APEM journal **Advances in Production Engineering & Management** 2 (2007) 4, 163-176
ISSN 1854-6250 Original scientific paper

A COMPUTER AIDED TOLERANCING: ALGORITHM FOR 3D MANUFACTURING TOLERANCING

Jaballi, K.[*,**]; Bellacicco, A.[**]; Louati, J.[*]; Rivière, A.[**] & Haddar, M.[*]
[*] Mechanics Modelling and Production Research Unit (U2MP) University of Sfax,
Sfax Engineering School (E.N.I.S.), B.P 3038-Sfax –Tunisia
[**] Laboratoire d'Ingénierie des Structures Mécaniques et des Matériaux, Institut Supérieur de Mécanique de Paris (SUPMECA),
3 rue Fernand Hainaut, 93 407 SAINT OUEN Cedex
E-Mail: jkarimj@yahoo.fr

Abstract:
Development of technologies for rational design and manufacture is required for various products which satisfy the high needs of individuals, considering the constraint factors of the various environments. Special attention is directed toward the analysis of dimensioning and tolerancing in manufacturing which ensures the quality of the product in manufacturing and takes account economy and functional behaviour of product by allowing the necessary and the right manufacturing requirement to be carried on manufacturing processes in accordance with relations between pieces joints forming the studied mechanisms. In this paper after reviewing some methods presented in the literature we propose a rational method of 3D tolerance, based on the studies already made in the functional method of tolerance CLIC. CLIC is based on the concepts of invariance surfaces, which is the base of "TTRS" approach "Technological and topological Related Surfaces"

Key Words: Functional Tolerancing, CLIC, Spider Graph, Rational Method Of 3D, Manufacturing Tolerancing, Manufacturing Specifications, Active Surfaces

Nomenclature

- *GFR* = geometric feature reference
- SR_1 = primary surface
- SR_2 = secondary surface;
- SR_3 = tertiary surface;
- $SP_{i,1}$ = primary surface of laying in phase i
- $SP_{i,2}$ = secondary surface of laying in phase i
- $SP_{i,3}$ = tertiary surface of laying in phase i
- S_{pec} = specification of the mobility permitted by surface ($o\vec{u}, r\vec{u}\ \ p\vec{u}, c\vec{u},\ $);
- *Sud* = the last machined surface;
- *SRef* = frame of reference (or of laying);
- $IT_{i,j}$ = interval of tolerance BM of the condition, in phase i of surface j;
- IT_{BE} = interval of tolerance of the functional condition;
- IT_{BM} = interval of tolerance of the condition developed;
- S_K = surfaces accumulated after each transfer (passage of a ring to another inferior).
- S_L = surfaces remaining in final phase.
- *Or* = Oriented Specification ($o\vec{u}, r\vec{u}$)
- *Pos* = Positioning Specification ($p\vec{u}, c\vec{u},$)
- *Sc* = surface chosen among accumulated surfaces which are machined in the same phase.
- SR_{ini} = surface belonging to the initial frame of reference given by engineering and design department

1. INTRODUCTION

It is necessary to understand the fundamental environments surrounding the manufacturing technologies in order to examine the manufacturing technologies of the future. The fundamental environments are social environment, natural environment, international relation environment, labour environment, economic environment, science and technology environment, etc.

The major objectives of developments of technological innovations in the field of manufacturing engineering are summarized as follows, taking into consideration the various environments surrounding the manufacturing technologies explained in the previous section:

- Cultivation of new innovative technologies,
- Increase of added value,
- Increase of productivity,
- Saving of resources and energies,
- Increase of flexibility,
- Preservation of environments,
- Improvement of safety and
- Adaptation to social and labour environments.

The manufacturing technology is desired to produce products, adapted to the needs of individuals, which are easy to obtain, use, and maintain by the most desirable means for humans.

2. INTEGRATING DIMENSIONING AND TOLERANCING IN CAPP

With today's drive towards automation, and the evolution of more complex mass produced products, the very highest quality of drawings is essential for successful production. Geometric tolerancing is the best available means to convert functional requirements into parts that can be produced at the lowest cost

Many interviews of engineers have shown that not only didn't know geometrical tolerancing, but they also didn't realize the three requirements that every dimension must have:

1. Tolerance of the feature and at least an idea of what factors influenced selection of the tolerance value.
2. Location of the feature, both position and tolerance.
3. Physical location of the dimension so that it is as clear to the person reading the piece part drawing as it was to the design personnel who have worked with the part and associated parts and assemblies for weeks or months.

Weil [1] considers that a process planning is today recognized as "the missing link" between computer-aided design (CAD) and computer-aided manufacturing (CAM). And Saggu [2] recognise that an integrated CADCAM package is a great priority of aircraft structural components.

Computer technology has greatly impacted the role of design and manufacturing engineers during life cycle of products (Figure 1). Computer Aided Process Planning (CAPP) is one tool which frees the process planner from many decisions which is required during the process planning task. Kamrani [3] demonstrate that a feature based modelling is considered as a key factor in the integrated CADD and CAPP, so geometric dimensions and tolerances are associated with the specification of the product design and manufacturing capabilities to ensure proper quality. Geometric feature are considered as a collection of geometric entities with significant impact on the process planning stage.

Tolerancing of mechanical parts, and especially geometrical tolerancing, and its relations to size tolerancing is under current review by the International Standards Organisation (ISO) which has produced international standards on form and position tolerancing ISO 1101

(2005) [4] constitutes a first stage towards a geometrical language of specification more rigorous and univocal. Work continues at the international level to propose a complete recasting of GPS "Geometrical Product Specifications".

3. GEOMETRICAL ACTIVITY OF TOLERANCE

With each stage, design, manufacture or inspection, the choice of a specification of adequate tolerance form is a significant ingredient in any project of engineering Fig. 2.
Dufaure in [5] distinguish two problems, "the analysis" and "the synthesis", which we will be able to still widen by adding the problem of "measurement":

1. The analysis of the tolerances relates to the checking of the functional conditions according to the individual variation of the parts of a mechanism, after having defined the tolerances.
2. The synthesis carries out on the contrary the distribution and the allowance of the tolerances according to the functional conditions to respect, while taking into account the phenomenon of transfer and optimization of allowance of the tolerances

- The transfer consists in affecting the tolerances of the part in the course of manufacture according to the aptitudes of production.
- The evaluation of the tolerances relates to the methods of measurement and the interpretation of measurements according to the specifications to be respected.

Mathieu [6] considers that Tolerance Specification is the main activity in the tolerancing process. For each geometric requirement, tolerance specification specifies assemblies and parts involved with a functional view point Fig. 2.

