Int J Interact Des Manuf (2008) 2:207–218
DOI 10.1007/s12008-008-0055-3

ORIGINAL PAPER

Variation management by functional tolerance allocation and manufacturing process selection

Alain Etienne · Jean-Yves Dantan · Jawad Qureshi · Ali Siadat

Received: 28 August 2008 / Revised: 19 September 2008 / Accepted: 22 September 2008 / Published online: 15 October 2008

Abstract The imperfections of the manufacturing process lead to functional characteristics degradation, and therefore product quality. To ensure a certain level of product quality, the synthesis of tolerance (tolerance design) aims to determine the acceptable limits of the characteristics of parts, assemblies... The allocation or synthesis of functional tolerances is an important step in the design process which takes place generally during the detailed design and greatly impacts the design of the manufacturing process, manufacturing and product control. That is why it is important, when functional tolerances are quantified, to take into account their impacts on the manufacturing cost and product quality. These two concepts (manufacturing cost and product quality) are usually considered as conflicting goals. The proposed approach aims to allocate the functional tolerances that provide the best ratio between functional performances and manufacturing cost. It is based on the "Key Characteristics" approach, developed by Boeing coupled with an activities approach. This optimization is carried out by a genetic algorithm. The process selection is performed by a constraint satisfaction algorithm. Finally, the impacts of process choices are assessed with the Monte Carlo simulation which calculates the behavior and quality of the resulting product.

A. Etienne · J.-Y. Dantan (✉) · J. Qureshi · A. Siadat
L.G.I.P.M., Arts et Métiers ParisTech Metz,
4 rue A. Fresnel, 57070 Metz Cedex, France
e-mail: jean-yves.dantan@metz.ensam.fr

A. Etienne
L.A.S.M.I.S., U.T.T., 12 rue Marie Curie, BP 2060,
10010 Troyes, France

J. Qureshi
Higher Education Commission, Sector H-9,
Islamabad, Pakistan

Keywords Tolerance · Quality · Tolerance synthesis and allocation · Key characteristics · Activity-based costing

1 Introduction

Considering the context of integrated engineering, the integration consists in taking into account all constraints appearing in the product lifecycle in the earliest stages of product design. As a consequence of this integration, products are more adapted to the manufacturing process and thus production costs are reduced. Indeed, the manufacturing costs of a product drastically depend on decisions taken during design stage. Mistakes made during design process stages may have an impact of up to 70% of manufacturing costs. So, it is important to consider manufacturing constraints in the early stages of the design process, to identify relevant parameters affecting the product performance and its cost and to evaluate them to ensure the global product optimization. Many factors, technological, organizational or economic, should be taken into account; however, in this paper, only geometric variations of parts are considered.

The inherent inaccuracies of manufacturing machines imply differences between the ideal shape of the parts of a mechanism and the produced shape. Moreover, these differences are variable when a series of mechanisms is considered. This well-known fact has a consequence, the need to control the geometrical variations of the products to manage their quality. For this purpose, it is necessary to be able to express tolerances or geometrical specifications. The aim of the tolerancing activity is to define acceptable limits of geometrical deviations of workpieces to ensure a certain level of quality defined by geometric requirements.

The field of tolerancing has been broadly divided in the areas of tolerance representation, tolerance analysis and

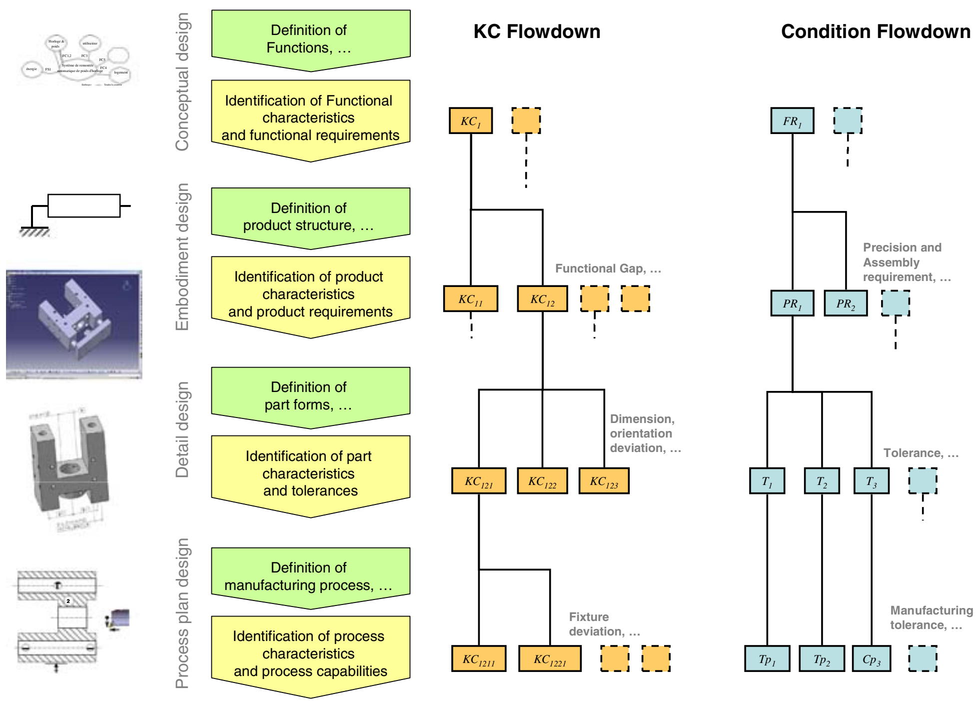


Fig. 1 Design process and characteristics modeling

tolerance allocation. Tolerance representation deals with the subject of providing the framework and common semantics for representing and modeling the tolerances on a component, where as tolerance analysis involves evaluating the effect of geometrical variations of individual part or subassembly dimensions on designated functional characteristics or assembly characteristics of the resulting assembly. Tolerance analysis takes a given set of component tolerances and calculates on the resultant the variation in the assembly. Through iteration, component tolerances are tightened to meet assembly tolerances. Tolerance allocation uses overall assembly tolerances and allocates component tolerances based on relative contributions to the assembly and production costs. Tolerance allocation can result in looser component tolerances and better matching of product and process. Yet, work is still required to make these systems more efficient for complex assemblies, standardized for 3D assembly analysis, and fully generative for functional equations. Statistical tolerance tools studied in response to excessive manufacturing costs associated with worst-case tolerance analyses rely on detailed process capability data. Process capability refers to the inherent variability in the parameters or properties of a processes output including specified dimension or its location.

Out of the three main fields discussed in the earlier sections, this article focuses on the areas of tolerance allocation. The allocation of functional tolerances is an important step in the design process which is generally set during the detailed design and has a great impact the design of the manufacturing process, manufacturing and product control. So, it is important to determine the functional tolerances to take into account their impacts on the *manufacturing costs* and *product quality*.

