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Activity Based Tolerance Allocation (ABTA) – Driving tolerance synthesis by evaluating its global cost

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4 **Activity Based Tolerance Allocation (ABTA) – Driving**
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7 **tolerance synthesis by evaluating its global cost**
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Abstract:

This paper deals with tolerance allocation driven by an activity based approach. Its main objective is to rationally give a good indicator of the relevance of tolerances values fixed by designers. Taking into consideration the impacts of tolerance allocation on the manufacturing process and so the production cost, several examples are given to illustrate this concept. Moreover this paper deals with how the geometrical analysis can be carried out in this activity framework, illustrated by several industrial cases. In addition, this paper explains how, coupled with an optimization algorithm, this method can generate the best compromise between cost and high performance. To illustrate the efficiency of this approach and its realization, models and user interfaces based on an industrial case are given.

Keywords:

Tolerance Synthesis, Tolerance allocation, Cost estimation, ABC method, Activity model, Data model, Manufacturing Process.

1. INTRODUCTION

As technology increases and performance requirements continually tighten, the cost and required precision of assemblies increase as well. That is the reason why designers have to take care of the tolerance design which allows them to produce at lower cost high-precision assemblies. Moreover a compromise must be found between designers which want tight tolerances to assure product performance and manufacturers who prefer loose tolerances to reduce cost. Consequently, tolerancing activities take a crucial role in the relationship between these usually isolated domains: namely the design and the manufacturing department... In brief, tolerancing activities become key characteristics for improving the productivity and the efficiency of manufacturing resources consumption.

A significant amount of literature is related to tolerance design. Hong *et al.* (2002) distinguishes seven domains of existing tolerancing research like tolerancing schemes, tolerance model, tolerance allocation... This paper deals with tolerance allocation. About tolerance allocation, Hong said *"Most of the tolerance allocation approaches that have been published are based on the optimization of the cost-tolerance function. They usually try to get optimal tolerance 'values' while the tolerance 'types' are assumed to be fixed. Unfortunately, however, the usage of these models in industry is fairly limited. One of the major reasons for this is that they usually try to take advantage of the superficial knowledge of processes, which is usually obtained from the machinist handbook or the company manual."* Therefore in this paper a new way of tolerance allocation, driven by an activity based approach, is proposed. Indeed, since

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3 design and manufacturing are truly interconnected, the developed method has to follow a more
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5 iterative way.
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8 The long-term objective of this work is the optimisation of the tolerance allocation phase
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10 allowing designers to specify their functional requirements taking into consideration their
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12 impacts on the manufacturing. The first step to this optimisation is the calculation of the
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14 tolerance allocation cost. Indeed this cost is a good indicator of the relevance of a tolerance
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16 allocation and can become an objective function for optimisation algorithms.
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20 This paper deals with methods and models developed to perform the analysis of the relevance
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22 of a tolerance allocation. The first part of this article regards the tolerancing process and the
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24 current solutions used to perform tolerance allocations and to evaluate their costs. Then an
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26 original approach, analysing the impact of a tolerance allocation and then its cost, is more
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28 particularly detailed on an illustrative example. Then knowledge representation and
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30 mathematical tools needed to support this solution are explained and structured in an UML
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32 model. Finally a short conclusion deals with limits of this method and some prospects.
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36
37 **[Figure 1 should be inserted here]**
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39 This concept of Activity Based Tolerance Allocation (ABTA) has been tested and validated
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41 on several products. One of them is illustrated in Figure 1: the linear guide unit. This hyperstatic
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43 assembly is interesting since functional and dimensional requirements are numerous.
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45

46 47 2. TOLERANCE DESIGN AND TOLERANCE ALLOCATION 48 49

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51 This section of the paper deals with the tolerance allocation, how it is performed, and more
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53 precisely the limit of the current methods used to evaluate its cost. Moreover, this section
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55 presents our tolerance design approach and our tolerance allocation framework.
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2.1. Tolerance design

The activity model given in figure 2 describes tolerance design functions and details their input and output data. The tolerance design activity is decomposed into three sub activities: Geometrical requirement definition (Activity A1), Tolerance specification - Qualitative determination of parts tolerances (Activity A2) and Tolerance allocation - Quantitative allocation of part tolerances (Activity A3). To assure the integration of design, manufacturing and tolerancing, we define an integrated approach, which ensures the continuous transition from functions to tolerances (Dantan *et al.* 2003, Roy *et al.* 2001), manufacturing cost and process capabilities.

[Figure 2 should be inserted here]

Activities A1 & A2, which determine geometrical specifications of each part to ensure the functional requirements, are based on technical functional analysis approach. In order to quickly determine the tolerances of each part of a mechanism, designers define the nominal model, the major functional requirements and technical requirements of the mechanism, by using functional analysis method. Moreover, the technical functional analysis allows determining the geometrical requirements, which limit the functional characteristics of the mechanism. To determine the geometrical specification of each part, designers study the impact of parts deviations and gaps on the considered geometrical requirement. The geometrical specifications corresponding to a requirement are related to all key surfaces of key parts (and strictly to them) and limit the key deviations (and strictly them) which impact the respect of the requirement. An amount of research has been devoted to the development of geometrical specification determination (Dantan *et al.* 2003, Roy *et al.* 2001, Mejbri 2005 *et al.*, Sellakh *et al.* 2001).

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3 Activity A3 allocates tolerances to ensure the functional requirement and to minimize the
4 manufacturing cost. This paper focuses on this activity. The input of this activity is the output of
5 activities A1 and A2.
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10 The following sections 2.2 and 2.3 show some approaches of tolerance allocation. The section
11 2.4 details the proposed indicator for tolerance allocation. And the section 2.5 deals with our
12 framework of tolerance allocation.
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17 18 **2.2. Strategies of tolerance allocation** 19

20 Among all solutions available to perform tolerance allocations, three can be distinguished:
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- 23 • The first consists in equally dividing the tolerance between the workpieces achieving
24 functional requirements (the *solution1* in Figure 3). This solution is the easiest one;
25 however it does not take into account the capability of the production resources. As a
26 consequence, the cost of this distribution is unrefined and the risk of having out of range
27 dimensions or not machinable workpieces is high.
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36 **[Figure 3 should be inserted here]**
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- 38 • The second solution, which tries to avoid the previous defects, is based on the resource
39 capability. This capability is an indicator commonly used to assess the relevance of using
40 a resource to produce a tolerance objective. This indicator is mathematically defined :
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$$45 \text{Capability} = \frac{\text{Tolerance}}{6.\sigma_i} \quad (1)$$

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47

48 σ models the standard deviation of the statistical distribution of the resource's deviations.

49 The aim of this method is to have the same capability (usually higher than 1.33) for all
50 resources (The *solution2* in Figure 3). However this solution is not enough efficient:
51 although the risk of having out of limits dimensions is reduced, the production plan
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looses its flexibility. Moreover, since this solution select only quality controlled process plan, the cost of products becomes expensive.

- The third allocation is performed regarding the tolerance cost. Methods used to carry out this assessment are described and explained in the further section.

2.3. Cost of the tolerances

Current methods designed to assess the tolerance cost are mainly based on parametric approaches. According to these methods, the cost depends on mathematical combination of the tolerance required and several constants. Among all parametric functions available, the reciprocal squared model (Spotts 1973), the reciprocal model (Chase *et al.* 1991) and the exponential model (Speckhart 1972) are currently the most used mathematical definitions. Some evolved models (Layek *et al.* 1996, Lööf *et al.* 2005) propose a synthesis of the cheapest solution to machine a specified tolerance regarding available resources in the company. One resulting process sequence chart is illustrated Figure 4.

[Figure 4 should be inserted here]

For instance, the reciprocal square model is:

$$Cost = A + \frac{B}{Tolerance^2} \quad (Spotts 1973) \quad (2)$$

'A' and 'B' are two constant parameters. Since they highly depend on the context (material, machining operation and condition, tool and machine used, cost labour...) it is both difficult and expensive to evaluate them, mainly with experimental designs (Diplaris *et al.* 2000). Moreover these parameters, when they are assessed, are considered as strategic data then companies do not publish any information about them...