GEOSPELLING is a model used to describe ideal and non ideal surfaces. It is based on the following basic concept:

- A specification is a condition on a characteristic defined from geometric features,
- These geometric features are features created from the model of the real surface of the part (skin model) by different operations.

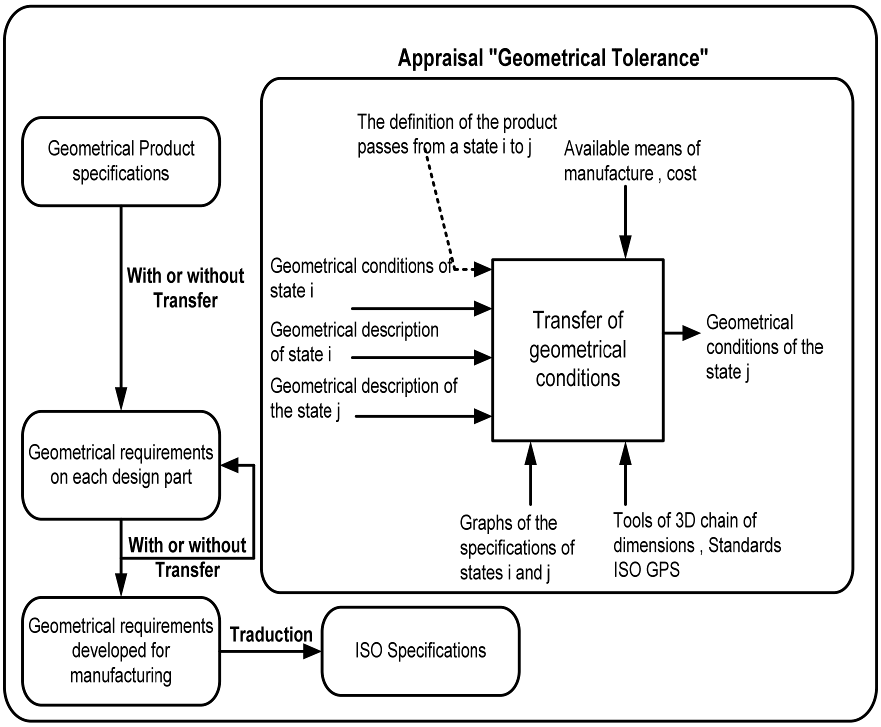


Figure 1: Diagram of the geometrical activity of tolerance.

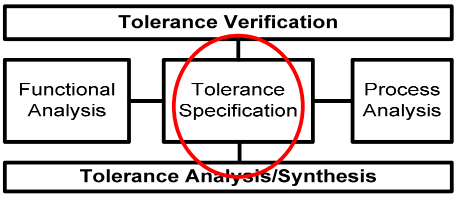


Figure 2: Process of tolerance.

4. FUNCTIONAL AND MANUFACTURED GEOM. TOLERANCING RELATIONSHIP

The functional requirements have to be translated into geometric requirements on parts and assembly. Tolerance specification must also take into account data coming from process analysis. Process analysis point is out the setting of machines on the shop floor. To be complete, the tolerancing process has to cover all the aspects of geometric variations during the product life cycle. It must include all the geometric features and all the parameters to describe the functionalities of a product.

A key problem in tolerance analysis is computing the tolerance envelope of a part from its tolerance specification.

4.1. Literature uses

The *ΔL* model of Bourdet [7-8] is used with a new algorithm which generalizes the optimisation for unilateral requirements and it may be possible to introduce production cost as a parameter in the algorithm.

P. Ji [9] in many work discuss the dimensioning problem in Design for Manufacturing (DFM) and Concurrent Engineering using the digraphic method and the reverse dimensional chains, and presents a mathematical approach to tackle this dimensioning problem in DFM/CE, even if datum surface was been changed during the study.

The unidirectional aspect does not meet any more the multiple requirements, day after day, the request Engineering and design department (DD), and especially does not take account of the orientation induced by the positioning and machining operations which can be generated.

3D approach: ANSELMETTI method

This method [10] proposed by Anselmetti is based on the distribution of the functional conditions of the mechanism as geometric specifications for each of the components.

The initial whole made up of all toleranced surfaces and all reference surfaces implied in the requirement is divided into three subsets:

1. Machined surfaces in phase n,
2. Surfaces which are used for the positioning in phase n,
3. Other surfaces obtained in the preceding phases.

In phase n, it is necessary to locate the machined surfaces of subset 1 compared to the frame of reference built on surfaces of positioning in this phase. It is necessary to remove the secondary references and tertiary sectors if they do not intervene in the definition of the specification. If surfaces of this reduced frame of reference all are not contained in subset 2, missing surfaces are identified in subset 4.

After this transfer in phase n, a new unit is formed with subsets 2, 3 and 4. It will have to be treated by the same rule until unit 3 is empty.

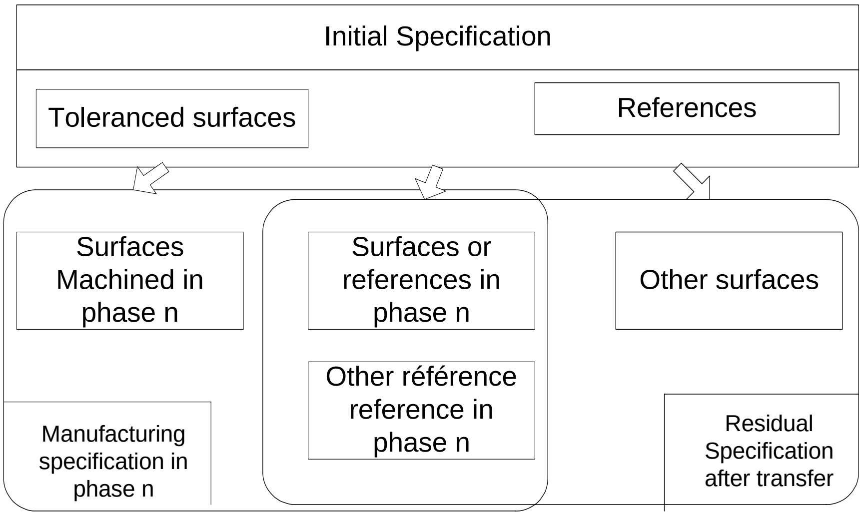


Figure 3: Transfer method: ANSELMETTI method [11].