In case of complex mechanisms, assessing the impact of tolerances on *product quality* requires the management of characteristics, their dependencies and causalities between tolerances. The approach based on key characteristics (KCs) meets this need by managing characteristics and causalities between tolerances (Dantan et al. [7] detailed this approach and an information model to manage Key Characteristics). The implementation of the KCs approach is based on a gradual decomposition of characteristics from the customer needs (illustrated in Fig. 1) to the parts characteristics and process characteristics: KCs are hierarchically represented into a tree. This "tree" structure or, more precisely this dependency graph, is known as KC flowdown (Fig. 1) [7,21]. Suh [19] suggests a similar approach that focuses not only on deviations but also on the values of the parameters. The tree levels are linked to the granularity level of the product description. In addition, they can be associated to the different stages of the design process (Fig. 1). It is possible to read this KCs tree way up or down.

At each level of this tree or at each stage of the design process, designers have to define and quantify conditions on the characteristics—these requirements are gathered into specifications for the next stage of the design process. The causalities linking requirements perform the translation of the customer needs to the parts specifications... The "Condition flowdown" (Fig. 1) describes the causal relationships between these requirements [7,10,15]. As a consequence, at each step the tolerance allocation issue rises.

This article concerns the optimization of tolerance allocation, analysing the impact on the manufacturing cost of design choices. First, the problems of tolerance allocation and the difficulty of evaluating its cost are detailed (Sect. 2). The proposed assessment of the manufacturing cost impacted by the tolerances is based on an activity approach, detailed in the Sect. 3. Then the optimization method is described step by step. Finally the software prototype, coded to prove the accuracy of the procedure, and some results are exposed.

2 Tolerance allocation

The tolerance synthesis (or usually named tolerance allocation) aims to distribute one or more requirements (tolerances) defined at a description level of the product or process on the characteristics defined in the lower level to ensure interchangeability of components of this level (as illustrated in the example in Fig. 2).

Tolerance allocation or tolerance synthesis is a design function. It is performed early in the product development cycle, before any parts have been produced or tooling ordered. It involves first, deciding what tolerance limits to place on the critical clearances and fits for an assembly, based on performance requirements; second, creating an assembly model to identify which dimensions contribute to the final assembly dimensions; third, deciding how much of the assembly tolerance to assign to each of the contributing components in the assembly [2].

In order to illustrate the benefits of tolerance allocation approaches, a simple example is detailed in Fig. 3, which shows an assembly composed by three parts. A requirement on the stacking of these three parts is identified and a tolerance on each part ensures compliance with this requirement. The tolerance allocation is to determine the values of IT_1, IT_2, and IT_3, several approaches are possible.

The first approach consists in balancing the distribution of the tolerance interval linked to the requirement (1). This approach takes no account of the tolerance impacts on the manufacturing process (cost, capability...).

$$\mathrm{IT}_i = \frac{\mathrm{IT}}{3} \tag{1}$$

The second approach consists of definition of the tolerance interval to ensure the capability balance of the manufacturing means [11] (2). This approach presumes that the manufacturing process is defined before the tolerance allocation, leading to a non-optimization of the cost.

$$Cp_1 = Cp_2 = Cp_3 = k; \quad \text{where } Cp_i = \frac{\mathrm{IT}_i}{6\sigma_i};$$
$$\text{thus IT} \geq 6k \sum_{i=1}^{3} \sigma_i \tag{2}$$

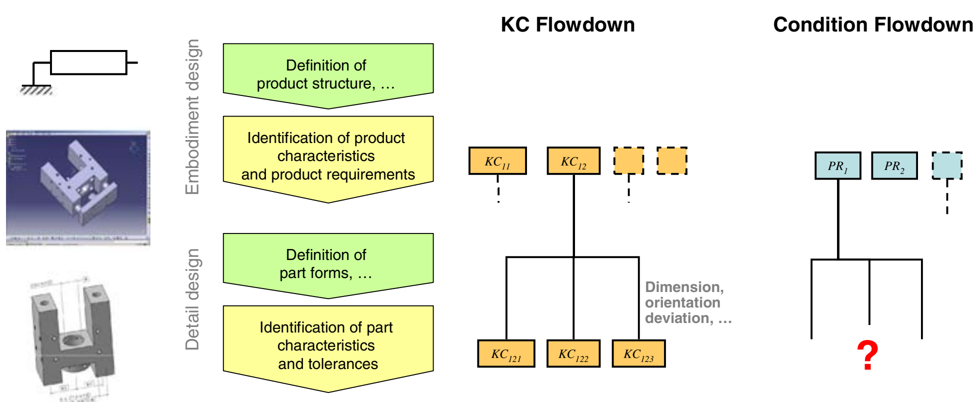


Fig. 2 The issue of tolerance allocation in the detailed design stage

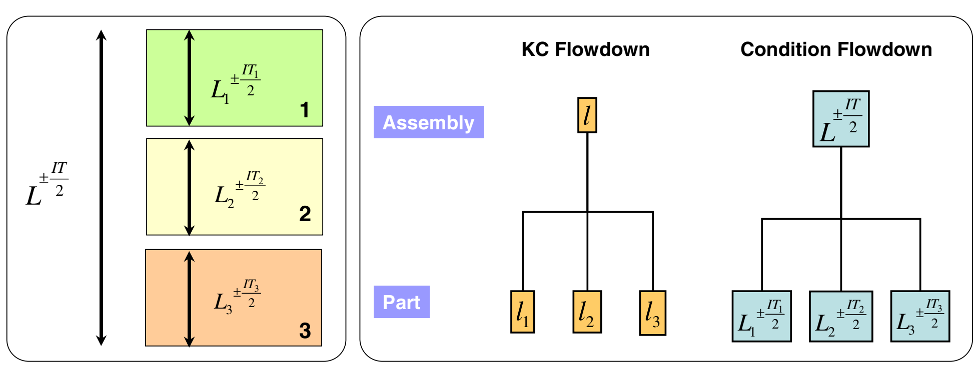


Fig. 3 Simple example of geometrical tolerance allocation

As noted in the introduction of this paper, the tolerance allocation must insure a certain level of product quality and must minimize the manufacturing costs. A third approach is based on the Taguchi loss function [20] which formalizes the loss due to a variation (3).

$$L_i = k_i(\sigma_i^2 + \mu_i^2) \tag{3}$$

In the same way, the fourth approach is based on parametric equations of the cost of each tolerance. This solution is mainly based on mathematical functions (such as power, exponential or polynomial functions [4,5,14,18]) which only express the manufacturing cost considering the tolerance interval to produce (4). They occur mainly in the following form:

$$C(t) = A + \frac{B}{t^{\beta}}. \tag{4}$$

This model is easy to use and can quickly estimate the tolerance cost knowing the values of A, B and β parameters. However, the determination of these parameters, such as k_i parameter in the case of TAGUCHI loss function, depends on the company context, the nature of the product and the nature of the geometric specification [6]. This determination is only relevant in the case of routine design and manufacture, since it requires quantified data on similar products. The majority of the published articles on tolerance allocation are based on optimization, most of which use the cost-tolerance models. In addition to the difficulty of evaluation of these parameters, their validity is strongly limited and thus difficult to generalize in the industrial framework. Indeed since work pieces are machined in several conditions (multiple operations, sites, machines and tools), there are too many parameters to isolate, model and evaluate. To do so, some approaches use design of experiments to identify the cost function parameters. Considering the above situation, these methods do not seem relevant for evaluating the cost of tolerance with parametric models.

