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Applications

Optimization of a workpiece considering production requirements

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As a contribution to the future of integrated CAD/CAM systems, this paper proposes a procedure to include the constraints of manufacturing in the dimensioning and the tolerancing of a workpiece. This algorithm is well adapted to consider the unilateral conditions extracted from the functional dimensioning and from the machining requirements in order to obtain a part model in medium dimensions. A rule for choosing dimensions which must be respected in machining is proposed. The system was implemented on an IBM RISC 6000 station and a simple example is presented.

Keywords: Optimization; Automation; Dimensioning; Tolerancing; CAD/CAM; Production; Machining dimensioning; Computer-aided process planning

1. Introduction

1.1. Aims

CAD/CAM systems have already greatly aided the designing of workpieces, namely with kinematic analysis and the verifications of the resistance of workpieces. Various methods define tolerance limits acceptable to the mechanism [1–3]. Some authors have introduced the engineering of quality and the loss function [4], using for example the work of Taguchi [5].

We now propose a new tool to consider the realizable accuracy of the manufacturing process and the constraints of machining. With this method, we are able to optimize a geometrical model which minimizes the manufacturing cost (for a given process). The shape of the workpiece must be completely defined with approximate dimensions in order to choose the manufacturing process. The definition drawing must display the functional dimensioning and tolerancing (with unilateral or bilateral tolerances). These conditions give the constraints of mating, guiding and mechanical resistance for a mechanism. The basic sizes of the workpiece can be calculated to determine the workpiece model in medium dimensions. For example, this could be used for calculation of the tool paths or for the definition of the stamping shape.

The presented computing method is general enough to be adapted to many needs:
- feasibility study of a manufacturing process with given machine-tools;
- choice of machine-tools according to the necessary accuracy;
- accuracy of a raw shape;
- tolerancing of the set-ups, etc.

The result also gives the manufacturing dimensioning and tolerancing, the adjustment limits and the definition of the Statistical Process Control boundary.

1.2. State-of-the-art

The method used analyses the functional dimensions of the definition drawing and the re-

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unilateral requirements and it may be possible to introduce production cost as a parameter in the algorithm.

2.2. Data and results

The workpiece is described by the definition drawing (NF E04 550) and its manufacturing process. Tolerances cannot be modified. Dimensions of workpieces for each phase will be optimized with different criteria. If some tolerances are too small, we can conclude that manufacturing is impossible with the proposed process.

2.3. Definition of a dimension for the simulation model

Usually, the principle of independence or the envelope principle (NFE 04 561 = ISO 8015) precisely defines the dimension of a workpiece. The calculation of tolerance transfer requires one common axis for the dimensions, in order to add simple scalars. So, with our approach, the dimension is also a specific model. We neglect form and location deviations, and we consider the dimensions on one single axis. We assume that one distance is given between two surfaces of a real workpiece. This distance is defined on the same axis for all dimensions. The tolerance zone is either a closed interval (bilateral tolerances) or a half-open interval (unilateral tolerances), and must contain the distance of each workpiece including measured deviations.

2.4. General definitions

In this article, we use this following terminology:

Definition drawing (used by the workshop). Description of the shape of the workpiece and set of requirements in accordance to NF E04 550.

Machining operation. Machining carried out by one tool to obtain one shape on the workpiece.

Sub-phase. An outline of operations which are carried out without removing the workpiece from its set-up and without moving the whole workpiece and set-up to another machine-tool.

Phase. Sequence of sub-phases made on one production cell or one production area.

Production area. Set of machine-tools, managed by one adjuster, which carry out the unbroken machining of a workpiece. The workpieces are machined on all machine-tools in the same order, so the settings are conserved and not independent for the different operations.

Examples:

- The milling of the two sides of a T-nut is carried out with two sub-phases when we turn it in the set-up (no variability between the machining of the two sides).
- Each stage of a transfer-line system corresponds to a sub-phase.

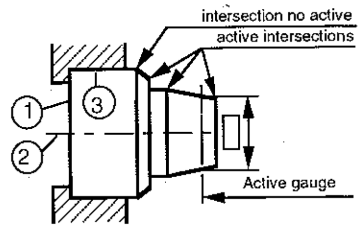

Fig. 2. Active surfaces.

