Machining dispersions based procedures for computer aided process plan simulation

Said Hamou, Abdelmadjid Cheikh, Jean-Marc Linares, Ali Benamar

Machining dispersions based procedures for computer aided process plan simulation

SAID HAMOU and ABDELMADJID CHEIKHJEAN MARC LINARESALI BENAMAR

Abstract. Among the whole manufacturing cycle of a product, a sequence of manufacturing stages needs to be optimized using the increasingly available computing resources. Computer aided process planning is seen as the missing link between CAD and CAM, which relates to the translation of design tolerances into manufacturing tolerances to be executed in the shop floor. A computerized module for process plan simulation, taking into account the manufacturing dispersions, has been developed. The process plan simulation program, which consists of three procedures, uses a combination of the minimal transfer method and a modified form of the dispersions method. The first procedure performs a verification of the feasibility of the project's process plans through tolerance transfer. The second procedure performs an optimization of the tolerance distribution using the process capability data. The third procedure computes the manufacturing dimensions, which ensure the quality of the components and products. The simulation module has been validated on complex problems and shows that it gives good results in a short time. The manual work requires several days to solving this manufacturing problem.

1. Introduction

The last two decades have seen an enormous increase in the use of computers in industrial engineering activities. In fact, nowadays, computer resources can be exploited to speed-up and improve the accuracy of design, manufacture and assembly activities. Several stages of the manufacturing process of a product are therefore increasingly benefiting, to different degrees, from this substantial computing power. However, despite the computerization of design (CAD) and manufacturing (CAM) it is extremely difficult to ensure a communication between the two activities when several types of technological data are used, especially tolerances (Cheikh 1997). Computer aided process planning (CAPP) is sometimes seen as the missing link between CAD and CAM (Weill 1988, Halevi and Weill 1995). In fact CAPP can provide direct links to the design activity in terms of geometric definition and component attributes, such as functional dimensions and tolerances (Graves and Biscard 1999). At the same time it can create links towards the control and inspection activities of manufacture. Therefore, special attention is directed towards the analysis of manufacturing dimensions and tolerances, which ensure the quality of the product as dictated by the functional requirements. The process plan simulation, sometimes called manufacturing dimensions planning (see figure 1), is a very difficult step to computerize in process planning. In fact the technical literature (Hamou 1998) shows that this procedure has been used manually and, in some cases, partially automated. Bourdet (1975) first laid down the basis for process plan simulation based on the manufacturing process capabilities in terms of minimal machining dispersions. The simulation was performed manually as a tolerance transfer and optimization from design to manufacture. Taking into account the minimal machining dispersions, Duret (1981) proposed the minimal transfer method, which automates the verification of the feasibility of a process plan. Fainguelernt *et al.* (1986) presented a computer program that automates the tolerance optimization procedure, starting from a data matrix of minimal reference dispersions. However, the program lacks any automated procedure for the feasibility check of the process plan and the solution to impossible tolerance transfer conditions prior to the optimization. This paper presents a programmed module that completely automates the process plan simulation of a manufacturing pre-project. The mini-

Authors: Said Hamou and Abdelmadjid Cheikh, Laboratoire d'Automatique de Tlemcen, Département de Mécanique, Faculté des Sciences de l'Ingénieur, Université Abou Bekr Belkaid, Tlemcen, B.P.230, Tlemcen 13000, Algeria. E-mail: acheikh@mai.univ-tlemcen.dz. Jean Marc Linares, Laboratoire EASM2, Département Génie mécanique et Productique, Institut Universitaire de Technologie, Université de la Méditerranée, France. Ali Benamar, Département de Mécanique, ENSET Oran, B.P. 1523, 31000, Algeria.

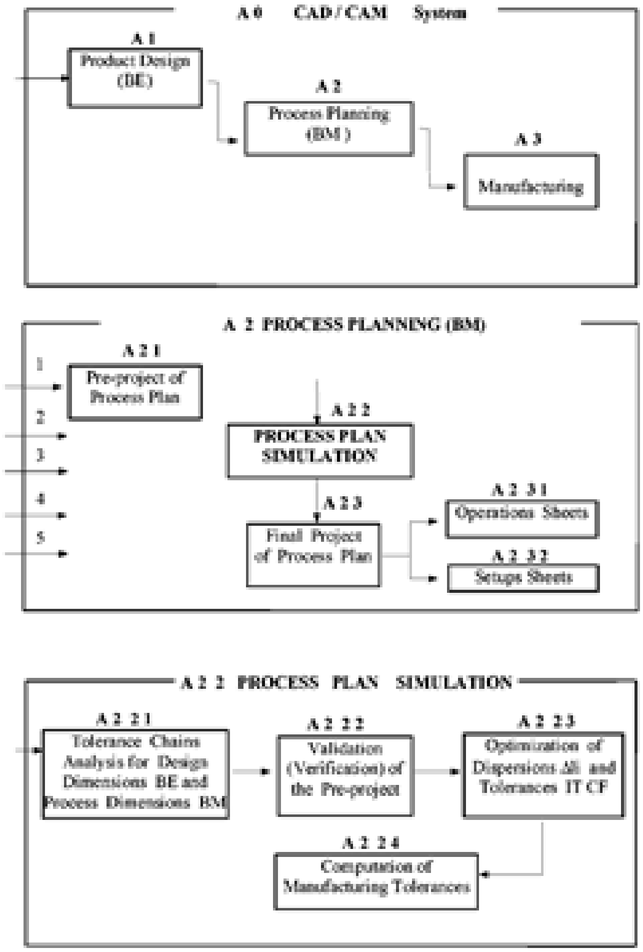

Figure 1. Process plan simulation module.

mal transfer method and the machining dispersions method are combined in order to automate the process plan feasibility veri®cation. In addition, the paper proposes a modi®ed and programmable methodology, which integrates the veri®cation and optimization in the same procedure, starting with a data matrix of unknown dispersions instead of a data matrix of minimal reference dispersions. A comparison between the two methodologies is given in this paper.