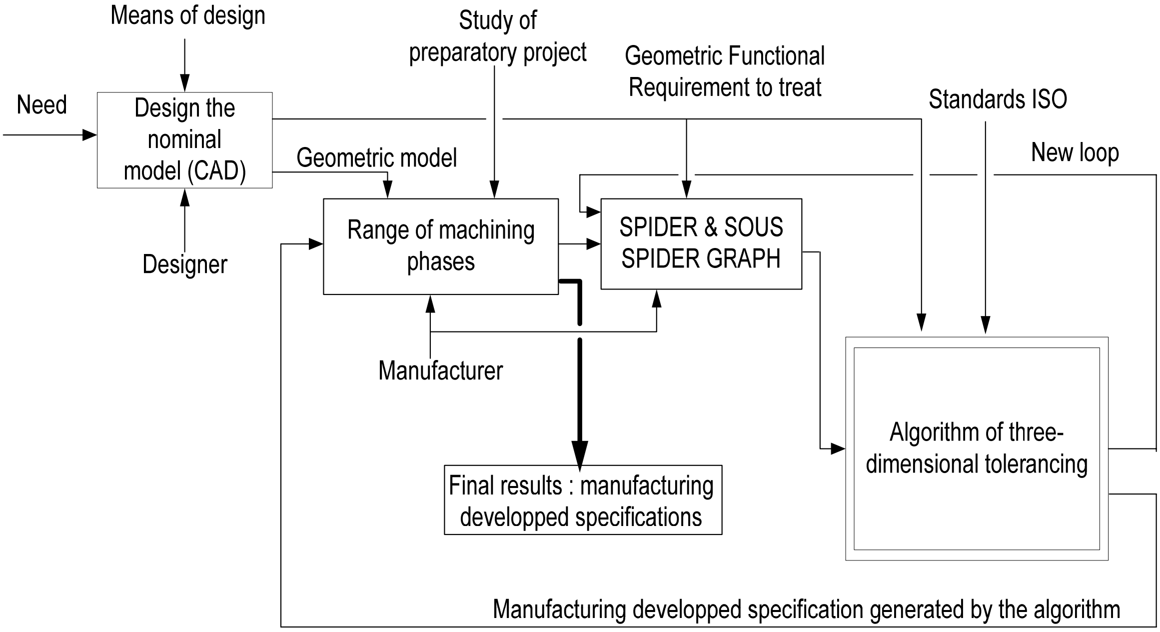


Figure 4: Graph of the developed Method of Manufacturing Tolerancing.

4.2. Proposed Approach (Fig. 4)

In this paper it is a question of enriching the algorithm developed by the rational 3D method of tolerance [12] and by using the method of transfer of reference and the method of functional quotation "CLIC" [8] and [13-14].

From the method of transfer, the idea is to inject new surfaces which replace the surface of which they were used as support in a phase immediately later and this whit the help of a new representation called a SPIDER GRAPH, developed in the Rational method of 3D Tolerancing.

Then, from the method CLIC, the use of the Figure of the development of the criteria of the generations of the rules of assignment of surfaces of references developed by Mejbri [14-15], which is formed by surfaces of support called also positioning surface.

Geometric functional requirement is a characteristic defined between ending geometric entities (plane, line, point, etc.). In general, this characteristic constitutes a distance or angle between two ending entities, yet can also be a location or orientation of an ending entity, with respect to a datum reference system formed by other ending entities.

Sellekh [15] represent the TTRS by model could be a good way to build a complete and a coherent tolerancing process. This model is able to describe all the ideal geometry involved in a nominal model for each stage of the tolerancing process. But it must now taken into account tolerances and explain how ideal geometry is connected to actual parts.

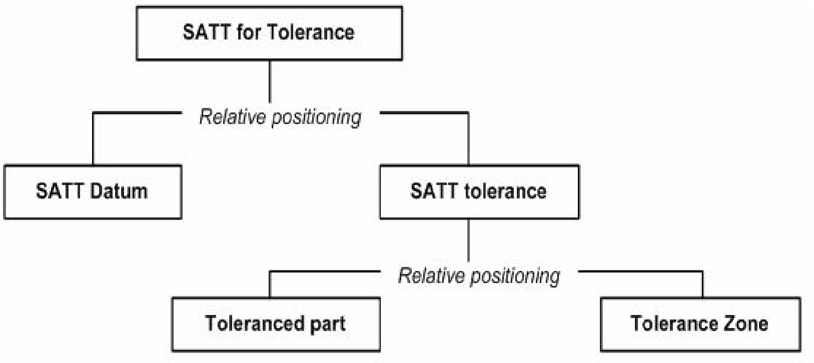


Figure 5: Structure of the TTRS of tolerance [15].

In order to satisfy GFR values, the ending geometric entity must lie within the associated tolerance zone. The displacement of this ending entity is caused by its own geometric variation, the variation of theirs positioning references.

The influence of the geometric variation in joint surfaces has been modeled and computed for a mechanism in Mejbri, Anselmetti and Mawussi [14].

4.3. Tools

Spider graph

The machining process is described in the form of a graph which is called SPIDER GRAPH which is made up developed by [12]:

1. Of an external ring which definite existing surfaces with the state of reception of the part before the stages of machining.
2. Of a ring for each phase of machining, where only active surfaces will be presented.

Surfaces of positioning are represented in hexagons, where putted small triangles which indicate the type of positioning are. But active surfaces which are not used for the positioning are put in simple circles.

One must note that all surfaces which constitute the part owe beings identified, and represent in each phase, where they act as machined surfaces or of Positioning, this identification can be in the form of numbers or letters.

Figure 6: Hexagon representing surface positioning (plane support (A)).

Figure 7: Ring representative a machined surface (b)

Notes To Be Inserted On SPIDER GRAPH

The various changes introduced on SPIDER GRAPH are:

1. On ST: we introduce the identification of allowed mobility "Spec".
2. On SP *i,j*: we introduce also the identification of allowed mobility "Spec", as well the order of priority (primary, secondary and tertiary reference) this order is already taken into account by the small triangles put on the hexagons).
3. On SR *i,j:* surfaces of references defined in the functional specification must carry indices of preponderance (,..).
4. After each transfer operation, we still generate new a spider graph which called SOUS SPIDER GRAPH where we will mention the new condition generated during the transfer.
5. After each transfer operation, one new SOUS SPIDER GRAPH is generated and new surfaces which enter in plays (*Sud* is replaced by its developed *SRi,j*) must be represented in full enclosures (coloured hexagon or simple circle).

Each feature is presented by his MRGE "Minimum Reference Geometric Element" [6] and [16].