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Added to this difficulty to evaluate these parameters, their validity are strongly limited and thus difficult to generalize in an industrial framework. Indeed since workpieces are machined in several conditions (multiple operations, sites, machines and tools), there are too many parameters to isolate, to model and to evaluate. To do so, some approaches use design of experiments (Schmitt *et al.* 2007) to identify the cost function parameters.

In conclusion, it seems not really relevant to use these methods evaluating the cost of tolerance with parametric models. Regarding these issues, it could be more interesting to evaluate the cost impacted by the tolerance allocation than directly the tolerances cost. This way is explain in the next section.

2.4. Cost impacted by the tolerance allocation - Cost weighted risk

Contrary to the previous solution which tries to directly evaluate the cost of tolerances this method consists in assessing the cost impacted by the designer's tolerances allocation. Moreover, since it seems impossible to truly evaluate the real cost of tolerances, the aim of this section is to find a way to calculate a good indicator of the relevance of design solutions. Indeed, designers just need to compare several solutions to choose the best not really their precise cost...

Among all parameters impacted by the tolerance choices, the most dependent on this allocation are manufacturing characteristics. That's why the cost weighted risk concept assesses cost by analysing the impact of the tolerance allocations on the manufacturing process. In our case, the concept of risk mainly means risk of manufacturing out of range or not functional products and so producing workpieces not sealable and decreasing profits. This analysis is built on a mathematical expression:

$$\text{Cost} = \frac{\text{Production Cost}}{P(\text{Product Ok})} + \text{Recycling Cost} \cdot P(\text{Out Of Range}) \quad (3)$$

$$+ \text{Labour Cost} \cdot P(\text{Not Assemblable}) + \dots$$

This formula is composed by three parts:

- The first member models the production cost of workpieces without any defect and then are saleable products. The variable *ProductionCost* is the sum of all manufacturing resources used to machine products (especially tools, labour and machines). *P(ProductionOk)* is the probability of having a product meeting all requirements (functional, and more particularly the specifications defined by the tolerance allocation).
- The second part underlines the indirect costs due to recycling: workpieces partially machined have to be dropped out (i.e. recycled) if one of its parameter is out of range. The variable *P(OutOfRange)* models this occurrence and the value of the parameter *RecyclingCost* is defined by the user.
- The last member of this formula models issues due to non compatible components of an assembly: labours have to try several combinations of workpieces to find fitted assemblies. This occurrence of this kind of manufacturing difficulty is modelled by the variable *P(NotAssemblable)*. The cost *LabourCost* is site-dependent and so fixed by the user.

This concept of cost weighted risk is a good indicator since it takes into account the concept of risk. Indeed, a wider tolerance range allows using less accurate but cheaper machines: machined products are cheaper too but the probability of producing defects increases. This indicator can help designers to find the best compromise between cost (wide tolerances easy and cheap to

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3 produce) and quality (tight tolerance making sure the respect of requirements). In addition, this
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5 concept can be automated: it can become a solution for the optimization of tolerance allocation...
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8 9 **2.5. Our framework of tolerance allocation**

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11 The aim of this framework is to quantify parts tolerances which minimize the cost weighted risk
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13 (Etienne *et al.* 2007). This optimization problem is too complex for traditional optimization
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15 algorithms which cannot solve non-analytical objective functions. Moreover, the assessment of
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17 probabilities needs numerical simulation. Recently, due to their outstanding performance in non-
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19 linear optimization, some stochastic optimization algorithms, such as genetic algorithms or
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21 simulate annealing algorithms, have been used to solve this kind of optimization problems.
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23 Therefore, in the framework of tolerance allocation, this optimization is performed by a genetic
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25 algorithm (Etienne *et al.* 2006, Ianuzzi *et al.* 1995, Lee *et al.* 1995, Shan *et al.* 2003).
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29 For each genetic algorithm step, the fitness evaluation includes the process selection, the cost
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31 estimation and the probability estimation. To do so, this evaluation needs a lot of information
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33 and data (mainly the cost and deviation of each resource taking a part in the manufacturing
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35 process) especially for evaluating the production cost and the different probabilities composing
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37 the cost weighted risk. This knowledge has been stored and modelled in the UML diagram. A
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39 detailed version of this model is described in section 3.4.
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45 **[Figure 5 should be inserted here]**
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48 The first step of fitness evaluation is the process selection which takes into consideration the
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50 impact of tolerances on manufacturing process (Figure 5). The output of this step is a set of
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52 admissible manufacturing processes composed by ordered activities as manufacturing activities,
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54 control activities... An amount of research has been devoted to the development of CAPP. The
55
56 Figure 6 illustrates its output: one manufacturing process of a part.
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[Figure 6 should be inserted here]

In this model, activities are the central squares, linked together and ordered into one process plan. The dark gray squares in this picture model only one example of production activities. This one is a drilling operation of two bores named '2D1' and '2D2' (the Figure 8 shows these geometrical features), machined in the fixture composed by three features ('2P1', '2P4' and '2P2'). It consumes two resources: the milling machine named 'FH45' and the cutting tool called 'DrillD20L130'.

[Figure 7 should be inserted here]

For each tolerance allocation, a set of manufacturing process is selected (Figure 5, Activity A31), and the cost weighted risk is evaluated (Figure 5, Activities A32, A33 & A34). The evaluation of the cost weighted risk is the goal of the activities based on model and the main topic of the next sections.

3. ACTIVITY BASED CONCEPT

The cost weighted risk is the relevance driver of a tolerance allocation. The objective is to combine this analytical definition, taking into account indirect costs due to both not respected tolerances or too tighten and expensive requirements, with the flexibility of the ABC (Activity Based Costing) concept. This section deals with the adaptation of the ABC method to the tolerance allocation issue. Furthermore several activities are described and an example is given to illustrate this new concept.

3.1. The ABC method

The Activity Based Costing method (ABC method) was principally developed during the 1980s (Johnson *et al.* 1987). This method consists in banning the usual and hierarchical view of the

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3 analytical approach which is based on the discrimination between the direct (and productive)
4 activities and the indirect (and considered as not productive) activities.
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8 The ABC method performs the decomposition into relevant activities of both the structure and
9 the production processes of the company. Then, it underlines the consumption links between
10 these activities and resources or products (Figure 7). These links are quantified with three
11 inductors: the resource inductor which describes the distribution of each resource consummated
12 by activities, the cost inductor which describes the activities consumed to produce products, and
13 the activity inductor.
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22 This method assesses more precisely the real product cost since it takes into account more
23 indirect costs than the analytical approaches. However, the difficulty to find and evaluate the
24 inductors remains the main issue of this method.
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30 **3.2. Improvement of the ABC method to the tolerance allocation issue**

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32 In order to use this ABC method to assess the cost impacted by the tolerance allocation, some
33 adaptations and improvements are needed.
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38 **[Figure 8 should be inserted here]**
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40 The first improvement consists in enriching the activities handled in the ABC method with two
41 parameters: the performance indicator and the parameter of instantiation occurrence. The
42 performance indicator quantifies the probability that the activity delivers products meeting their
43 associated tolerance requirements. The occurrence of emergence evaluates the probability that
44 the activity appears in the process plan. Moreover, to the static and structural description of
45 activities modelled by the ABC method, the new concept adds a dynamic view: activities can,
46 from now on, generate other activities if some criteria are fulfilled. These criteria are described
47 and illustrated on further sections.
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3 Since tolerance allocation belongs to the production framework, the second main improvement is
4 the enriching of the ABC method with the notion of order. Indeed, contrary to ABC method
5 where order is useless (since it only structures the consumption links), a process plan is the
6 arrangement of all activities taking a part in the product lifecycle. So, for one ABC structure
7 there are as many process plans generated as ABC activities combinations.
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9
10 Considering the flexibility of the ABC method, infinite types of activities can be designed to
11 describe and analyse products lifecycle (Bramail *et al.* 2002). However, it seems that relevant
12 results can be obtained with only a dozen activities:
13