Active surfaces [10]. In a phase, active surfaces are those that are in contact with the set-up, are being machined or are being probed. (The operator can control the relative position of two active surfaces.) Three rules complete this definition:

- The axis of two active surfaces is active.
- The intersection of two active surfaces is active.
- The gauge (of a cone) of an active surface is active.

In the example of Fig. 2, fixture surface 1 is active (its position is defined by the gripper). The jaws make the position of axis 2 concentric. Axis 2 is also active. But cylinder 3 is not active, because the variability of its diameter modifies the position of the external surface with regard to the reference of machining.

Machining dimension. This tolerance defines a requirement between two active surfaces in the same phase.

2.5. Comments

Manufacturing is done by many different machine-tools. Each phase has an adjuster in charge. The workpieces can be mixed between two production areas. So, the settings must be independent. For each functional or production requirement, the dimension transfer gives only one machined dimension. Symmetry tolerances are a

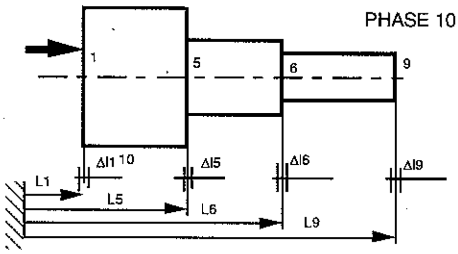

Fig. 3. Simulation model.

- Raw tolerances can be written (for example, if i and j are raw surfaces, $\Delta l_i + \Delta l_j < 1$).
- The standard dimensions for a raw material can be defined: steel bar toleranced by the dimension 60 h10 gives:

$$L_j - L_i + (\Delta l_i + \Delta l_j)/2 = 60,$$

$$L_j - L_i - (\Delta l_i + \Delta l_j)/2 = 59.88.$$

To limit the tool flexion, we can restrict the variation of thickness as a function of the finishing accuracy. If i is the finishing surface and j the roughing surface, the condition is $\Delta l_i + \Delta l_j \leqslant 10\ \Delta l_i$.

These manufacturing requirements must be respected only during the machining (not on the final component shape).

3.4. Set of inequalities

The problem formulation gives a linear matrix, with three types of conditions: $\geqslant$, $\leqslant$, $=$. For each condition x, the inequality has the form:

$$\sum e_{xi} L_i + \left(\sum \lambda_{xi}\ \Delta l_i\right) \geqslant C_{x\ \min}$$

$$\sum e_{xi} L_i + \left(\sum \lambda_{xi}\ \Delta l_i\right) \leqslant C_{x\ \max},$$

where L_i and Δl_i are unknown ($\geqslant 0$) and e_{xi} are 0; 0.5; -0.5; $+1$; -1....

For example: $Cf_{8,10\ \min} \leqslant 13.6$ gives

$$L_{10} - L_8 - 0.5\ \Delta l_8 - 0.5\ \Delta l_{10} \leqslant 13.6.$$

If i is the symmetry axis of surfaces g and h, there is a new condition:

$$L_i = (L_g + L_h)/2.$$

If i and j are hole axis with location tolerances (nominal distance V and tolerance t) there are three conditions:

$$L_j - L_i = V, \qquad \Delta l_i \leqslant t, \qquad \Delta l_j \leqslant t.$$

If the location uses a reference surface k, we have:

$$L_j - L_i = V, \qquad L_k - L_i = V',$$

$$\Delta l_i + \Delta l_k \leqslant t, \qquad \Delta l_j + \Delta l_k \leqslant t/2,$$

$$L_j - L_i = V, \qquad \Delta l_i \leqslant t, \qquad \Delta l_j \leqslant t.$$

The simplex method can solve this problem with an objective function based on minimal cost for tooling, adjustment and raw material.

3.5. Objective function

This function use the parameters L_i and Δl_i. The adjustment cost depends on Δl_i. The raw material and tooling cost depend on L_i.

3.5.1. Adjustment cost

Cheikh and McGoldrick [17] propose an estimation of the cost according to the manufacturing process and the tolerances of the definition drawing. To optimize the calculation, we detail this cost function for each adjustment.