ISO Specification and SPIDER GRAPH representation

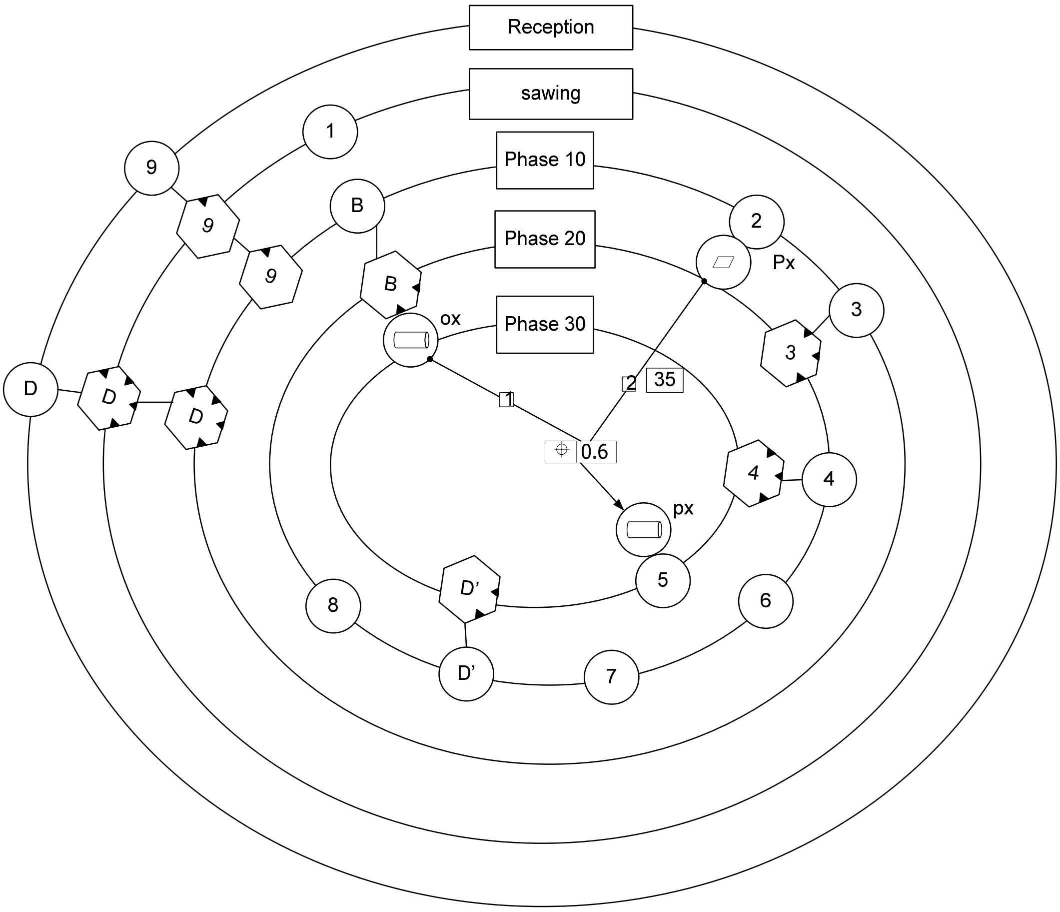


Figure 8: Representation of the functional specification SGi on SPIDER GRAPH

4.4. Rules

The specified orientation and position symbols are, by default, the parallelism and location, respectively; they rely upon the mutual orientation between specified entity and DRFs.

The geometric specification, the invariant rotations and translations of the related tolerance zone, and the type of datum reference frame, along with the associated topological constraint between geometric parameters to be satisfied, are all defined in next Figures. If the specified constraint is not satisfied for the primary DRF, then both the primary and secondary DRFs must be reclassified in order to obtain a new frame. This new frame would then be tested, and so forth and so on. In Fig. 12 and Fig. 13, the entry 'yes' indicates that the corresponding DRF is always valid for the considered tolerance zone, while 'no' means that the DRF is not valid and we must consider both this DRF and the next one (in the order of preponderance) built on the part to obtain a new frame.

In order to test the validation, we will begin with the primary frame SP_1. Then, if the last frame is not sufficient, we will reclassify both primary frame SP_1 and secondary frame SP_2 so as to obtain a new frame SP_1/SP_2. Should this reclassified new frame not be sufficient, it will be reclassified with the next frame SP_3 to form system $SP_1/SP_2/SP_3$

The rules of transfer and assignment of the references make it possible to identify, for each manufacturing specification, tolerancing surface (ST) and surfaces of references ($SR_{1/2/3}$).

The geometric specification, the invariant rotations and translations of the related tolerance zone, and the type of datum reference frame, along with the associated topological constraint between geometric parameters to be satisfied, are all defined in these Figures.

Note:

The intrinsic characteristics on the surfaces (surface quality, defect of form, angle, diameter…) are directly recopied on the drawings of phase in which are carried out surfaces. There is no transfer in those cases.

1. The reference is already defined on the functional requirement or of manufacture. The specification manufacturing takes again this complete frame of reference, if all surfaces which take part in the study are active in the same phase and none is a surface of positioning in this phase. (It should well be announced that the interval of tolerance of the design drawing required by engineering and design department will not be the same one as that put during manufacturing analysis).
2. If one is in the presence of a transfer then one owes specified well the machined surface in last "Sud" and phase *i* where it is carried out as well as the system of positioning adopted at the time of the operation..
   Just to formalize this step, this analysis is divided into two stages:
   (1) Study of the degrees of freedom in translation (by supposing that the orientations are controlled).
   (2) Study of the degrees of freedom in orientation.

4.5. How to valid a Datum Reference System

The geometric specification, the invariant rotations and translations of the related tolerance zone, and the type of datum reference frame, along with the associated topological constraint between geometric parameters to be satisfied, are all defined in these Figures.

If the specified constraint is not satisfied for the primary DRF, then both the primary and secondary DRFs must be reclassified in order to obtain a new frame. This new frame would then be tested, and so forth and so on. In Fig. 5 and Fig. 6, the entry 'yes' indicates that the corresponding DRF is always valid for the considered tolerance zone, while 'no' means that the DRF is not valid and we must consider both this DRF and the next one (in the order of preponderance) built on the part to obtain a new frame, whose validation is then to be tested.

For example:

Example 1: The geometric specification is the location of a plane exhibiting u as a functional direction (first specification in the Column 1 list) and the reclassified datum reference frame is planar with v as a functional direction (Column 2). If the two planes are parallel (u±v), then this datum reference frame is sufficient.

Example 2: The geometric specification is the location of a point F within a cylindrical tolerance zone exhibiting u as the axis direction (fourth specification in the Column 1 list) and the reclassified DRF is cylindrical with v as the axis direction and line of revolution D (Column 3). If (F∈D and u±v), then this DRF is sufficient.

Example 3: The geometric specification is the orientation of the axis of a cylinder with axis direction u (third specification in the Column 1 list) and the reclassified DRF is planar with functional direction v (Column 2). If (u±v), then this DRF is sufficient.