In this case, the tolerance allocation based on the losses or cost minimizing, by using the approaches 3 and 4, is applicable in a limited context. Moreover, "Minimizing and constraining the manufacturing cost of the product, in order to product requirements and tolerances are met," is an optimization problem generally over-constrained: there is no solution satisfying all these conflicting constraints. A solution to this issue consists in using the concepts of fuzzy logic to satisfy *the best* of all these conflicting constraints and find a *reasonable compromise* [1].

This paper suggests another solution based on the following definition of cost: "A cost is only a measure [...] of consequences (past or future, *but very likely*) of a specific action" [12,13]. To assess costs, the path of a product through the company's activities has to be recognized and the consequences in terms of resource consumption have to be identified too. Thus, this paper proposes to weigh the costs of each activity by the *occurrence* of this activity and its *efficiency* [6,8]:

$$\begin{aligned}\text{Cost} = {} & \frac{C_{\text{production}}}{P(\text{Ok})} + C_{\text{recycling}} \cdot P(\text{Out of Range}) \\ & + C_{\text{labor}} \cdot P(\text{Not Assemblable}) + \cdots \end{aligned} \tag{5}$$

In Eq. 5, $C_{\text{production}}$ models the cost of resources necessary to the product manufacturing and its associated tolerances, this cost can be estimated after the selection of the manufacturing process by using the ABC method; $P(\text{Ok})$ is the production activities efficiency (probability of manufacture products respecting all tolerances. $C_{\text{recycling}}$ models the reworking or recycling cost of products having out of range parameters; $P(\text{Out of Range})$ is the probability of the occurrence of reprocessing activity. C_{labor} evaluates the cost of dismantling workpieces and their reintegration into the assembly line; $P(\text{Not Assemblable})$ is the occurrence of these reassembling activities. The evaluation of these parameters can be carried out with activities based approaches.

3 Activity-based approach

Indeed, the *cost* or a *deviation* is only the past or future *consequence* of one *activity*. To estimate each term defined in Eq. 5, an approach based on activities seems the most relevant.

3.1 Activity-based costing

The ABC method which has been mainly expanded in the 1980s [12,13], consist of breaking the activities hierarchy within a company (the difference between direct activities, considered as productive, and support activity, seen as unproductive, is not allowed).

The ABC method starts by splitting the company work into several significant activities. This method is then based on the analysis of links and causalities among these activities. Indeed, the ABC method concept can be summarized as follows: "products consume activities, and activities consume resources" (as shown in Fig. 4).

After the identification of activities, costing requires the definition of drivers quantifying them:

- *Resources driver*: this driver is used to allocate resources between activities (for instance: number of hours devoted to each activity, to study the wage distribution, quantity raw materials needed by each activity...). Such driver eases costs management.
- *Cost driver*: the performance level of activity and its resources consumption depend on this parameter (quality of raw materials received, staff training and experience, skill level of labor...).

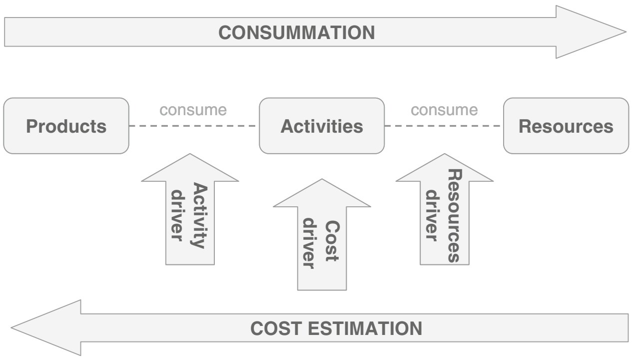


Fig. 4 The activity-based costing approach

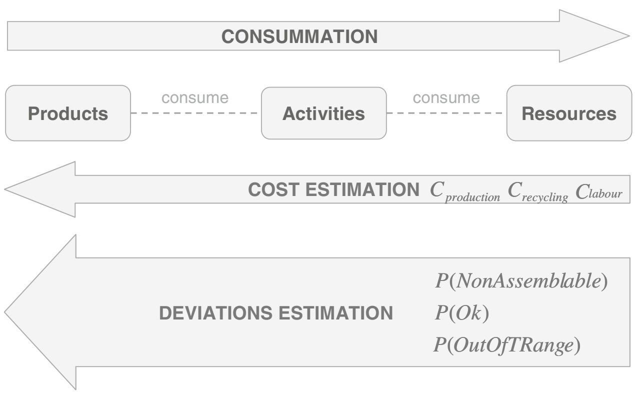


Fig. 5 ABC improvements for the tolerance allocation support

- *Activity driver*: it is equal to the unit work. This driver helps to distribute the activities costs between objects cost (as, for instance: hours of direct labor, workpieces manufactured, number of orders...).

The ABC method is very interesting since it both improves the accuracy of cost assessments and follows easily the cost structure evolution where the weight of indirect costs is increasingly important. It is based on the use of cost drivers that link the activity costs to the products associated to the resources consumed by these activities. This approach helps to evaluate the parameters defined in Eq. 5: $C_{\text{production}}$, $C_{\text{recycling}}$, C_{labor}.

3.2 Extension of the ABC method: ABx

The product imperfections which are modeled into the KC flowdown as "product" characteristics deviations are generally due to the manufacturing process and manufacturing resources. This approach suggests assessing both the costs and the deviations, in order to simulate tolerances (Fig. 5).