- 14 • Production activities. The production activity designates all activities taking part to the
15 modification of the morphology of geometrical features composing workpieces. This
16 activity which carries out only one elementary machining operation (OP); on at least one
17 feature is considered consuming one tool, one machine and one machining fixture. The
18 cost of this activity is easy to assess since tools and machines cost are known and stored.
19
- 20 • Other production activities. The other production activities are 'preparation' activities.
21 Changes of tool, rotations of the milling table or changes of machining fixture are some
22 of them. The cost of these activities is defined by the user function to their time.
23
- 24 • Quality control activity. Quality activity performs this conformity control. When a
25 production activity has a process capability under a critical level, it generates one control
26 quality activity. Like a production activity, the cost of this activity is easy to assess since
27 tools and machines cost are known and stored.
28
- 29 • Recycling and Adjustment activities. When control activity establishes that some
30 workpiece parameters are out of range, considering its dimensional requirements, the
31 product has to be exited from the production line to rectify its defects. Two kinds of
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3 issues can be distinguished and for each of them, an activity has been designed. The first
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5 regards the respect of dimensional requirements of features composing workpieces. In
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7 case of out of range parameter, the control activity generates a recycling activity. This
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9 operation simulates the treatment of a rate of the production workpieces considered as
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11 rejects products. The cost of this activity is the sum of all previous activities (and
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13 consequently resources) used to produce these uncompleted and out of range workpieces.
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15 Thus, owing to this activity, impacts of producing difficult and risked to machine features
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17 are taking into account. The second difficulty regards issues appearing during the
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19 assembling of the final product. Indeed, even if workpieces composing the final product
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21 meet their tolerance requirements, the probability of not succeeding in assembling them
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23 together is not null. In this case, labours have to try several combinations of these
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25 workpieces until they fit together. This operation is simulated by the adjustment activity.
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34 In conclusion, several activities are designed to describe and quantify the process plan followed
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36 by the product. Each of them respects the definition of the concept of activity, and their impact
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38 on cost (Figure 5, Activity A32 - Figure 7, step 2).
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41 The ABC approach allows estimating *ProductionCost*, *RecyclingCost*, and *LabourCost* of the
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43 cost weighted risk. The following section details the estimation of the others parameters of this
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45 indicator: $P(\text{ProductionOk})$, $P(\text{OutOfRange})$, and $P(\text{NotAssemblable})$.
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49 3.3. Tolerance analysis and probability distribution estimation

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52 In fact, the evaluation of the cost weighted risk needs a statistical tolerance analysis (Activity
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54 A33 – Figure 5). Tolerance analysis has been the topic of a tremendous number of research
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56 publications (Hong *et al.* 2002), especially in the field of mechanical tolerancing. While analysis
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3 methods can be either deterministic or statistical, design models to analyse can be expressed in
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5 1D, 2D or 3D. The statistical tolerance analysis aims to characterize the sum dimension Y of the
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7 design equation $Y = f(X)$ in statistical terms, starting from an assumption a certain distribution of
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11 X s.

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13 This analysis is mainly based on the displacements composition. The products deviations are one
14
15 of the several displacements belonging to the product description: part deviations, gaps,
16
17 uncertainties of fixture, uncertainties of machining resources and functional characteristics.
18
19 These displacements can be modelled with the equation (Skowronski *et al.* 1997):
20
21

$$22 \quad Y = f(X) \quad (4)$$

23
24
25 Y and $X = \{x_1, x_2, x_3 \dots\}$ are both displacements. All of them are considered as continuous
26
27 random variables. The function f , which is a determinist relationship, links all of these
28
29 displacements. The aim of the further sections is to describe the different functions f used to
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31 evaluate and quantify the relationship between these displacements. For each specification, there
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33 are important questions that would need to be looked upon:
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37 • What is specified? A specification is a condition on a characteristic between
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39 geometrical features or on geometrical features.
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41 • Therefore, for each type of geometrical specification, what is the type of features
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43 and the type of characteristic involved?
- 44
45 • What is its mathematical representation?
- 46
47 • What is the cause of the variation of this characteristic?
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49 • How to define the function f ?
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51 • How to analyze these tolerances?
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The further sections answer these different questions on several types of specifications used by the ABTA method. Moreover for each of them, an example is given to illustrate the described specification and to show how it is managed in the activity based method.

3.3.1. Geometrical part specification analysis

The geometrical part specification analysis allows us to estimate $P(OutOfRange)$, which is similar to the assessment of a process plan. To do so, we adopt the same approaches as Legoff and Villeneuve to simulate in three dimensions the behaviour of a workpiece set-up and machining process. They applied the Small Displacement Torsor model to the process planning environment.

- **Feature specified:** These dimensional and form specifications concern only one feature; Geometrical specifications are a little more complicated than the previous case since it concerns at least two geometrical features of one part. Several specifications belong to these geometrical specifications: parallelism, perpendicularity, location...
- **Type of characteristics handled:** For these geometrical features, designers want to limit with these specifications:
 - Deviations of intrinsic characteristics (noted d_i) such as a boring diameter or its surface roughness... $T_{j\min} \leq d \leq T_{j\max}$,
 - Deviations of situation characteristics between the geometrical features (noted d_i) which is modelled by a Small Displacement Torsor. The mathematical representation of these geometrical part specifications is a set of constraints:
$$T_{j\min} \leq g_j(d_i) \leq T_{j\max} \text{ (Hong 2003).}$$
- **Cause of this variation and mathematical representation (function f):**

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- Since only intrinsic characteristics of features are regarded, these deviations are mainly due to only manufacturing resources uncertainties ($d_{resources}$) and thus on the activity. Consequently, this relationship can be mathematically expressed by enriching the formula (4): $d_i = f_1(d_{resources})$. Fitted to the ABTA method, only production activities are responsible for these intrinsic characteristics variations.
 - Since this kind of specification regards several geometrical features, several activities can take a part to the production of geometrical specifications: production activities, change of tools activities, change of set-up activities... Then, the resulting final part deviations and the respect of this kind of specification are not only due to resources uncertainties but several parameters are involved as the fixture uncertainties or the order of the used activities. A mathematical model is proposed: $d_i = f_2(d_{Fixtures}, d_{Resources}, ProcessPlan)$ (Anselmetti *et al.* 2005, Vignat *et al.* 2003, Tichadou 2005). In order to determinate activities responsible for part deviations, the analysis of the process is carried out in the same way than the ΔL method (Bourdet 1973, Tsai *et al.* 2005, Irani *et al.* 1989) (Figure 8).
 - In this case, the function f models the propagation of process dispersions between the datum and manufactured feature.
 - **Tolerance analysis technique:** For the statistical analysis of the real world problems, the Monte Carlo simulation method is frequently used (Karoufeh *et al.* 2002, Nigam *et al.* 1995, Laperriere *et al.* 2001). By generating the random variables for resource deviations from a certain distribution, the moments for part deviations can be estimated statistically. Therefore, the probability $P(OutOfRange)$ is estimated by Monte Carlo simulation.

3.3.1. Geometrical product requirement analysis

The geometrical product requirement analysis allows us to estimate $P(\text{ProductionOk})$, and $P(\text{NotAssemblable})$. Hong *et al.* (2002) distinguish two distinct categories, based on the type of input variations analysed: dimensional variations and geometric variations. The aim of this analysis is to evaluate the impact of manufacturing variations on the assembly requirements and the functional requirements; therefore, we adopt a 3D Tolerance propagation as Bourdet *et al.* (1997) to obtain the explicit function f ; and we use Monte Carlo simulation. The Monte Carlo simulation method is frequently used and adopted by most commercial software packages (Nigam *et al.* 1995, Laperriere *et al.* 2001). Based on the same approach for tolerance analysis, Clozel developed MecaMaster® (tolerance analysis software) which is used by AIRBUS, PEUGEOT...

- **Feature specified:** The assembly requirements and functional requirements can concern product features.
- **Type of characteristics handled, cause of their variation and mathematical representation (function f):** In this case, specified characteristics are:
 - Gaps which depend on the geometrical feature deviations of each part belonging to the assembly. By refining the global equation (4) these gaps can be mathematically modelled as: $g_j = f_3(d_i)$ where d_i parameter is a part deviation. The non interference between parts is the main constraint on gaps, as a consequence, gaps are mathematically limited: $0 \leq T_j \leq g_j$. T_j which is optional is designed essentially for ease the assembly. Several works have been carried out to find a way to describe this function f_3 in three dimensional issues (Roy *et al.* 1999, Ballot *et al.* 1997 and Giordano *et al.* 1993).