The estimation of the adjustment time of a tool yields the graph of Fig. 4. The adjustment time depends on the quality of the surfaces. With this first graph, the different adjustment cost can be estimated with a "difficulty factor of adjustment" based on the value which necessitates 5 minutes of adjustment:

$k = 1$: positioning of a tooled surface ($\Delta l = 0.05$);
$k = 10$: realization of a raw surface ($\Delta l = 0.5$);
$k = 1$: positioning of a workpiece on a machining surface ($\Delta l = 0.05$);
$k = 8$; positioning of a workpiece on a raw surface ($\Delta l = 0.4$).

The adjustment time is $t = f(\Delta l/k)$. Figure 4 gives for $k = 1$, in the interval M1M2, a slot: $-5/0.3$. The cost function is

$$C = \mathrm{Ct} - (5/0.3 \times \mathrm{CH}/n)\ \Delta l_i,$$

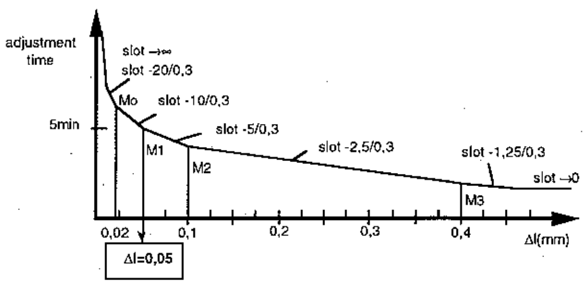

Fig. 4. Graph of adjustment time.

Table 1
Machining process

Phase	Fixture surface	Tooled surface	Tool	Machine
10	12	2	1	NC lathe
10	11	6	1	NC lathe
20	2	3	1	NC lathe
20	2	7	2	NC lathe
20	2	8	3	NC lathe
20	2	7	4	NC lathe
20	2	10	4	NC lathe
20	2	11	5	NC lathe
30	11	4	1	Drilling
30	11	5	1	Drilling

bered as shown in Fig. 7. The machining process is represented in Fig. 8 and in Table 1.

Drawing requirements are shown in Table 2. They must be completed by implicit conditions which are not defined on the drawing; these are marked by an asterisk (*) in Table 2.

Table 3 shows the decomposition in machining dimensions (M = maximum, m = minimum).

4.2. Set of inequalities

Initial system. The unknown values are L_i, Δl_i and Δl_i^j. The first line of the matrix shows requirement No. 2 (Table 3). The constraint $Cf_{8,10max} \leqslant 14$ gives:

$$L_{10} - L_8 + 0.5\ \Delta l_8 + 0.5\ \Delta l_{10} \leqslant 14.$$

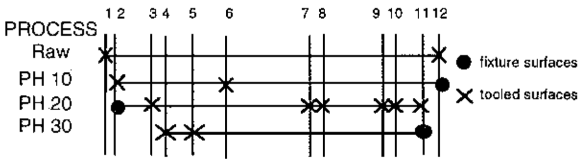

Fig. 8. Representation of the process.

System after change of variables The transformations are: $\Delta l_8 = \Delta + d_8$ and $\Delta l_{10} = \Delta + d_{10}$ ($k = 1$). The condition $Cf_{8,10}$ now gives:

$$L_{10} - L_8 + 0.5 d_8 + 0.5 d_{10} + \Delta \leqslant 14.$$

The new system is given in Fig. 9.

Objective function. Before the change of variables, the objective function is the sum of the three cost functions analysed in section 3.5. The following array gives the coefficient of each variable:

L_2	L_3	L_4	L_5	L_6	L_7
0.00	−0.04	0.00	0.00	0.08	−0.05
L_8	L_9	L_{10}	L_{11}	L_{12}	
−0.04	0.00	0.00	0.04	1.10	
Δl^{10}	Δl^{20}	Δl^{30}	Δl_1	Δl_2	
−2.67	−2.67	−2.67	−2.67	−2.67	
Δl_3	Δl_4	Δl_5	Δl_6	Δl_7	
−2.67	−2.67	−2.67	−2.67	−2.67	
Δl_8	Δl_9	Δl_{10}	Δl_{11}	Δl_{12}	
−2.67	−2.67	−2.67	−2.67	−2.67	