2. Modelling of the process plan simulation

In order to automate completely the process plan simulation, a programmable methodology is proposed as a combination of the machining dispersions method introduced by Bourdet (1975) and the minimal transfer method introduced by Duret (1981). On one hand, these two methods are rebuilt so that they can solve any tolerance transfer problem. On the other hand, the methodology is built so that it can calculate an optimal distribution of the machining dispersions (capabilities) and ®nally to compute optimal manufacturing dimensions and tolerances. The ®nal simulation module is designed in the form of three chronological procedures. The ®rst procedure performs a veri®cation of the manufacturing pre-project (A222 in ®gure 1). The second procedure consists of the optimization of dispersions (A223 in ®gure 1). The third procedure computes the ®nal optimized manufacturing dimensions (A224 in ®gure 1).

2.1. Fundamental dispersions model

If a machine is set up to execute a given operation in quantity production there are inevitably various uncontrollable stochastic factors that affect the ®nal size for the dimension l of a machined component. The measured sizes usually give a variation (scattering) Dl called machining dispersion. It is the difference between the largest size l_n and the lowest size l_1 for a given batch as follows:

$$Dl < l_n ÿ l_1: \qquad -1f$$

These different dispersions will affect the process capability and consequently the manufacturing dimensions. They are usually due to localization and ®xture errors, machine rigidity and tool rigidity. The objective of the simulation is to verify the feasibility of the design speci®cations (dimensions BE) and the manufacturing conditions (dimensions BM) using a dispersions based fundamental model introduced by Bourdet (1975). In this model, for each phase in the process plan, the total dispersions Dl_i for a machined surface or Dl'_i for a positioning surface represents the positions occupied by surface i in relation to the machine referential system.

2.2. Procedure for the veri®cation of the pre-project based on minimal dispersions

The veri®cation of the process plan pre-project is carried out by checking the feasibility of the process plan with regards to the capabilities of the available manufacturing processes in the workshop. This condition is ful®lled when the manufacturing means can produce the design set dimensions imposed by the design of®ce. In technical terms, this condition is satis®ed when the tolerance interval (IT) of the design dimension BE is greater than or equals the manufacturing tolerance due to the summation of all dispersions Dl_i and is given as:

$$IT\text{–dimension BE} \geq \sum \Delta l_i \qquad (2)$$

In order to automate the task of the veri®cation using the minimal transfer method in conjunction with equation (2), the manufacturing pre-project of a sample, an example of which is shown in ®gure 2 for a mechanical part, is written in a matrix format of l_p lines and l_s columns. Figure 3 highlights a sample veri®cation sequence for design dimension BE = 16 + 0.6. In this ®gure, l_s represents a surface varying between 1 to 8 and l_p represents a phase varying between 1 to 5. The element A (l_p, l_s) of the initial matrix contains a dispersion value only when surface l_s intervenes in phase l_p as a machined surface (Dl) or as a positioning surface (Dl', Dl'', Dl''', ...) in an subsequent phase. Otherwise the value is set to zero. The manufacturing tolerance interval given by SDl_i is computed using the method of minimal transfer and is then compared to IT, the tolerance interval of the design dimension (BE). This method is explained in the sample example of ®gure 3 and the ¯owchart steps of ®gure 4. The veri®cation procedure is carried out for each design dimension (BE) by successive elimination of the dispersions from single element columns and lines, except for columns whose surfaces are limits to a design dimension (BE). In fact, on one hand, columns (surfaces) with one dispersion Dl are eliminated because they are not taking part in the localization of a surface. On the other hand, lines (phases) having only one dispersion Dl are eliminated because a phase needs at least two dispersions Dl, one for the machined surface and another for the positioning surface. This elimination process is carried out until the minimal transfer condition is satis®ed, which is the presence of zero Dl or two Dl per column, except for surfaces that are limits to the design dimension (BE). At the end, we verify equation (2) by summing all the remaining Dl_i dispersions in the matrix.

In the case when equation (2) is not satis®ed, the pre-project is not veri®ed. The tolerance transfer is impossible. This problem can be solved in three ways. The ®rst solution consists of changing the tolerance interval IT for the design functional dimension (BE). This decision is the responsibility of the design of®ce. The second one involves changing datum elements and reference planes, which means changing the rooting and operations sheets of the whole process plan. This solution means rewriting a new process plan pre-project. The third solution is more adequate and consists of diminishing the IT of one or more manufacturing dimensions (CF) in the tolerance chain that makes up the IT of the design dimension as given by

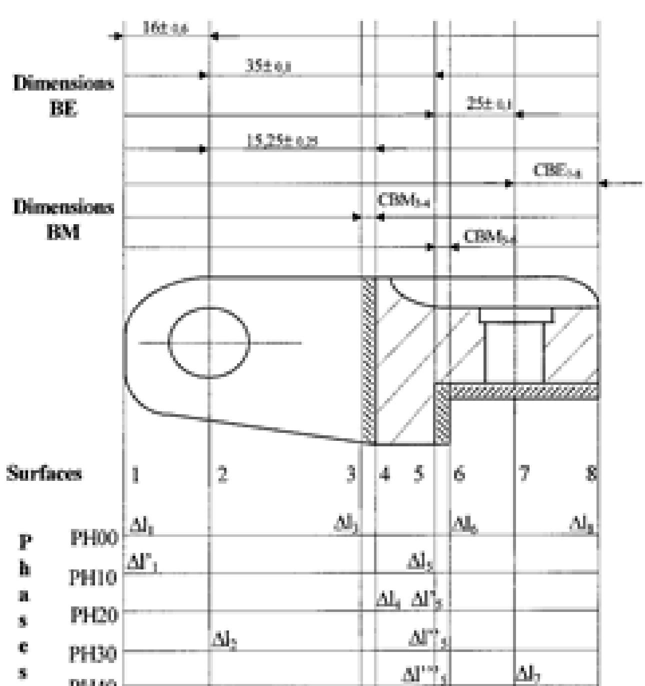

Figure 2. Sample example of a mechanical part pre-project.

Pre-project in matrix format

	1	2	3	4	5	6	7	8
PH 00	Δl_1		Δl_3			Δl_6		Δl_8
PH100	$\Delta l'_1$				Δl_5			
PH200				Δl_4	$\Delta l'_5$			
PH300		Δl_2			$\Delta l''_5$			
PH400					$\Delta l'''_5$		Δl_7	

Sand cast part ⇒ $\Delta l_1 = \Delta l_3 = \Delta l_6 = \Delta l_8 = 0{,}5$

Positioning on cast surface of part ⇒ $\Delta l'_1 = 0{,}5$

Mounting drilling ⇒ $\Delta l_5 = 0{,}07$ etc...

