An approach to unique transfer and allocation of tolerances considering manufacturing difficulty

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Abstract:

Tolerancing is a key step in the product life cycle and aims at improving the product quality and its assemblablity as well as reducing the overall costs and time to market. Especially, the tolerance allocation and transfer are two important engineering functions involving a direct impact on compliance with functional and manufacturing requirements. However, on the one hand the traditional approaches reduce the tolerance values during the transfer of design dimension on manufacturing dimensions, and on the other hand neglect the difficulty of manufacturing dimension obtaining. Thus, this paper proposes an unique transfer approach of mechanism-dimension allowing the transposition of the functional requirement into part manufacturing dimensions. In addition, this work uses an innovative tolerance allocation method considering the difficulty of obtaining manufacturing dimensions. This difficulty is evaluated through a mathematical coefficient calculated using the Failure Mode, Effects and Criticality Analysis (FMECA) tool. The failure causes are the different sources of the manufacturing difficult. The obtained results lead to avoid tolerance reduction generated by the double dimensions transfer of traditional industrial approaches. Moreover, the manufacturing dimension tolerances, which are difficult to obtain, are widen. Therefore, the total costs, considering manufacturing cost and quality loss, decreases. The main contributions of the proposed model are shown through a case study.

Keywords: Tolerance allocation, Dimension Transfer, Manufacturing difficulty, FMECA.

Résumé:

Le tolérancement est une étape clé dans le cycle de vie du produit. IL vise à améliorer la qualité du produit tout en réduisant le coût de fabrication. En particulier, l'allocation et le transfert de tolérance sont deux importantes fonctions d'ingénierie ayant un impact direct sur le respect des exigences fonctionnelles et de fabrication. Cependant, d'une part, les approches traditionnelles réduisent les valeurs de tolérance lors du transfert des cotes études en cotes de fabrication et, d'autre part, négligent la difficulté d'obtention les dimensions usinés. Ainsi, cet article propose une approche de transfert unique de cote-mécanisme qui est l'exigence fonctionnelle en cotes de fabrication des pièces. En outre, ce travail se base sur une méthode innovante d'allocation de tolérance considérant la difficulté d'obtention des cotes de fabrication. Cette difficulté est évaluée par un coefficient mathématique calculé à l'aide de l'outil d'Analyse du Mode de Défaillance, des Efets et de la Criticité (AMDEC). Les causes de défaillance sont les différentes sources de la difficulté de fabrication. Ils sont exposés grâce au diagramme d'Ishikawa. Les résultats obtenus conduisent à éviter la réduction de la tolérance engendrée par le double transfert des cotes dans les approches classiques industrielles. De plus, les tolérances des cotes de fabrication, difficiles à obtenir, s'élargissent. Par conséquent, les coûts totaux, compte tenu du coût de fabrication et de la perte de qualité, diminuent. Les principales contributions du modèle proposé sont illustrées par une étude d'un exemple d'application.

Mots clefs : Allocation des tolérances, Transfert des cotes, difficulté de fabrication, AMDEC.

Abbreviations

CAD: Computer Aided Design
CAM: Computer Aided Manufacturing
DCC: Difficulty Coefficient Computation
β : Difficulty coefficient
FMECA: Failure Mode, Effects and Criticality Analysis
RPN: Risk Priority Number
MD: Manufacturing Dimension
MO: Manufacturing Operation
FR: Functional Requirement
PD: Part Dimensions
WC: Worst Case
TT: Traditional transfer
UT: Unique transfer
TTDCC: Traditional Transfer using DCC tolerance allocation method
UTDCC: Unique Transfer using DCC tolerance allocation method
C_m: Manufacturing Cost
C_{Tm}: Total Manufacturing Cost
QL: Quality Loss
C_T: Total Cost
C_m: Manufacturing Cost

1 Introduction

Tolerancing has a crucial role in the different stages of the product's life cycle In fact, tolerance present a communication support and key stage in design, manufacturing and control phases. Whence, the functionality, quality and product cost depend essentially on manufacturing dimension tolerances. The manufacturing dimensions are obtained classically doing two transfers: (1) A first transfer of each mechanism-dimension, which are the Functional Requirement (FR), into Part Dimension (PD) which are the blueprint dimensions: FR→PD; (2) A second transfer of each (PD) into Manufacturing Dimension (MD): PD→MD. Each new transfer of dimension reduces the tolerances and thereafter increases the production cost. Thus, process engineers search often to avoid the dimension as soon as possible. In addition, a tolerance allocation technique must include manufacturing aptitude evaluation in order to a coupling between design, manufacturing, and quality.

In this respect, this paper present a new method for dimension transfer and tolerance allocation based on Unique Transfer (UT) and Difficulty Coefficient Computation (DCC). In this regard, Figure 1 clarifies the framework of the proposed approach named accordingly UTDCC.