- Functional characteristics which depend on both geometrical features deviations and parts gaps. The expression (4) adapted to this case can be modelled as: $FC_j = f_4(d_i, g_i)$. The aim of the function requirement is to bounder these functional characteristics by specified limits: $FR_{i_{\min}} \leq G(FC_j) \leq FR_{i_{\max}}$ Several works deals with the definition of this function f_4 .

In brief, the geometrical tolerance analysis is based on displacements composition. The previous sections underline two major points. The first is that all displacements are directly or indirectly due to resources uncertainties and the activities order (ie. process plan). The second is that to be carried out this tolerance analysis has to find a reliable way to mathematically express all these function f_i to link this uncertainties to all other displacements (gaps, deviations, and so on...).

3.4. ABTA prototype Implementation:

The entire ABTA concept has taken shape into prototype software to evaluate the cost impacted by tolerance choices principally on the manufacturing processes.

[Figure 9 should be inserted here]

The static data model (Figure 9) has been proposed to describe four semantics views needed to realize ABTA method:

Activity handling: The activity class is characterised by the performance indicator and the probability of appearance. It has provides methods to generate sub-activities and calculate its cost. All activities types inherit from this class and so they inherit all of its capabilities.

Resources description: Each activity is linked to its needed resources. Resource class contained two essential parameters the cost and the deviations. All resources inherit from the 'Resource' class and make a resource catalogue model.

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4 **Product geometrical definition:** This geometrical product description is based on features
5 concept (Cunningham *et al.* 1988, Shah *et al.* 1988). A product is composed by several parts and
6 each part is composed by some features. These geometrical features are elementary geometrical
7 semantic sets of parameters used to describe an indecomposable geometrical object (Etienne *et*
8 *al.* 2006)0. The class '*Interaction*' models and quantifies the geometrical specification between
9 several features. Each feature is linked to activities which create the feature and control feature
10 characterises.
11

12
13 **Manufacturing information:** This package of data model presents the information of
14 manufacturing system that needed to produce geometrical features. '*Machining Fixture*' class
15 models how the part is geometrically located during the machining and how geometrical features
16 are produced. Indeed the class '*Geometrical Fixture*' describes, for a machining set up, the
17 geometrical features composing it. The link between manufacturing fixture and manufacturing
18 resources is realised by '*Compatibility*' class. Moreover it describes compatibilities between
19 resources themselves too. This part of the UML model is the support of capitalization interfaces
20 which are designed to help manufacturing experts to express how their technical choices are
21 motivated. An example of these user interfaces, based on the cutting tool charts concept
22 (Villeneuve *et al.* 1993) 0is given in Figure 10.
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This modelling solution is enough flexible to be enriched with the addition of new resources,
knowledge or activities. However, the object structure of design requirements (functional and
tolerance goals) which are handled by the ABTA is not presented in this model.

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3 ABTA prototype is developed and coded into an object oriented environment (Visual Basic.net)
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5 and can perform the main objective of the ABTA concept. Several user interfaces allow expert to
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7 express their knowledge:
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- 10 - One to express the ordered list of mountings. Indeed the program does not generate any
11 mounting. In this case, users have to describe for each mounting: entities to machine,
12 entities needed to locate the workpiece and the type of the machine used,
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- 15 - One to describe the machining resources available and how to use them,
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- 18 - One to describe the product, entities composing it and their geometry,
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- 21 - And one to quantify algorithm's parameters.
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25 **[Figure 10 should be inserted here]**
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27 Some user interfaces are given in the Figure 10. The results of this software are the cost resulting
28 of the best process plan generated, the resources needed and the ordered list of activities used.
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30 This information are synthesised into a simple diagram as illustrated in Figure 6.
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33 34 35 4. CONCLUSION 36

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38 In conclusion, this paper describes an original method to evaluate the relevance of a tolerance
39 synthesis (more precisely the tolerance allocation) considering the manufacturing cost impacted
40 by tolerances. As opposed to current methods trying to directly calculate the cost of tolerances,
41 this way, more flexible, assesses the cost of a solution due to designers' choices.
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45 Based on activity concept, this method considers the links between design and manufacturing
46 phases and takes into account all issues regarding tolerances production. Supported by statistical
47 tools such as Monte Carlo simulation or variances analysis of resources deviations, the main
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3 activities playing a part in the quality of the product are analysed to check if workpieces
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5 produced meet functional requirements.
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8 Nevertheless, this solution has some defects. Combinatory explosion in the process generation is
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10 the worst of them. In order to avoid it, the constraints programming is currently studied to delete
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12 not machinable or too expensive solutions the earliest possible.
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15 **[Figure 11 should be inserted here]**
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18 This activity based on method remains the first step to the tolerances optimisation. Since this
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20 method compares and evaluates different tolerances allocations, automating it and linking it with
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22 an optimization tool, as a genetic algorithm, can become a good way to optimize tolerances. This
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24 association has been performed (Figure 11).
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REFERENCES

- 1
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4
5
6 Anselmetti, B. and Louati, H., 2005. Generation of manufacturing tolerancing with ISO
7 standards. *International Journal of Machine Tools and Manufacture*, 45, pp.1124-1131.
8
9
10 Ballot, E. and Bourdet, P., 1997. A computation method for the consequences of geometric
11 errors in mechanisms, *Proceedings of the CIRP Seminar on Computer Aided Tolerancing*,
12 Toronto, Canada.
13
14
15 Bourdet, P., 1973. Chaînes de cotes de fabrication. In: *L'ingénieur technicien de l'enseignement*
16 *technique*, pp.191.
17
18
19
20
21
22 Bramail, D.G., McKay, K.R. and Maropoulos P.G., 2002. Manufacturability evaluation of early
23 product designs. *Proceedings of the first CIRP Seminar on the Digital Enterprise*
24 *Technology*, pp. 141-146.
25
26
27
28
29 Chase, K. and Parkinson, A. R., 1991. A Survey of Research in the Application of Tolerance
30 Analysis to the Design of Mechanical Assemblies, *ADCATS Report*, 91(1).
31
32
33
34 Cunningham, J.J. and Dixon, J.R., 1988. Designing with Features: the Origin of Features.
35 *Proceedings of the ASME Symposium on Computers in Engineering*, CIE, San Francisco
36 CA, pp.237-243.
37
38
39
40
41 Dantan, J.Y., Nabil A. and Mathieu L., 2003. Integrated Tolerancing Process for Conceptual
42 Design. *Annals of CIRP 2003*, 52(1), pp. 135-138.
43
44
45
46 Diplaris, S.C. and Sfantsikopoulos, M. M., 2000. Cost-tolerance function. A new approach for
47 cost optimum machining accuracy. *International Journal of Advanced Manufacturing*
48 *Technology*.
49
50
51
52
53
54
55
56
57
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60

- 1
2
3 Etienne, A., Dantan, J.Y., Siadat, A. and Martin, P., 2007. Cost estimation for tolerance
4 allocation. *In: Proceedings of the 10th CIRP International Seminar on Computer Aided*
5
6 *Tolerancing*, Erlangen, Germany.
7
8
9
10 Etienne, A., Dantan, J.Y., Siadat, A. and Martin, P., 2006. An improved approach for automatic
11 process plan generation of complex boring. *Computers in Industry*, 57(7), pp.663-675.
12
13 Etienne, A., Dantan, J.Y., Siadat, A. and Martin, P., 2006. Process plan selection integrating
14 tolerance allocation by genetic algorithm and constraints satisfaction algorithms. *In:*
15 *Proceedings of the 5th CIRP International Seminar on Intelligent Computation in*
16 *Manufacturing Engineering (CIRP ICME '06)*; Naples, Italy, pp.513-517.
17
18
19
20 Giordano, M. and Duret, D., 1993. Clearance space and deviation space, application to three
21 dimensional chains of dimensions and positions. *Proceedings of the CIRP Seminar on*
22 *Computer Aided Tolerancing*, ENS Cachan, France.
23
24
25
26
27
28
29
30
31
32 Hong, Y. S. and Chang, TC, 2003. Tolerancing algebra: a building block for handling tolerance
33 interactions in design and manufacturing. *International Journal of Production Research*,
34 41(1), pp.47-63.
35
36
37
38
39 Hong, Y. S. and Chang, T-C., 2002. A Comprehensive Review of Tolerancing Research.
40 *International Journal of Production Research*, 40(11), pp. 2425-2459.
41
42
43
44 Iannuzzi, M.P. and Sandgren, E., 1995. Tolerance optimization using genetic algorithms:
45 Benchmarking with manual analysis. *In: Proceedings of the Fourth CIRP Design Seminar*
46 *on Computer-Aided Tolerancing*.
47
48
49
50
51 Irani, S.A., Mittal, R.O. and Lehtihet, E.A., 1989. Tolerance Chart Optimization. *International*
52 *Journal of Production Research*, 27(9), pp. 1531-1552.
53
54
55
56
57
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59
60