As shown in the article [7], deviations of workpieces characteristics $\Delta_{\text{Characteristic}_i}$ are generally linked to manufacturing activities $\Delta_{\text{Activity}_j}$ (Eq. 6; Fig. 6a). The manufacturing activity definition allows to define two data sets: process capability data and the manufacturing variation model, and to quantify the impact of Manufacturing Process KCs on Part KCs. Process capability data is defined as the expected and obtained standard deviations and mean shifts for a feature produced by manufacturing activities.

$$\Delta_{\text{Characteristic}_i} = g(\Delta_{\text{Activity}_j}) \tag{6}$$

Moreover, deviations of product characteristics, quoted $\Delta_{\text{Characteristic}_k}$, are due to the deviations of workpieces characteristics (Eq. 7; Fig. 6a). As a product is assembled, individual errors combine and the total effect of errors is seen when assembly is complete. It is necessary to have a model of variation to predict final product quality. Several papers discuss using product variation models to calculate optimal tolerances, predict yields, or model the effects of process capability uncertainty [7].

$$\Delta_{\text{Characteristic}_k} = f(\Delta_{\text{Characteristic}_i}) \tag{7}$$

From the identification of these relationships and the characterization of deviations associated to activities, it is possible to check the compliance with the limits set on each piece and the product (Eq. 8; Fig. 6b). Thus, this approach can assess, for instance, by Monte Carlo simulation the occurrence defined in Eq. 5: $P(\text{Ok})$, $P(\text{Not Assemblable})$, $P(\text{Not Assemblable})$. In fact, for tolerance analysis, the Monte Carlo simulation method is frequently used. 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 to obtain the explicit function f; and we use Monte Carlo simulation.

$$\begin{cases} h_1(\Delta_{\text{Characteristic}_i}) \leq T_m \\ h_2(\Delta_{\text{Characteristic}_k}) \leq T_n \end{cases} \tag{8}$$

This extension of the activity-based approach adds to the three drivers two new concepts [6,8]:

- *Activity occurrence*: Probability that an activity appears in the process (for example, the probability of a reprocessing activity occurs in the manufacturing process).
- *Activity efficiency*: The probability that an activity lead to good products (meeting geometrical tolerances).

4 ABTA: activity-based tolerance allocation

In the previous section, the activity-based approach which assesses the cost of a tolerance allocation solution, is detailed and illustrated with an example. Starting from this approach, it is possible to optimize the tolerance allocation. The aim "*Minimize the manufacturing cost*" requires the use of an optimization method. Among the optimization methods (gradient method, simplex method...), this paper focuses on

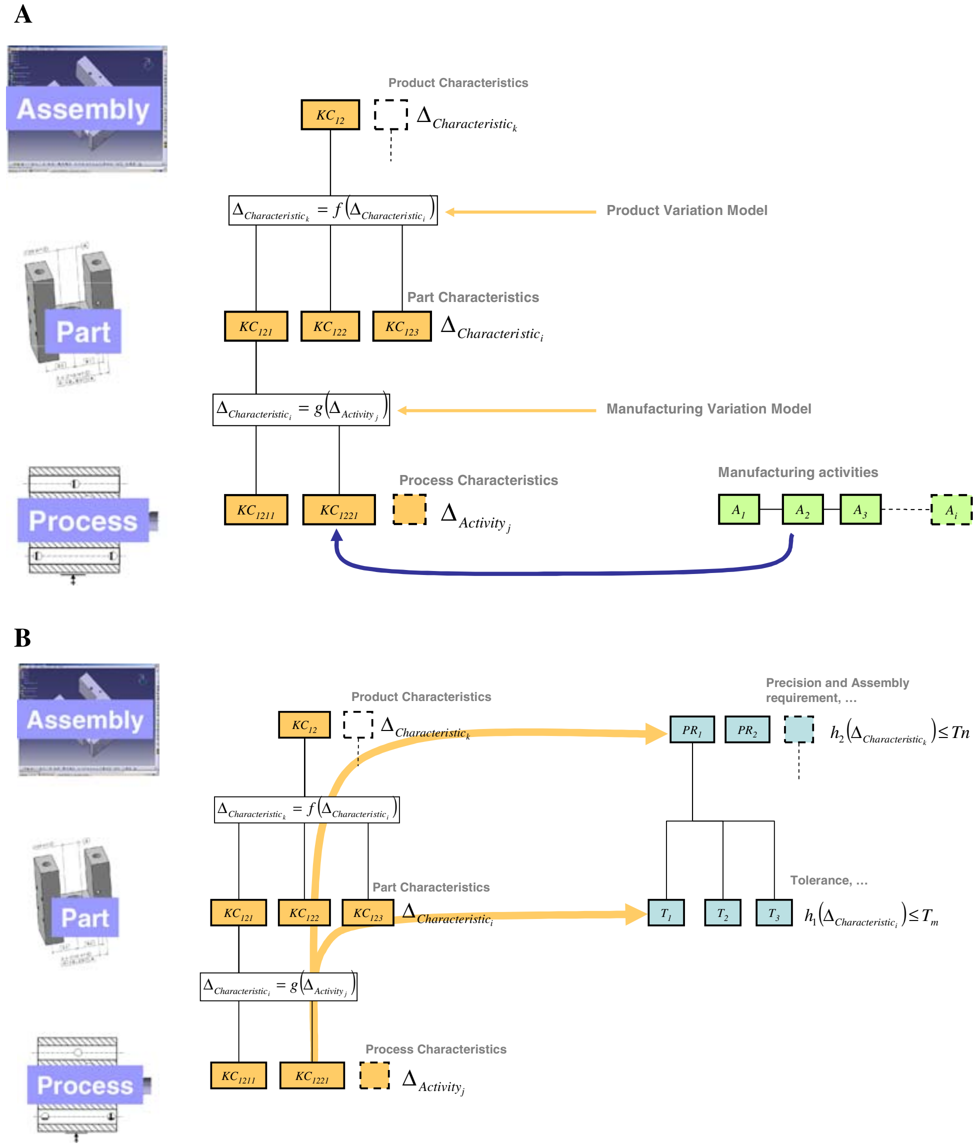


Fig. 6 Activity-based approach and characteristic dependencies

genetic algorithms. Indeed, these tools are very efficient when the objective function is not necessarily analytical or continuous and when the evaluation of each point belonging to the objective function may require a numerical simulation (as Monte Carlo simulation, for instance) [6, 8, 14, 17].

The genetic algorithm is based on the Darwinian evolution theory. According to him only the best adapted individuals to their environment survive and can transmit their genetic characteristics to their offspring. Consequently, this transmission increases the population fitness over the generations... In our case, an individual is modeled by a set of quantified tolerances associated to a workpiece; each tolerance is recorded into the individual gene. The criterion to optimize the individual fitness being it's cost.

This approach, optimizing the tolerance allocation, is based on the use of a genetic algorithm, which is composed by several stages:

- *Initialization of the first population*: the genes of the first individuals are randomly generated into the evolution field, previously defined by the user.
- *The evaluation of individual fitness*: for an optimization problem given, an individual models a potential tolerance allocation solution. This solution is then associated to the criterion value to optimize: its fitness. In the tolerance allocation case, the individual fitness is quantified by its manufacturing cost weighted by its compliance with requirements and tolerances.

Then, the main loop of the algorithm is run:

- Random selection of « parents ».
- Generation of a new individual by linear combination of the individuals "parents" genes.
- Fitness assessment of this new offspring.