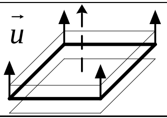
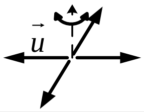
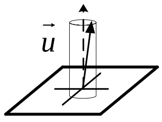
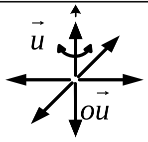
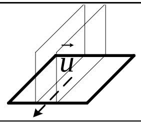
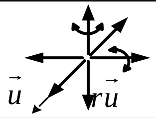
Entity	Geometric specification	Type of the tolerance zone	Illustration	Invariant DOFs of the tolerance zone
Plane	⌖ t	$p\vec{u}$		
	∠ t	$o\vec{u}$		
		$r\vec{u}$		

Figure 9: General characterizations of geometric variations [13].

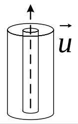
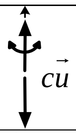
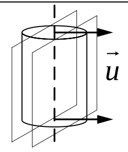
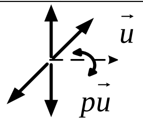
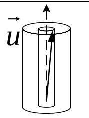
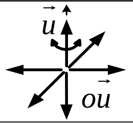
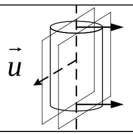
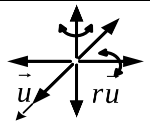
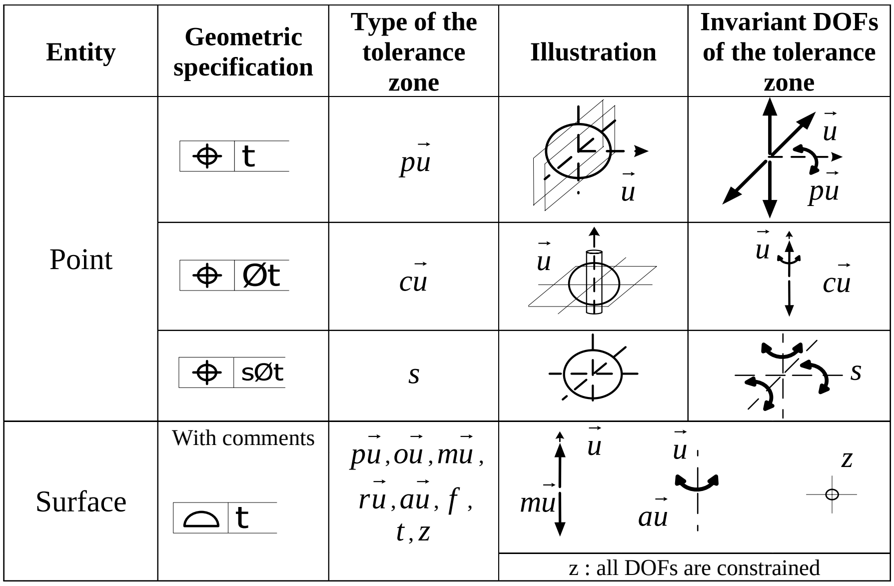
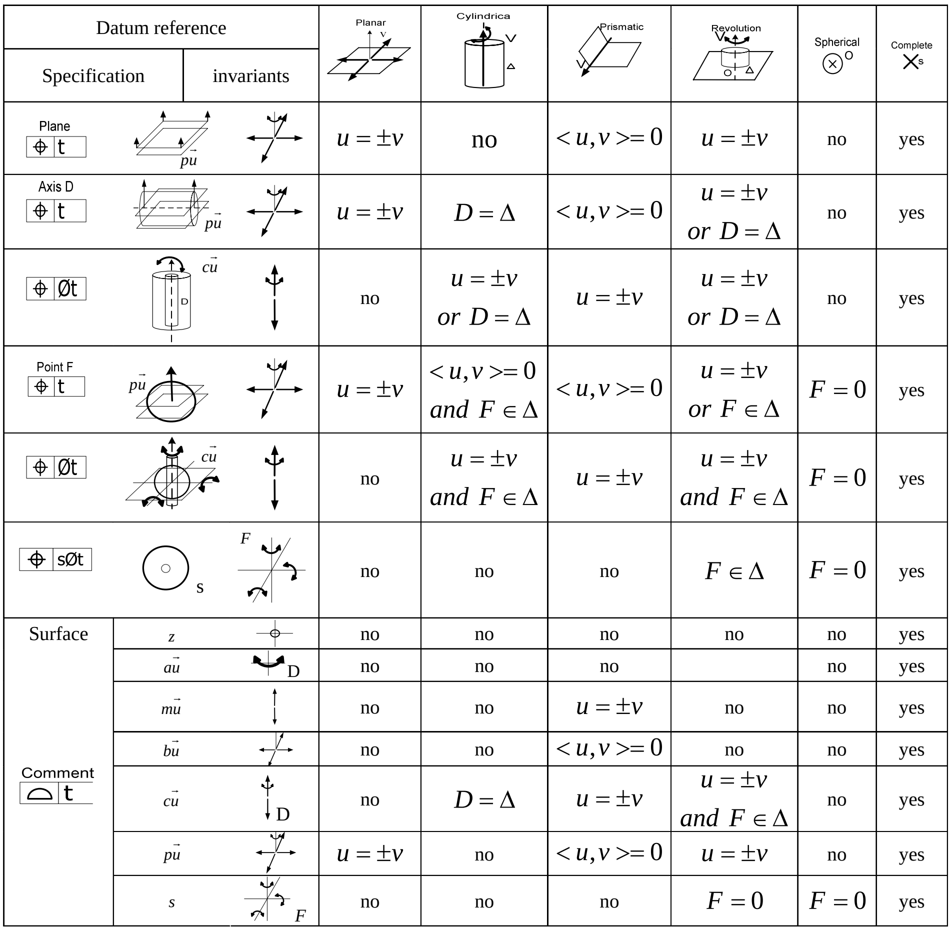
Entity	Geometric specification	Type of the tolerance zone	Illustration	Invariant DOFs of the tolerance zone
Axis (or Line)	⌖ Øt	$c\vec{u}$		
	⌖ t	$p\vec{u}$		
	∠ Øt	$o\vec{u}$		
	∠ t	$r\vec{u}$		

Figure 10: General characterizations of geometric variations [13].