- 1
2
3 Johnson, H.T. and Kaplan, R.S., 1987. *Relevance cost, the rise and fall of management*
4 *accounting*, Harvard Business School Press.
5
6
7
8 Kharoufeh, J.P., Chandra, M.J., 2002. Statistical tolerance analysis for non-normal or correlated
9 normal component characteristics. *International Journal of Production Research*, 40(2),
10 pp.337-352.
11
12
13
14 Laperriere, L. and Kabore, T., 2001. Monte Carlo simulation of tolerance synthesis equations.
15 *International Journal of Production Research*, 39(11), pp.2395-2406.
16
17
18
19 Layek, A.M. and Nutthapol, A., 1996. An analytical approach to process planning with rework
20 option. *International Journal of Production Economics* 46-47, pp. 511-520.
21
22
23
24 Lee, J. and Johnson, G.E., 1995. Optimal tolerance allotment using a genetic algorithm and
25 truncated Monte Carlo simulation. *Computer Aided Design*, 25, pp.601-611.
26
27
28
29 Lööf, J., Hermansson, T. and Söderberg, R., 2005. An Efficient Solution to the Discrete Least-
30 Cost Tolerance Allocation Problem with General Loss Functions. In: *Proceedings of the 9th*
31 *CIRP International Seminar on Computer Aided Tolerancing*, April 11-12, Tempe, Arizona,
32 USA.
33
34
35
36
37
38
39 Mejbri, H., Anselmetti, B. and Mawussi, K., 2005. Functional tolerancing of complex
40 mechanisms: Identification and specification of key parts. *Computers & Industrial*
41 *Engineering*, 49(2), pp. 241-265.
42
43
44
45
46 Nigam, S.D. and Turner, J.U., 1995. Review of statistical approaches to tolerance analysis.
47 *Computer Aided Design*, 27(1), pp.6-15.
48
49
50
51 Roy, U. and Li, B., 1999. Representation and interpretation of geometrical tolerances for
52 polyhedral objects. *Computer Aided Design*, 31(4), pp. 273-285.
53
54
55
56
57
58
59
60

- 1
2
3 Roy, U., Pramanik, N., Sudarsan, R., Sriram, R.D. and Lyons, K.W., 2001. Function to form
4 mapping: model, representation and application in design synthesis. *Computer Aided*
5
6 *Design*, 33, pp. 699-719.
7
8
9
- 10 Schmitt, R. and Behrens, C., 2007. A Statistical Method for analyses of Cost- and Risk optimal
11 Tolerance Allocations based on Assured Input Data. *In: Proceedings of the 10th CIRP*
12 *International Seminar on Computer Aided Tolerancing*, Erlangen, Germany.
13
14
15
- 16 Sellakh, R., Riviere, A., Chevassus, N. and Marguet, B., 2001. An assisted method for specifying
17 ISO tolerances applied to structural assemblies. *In: Proceeding of CIRP Seminar on*
18 *Computer Aided Tolerancing*, France.
19
20
21
22
23
- 24 Shah, J.J., Sreevalsan, P., Rogers, M., Billo, R. and Matthew, A., 1988. Current status of features
25 technology. *Technical Report R-88-GM-04.4*, CAM-I Inc., Arlington, TX.
26
27
28
- 29 Shan, A. and Roth, R.N., 2003. Genetic algorithms in statistical tolerancing. *Mathematical and*
30 *Computer Modeling*, 38, pp. 1427-1436.
31
32
33
- 34 Skowronski, V.J. and Turner, J.U., 1997. Using Monte Carlo variance reduction in statistical
35 tolerance analysis. *Computer Aided Design*, 29(1), pp. 63-69.
36
37
38
- 39 Speckhart, F.H., 1972. Calculation of tolerance based on minimum cost approach. *Journal of*
40 *engineering for industry*, Transactions of ASME, 4, pp. 447-453.
41
42
43
- 44 Spotts, M.F., 1973. Allocation of tolerances to minimize cost of assembly. *Journal of*
45 *engineering for Industry*, Transactions of the ASME, 95, pp. 762-864.
46
47
48
- 49 Tichadou, S., 2005. *Modélisation et quantification tridimensionnelles des écarts de fabrication*
50 *pour la simulation d'usinage*, Génie Mécanique, Ecole centrale de Nantes et Université de
51 Nantes.
52
53
54
55
56
57
58
59
60

- 1
2
3 Tsai, J. C. and Cheng, K.C., 2005. Cost-Effective Tolerance Allocation for Machining Processes.
4
5 *In: Proceeding of the 9th CIRP International Seminar on Computer Aided Tolerancing,*
6
7
8 Tempe, Arizona, USA.
9
- 10 Vignat, F. and Villeneuve, F., 2003. 3D Transfer of tolerances using a SDT approach:
11
12 application to turning process. *Journal of computing and information science in engineering,*
13
14 3(1), pp.45-53.
15
16
- 17 Villeneuve, F. and Barrabes, M., 1993. Object Data Base, AI and CAD-CAM : Application to
18
19 the process Ascending Generation (PAG) concept, *Computers in Design, Manufacturing and*
20
21 *Production*, 7th Annual European Computer Conference (IEEE), Compeuro 93, France,
22
23 LURPA, pp.320-329.
24
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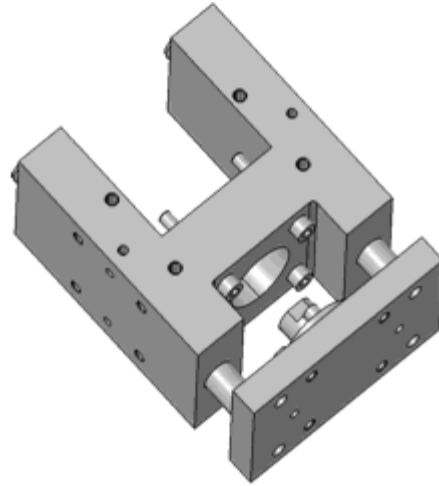