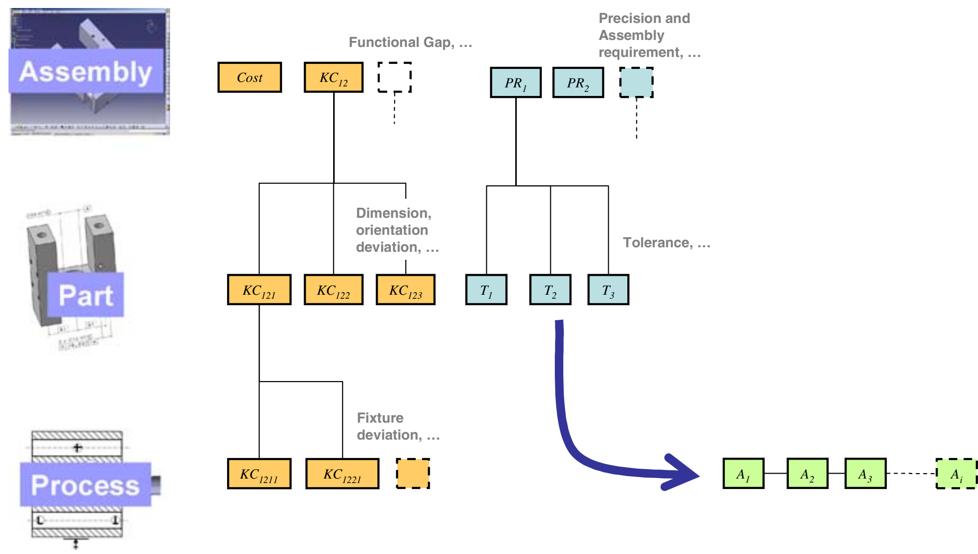


Fig. 7 Activity-based approach—activities selection

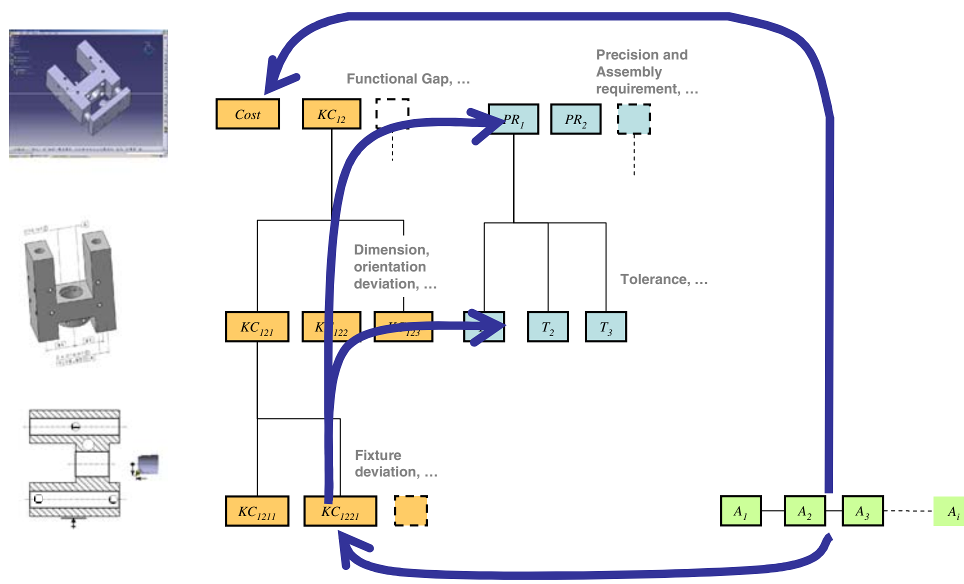


Fig. 8 Activity-based approach—assessment of activities impacts

Then this new offspring is compared with the worst individual of the population. If its fitness is better then the offspring is added to the population else a new offspring is generated. The main loop is repeated until the convergence criterion is met.

The most important stage of this algorithm is the fitness assessment. This evaluation is performed in three steps:

- Manufacturing processes selection and generation of the associated activities (Fig. 7).
- Statistical analysis of tolerances based on Monte Carlo simulation: the occurrence and the efficiency of each activity is then assessed (Fig. 8).
- Evaluation of the fitness (cost-weighted quality) (Fig. 8).

The selection of manufacturing processes can be carried out from a set of criteria (material, quantity, shape parts, tolerance. . .). It requires significant knowledge from manufacturing experts [9,10]. This selection is carried out by one simple algorithm which runs like a constraint satisfaction program. For each entity composing the part, the system generates all triplets OP + Tool + Machine compatible with the user habits and selects those who meet all the constraints expressed previously. The data needed to execute this activity is expressed by process planning experts and is capitalized and stored in an object oriented data base.

The assessment of impacts due to activities deviations on the manufacturing cost needs both the activity approach and characteristic formalization. Statistical tolerance analysis can be modeled with Eqs. 6 and 7. The objective of statistical tolerance analysis is to compute the probability distribution of $\Delta_{\text{Characteristic}_k}$ (Product KCs) and $\Delta_{\text{Characteristic}_i}$ (Part KCs) given the distributions of $\Delta_{\text{Activity}_j}$ (Process KCs) and the