Pre-project verification for dimension BE = 16 ± 0,6

Inputs : $l = 1$, $m = 2$, $IT = 1{,}2$

Tolerance analysis for dimension BE :

1^(1)- Set single element columns to zero except l and m :

	1	2	3	4	5	6	7	8
PH 00	Δl_1		0			0		0
PH100	$\Delta l'_1$				Δl_5			
PH200				0	$\Delta l'_5$			
PH300		Δl_2			$\Delta l''_5$			
PH400					$\Delta l'''_5$		0	

2^(1)- Set single element lines to zero :

	1	2	3	4	5	6	7	8
PH 00	0							
PH100	$\Delta l'_1$				Δl_5			
PH200					0			
PH300		Δl_2			$\Delta l''_5$			
PH400					0			

Minimal transfer satisfied.

$\sum \Delta li = (\Delta l'_1 + \Delta l_5) + (\Delta l''_5 + \Delta l_2) = (0{,}5 + 0{,}05) + (0{,}03 + 0{,}05) = 0{,}63$

$0{,}63 < 1{,}2 = IT$ BE

Pre-project is verified for this design dimension

Figure 3. Veri®cation example of dimension BE = 16 + 0,6.

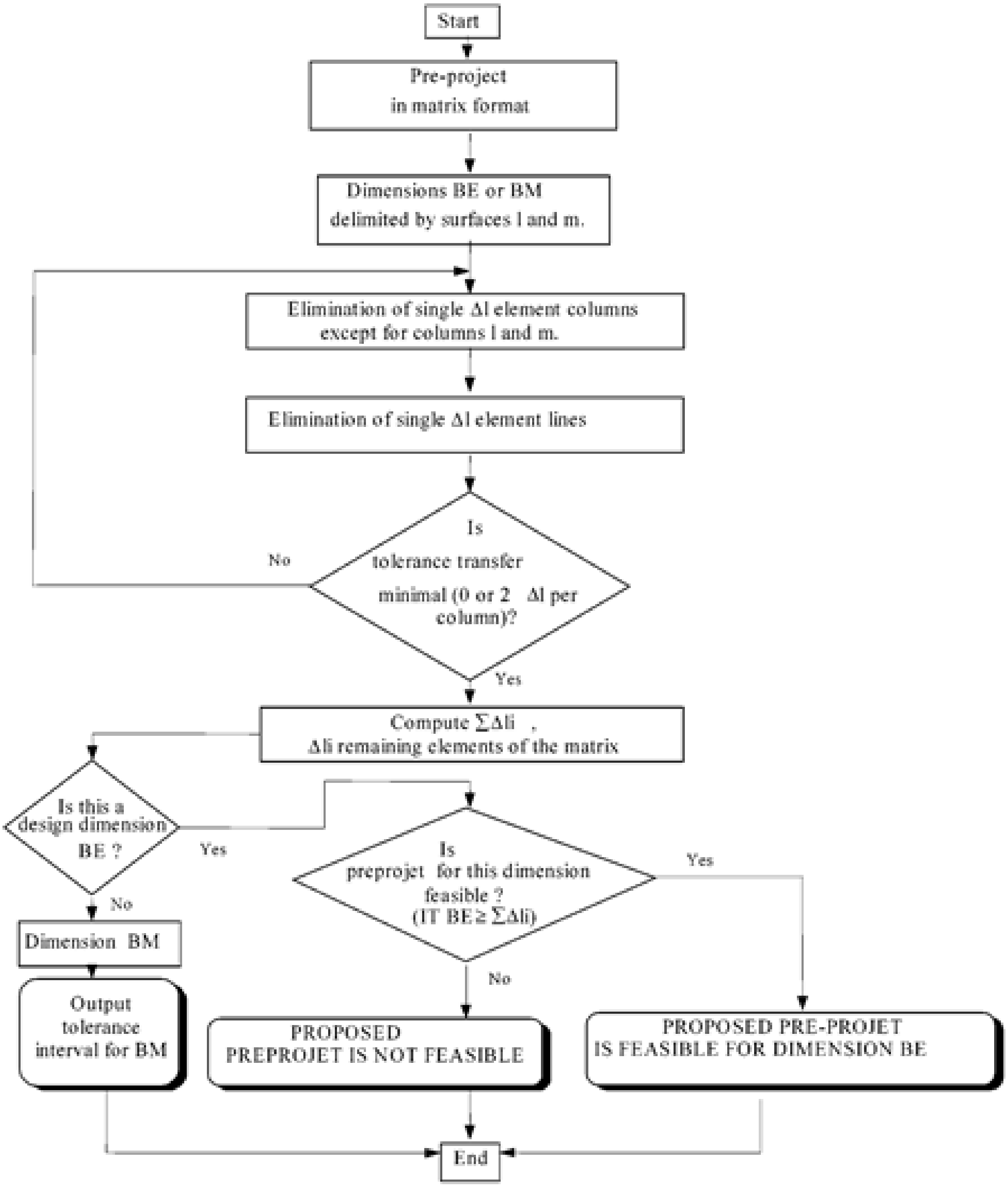

Figure 4. Flowchart of the veri®cation procedure.

equation (2). Based on minimal reference dispersions for different processes, which are usually given by experience (Hamou 1998), this solution is based on a successive diminution of the dispersions DI_i (DB_i for raw material dispersions) without going under any known minimal reference value.