Figure 1: The example part illustrating the ABTA concept

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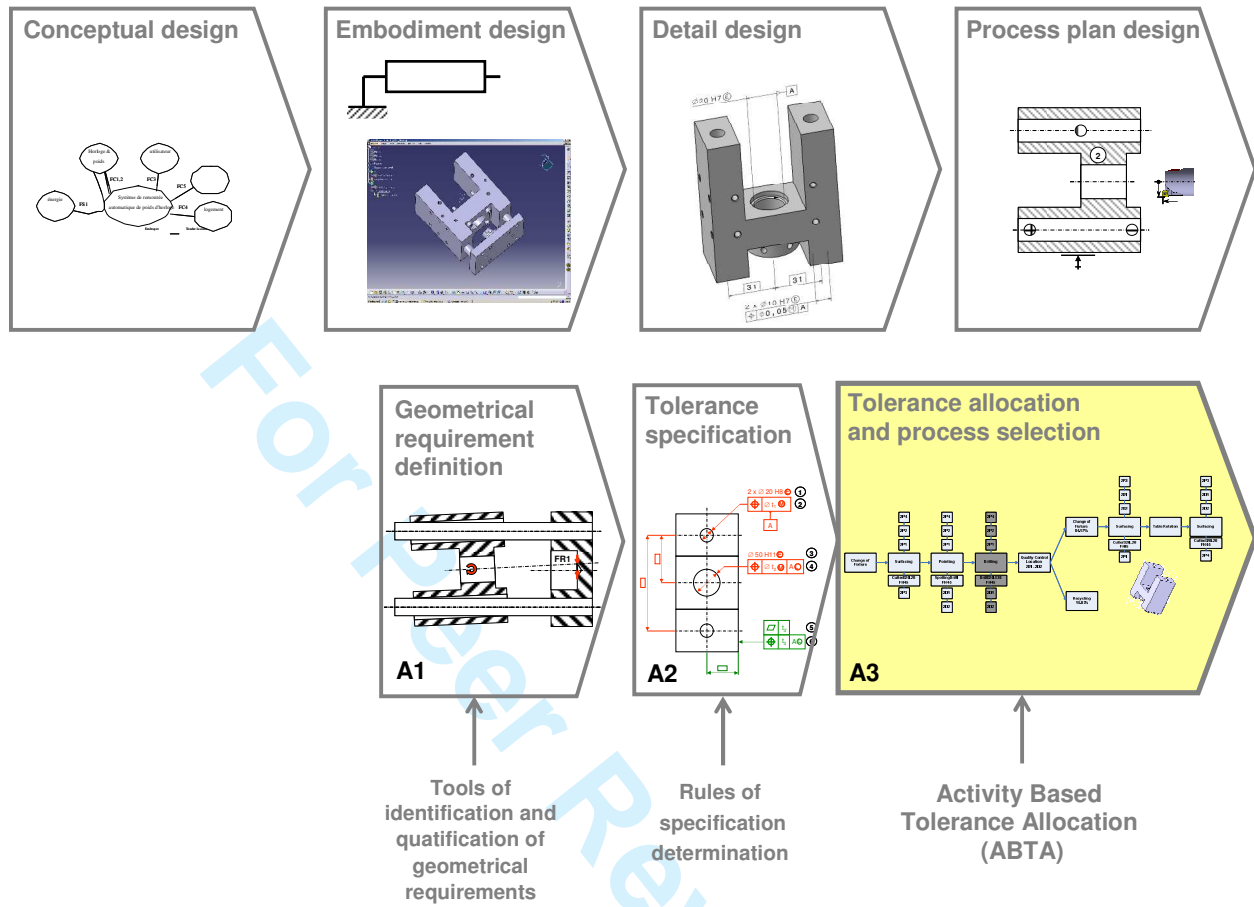


Figure 2: Design and Tolerancing processes

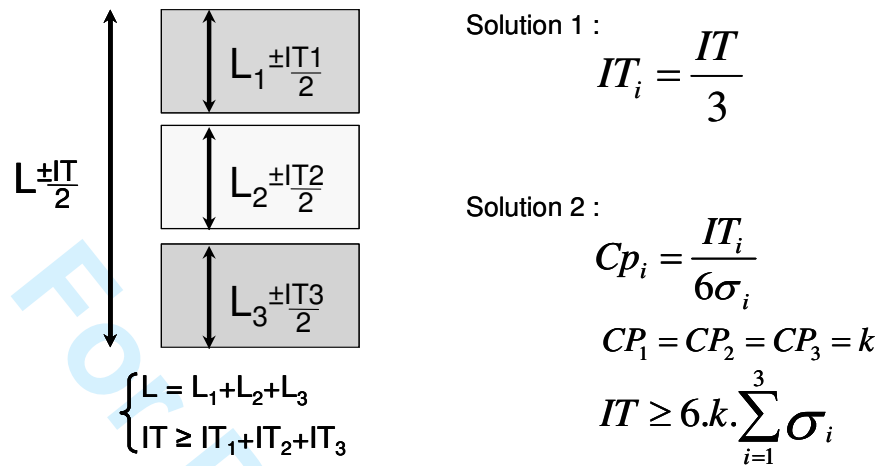


Figure 3: Two examples of tolerances allocations

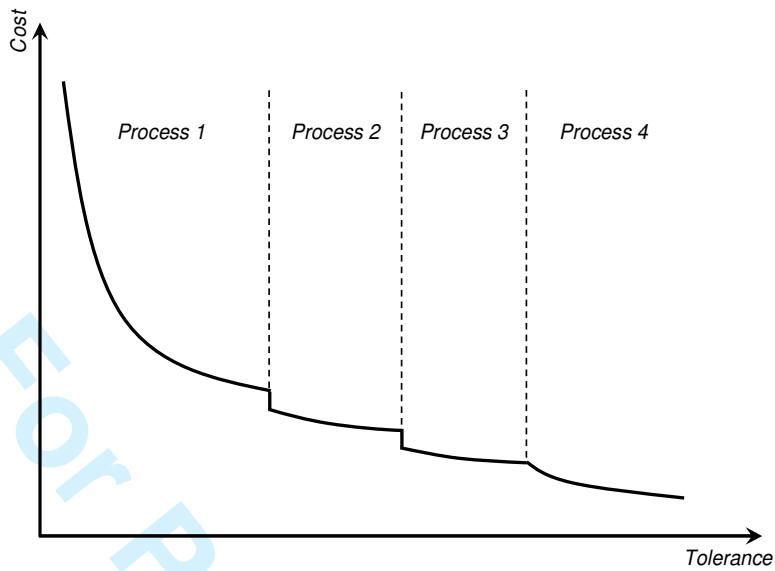


Figure 4: Tolerance cost of combined processes

For Peer Review Only

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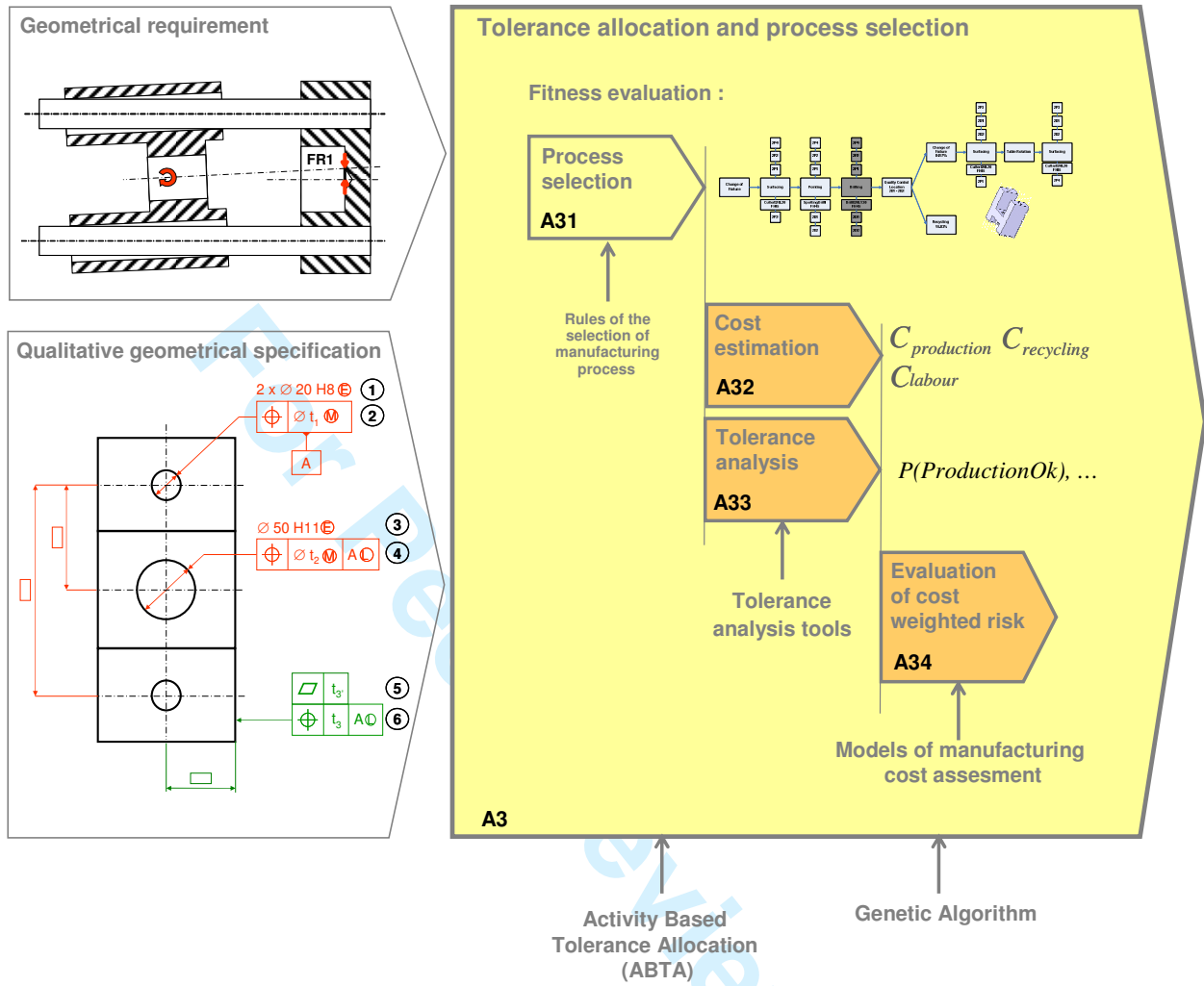