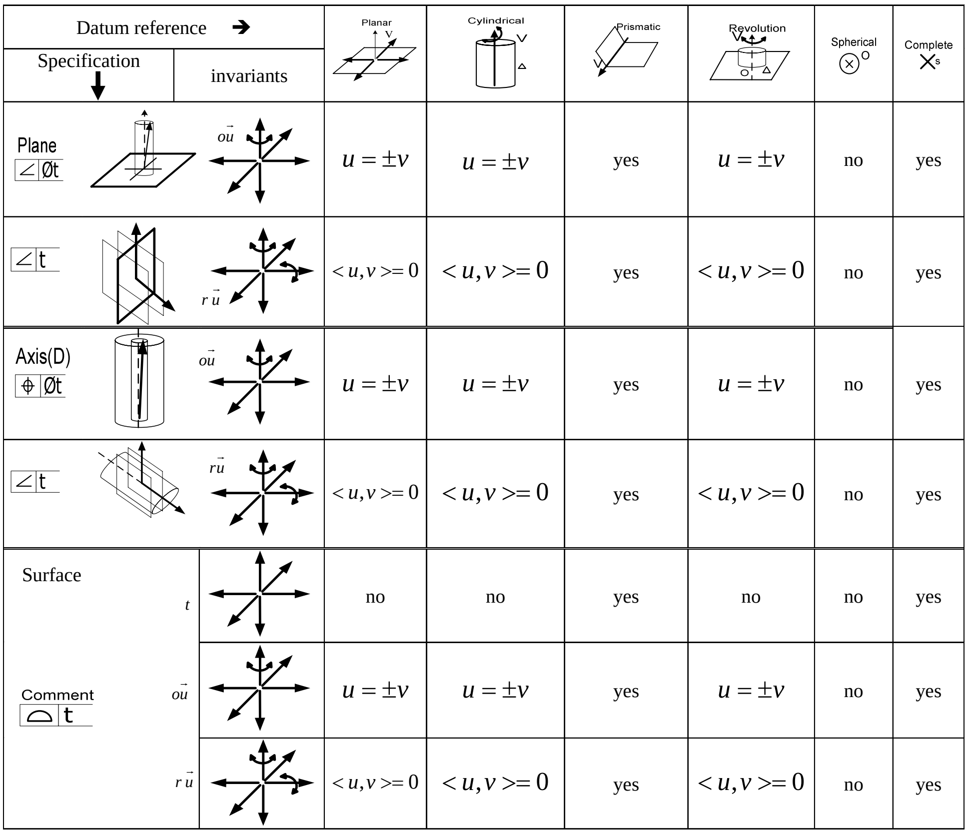
Entity	Geometric specification	Type of the tolerance zone	Illustration	Invariant DOFs of the tolerance zone
Point	⌖ t	$\vec{pu}$	$\vec{u}$	$\vec{u}$ $\vec{pu}$
	⌖ Øt	$\vec{cu}$	$\vec{u}$	$\vec{u}$ $\vec{cu}$
	⌖ sØt	s		s
Surface	With comments ⌓ t	$\vec{pu}, \vec{ou}, \vec{mu},$ $\vec{ru}, \vec{au}, f,$ t, z	$\vec{u}$ $\vec{mu}$ $\vec{u}$ $\vec{au}$ z	
			z : all DOFs are constrained	

Figure 11: General characterizations of geometric variations [13].



Datum reference		Planar V	Cylindrica V Δ	Prismatic V	Revolution V O Δ	Spherical O	Complete S
Specification	invariants						
Plane ⌖ t $\vec{pu}$		$u=\pm v$	no	$<u,v>=0$	$u=\pm v$	no	yes
Axis D ⌖ t $\vec{pu}$		$u=\pm v$	$D=\Delta$	$<u,v>=0$	$u=\pm v$ $or\ D=\Delta$	no	yes
⌖ Øt $\vec{cu}$ D		no	$u=\pm v$ $or\ D=\Delta$	$u=\pm v$	$u=\pm v$ $or\ D=\Delta$	no	yes
Point F ⌖ t $\vec{pu}$		$u=\pm v$	$<u,v>=0$ $and\ F\in\Delta$	$<u,v>=0$	$u=\pm v$ $or\ F\in\Delta$	$F=0$	yes
⌖ Øt $\vec{cu}$		no	$u=\pm v$ $and\ F\in\Delta$	$u=\pm v$	$u=\pm v$ $and\ F\in\Delta$	$F=0$	yes
⌖ sØt s	F	no	no	no	$F\in\Delta$	$F=0$	yes
Surface	z	no	no	no	no	no	yes
	$\vec{au}$ D	no	no	no		no	yes
	$\vec{mu}$	no	no	$u=\pm v$	no	no	yes
	$\vec{bu}$	no	no	$<u,v>=0$	no	no	yes
Comment ⌓ t	$\vec{cu}$ D	no	$D=\Delta$	$u=\pm v$	$u=\pm v$ $and\ F\in\Delta$	no	yes
	$\vec{pu}$	$u=\pm v$	no	$<u,v>=0$	$u=\pm v$	no	yes
	s F	no	no	no	$F=0$	$F=0$	yes

Figure 12: Topological rules relative to a location specification for validating a DRF [13].



Datum reference →		Planar	Cylindrical	Prismatic	Revolution	Spherical	Complete
Specification ↓	invariants						
Plane ∠ Øt	$\vec{ou}$	$u = \pm v$	$u = \pm v$	yes	$u = \pm v$	no	yes
∠ t	$r\vec{u}$	$< u,v >= 0$	$< u,v >= 0$	yes	$< u,v >= 0$	no	yes
Axis(D) ⌖ Øt	$\vec{ou}$	$u = \pm v$	$u = \pm v$	yes	$u = \pm v$	no	yes
∠ t	$r\vec{u}$	$< u,v >= 0$	$< u,v >= 0$	yes	$< u,v >= 0$	no	yes
Surface	t	no	no	yes	no	no	yes
Comment ⌓ t	$\vec{ou}$	$u = \pm v$	$u = \pm v$	yes	$u = \pm v$	no	yes
	$r\vec{u}$	$< u,v >= 0$	$< u,v >= 0$	yes	$< u,v >= 0$	no	yes

Figure 13: Topological rules relative to an orientation specification for validating a DRF [13].

5. TREATMENT OF AN EXAMPLE

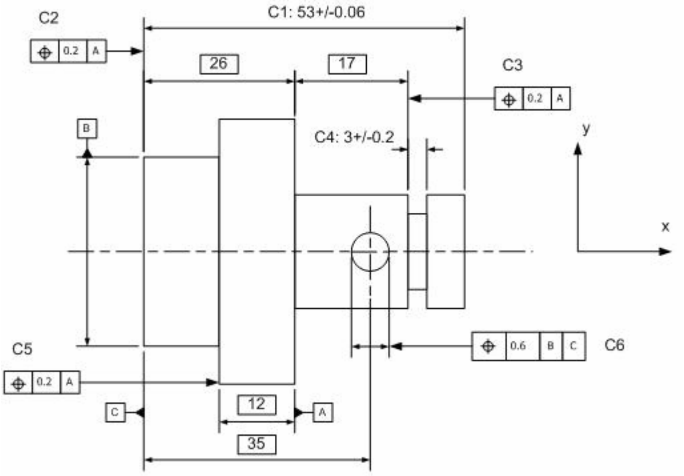


Figure 14: Drawing part, with functional specifications.