Table 2
Drawing requirements

No.	Phase Phase	Left surface	Right surface	Medium value	Tolerance	Min. value	Max. value
1	Drawing	8	10	13.80	0.400		
2	Drawing	2	3			3.612	
3	Drawing	4	6			11.000	
* 4	Drawing	5	6			2.000	
5	Drawing	6	8			7.820	
6	Drawing	7	8			2.000	
7	Drawing	8	9			11.500	
8	Drawing	9	10			1.600	
9	Drawing	10	11			2.000	
10	Drawing	2	6				20.000
11	Drawing	5	6				9.000
12	Drawing	6	10				21.840
13	PH 10	1	2			1.000	
14	PH 10	1	2				2.500
15	PH 20	11	12			1.000	
16	PH 20	11	12				2.500
* 17	PH 30	3	4			0.000	
* 18	PH 30	5	7			7.231	

* Implicit requirement, not defined on the drawing.

L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	dl^{10}	dl^{20}	dl^{30}	dl_1	dl_2	dl_3	dl_4	dl_5	dl_6	dl_7	dl_8	dl_9	dl_{10}	dl_{11}	dl_{12}	Δ	cond
.0	.0	.0	.0	.0	.0	-1.0	.0	1.0	0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.5	.0	.5	.0	.0	1.0	≤14.000
-1.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.5	.0	.0	.0	.5	.0	.0	.0	.0	.0	.0	1.0	≤20.000
.0	.0	.0	-1.0	1.0	.0	.0	.0	.0	.0	.0	.0	.5	.5	.0	.5	.0	.0	.5	.5	.0	.0	.0	.0	.5	.0	3.0	≤9.000
.0	.0	.0	.0	-1.0	.0	.0	.0	1.0	.0	.0	.0	.5	.0	.0	.5	.0	.0	.0	.5	.0	.0	.0	.5	.0	.0	2.0	≤21.840
1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.5	.0	.0	.5	.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.5	14.5	≤2.500
.0	.0	.0	.0	.0	.0	.0	.0	.0	-1.0	1.0	.5	.5	.0	.0	.5	.0	.0	.0	.0	.0	.0	.0	.0	.5	.0	5.5	≤2.500
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	≤.001
.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	≤.001
.0	.0	.0	.0	.0	.0	-1.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.5	.0	-.5	.0	.0	-1.0	≥13.600
-1.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.5	.0	.0	.0	-.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	-1.0	≥3.612
.0	.0	-1.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	-.5	-.5	.0	-.5	.0	-.5	.0	-.5	.0	.0	.0	.0	-.5	.0	-3.0	≥11.000
.0	.0	.0	-1.0	1.0	.0	.0	.0	.0	.0	.0	.0	-.5	-.5	.0	-.5	.0	.0	-.5	-.5	.0	.0	.0	.0	-.5	.0	-3.0	≥2.000
.0	.0	.0	.0	-1.0	.0	1.0	.0	.0	.0	.0	.0	-.5	.0	.0	-.5	.0	.0	.0	-.5	.0	-.5	.0	.0	.0	.0	-2.0	≥7.820
.0	.0	.0	.0	.0	-1.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.5	-.5	.0	.0	.0	.0	-1.0	≥2.000
.0	.0	.0	.0	.0	.0	-1.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.5	-.5	.0	.0	.0	-1.0	≥11.500
.0	.0	.0	.0	.0	.0	.0	-1.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.	-.5	.0	.0	-1.0	≥1.600
.0	.0	.0	.0	.0	.0	.0	.0	-1.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.5	-.5	.0	-1.0	≥2.000
1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.5	.0	.0	-.5	-.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.5	-14.5	≥1.000
.0	.0	.0	.0	.0	.0	.0	.0	.0	-1.0	1.0	-.5	-.5	.0	.0	-.5	.0	.0	.0	.0	.0	.0	.0	.0	-.5	.0	-5.5	≥1.000
.0	-1.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.5	.0	.0	-.5	-.5	.0	.0	.0	.0	.0	.0	-.5	.0	-2.0	≥.000
.0	.0	.0	-1.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	-.5	.0	.0	.0	.0	-.5	.0	-.5	.0	.0	.0	-.5	.0	-2.0	≥7.231

OBJECTIVE FUNCTION

L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	dl^{10}	dl^{20}	dl^{30}	dl_1	dl_2	dl_3	dl_4	dl_5	dl_6	dl_7	dl_8	dl_9	dl_{10}	dl_{11}	dl_{12}	Δ
0	-.04	.0	.0	.08	-.05	-.04	.0	.0	.04	1.10	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-2.67	-231.75

Fig. 9. Set of inequalities and objective function.