2.3. Procedure for the optimization of dispersions

2.3.1. Optimization based on the minimal dispersions. Once the pre-project has been veri®ed and retained, the manufacturing tolerance intervals can be computed. To do this, we build an optimization matrix $B(I_c$,

l_d) of p lines and q columns where p represents the number of design dimensions and manufacturing dimensions and q the number of dispersions. The first table of figure 5 contains this matrix (column 3 to column 12) corresponding to the mechanical part of figure 2. Each column represents a dispersion Δl which is affected by a surface beginning with the first one, the second one and so on. Then we compute the residuals ε given by the following equation:

$$\varepsilon = IT_{\text{dimension}} - \sum \Delta l_i. \qquad (3)$$

After the initial distribution matrix has been built and the residuals ε computed, we determine the processing order of the lines in this matrix depending on the values of these residuals. This order is given by the increasing values of the residuals. As explained in figure 5, this optimization process consists of an equal

Optimization and distribution data matrix for dispersions

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT	$\sum\Delta li$	ε	done
1	1-2	-	0.5	0.05	-	-	0.05	-	0.03	-	-	-	-	1.2	0.63	0.57	
2	2-5	-	-	0.05	-	-	-	-	0.03	-	-	-	-	0.2	0.08	0.12	
3	5-7	-	-	-	-	-	-	-	-	0.03	-	0.07	-	0.2	0.10	0.10	
4	2-4	-	-	0.05	-	0.05	-	0.03	0.03	-	-	-	-	0.5	0.16	0.34	
5	7-8	0.5	0.5	-	-	-	0.05	-	-	0.03	-	0.07	0.5	0	1.65	-	
6	3-4	0.5	0.5	-	0.5	0.05	0.05	0.03	-	-	-	-	-	0	1.63	-	
7	5-6	0.5	0.5	-	-	-	0.05	-	-	-	0.5	-	-	0	1.55	-	

Distribution order for lines is : **3 - 2 - 4 - 1**

Step 1 :

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT	$\sum\Delta li$	ε	n	ε/n
3	5-7	-	-	-	-	-	-	-	-	0.03	-	0.07	-	0.2	0.10	0.10	2	0.05

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$ opt.	Δl_6	Δl_7 opt.	Δl_8	IT	$\sum\Delta li$	ε	n	ε/n
3	5-7	-	-	-	-	-	-	-	-	0.08	-	0.12	-	0.2	0.2	0	-	-

Step 2 :

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$ opt.	Δl_6	Δl_7 opt.	Δl_8	IT	$\sum\Delta li$	ε	n	ε/n
2	2-5	-	-	0.05	-	-	-	-	0.03	-	-	-	-	0.2	0.08	0.12	2	0.06

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2 opt.	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$ opt.	$\Delta l'''_5$ opt.	Δl_6	Δl_7 opt.	Δl_8	IT	$\sum\Delta li$	ε	n	ε/n
2	2-5	-	-	0.11	-	-	-	-	0.09	-	-	-	-	0.2	0.2	0	-	-

Step 3 :

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2 opt.	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$ opt.	$\Delta l'''_5$ opt.	Δl_6	Δl_7 opt.	Δl_8	IT	$\sum\Delta li$	ε	n	ε/n
4	2-4	-	-	0.11	-	0.05	-	0.03	0.09	-	-	-	-	0.5	0.28	0.22	2	0.11

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2 opt.	Δl_3	Δl_4 opt.	Δl_5	$\Delta l'_5$ opt.	$\Delta l''_5$ opt.	$\Delta l'''_5$ opt.	Δl_6	Δl_7 opt.	Δl_8	IT	$\sum\Delta li$	ε	n	ε/n
4	2-4	-	-	0.11	-	0.16	-	0.14	0.09	-	-	-	-	0.5	0.5	0	-	-

Step 4 :

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2 opt.	Δl_3	Δl_4 opt.	Δl_5	$\Delta l'_5$ opt.	$\Delta l''_5$ opt.	$\Delta l'''_5$ opt.	Δl_6	Δl_7 opt.	Δl_8	IT	$\sum\Delta li$	ε	n	ε/n
1	1-2	-	0.5	0.11	-	-	0.05	-	0.09	-	-	-	-	1.2	0.75	0.45	2	0.22

Line	Dim	Δl_1	$\Delta l'_1$ opt.	Δl_2 opt.	Δl_3	Δl_4 opt.	Δl_5 opt.	$\Delta l'_5$ opt.	$\Delta l''_5$ opt.	$\Delta l'''_5$ opt.	Δl_6	Δl_7 opt.	Δl_8	IT	$\sum\Delta li$	ε	n	ε/n
1	1-2	-	0.72	0.11	-	-	0.27	-	0.09	-	-	-	-	1.2	1.2	0	-	-

After computation, optimized dispersions are :

Δl_1opt.	$\Delta l'_1$opt.	Δl_2opt.	Δl_3opt.	Δl_4opt.	Δl_5opt.	$\Delta l'_5$opt.	$\Delta l''_5$opt.	$\Delta l'''_5$opt.	Δl_6opt.	Δl_7opt.	Δl_8opt.
0.5	0.725	0.11	0.5	0.16	0.275	0.14	0.09	0.08	0.5	0.12	0.6

Final distribution matrix for dispersions

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT	$\sum\Delta li$	ε	done
1	1-2	-	0.72	0.11	-	-	0.27	-	0.09	-	-	-	-	1.2	1.2	0	Yes
2	2-5	-	-	0.11	-	-	-	-	0.09	-	-	-	-	0.2	0.2	0	Yes
3	5-7	-	-	-	-	-	-	-	-	0.08	-	0.12	-	0.2	0.2	0	Yes
4	2-4	-	-	0.11	-	0.16	-	0.14	0.09	-	-	-	-	0.5	0.5	0	Yes
5	7-8	0.5	0.72	-	-	-	0.27	-	-	0.08	-	0.12	0.6	0	2.3	-	-
6	3-4	0.5	0.72	-	0.5	0.16	0.27	0.14	-	-	-	-	-	0	2.3	-	-
7	5-6	0.5	0.72	-	-	-	0.27	-	-	-	0.5	-	-	0	2	-	-

Figure 5. Classical optimization procedure for the sample example.

.

distribution of each residual e on the dispersion elements Δl of each line in the matrix so that the following equation is satisfied:

$$IT_{\text{dimension BE}} < \sum \Delta l_i. \qquad (4)$$

After processing a line, the optimized elements of the matrix are saved and their values are memorized before going to the next line. The tolerance intervals are updated during this process using the optimized dispersions from the previously processed ones. Figure 5 gives the optimization results for the sample example of figure 2.