5.1. Results

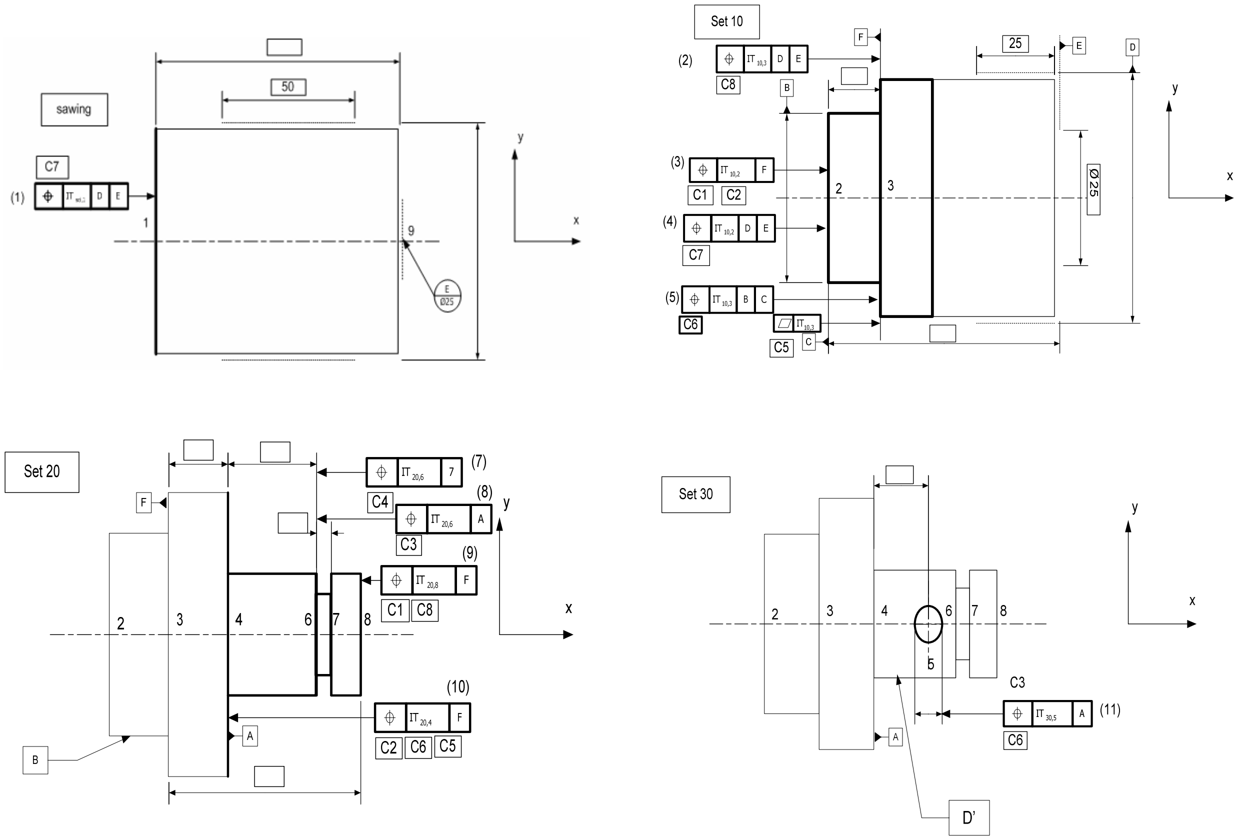


Figure 15: Representation of the C6 specification transferred.

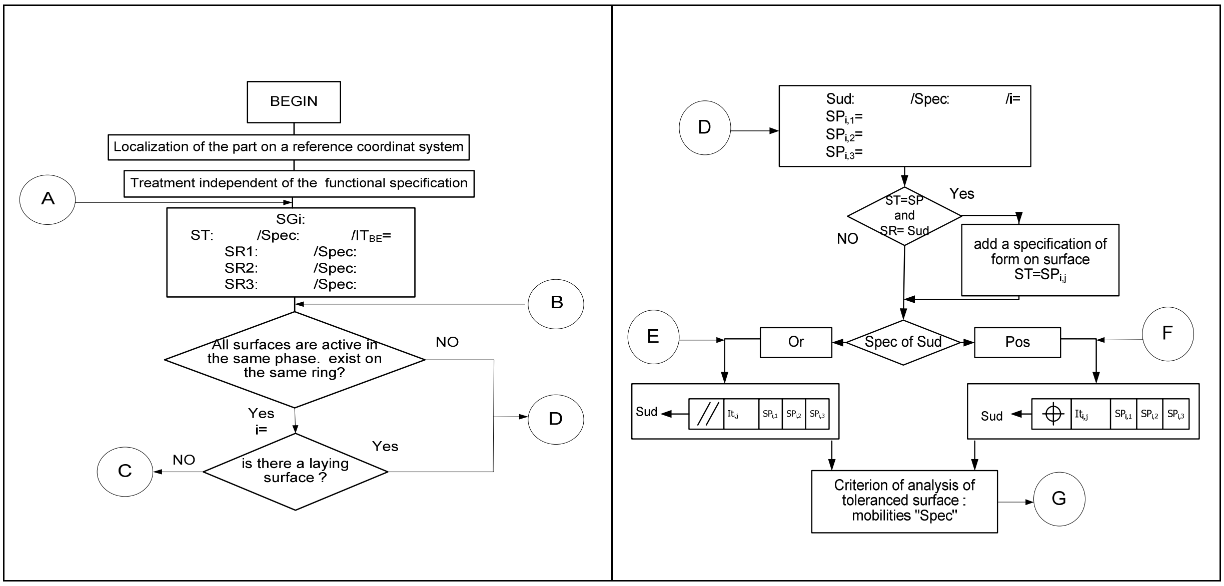


Figure 16: FINAL Algorithm.