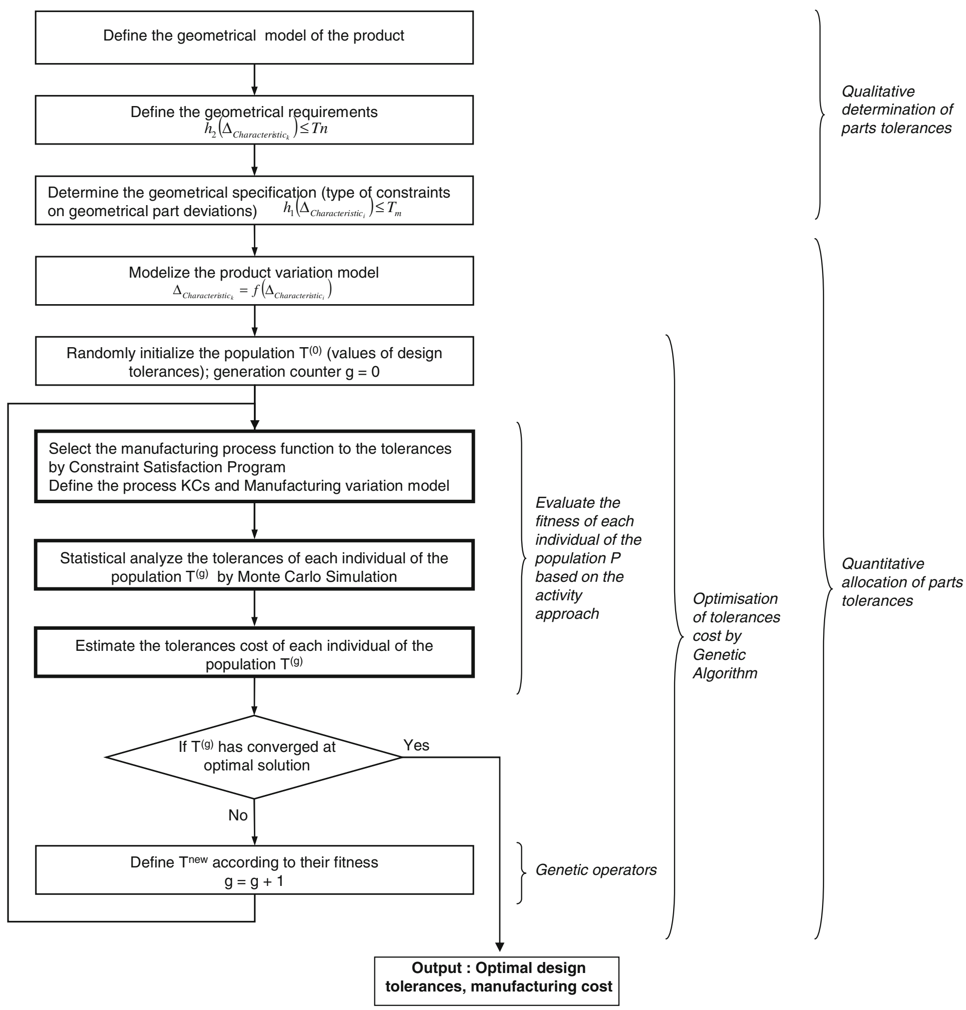


Fig. 9 The flow diagram of the global approach

functions f and g (Eqs. 6 and 7). This computing is based on the Monte Carlo simulation, a statistical method. The principle of this simulation is to use a random generator to simulate the variations of process KCs. This random generation follows the statistical distribution of the analyzed parameter which is easily calculated from the deviations of the production resources previously selected and used to machine the analyzed entity. Then all parameters of each entity composing the workpiece are randomly quantified, and mathematical constraints (essentially inequations—Eq. 8) are applied to check the validity of the whole product. This procedure of quantification/test must be replicated a large number of times to be accurate (the precision depends on the square root of the number of iterations).

The global approach includes two steps: qualitative determination of parts tolerances and quantitative allocation of parts tolerances (Fig. 9).

This algorithm has taken shape into one prototype software. This one, coded in Visual Basic, finds the optimal tolerance allocation considering the knowledge (expressed by process planning experts) saved into databases. Regarding all the needed data (compatibility of resources, cost or deviations…) to carry out the optimization, several user interfaces (Fig. 10) have been designed:

- One to express the ordered list of mountings. Indeed the program does not generate any mounting. In this case, users have to describe for each mounting: the entities to machine, entities needed to support the workpiece and the type of the machine used.
- One to describe the machining resources available and how to use them.
- One to describe the product, the entities composing it and their geometry.
- And one to quantify algorithm's parameters.

The software and the method have been tested and validated on several examples. One of them, the linear guide unit (illustrated on the left top of Fig. 11), which is a hyperstatic assembly, is interesting since functional and assembly requirements are numerous and easy to formalize. The functional requirement studied is the deviation of the mobile part, with

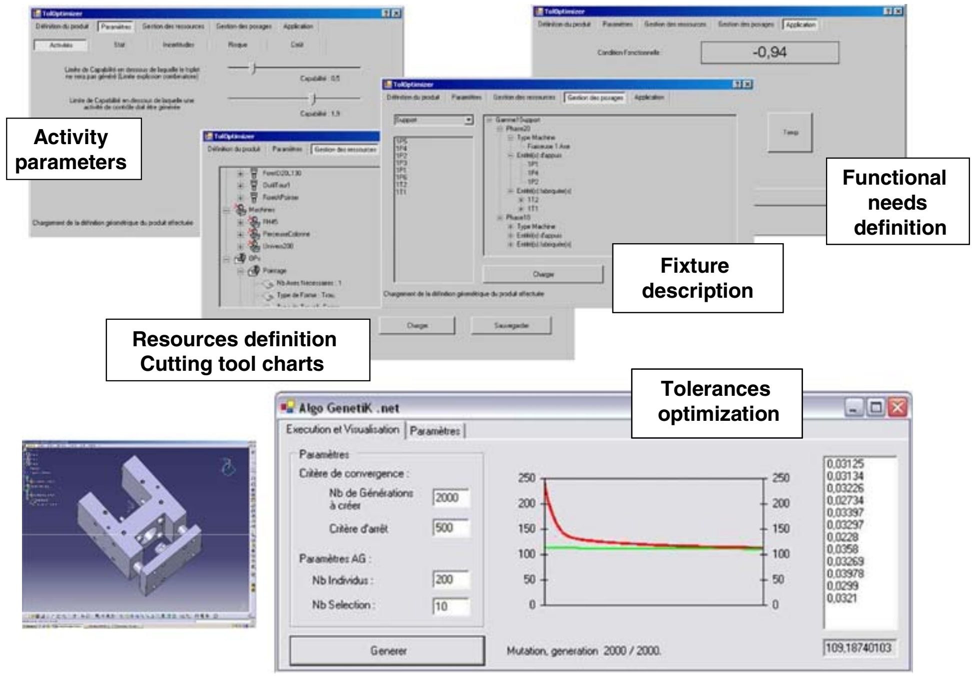


Fig. 10 Tolerance optimization tool–user interfaces

respect to the cylinder axis b of the part 2 (Fig. 11). In order to show the convenience of the proposed approach, it was used to calculate optimal tolerances: diameter tolerance and localization tolerance (partially illustrated in Fig. 11).

Figure 11 is focused on the fitness evaluation by illustrating this assesment with the linear guid unit example. Une first step of this algorithm needs several data as: the product geometrical description (which is decomposed into features), the quantification of specifications (generated by the evolutionnary algorithm) and the relationships linking all variations (for instance the diameter of the drilling...). In the case of the linear guid unit, these relationships are available in [3].

The result of the first step of the fitness evaluation is a set of process plans compatible with: tools and machines availability and capacities, parts geometry, and process plan expertise. Figure 11 shows a part of these potential process plans. In this representation, are given the ordered list of activities, tools and machines used and the geometrical features machined.

The statistical analysis of each tolerance leads to the enrichment of the previous process plans with quality control activities and recycling/dumping activities. This algorithm firstly quantifies manufacturing variations dued to tools and machines belonging to each process plan. Then, it evaluates upper variation characteristics with the relationships given by the tolerance expert. Considering these variations the probability of having non assemblable or out of range parts can be evaluated and then, some improvements can be performed on previous process plans [3,16].

The final step consists in evaluating the performance of the randomly generated tolerance allocation by assessing its cost weighted risk (the formula is given in (5)). The result of this evaluation is considered as the fitness of the individual, and so, its adaptation to the tolerance issue. The fewer this fitness is, the better is the tolerance allocation.

Figure 12a illustrates the convergence of the optimization by genetic algorithm: the evolution of the best fitness (smaller fitness of the population) and the mean fitness; these fitness decrease. Figure 12b and c shows the sets of diameter tolerance values and of localization tolerance values of each population during the iterations of the genetic algorithm. We observe the convergence of the tolerance values during the GA iterations. In this case, the best diameter tolerance is 0.06 and the best localization tolerance is 0.2.