2.3.2. Optimization based on unknown dispersions. A modified form of the dispersions method (Marty

Dispersions data matrix for simultaneous optimization and verification

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}
1	1-2	0	x'_1	x_2	0	0	x_5	0	x''_5	0	0	0	0	1,2
2	2-5	0	0	x_2	0	0	0	0	x''_5	0	0	0	0	0,2
3	5-7	0	0	0	0	0	0	0	0	x'''_5	0	x_7	0	0,2
4	2-4	0	0	x_2	0	x_4	0	x'_5	x''_5	0	0	0	0	0,5
5	7-8	x_1	x'_1	0	0	0	x_5	0	0	x'''_5	0	x_7	x_8	mini
6	3-4	x_1	x'_1	0	x_3	x_4	x_5	x'_5	0	0	0	0	0	mini
7	5-6	x_1	x'_1	0	0	0	x_5	0	0	0	x_6	0	0	mini

Distribution order for lines is : **2 – 3 – 4 - 1**

Step 1 :

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}
2	2-5	0	0	x_2	0	0	0	0	x''_5	0	0	0	0	0,2

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}	k
2	2-5	0	0	**0,1**	0	0	0	0	**0,1**	0	0	0	0	0,2	0,1

Step 2 :

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}
3	5-7	0	0	0	0	0	0	0	0	x'''_5	0	x_7	0	0,2

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}	k
3	5-7	0	0	0	0	0	0	0	0	**0,1**	0	**0,1**	0	0,2	0,1

Step 3 :

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}
4	2-4	0	0	x_2	0	x_4	0	x'_5	x''_5	0	0	0	0	0,5

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}	k
4	2-4	0	0	0,1	0	**0,15**	0	**0,15**	0,1	0	0	0	0	0,5	0,15

Step 4 :

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}
1	1-2	0	x'_1	x_2	0	0	x_5	0	x''_5	0	0	0	0	1,2

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}	k
1	1-2	0	**0,5**	0,1	0	0	**0,5**	0	0,1	0	0	0	0	1,2	0,5

After computation , optimized dispersions are :

$\Delta l_{1\,opt}$	$\Delta l'_{1\,opt}$	$\Delta l_{2\,opt}$	$\Delta l_{3\,opt}$	$\Delta l_{4\,opt}$	$\Delta l_{5\,opt}$	$\Delta l'_{5\,opt}$	$\Delta l''_{5\,opt}$	$\Delta l'''_{5\,opt}$	$\Delta l_{6\,opt}$	$\Delta l_{7\,opt}$	$\Delta l_{8\,opt}$
0,5	0,5	0,1	0,5	0,15	0,5	0,15	0,1	0,1	0,5	0,1	0,5

Final distribution matrix for dispersions

Line	Dim	Δl_1	$\Delta l'_1$	Δl_2	Δl_3	Δl_4	Δl_5	$\Delta l'_5$	$\Delta l''_5$	$\Delta l'''_5$	Δl_6	Δl_7	Δl_8	IT_{cmi}
1	1-2	0	0,5	0,1	0	0	0,5	0	0,1	0	0	0	0	1,2
2	2-5	0	0	0,1	0	0	0	0	0,1	0	0	0	0	0,2
3	5-7	0	0	0	0	0	0	0	0	0,1	0	0,1	0	0,2
4	2-4	0	0	0,1	0	0,15	0	0,15	0,1	0	0	0	0	0,5
5	7-8	0,5	0,5	0	0	0	0,5	0	0	0,1	0	0,1	0,5	mini
6	3-4	0,5	0,5	0	0,5	0,15	0,5	0,15	0	0	0	0	0	mini
7	5-6	0,5	0,5	0	0	0	0,5	0	0	0	0,5	0	0	mini

Figure 6. Modified optimization procedure for the sample example.

and Linares 1994) is used in combination with the minimal transfer method to build the dispersions data matrix for the simultaneous verification and optimization procedure. However, since no reference values are used, each dispersion participating in the tolerance chain for the design and manufacturing dimensions is given the letter x as a value. Others are given the value zero in the starting data matrix as highlighted by the first table of figure 6. Then, we compute the distribution coefficient k for each design dimension BE using equation (5). The increasing values of this coefficient give the processing order for the tolerance distribution. It is noticed that for the first iteration k equals the BE tolerance value. Following this order, each line is processed by distributing the design tolerance value among the participating dispersions and their values are saved in the distribution matrix, as explained in figure 6 for the example of figure 2. In opposition to the minimal dispersions method, where a complete distribution of the residuals is not guaranteed, the unknown dispersions method always distributes the full tolerance values among the unknown dispersions.

$$k_j = \frac{IT_{CBE} - \sum_i^m \Delta li}{p}, \qquad (5)$$

where

IT_{CBE} is the tolerance interval for design dimension (BE),

m is the number of known dispersions,

p is the number of unknown dispersions,

j is the iteration order.

2.4. Procedure for computing manufacturing dimensions

In the verification procedure of the design dimensions, and when the condition of minimum transfer is satisfied, the manufacturing dimensions participating in the design dimensions are those bounded by surfaces having the two dispersions stationed on the same stage. Thus, we obtain all the manufacturing dimensions in the pre-project. Based on the fundamental model developed by Bourdet (1975) and on the matrix of the pre-project, we can calculate an average length l_i limited by two Δl_i. For each phase, the origin of basic average lengths is taken on the leftmost surface (surface 1, $l_1 = 0$). Using the design dimensions (BE) and the manufacturing dimensions (BM) we build a system of equations to determine the basic average lengths l_i using relations (6) and (7) as follows:

$$Cf_{i-j\ ave.} = l_j - l_i, \qquad (6)$$

$$Cpm_{i-j\ ave.} = l_j - l_i, \qquad (7)$$

where

$Cf_{i\text{-}j\ ave.}$ is the average design dimension (BE),

$Cpm_{i\text{-}j\ ave.}$ is the average minimal stock removal (BM).