Figure 5: Tolerance allocation process

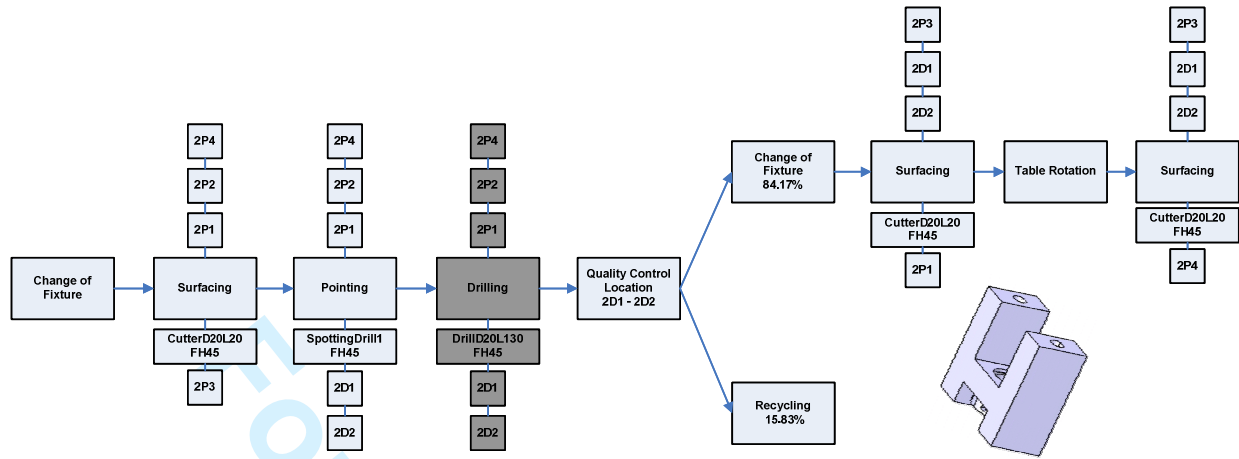


Figure 6: Extract of one generated process plan producing the example workpiece

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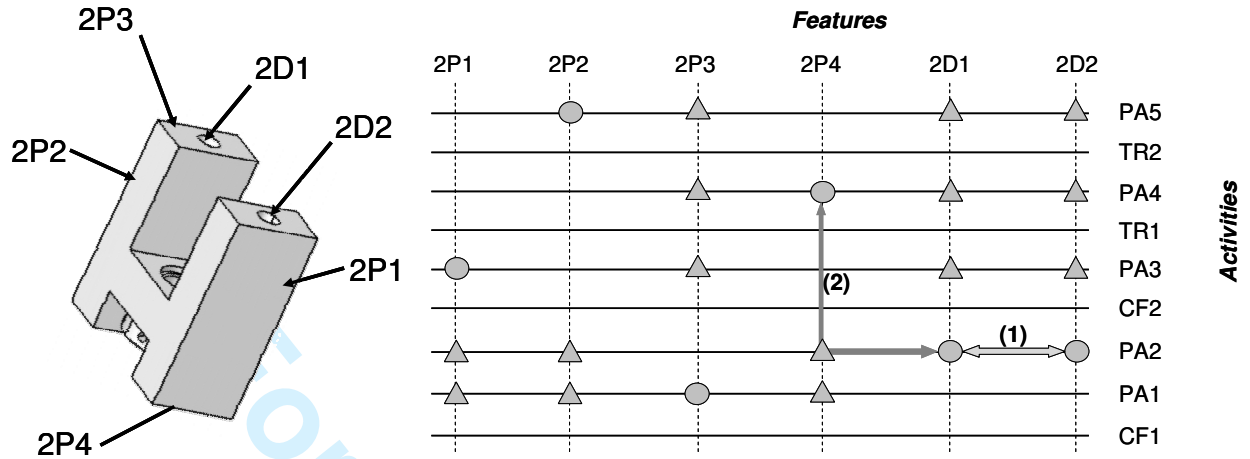


Figure 7: Tolerance analysis in 2D representation (ΔL)

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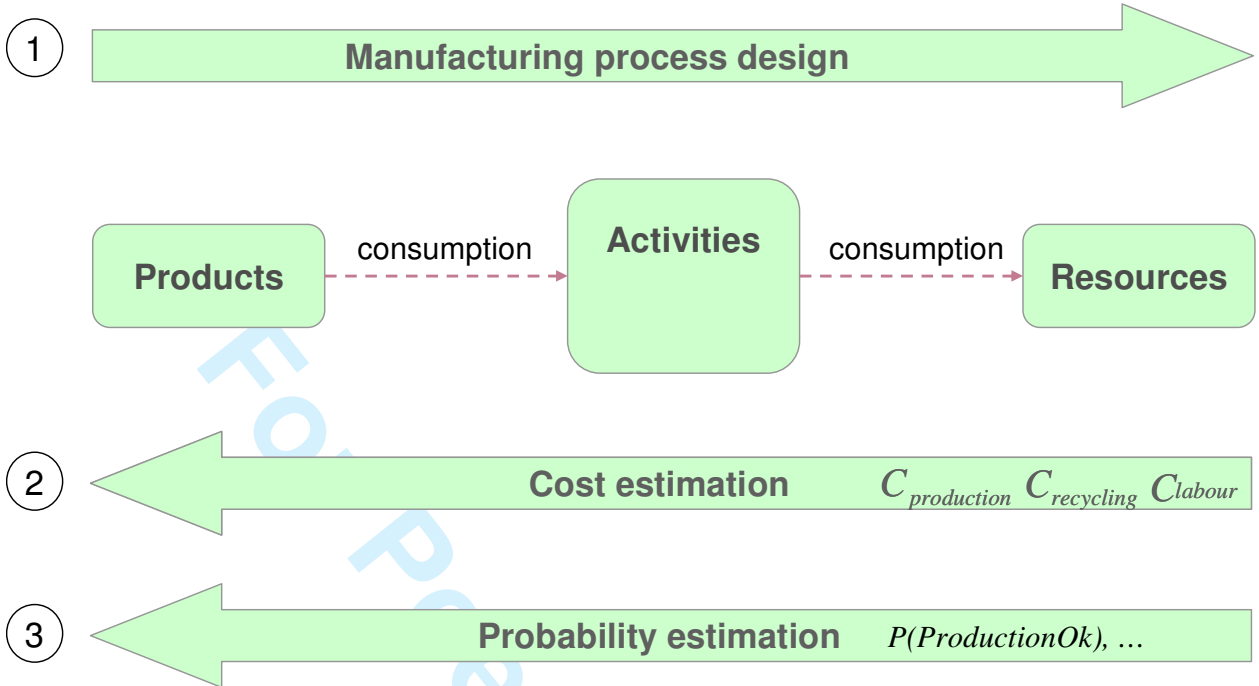