5 Conclusion

This tolerance allocation, which has been validated on the specific issue of geometric tolerance allocation [8], can be applied to any kind of tolerance. This tolerancing approach performs the management of characteristics and the causalities between tolerances, and a quantitative determination of tolerances during the design process in order to ensure a certain level of product quality. Moreover it takes into account the impact of tolerances mainly on the manufacturing process, and thus on the manufacturing cost in order to optimize the quantitative determination of tolerances.

This allocation is based on two developed approaches and several concepts:

- Characteristics modeling approach (detailed in the article [7]):

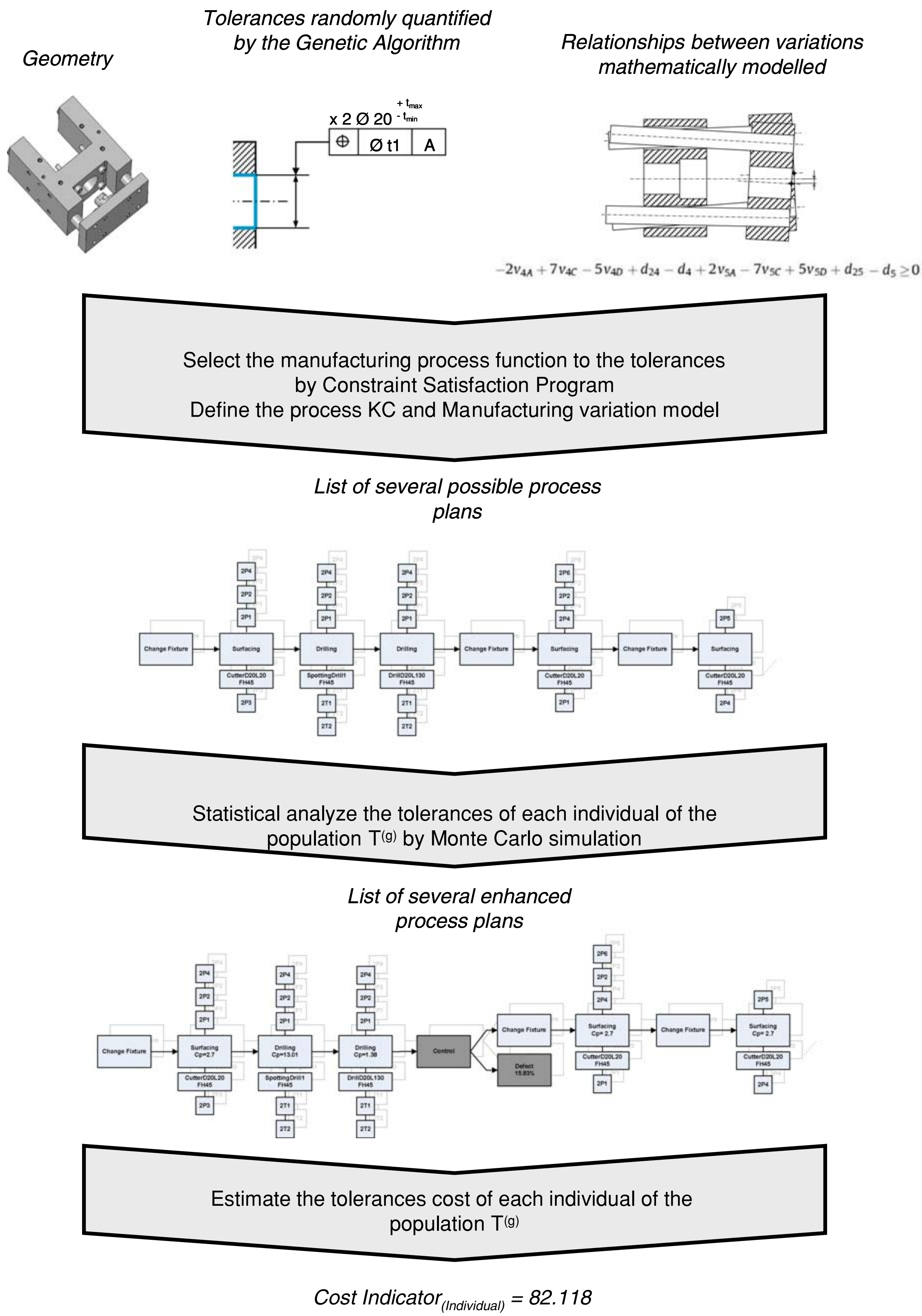
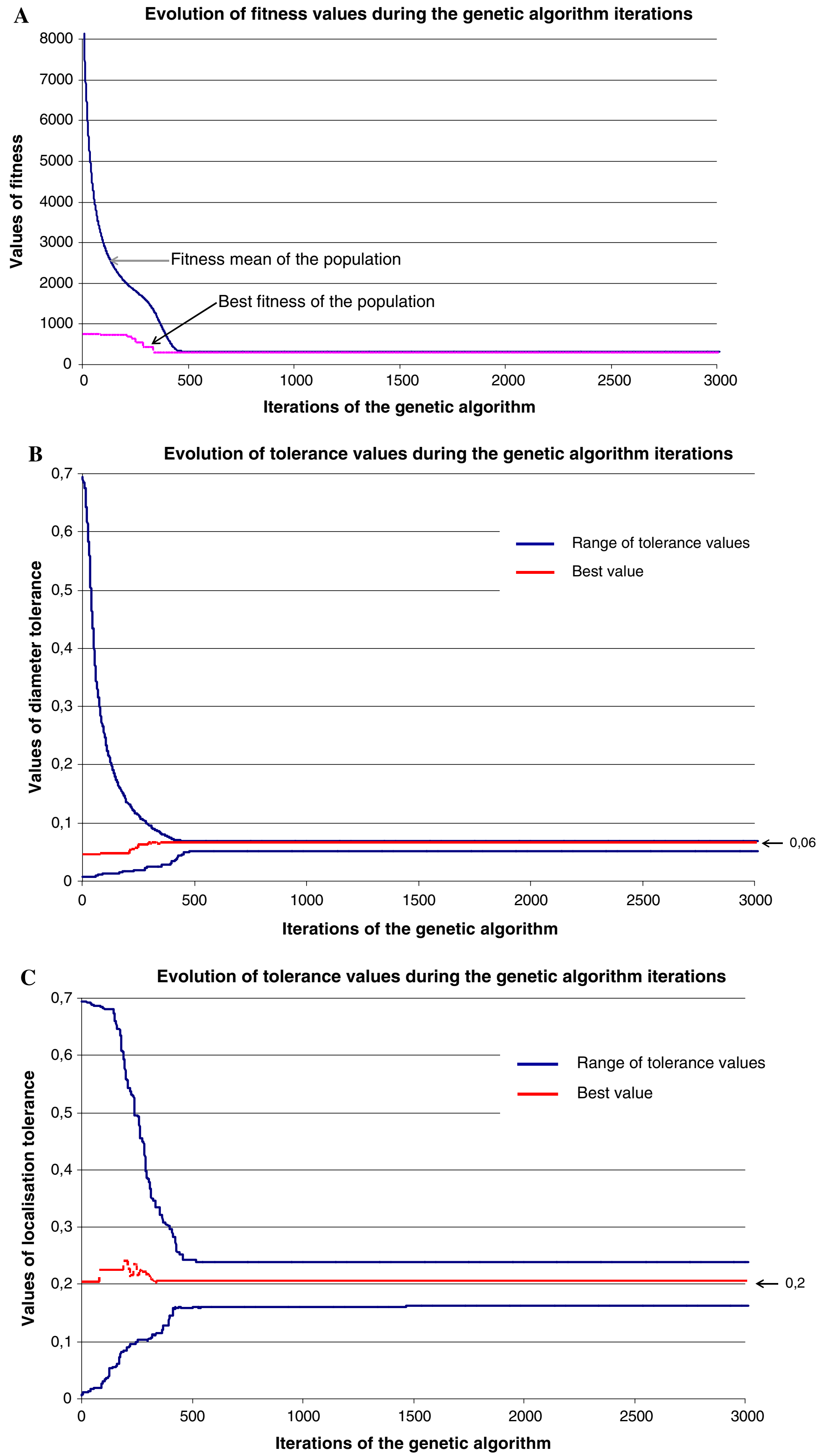