Figure 7 explains this procedure for the example of figure 2. This figure highlights the system of 12 linear algebraic equations obtained using the data of the pre-project. After the solution of the system of equations, the computed values of the average lengths l_i for the eight surfaces are used to calculate the average manufacturing dimensions $CF_{i\text{-}j\ ave.}$. The tolerance interval IT is then computed for each dimension $CF_{i\text{-}j}$ using the previously optimized dispersions Δl_i on each surface i delimiting the dimension. Figure 7 shows that

For each element Δl_i, we correspond a basic average length l_i.
That is : l_1, l_2, l_3, l_4, l_5, l_6, l_7 and l_8. There are 12 basic average lengths.
So q = 12 (number of unknowns). We need 12 equations, as follows :
$l_1 = 0$ (origin)
$l_1 = l'_1$
$l_5 = l'_5 = l''_5 = l'''_5$
We have 7 design dimensions BE and BM, so p = 7 + 5 = 12 *(p = q)*
Equations given by dimensions BE and BM are :
Equation n°1 : (1-2) $l_2 - l_1 = 16$
Equation n°2 : (2-5) $l_5 - l_2 = 35$
Equation n°3 : (5-7) $l_7 - l_5 = 25$
Equation n°4 : (2-4) $l_4 - l_2 = 15{,}25$
Equation n°5 : (7-8) $l_8 - l_7 = 16{,}15$
Equation n°6 : (3-4) $l_4 - l_3 = 1{,}35$
Equation n°7 : (5-6) $l_6 - l_5 = 1{,}20$
We construct a system of linear equations.
After system solution, we have :

l_1	l'_1	l_2	l_3	l_4	l_5	l'_5	l''_5	l'''_5	l_6	l_7	l_8
0	0	16	29,9	31,25	51	51	51	51	52,2	76	92,15

Computation of average values for the manufactured dimensions CF :

$CF_{1\text{-}5}$ave.	$CF_{5\text{-}2}$ave.	$CF_{5\text{-}7}$ave.	$CF_{5\text{-}4}$ave.	$CF_{1\text{-}8}$ave.	$CF_{1\text{-}3}$ave.	$CF_{1\text{-}6}$ave.
$l_5 - l_1$	$l_5 - l_2$	$l_7 - l_5$	$l_5 - l_4$	$l_8 - l_1$	$l_3 - l_1$	$l_6 - l_1$
51	35	25	19,75	92,15	29,9	52,2

Computation of tolerances for manufacturing dimensions CF : classical optimization
IT $CF_{1\text{-}5} = \Delta l'_5$opt. + Δl_1opt. = 0,725 + 0,275 = 1
IT $CF_{5\text{-}2} = \Delta l''_5$opt. + Δl_2opt. = 0,09 + 0,11 = 0,2
IT $CF_{5\text{-}7} = \Delta l'''_5$opt. + Δl_7opt = 0,08 + 0,12 = 0,2
IT $CF_{5\text{-}4} = \Delta l'_5$opt. + Δl_4opt. = 0,14 + 0,16 = 0,3
IT $CF_{1\text{-}8} = \Delta l_1$opt. + Δl_8opt. = 0,5 + 0,6 = 1,1
IT $CF_{1\text{-}3} = \Delta l_1$opt. + Δl_3opt. = 0,5 + 0,5 = 1
IT $CF_{1\text{-}6} = \Delta l_1$opt. + Δl_6opt. = 0,5 + 0,5 = 1
Final values for manufacturing dimensions CF :

$CF_{1\text{-}5}$	$CF_{5\text{-}2}$	$CF_{5\text{-}7}$	$CF_{5\text{-}4}$	$CF_{1\text{-}8}$	$CF_{1\text{-}3}$	$CF_{1\text{-}6}$
$51 \pm 0{,}5$	$35 \pm 0{,}1$	$25 \pm 0{,}1$	$19{,}75 \pm 0{,}15$	$92{,}15 \pm 0{,}55$	$29{,}9 \pm 0{,}5$	$52{,}2 \pm 0{,}5$

Computation of tolerances for manufacturing dimensions CF : modified optimization
IT $CF_{1\text{-}5} = \Delta l'_5$opt. + Δl_1opt. = 0,5 + 0,5 = 1
IT $CF_{5\text{-}2} = \Delta l''_5$opt. + Δl_2opt. = 0,1 + 0,1 = 0,2
IT $CF_{5\text{-}7} = \Delta l'''_5$opt. + Δl_7opt = 0,1 + 0,1 = 0,2
IT $CF_{5\text{-}4} = \Delta l'_5$opt. + Δl_4opt. = 0,15 + 0,15 = 0,3
IT $CF_{1\text{-}8} = \Delta l_1$opt. + Δl_8opt. = 0,5 + 0,5 = 1
IT $CF_{1\text{-}3} = \Delta l_1$opt. + Δl_3opt. = 0,5 + 0,5 = 1
IT $CF_{1\text{-}6} = \Delta l_1$opt. + Δl_6opt. = 0,5 + 0,5 = 1
Final values for manufacturing dimensions CF :

$CF_{1\text{-}5}$	$CF_{5\text{-}2}$	$CF_{5\text{-}7}$	$CF_{5\text{-}4}$	$CF_{1\text{-}8}$	$CF_{1\text{-}3}$	$CF_{1\text{-}6}$
$51 \pm 0{,}5$	$35 \pm 0{,}1$	$25 \pm 0{,}1$	$19{,}75 \pm 0{,}15$	$92{,}15 \pm 0{,}5$	$29{,}9 \pm 0{,}5$	$52{,}2 \pm 0{,}5$

Figure 7. Computation of manufacturing dimensions for the sample example.

SIMULATION OF EXAMPLE OF FIGURE 2 :

```
Number of Phases                  : 5
Number of Surfaces                : 8
Number of dimensions BE and BM    : 7

Matrix of the pre-project
0.50 0.00 0.50 0.00 0.00 0.50 0.00 0.50
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.05 0.03 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.07 0.00

Dimensions of BE and BM
N° Roots S. Target S. IT   Bil(1/0)  Min.D   Max.D
1    1        2        1.20   1       15.40   16.60
2    2        5        0.20   1       34.90   35.10
3    5        7        0.20   1       24.90   25.10
4    2        4        0.50   1       15.00   15.50
5    7        8        0.00   0       15.00    0.00
6    3        4        0.00   0        0.20    0.00
7    5        6        0.00   0        0.20    0.00
```

VERIFICATION OF THE PRE-PROJECT

```
Computation of ΣΔli of design dimension 1 between
surfaces l= 1  and  m= 2 :
The matrix after elimination of columns having one
element except l and m :
0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00

The matrix after elimination of lines having one
element:
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Somme[1]=0.63 IT[1]=1.20 Residual[1]=0.57
```