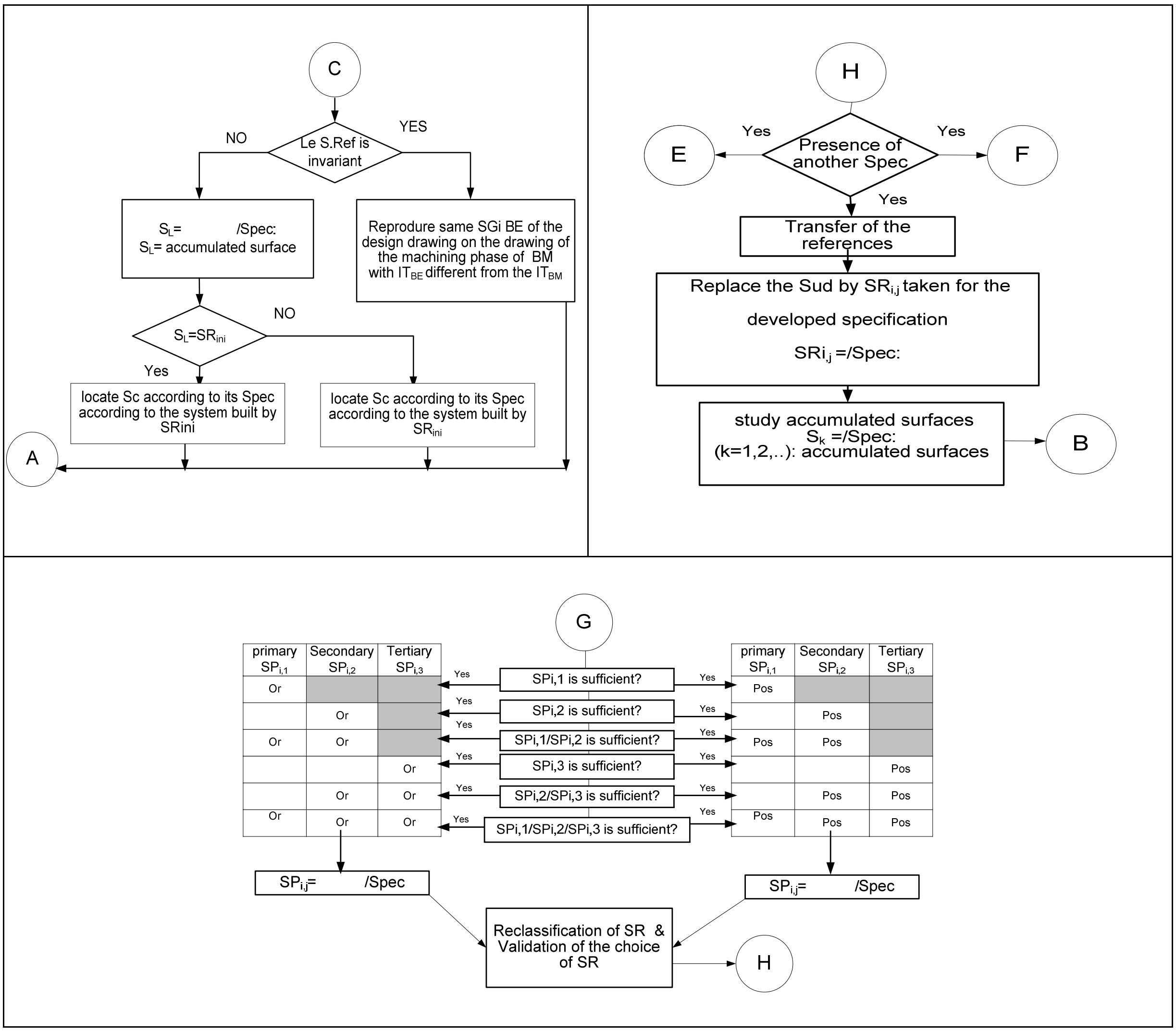


Figure 17: FINAL Algorithm.

6. CONCLUSION

We remark that by our work, we obtain all the results found by the method of transfer and the rational method of tolerance 3D taking into account of the three-dimensional aspect of the studied functional specifications.

The algorithm developed in this paper, presented below in Figures 16 and 17, represents a new rational method that allows finding only the necessary manufactured specifications. The main aim of our algorithm is to generate “Process Specification”.

In this method we use the concept of influential contact surfaces, modelled by positioning surfaces and their roles in the development of the manufactured specifications.

We conclude that, the final and main objective of this work is to find the shortest way, train one specified surface to another by browsing the SPIDER GRAPH.

We hope that in with our work, the SPIDER GRAPH will replace the 1D matrix representation of the diagram sheet.

REFERENCES

[1] R. Weill (1988). Integrating dimensioning and tolerancing in computer- aided process planning, *Robotics & Computer-Integrated Manufacturing*, Vol. 4, 1/2, 41- 48

[2] J. S. Saggu, J. P. Fielding (1989). An Integrated CADCAM Method for the Design and Construction of Aircraft Wing Components, *Computers in Industry*, 12, 123- 130

[3] Ali K. Kamrani, P. Sferro, J. Handelman (1995). Critical Issues in Design and Evaluation of Computer Aided Process Planing Systems, *17th International Conference on Computers and Industrial Engineering,* Vol. 29, 1 - 4, 619-623

[4] NF ISO 1101 Fevrier (2005). Spécification géométrique des produits (GPS) Tolérancement géométrique, Tolérancement de forme, orientation, position et battement

[5] J. Dufaure, (2005). Intégration et traçabilité du transfert de spécifications géométriques dans le cycle de conception d'un produit, thèse présentée a L'université bordeaux 1, école doctorale des sciences physiques et de l'ingénieur

[6] L. Mathieu, A. Ballu (2005). A Model for a Coherent and Complete Tolerancing Process, *9th CIRP Seminar on Computer Aided Tolerancing*, Phoenix (Arizona USA)

[7] B. Anselmetti And P. Bourdet (1993). Optimization of a workpiece considering production requirements, *Computers in Industry,* 21, 23-34

[8] B. Anselmetti, (2003). Cotation de fabrication et métrologie, Edition PYC

[9] P. Ji, K. H. Lau (1999). Design for manufacturing: a dimensioning aspect, *Journal of Materials Processing Technology*, 91, 121– 127

[10] B. Anselmetti, F. Thiebaut, K. Mawussi, (2002). Functional tolerancing based on the influence of contacts, *ASPE 2002 Summer Topical Meeting on Tolerance Modeling and Analysis*, Charlotte, North Carolina, 15-16

[11] B. Anselmetti, (2000). Tolérancement fonctionnel ISO avec influence 3D, *Actes du colloque IDMME 2000*, Montréal, Canada

[12] A. Bellacicco, R. Sellakh, Philippe Arotcarena, Alain Riviere, (2005). Méthode Rationnelle de Tolérablement 3D du process, *9th CIRP Seminar on Computer Aided Tolerancing*, Phoenix (Arizona USA)

[13] H. Mejbri, (2004). Contribution au développement d'une méthode de cotation fonctionnelle des mécanismes complexes, Thèse de l'ENS de Cachan

[14] H. mejbri, b. anselmetti, k. mawussi, (2005). Fonctional tolerancing of complex mechanisms: Identification and specification of key parts, *Computers & Industrial Engineering,* 49, 241-265

[15] R. Sellakh, (1999). Contribution a l'intégration de la définition multi niveaux de la géométrie des système mécanique pour le tolérancement, *thèse à l'Institut Nationale des Sciences Appliquées de Lyon.*

[16] A. Clement, A. Riviere, M. Temmerman (1994). Cotation tridimensionnelle des systèmes mécaniques, *Edition PYC.*