to assess this potential limit or to find robust rules for choosing these thresholds.

The approach described in the paper received positive feedbacks from domain experts. First of all, the method, even though simple and understandable, enabled the authors to point out the real core problem of the situation, the kind of problem that experts are aware of but prefer to try to bypass. The DoE was analyzed, with few and no questionable steps, and led to the formulation of an appropriate system of contradictions.

- (3) One question still remains. In the case study, the application of the TRIZ separation principles was made possible by the existence of a contextual physical contradiction. Throughout all the studies conducted by the authors, this kind of contradiction has always been present. However, until now, there has been no proof that such a contradiction will always exist. Furthermore, the applicability of the separation principles, if confronted with a complex Generalized Physical Contradiction, do not give a satisfactory answer. However, one can argue that the difficulty the authors face in such cases is perhaps an argument in favor of the robustness of the proposed approach.
- (4) The two presented concepts, formulated through the resolution of contradiction, lead to two promising ideas. These two solutions are really inventive ones, as the experts did not know them. Studies are now conducted to validate the feasibility and real benefits of these concepts.

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