Pre-project is verified for design dimension 1

```
Computation of ΣΔli of design dimension 2 between
surfaces l= 2  and  m= 5 :
The matrix after elimination of columns having one
element except l and m :
0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00

The matrix after elimination of lines having one
element:
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

The matrix after elimination of columns having one
element except l and m :
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

The matrix after elimination of lines having one
element:
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Sum[2]=0.08 IT[2]=0.20 Residual[2]=0.12
```

Pre-project is verified for design dimension 2

```
Computation of ΣΔli of design dimension 3 between
surfaces l= 5  and  m= 7 :
The matrix after elimination of columns having one
element except l and m :
0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.07 0.00

The matrix after elimination of lines having one
element:
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.07 0.00

The matrix after elimination of columns having one
element except l and m :
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.07 0.00

The matrix after elimination of lines having one
element:
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.07 0.00
Sum[3]=0.10 IT[3]=0.20 Residual[3]=0.10
```

Pre-project is verified for design dimension 3

```
Computation of ΣΔli of design dimension 4 between
surfaces l= 2  and  m= 4 :
The matrix after elimination of columns having one
element except l and m :
0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.05 0.03 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00

The matrix after elimination of lines having one
element:
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.05 0.03 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

The matrix after elimination of columns having one
element except l and m :
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.05 0.03 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

The matrix after elimination of lines having one
element:
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.05 0.03 0.00 0.00 0.00
0.00 0.05 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Sum[4]=0.16 IT[4]=0.50 Residual[4]=0.34
```

Pre-project is verified for design dimension 4

```
Computation of ΣΔli of design dimension 5 between
surfaces l= 7  and  m= 8 :
The matrix after elimination of columns having one
element except l and m :
0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.50
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.07 0.00

The matrix after elimination of lines having one
element:
0.50 0.00 0.00 0.00 0.00 0.00 0.00 0.50
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.07 0.00
```

(continued opposite)

```
Sum [ 5] =  1.65

Computation of ΣAli of design dimension 6 between
surfaces l= 3  and  m= 4 :
The matrix after elimination of columns having one
element except l and m :
0.50 0.00 0.50 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.05 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00

The matrix after elimination of lines having one
element:
0.50 0.00 0.50 0.00 0.00 0.00 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.05 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Sum [ 6] =  1.63

Computation of ΣAli of design dimension 7 between
surfaces l= 5  and  m= 6 :

The matrix after elimination of columns having one
element except l and m :
0.50 0.00 0.00 0.00 0.00 0.50 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00

The matrix after elimination of lines having one
element:
0.50 0.00 0.00 0.00 0.00 0.50 0.00 0.00
0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Sum [ 7] =  1.55

    OPTIMIZATION AND DISTRIBUTION DATA MATRIX FOR
                      DISPERSIONS

0.00 0.50 0.05 0.00 0.00 0.05 0.00 0.03 0.00 0.00 0.00 0.00
0.00 0.00 0.05 0.00 0.00 0.00 0.00 0.03 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.03 0.00 0.07 0.00
0.00 0.00 0.05 0.00 0.05 0.00 0.03 0.03 0.00 0.00 0.00 0.00
0.50 0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.03 0.00 0.07 0.50
0.50 0.50 0.00 0.50 0.05 0.05 0.03 0.00 0.00 0.00 0.00 0.00
0.50 0.50 0.00 0.00 0.00 0.05 0.00 0.00 0.00 0.50 0.00 0.00

              OPTIMIZATION OF DISPERSIONS

S[1]=0.630 IT[1]=1.200 Residual[1]=0.570
S[2]=0.080 IT[2]=0.200 Residual[2]=0.120
S[3]=0.100 IT[3]=0.200 Residual[3]=0.100
S[4]=0.160 IT[4]=0.500 Residual[4]=0.340

Rank     Residual  Processing order
 1         0.100          3
 2         0.120          2
 3         0.340          4
 4         0.570          1

Rank : 1
Before optimization of dispersions for dimension 3
0.05 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.03 0.00
0.07 0.00
IT of the dimension------------->=  0.200
ΣAli---------------------------->=  0.100
Residual of the dimension  ---->=  0.100
Number of dispersions to be optimized for the
dimension---------------------->=  2
Distribution of  the residual ->=  0.050

After optimization of dispersions for dimension 3
0.05 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.08 0.00
0.12 0.00
IT of the dimension------------->=  0.200
ΣAli --------------------------->=  0.200
Residual of the dimension ----->=  0.000

Rank : 2
Before optimization of dispersions for dimension 2
0.00 0.00 0.05 0.00 0.00 0.00 0.00 0.03 0.00 0.00
0.00 0.00
IT of the dimension------------->=  0.200
ΣAli --------------------------->=  0.080
Residual of the dimension ----->=  0.120
Number of dispersions to be optimized for the
dimension---------------------->=  2
Distribution of  the residual ->=  0.060

After optimization of dispersions for dimension 2
0.00 0.00 0.11 0.00 0.00 0.00 0.00 0.09 0.00 0.00
0.00 0.00
IT of the dimension------------->=  0.200
ΣAli --------------------------->=  0.200
Residual of the dimension ----->=  0.000

Rank : 3
Before optimization of dispersions for dimension 4
0.00 0.00 0.11 0.00 0.05 0.00 0.03 0.09 0.00 0.00
0.00 0.00
IT of the dimension------------->=  0.500
ΣAli --------------------------->=  0.280
Residual of the dimension ----->=  0.220
Number of dispersions to be optimized for the
dimension --------------------->=  2
Distribution of  the residual ->=  0.110

After optimization of dispersions for dimension 4
0.00 0.00 0.11 0.00 0.16 0.00 0.14 0.09 0.00 0.00
0.00 0.00
IT of the dimension------------->=  0.500
ΣAli --------------------------->=  0.500
Residual of the dimension ----->=  0.000

Rank : 4
Before optimization of dispersions for dimension 1
0.00 0.50 0.11 0.00 0.00 0.05 0.00 0.09 0.00 0.00
0.00 0.00
IT of the dimension------------>=  1.200
ΣAli -------------------------->=  0.750
Residual of the dimension ---->=  0.450
Number of dispersions to be optimized for the
dimension -------------------->=  2
Distribution of  the residual->=  0.225

After optimization of dispersions for dimension 1
0.00 0.72 0.11 0.00 0.00 0.27 0.00 0.09 0.00 0.00
0.00 0.00
IT of the dimension------------>=  1.200
ΣAli -------------------------->=  1.200
Residual of the dimension ---->=  0.000

Optimized dispersions
0.500  0.725  0.110  0.500  0.160  0.275  0.140  0.090
0.080 0.500 0.120  0.500

      COMPUTATION OF THE MANUFACTURING DIMENSIONS

Equation[1]:      0.000 = L 1
Equation[2]:     16.000 = L 2 - L 1
Equation[3]:     35.000 = L 5 - L 2
Equation[4]:     25.000 = L 7 - L 5
Equation[5]:     15.250 = L 4 - L 2
Equation[6]:     16.100 = L 8 - L 7
Equation[7]:      1.350 = L 4 - L 3
Equation[8]:      1.200 = L 6 - L 5

System of equations:

1L1+0L2+0L3+0L4+0L5+0L6+0L7+0L8 = 0.000
-1L1+1L2+0L3+0L4+0L5+0L6+0L7+0L8=16.000
0L1-1L2+0L3+0L4+1L5+0L6+0L7+0L8 =35.000
0L1+0L2+0L3+0L4-1L5+0L6+1L7+0L8 =25.000
0L1-1L2+0L3+1L4+0L5+0L6+0L7+0L8 =15.250
0L1+0L2+0L3+0L4+0L5+0L6-1L7+1L8 =16.100
0L1+0L2-1L3+1L4+0L5+0L6+0L7+0L8 = 1.350
0L1+0L2+0L3+0L4-1L5+1L6+0L7+0L8 = 1.200

Solution L :
L[ 1]=  0.000
L[ 2]= 16.000
L[ 3]= 29.900
L[ 4]= 31.250
L[ 5]= 51.000
L[ 6]= 52.200
L[ 7]= 76.000
L[ 8]= 92.100

Manufacturing dimensions

CF[1 5]=51.00 ±0.50
CF[2 5]=35.00 ±0.10
CF[5 7]=25.00 ±0.10
CF[4 5]=19.75 ±0.15
CF[1 8]=92.10 ±0.50
CF[1 3]=29.90 ±0.50
CF[1 6]=52.20 ±0.50
```