5. Using the results

5.1. Feasibility of the manufacturing process

A system without solution means that the constraints are incompatible. The definition drawing and the manufacturing process must be better analysed. In the opposite case, we can search for machine-tools which have the adequate machining capability [18].

5.2. Updating of the model

The model gives the L_i values which define the average position of the surfaces. The workpiece model must be actualized to generate the tool path and the NC data with the CAD/CAM system (see Fig. 11, column 2).

5.3. Extension of machining dimensions

5.3.1. Problem

The analysis of the machining dimensions Cf in Table 3 shows that there are conditions which are fulfilled within the required margin, leaving a residue. This residue may be used for the adjustments. Figure 10 gives an example.

The exact constraint for the middle of the workpiece is 30 ± 0.2, but the Δl model, based on the independance of surfaces, imposed $Cf_{23} = 30 \pm 0.02$. Only Cf_{12} and Cf_{34} are constrained by the condition 20 ± 0.02 and 25 ± 0.02. The machining dimension Cf_{23} has a residue of 0.36. So, $Cf_{23} = 30 \pm 0.4$ again.

5.3.2. Calculation of extended machining dimensions

The analysis of Table 3 determines the residue for each condition. When the residue is zero, all machining dimensions which depend on this condition are constrained. Non-zero residues may be distributed on the unconstrained machining dimensions, beginning with the smallest increase. Results are shown in Table 5. The machining tolerances which were extended are marked by an asterisk (*) (see Fig. 11, column 1).

The extension of the machining dimensions facilitates the adjustment and can reduce any verification tolerances in other phases. For this reason, the extension must be a choice for the planner.

Table 5
Extended machining dimensions (see Fig. 11, column 1)

1	RAW	Cf(1, 12)M = 43.730
2	RAW	Cf(1, 12)m = 42.695
3	PH 10	Cf(2, 6)M = 16.441
4	PH 10	Cf(2, 6)m = 16.298
5	PH 10	Cf(2, 12)M = 41.695
6	PH 10	Cf(2, 12)m = 41.230
7	PH 20	Cf(2, 3)m = 3.612
8	PH 20	Cf(2, 8)m = 24.261
9	PH 20	Cf(2, 10)M = 38.138
10	PH 20	Cf(2, 11)M = 40.230
11	PH 20	Cf(2, 11)m = 40.046
12	PH 20	Cf(3, 11)m = 35.933
13	PH 20	Cf(7, 8)m = 2.000
14	PH 20	Cf(7, 11)M = 21.375 * (18.376 condition 19)
15	PH 20	Cf(8, 9)m = 11.500
16	PH 20	Cf(8, 10)M = 14.000 * (13.784 condition 2)
17	PH 20	Cf(8, 10)m = 13.600
18	PH 20	Cf(9, 10)m = 1.600
19	PH 20	Cf(10, 11)m = 2.000
20	PH 30	Cf(4, 11)M = 35.933
21	PH 30	Cf(4, 11)m = 34.933
22	PH 30	Cf(5, 11)M = 32.604
23	PH 30	Cf(5, 11)m = 28.606 * (31.604 conditions 5 and 19)

* Extended tolerances

5.3.3. Operations phases restrictions

This document gives all information for the machining (clamping, process, cutting condition) and the machining dimensions and tolerances. So, a machine tool is well adjusted if all machining workpieces respect the machining tolerances.

5.4. Extension of the method

5.4.1. Adjustment, verification and statistical process control

The result of the simulation gives a model of the behaviour of manufacturing and the tolerances for each phase. This information may be used to define the adjustment tolerances with different approaches [19] (see Fig. 11, column 3):
- adjustment with independent tools;
- continuous control or sampling control;
- analysis of tool wearing.

The boundary of SPC (statistical process control) may be defined [18].

5.4.2. Numerically controlled machine-tool

This method can integrate specific processes in NC machining, for example to incorporate the