Fig. 11 Flow chart diagram—zoom on the fitness evaluation

Fig. 12 Cost and tolerance evolution during the GA iterations



- A *characteristic* is a parameter or a property of one or more product entities, or an activity of the process, or a resource that impact the cost, the reliability or the quality of the product when it varies around its target.
- A requirement is a condition on one or several characteristics.
- Identification and the analysis of both *causalities* linking requirements or tolerances and the dependencies associating characteristics.

- Activity-based approach

  - *Resources driver*. A key parameter allocating resources between activities. Such driver eases costs management.
  - *Cost driver*. The performance level of activity and its resources consumption depend on this parameter.
  - *Activity driver*. It is equal to the unit work. This driver helps to distribute the activities costs between objects cost.
  - *Activity occurrence*. Probability that an activity appears in the process.
  - *Activity efficiency*. The probability that an activity lead to acceptable products.

With these two approaches, the estimation of the cost of a tolerance allocation solution is possible. This assessment, in the design stages can be useful for:

- identifying the best product meeting design objectives,
- assisting in decisions and making choices,
- comparing viewpoints from all experts,
- ...

This evaluation is a key activity in the design process, since tolerances greatly affect the manufacturing process design, manufacturing and product control.

References

1. Anselmetti, B., Mejbri, H., Mawussi, K.: Synthesis of tolerances starting from a fuzzy expression of the functional requirements. In: Proceedings of the 7th CIRP International Seminar on Computer Aided Tolerancing, Cachan, France, 2001
2. Anselmetti, B.: "Tolérancement – Méthode de cotation fonctionnelle", vol. 3, Ed. Hermes, 2003
3. Ballu, A., Plantec, J.-Y., Mathieu, L.: Geometrical reliability of overconstraint mechanisms with gaps. CIRP Ann. Manuf. Technol. **57**, 159–162 (2008)
4. Chase, K.W., Greenwood, W.H.: Computer aided tolerance selection: CATS User Guide, ADCATS Report no. 86-2, Brigham Young University, May 1986
5. Chase, K.W., Parkisson, A.R.: A survey of research in the application of tolerance analysis to the design of mechanical assemblies. J. Res. Eng. Des. **3**, 23–37 (1991)
6. Dantan, J.Y., Etienne, A., Wu, F., Siadat, A., Martin, P.: Allocation des tolérances fonctionnelles par optimisation du coût de fabrication, Journée thématique PRIMECA – Tolérancement, Septembre 2005, Cachan, France
7. Dantan, J.Y., Hassan, A., Etienne, A., Siadat, A., Martin, P.: Information modeling for variation management during the product and manufacturing process design. Int. J. Interact. Des. Manuf. **2**(2), 107–118 (2008)
8. Etienne, A., Dantan, J.Y., Siadat, A., Martin, P.: Process plan selection integrating tolerance allocation by genetic algorithm and constraints satisfaction algorithms. In: Proceedings Of 5th CIRP int. seminar in Intelligent Computation in Manufacturing Engineering, Naples, Italy, 2006
9. Etienne, A., Dantan, J.Y., Siadat, A., Martin, P.: Machinable axial features concept and process ascending controlled generation. Comput. Ind. **57**(7), 663–675 (2006)
10. Etienne, A., Dantan, J.Y., Siadat, A., D'Acunto, A., Martin, P.: Data model for CAPP Systems to Manage Key Characteristics variations. Mach. Eng. **4**(1–2), 107–115 (2004)
11. Frey, D., Otto, K.: The process capability matrix: a tool for manufacturing variation analysis at the system level. In: Proceedings of ASME Design Theory and Methodology Conference, CA, USA, 1996
12. H'Mida, F.: Contribution à l'estimation des coûts de production mécanique : L'approche Entité Coût appliquée dans un contexte d'ingénierie intégrée, Thèse de doctorat, LGIPM de Metz, 2002
13. Johnson, H.T., Kaplan, R.S.: Relevance Cost, the Rise and Fall of Management Accounting. Harvard Business School Press, Boston, MA (1987)
14. Lee, J., Johnson, G.E.: Optimal tolerance allotment using a genetic algorithm and truncated Monte Carlo simulation. J. Comput. Aided Des. **25**, 601–611 (1995)
15. Marguet, B., Mathieu, L.: Integrated design method to improve productibility based on product key characteristics and assembly sequences. Ann. CIRP **50**(1), 85–91 (2001)
16. Martin, P., Schneider, F., Dantan, J.Y.: Optimal adjustment of a machine tool for improving quality of mechanical part. Int. J. Adv. Manuf. Technol. **26**(5–6), 559–564 (2005)
17. Shan, A., Roth, R.N.: Genetic algorithms in statistical tolerancing. J. Math. Comput. Model. **38**, 1427–1436 (2003)
18. Spotts, M.F.: Allocation of tolerances to minimize cost of assembly. J. Eng. Ind. Trans. ASME **95**, 762–764 (1995)
19. Suh, N.P.: Axiomatic Design. Oxford University Press, New York (2001)
20. Taguchi: Taguchi on Robust Technology Development: Bringing Quality Engineering Upstream. ASME Press, New York (1993)
21. Thornton, A.C.: Variation risk management using modeling and simulation. J. Mech. Des. **121**, 297–304 (1999)