Figure 8.   Results of the automated simulation for the sample example.

the ®nal tolerance values given by the modi®ed dispersions optimization method for the simple example are similar to the results given by the classical dispersions optimization method. However, in reality, the former always gives better results than the latter, as was veri®ed with more complex examples. Furthermore, the modi®ed dispersions method overcomes the problem of unknown minimal reference dispersions that are not always available in the industrial literature or are dif®cult to assess from experience.

3. Programming and validation tests for the simulation

The procedures forming the simulation have been integrated in one module and programmed in order to be tested. The ®nal computer program consists of ®ve functions. The ®rst function permits the input and preparation of the pre-project data in matrix format. The second function performs the pre-project veri®cation and eventual solution of impossible tolerance transfer. The third function executes the optimization procedure of dispersions. The fourth function computes the manufacturing dimensions. The ®fth function computes the setting dimensions. The program is validated by practical and complex process plan simulations and is compared to classical manual simulations (Hamou 1998). Figure 8 gives an overview of the output results of the developed module for the pre-project sample of ®gure 2. This software, which is designed as a standalone module, can be easily integrated in a CAPP system or a more general CAD/CAM system. The program can extract its initial pre-project data from the upstream CAPP modules. On the other side, it can communicate its simulation results to the downstream departments of manufacturing, such as numerical control processing activities.

4. Conclusions and perspectives

The objectives set forth by this research work were to automate the process plan simulation activity as a separate module or within a CAPP system. The manufacturing dispersions or capabilities are at the root of the development of a combined programmable methodology, based on the minimal transfer method, the minimal reference dispersions method and a proposed modi®ed dispersions method. It is shown that the modi®ed dispersions method performs a simultaneous veri®cation and optimization without the need of the minimal reference dispersions that are not always available for all processes. On the basis of the developed programmed methodology, a computerised module has been designed in the form of three procedures. The ®rst procedure permits the veri®cation of the process plan pre-project. The second procedure permits an optimization of dispersions. The third procedure permits the computation of the optimized manufacturing dimensions and tolerances. The ®nal module of simulation has been tested on complex examples. These results have shown that the methodologies used can help process designers in the activity of manufacturing tolerance analysis and distribution within a CAPP system. Further research is undergone on one side, in order to perform a non-equal redistribution of excess tolerance depending on the complexity of the manufacturing dimensions. On the other side, investigations are being conducted for automating the extraction of a manufacturing tolerance chain in order to perform a cost-based statistical optimization of tolerance transfers and distribution on the manufacturing dimensions.

References

Bourdet, P., 1975, Les chaînes de cotes de fabrication. *Revue de l'Ingénieur et du Technicien de L'enseignement Technique*, 191, 15 ± 23.

Cheikh, A., 1997, Integrating functional tolerancing in computer aided engineering environments. *Proceedings of the Second Jordanian International Mechanical Conference*, Amman, Jordan, pp. 960 ± 968.

Duret, T., 1981, Simulation de gamme d'usinage. *Revue de l'Ingénieur et du Technicien de L'enseignement Technique*, 229, 34 ± 37.

Fainguelernt, D., Weill, R. and Bourdet, P., 1986, Computer aided tolerancing and dimensioning in process planning. *Annals of the CIRP*, 35(1), 311 ± 315.

Graves, S. and Bisgaard, S., 1999, Integrated tolerance management. *Proceedings of the Sixth CIRP International Seminar on Computer Aided Tolerancing*, Twente, Netherlands, pp. 385 ± 394.

Hamou, S., 1998, A module for process plan simulation and tolerance transfer in computer aided manufacturing. Master thesis, ENSET, Oran, Algeria.

Halevi, G. and Weill, R. D., 1995, *Principles of Process Planning a Logical Approach* (London: Chapman and Hall).

Marty, C. and Linares, J. M., 1994, *Industrialisation des produits mécaniques: conception et industrialisation* (Paris: Hermès, Tome 1).

Weill, R., Integrating dimensioning and tolerancing in computer aided process planning. *Robotics and Computer Integrated manufacturing*, 4(1/2), 41 ± 48.