Figure 8: ABC / ABTA concepts

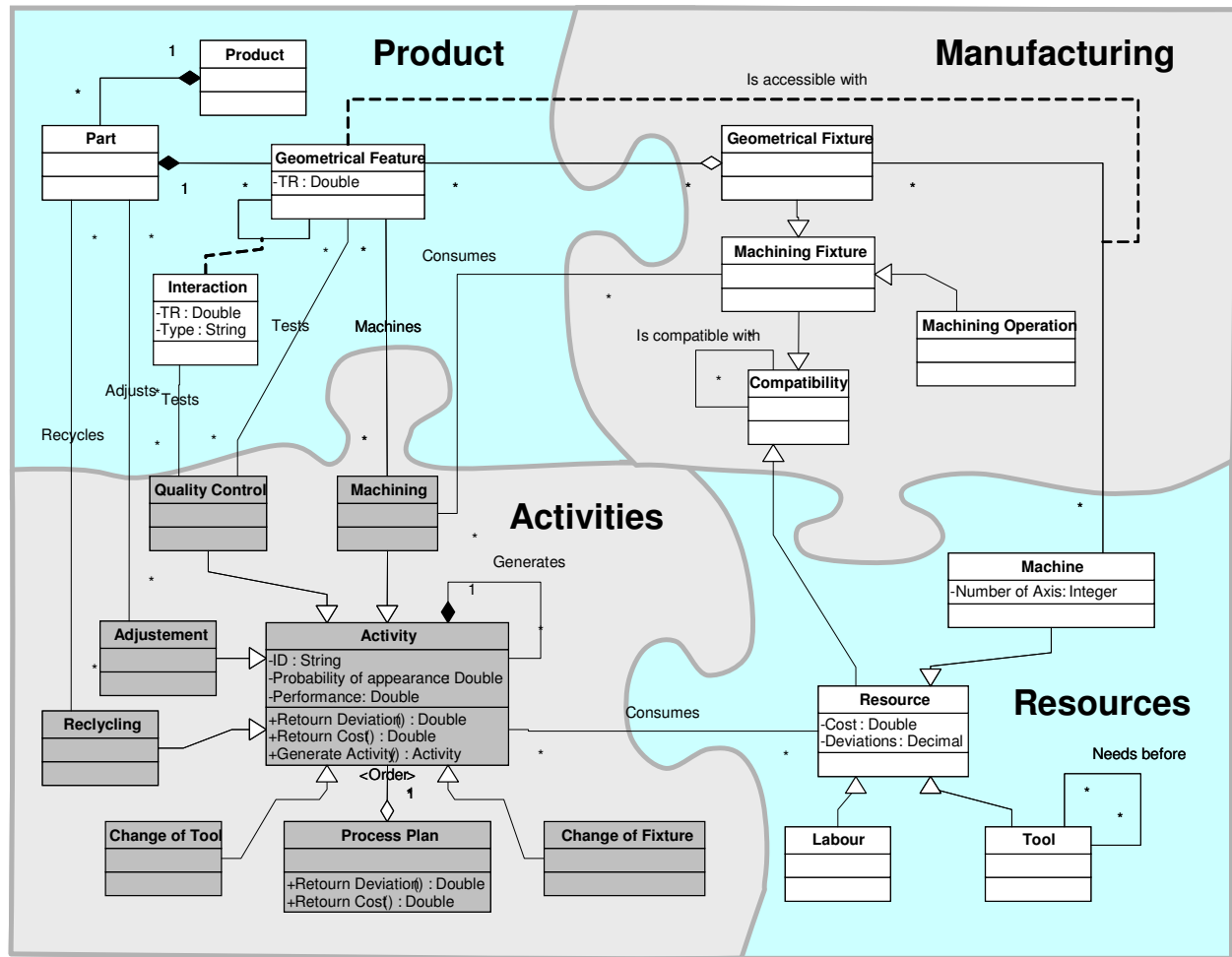


Figure 9: UML representation of the activity concept

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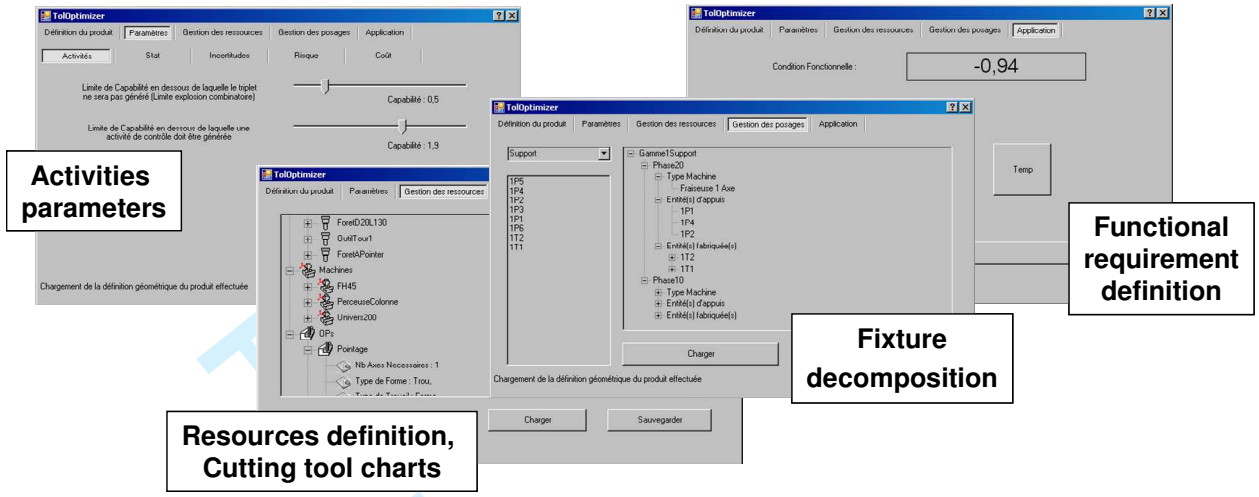
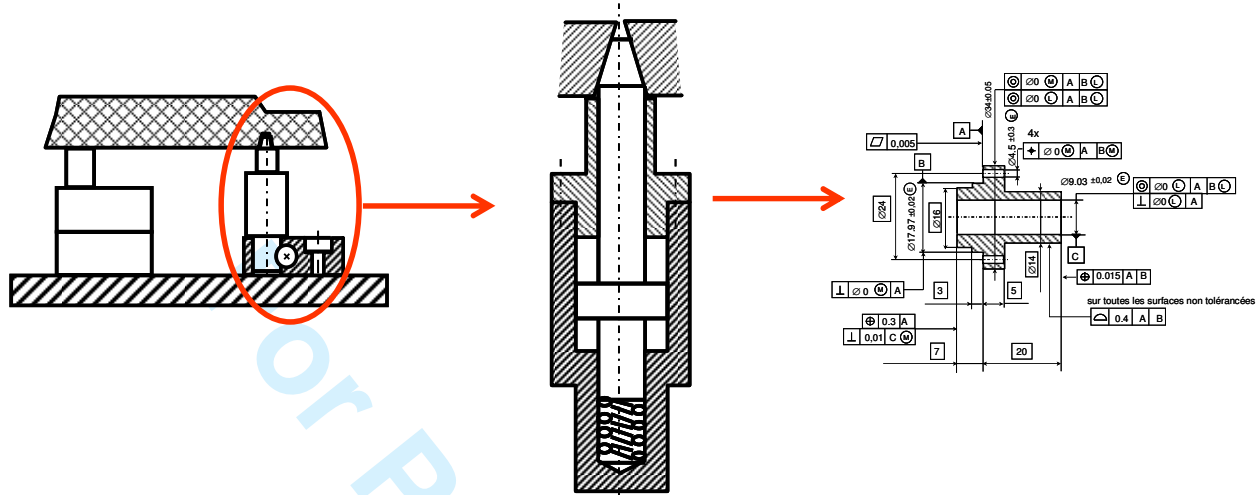


Figure 10: Some user interfaces of the developed software



Allocation approach :	Proportional scaling	Proposed approach
Tolerance analysis approach :	Worse Case approach	Monte Carlo Simulation
t1	1	0,8639
t2	0,04	0,06914
t3	0,033	0,05262
t4	0,033	0,02051
t5	0,04	0,08691
t6	0,04	0,06465
t7	0,04	0,03249
t8	0,04	0,0771
Cost :	3,3	2,7

Figure 11: Example of tolerance allocation – Comparison with the worse case approach