This paper is organized as follows: In Section 1, a literature review is presented followed by synthesis and research objectives. Section 2 describes the proposed approach. In Section 3, a case study is introduced to illustrate a comparison between different approaches. Then, the results of dimension transfer and tolerance allocation using the different approaches are shown. Section 4 highlights contributions of the proposed method from a view of cost criterion as well as conducts comparative discussion. Finally, Section 5 summarizes the conclusions of this work.

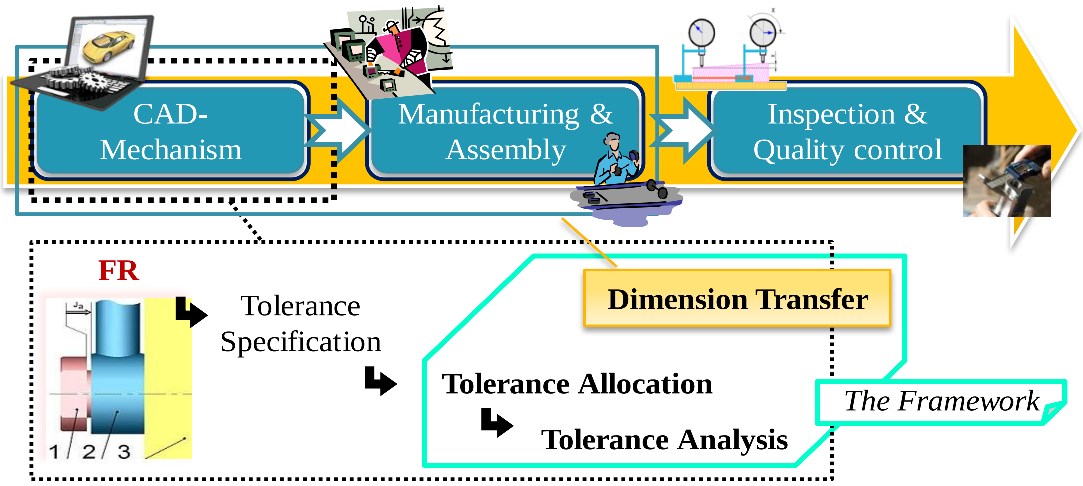


Figure 1 Framework of the proposed approach

1.1. Literature review

Optimal tolerance allocation is a trade-off between functional requirements and manufacturing cost. During the early decades, various manufacturing cost-tolerance models have been proposed as in [1]. Various optimization methods are developed to optimal tolerance allocation as exposed in [2-5]. Advanced optimization techniques such as the Genetic Algorithm (GA), particle swarm optimization, colony algorithm, Teaching-Learning-Based Optimization (TLBO) algorithm and Bat Algorithm (BA) are used as an optimization method for both the quality improvement and optimal tolerance allocation in many research works [6-13]. In this context and based on the analysis of fuzzy factors in the tolerance allocation, different methods have been published in many literatures [14-16]. Liu et al. [17] presented a method of tolerance grading allocation based on the uncertainty analysis of the remanufacturing assembly.

Concerning dimension transfer, two methods are commonly used to determine MDs: Wade [18] and Bourdet [19-21] methods. Comparison studies of these two methods are established in [22-24]. The Wade dimension can correct deviation on MD by modifying the tool position because MD depends only on one tool. Therefore, the Wade method is a feasible solution from the machine steering point of view. In contrast, the set of dimensions obtained can be rather different from the set of design dimensions and generates a significant tolerance reduction. The Bourdet method uses a minimum dimension chain. Indeed, all design dimensions become MDs if all surfaces are machined in the same workpiece carrier. This method is optimal for tolerance values and the conformity product verification. However, the obtained MDs can depend on several tool-parameters and the method is practically unusable for the machine steering.

1.2. Synthesis and research objectives

The major drawbacks of traditional dimension transfer and the tolerance allocation methods are the following:

- The classical dimension transfer is carried out by double transfer involving tolerance reduction and consequently production cost increase.
- This tedious task is mostly established manually without software assistance,
- The difficulty of manufacturing operation is neglected in the tolerance allocation and product cost computation steps.
- The traditional dimension transfer and tolerance allocation methods do not enhance the concurrent engineering environment.

In order to improve and consider the inconveniences of the above methods, this paper proposes a new method allowing the direct transfer of FR to MDs without using PDs, and tolerance allocation based on DCC using difficulty coefficient β. The DCC is founded on tools for the study and analysis of reliability of the mechanical design: FMECA tool and Ishikawa diagram. Therefore, the originality and novelty of the proposed approach are the integration of UT and DCC approaches in the tolerance allocation process to involve the co-design: product-process-quality in concurrent engineering environment.

2 Proposed approach

2.1. Transfer approaches and DCC procedure

Instead of combining two transfers, FR→PD then PD→MD, this work proposes a unique transfer methodology avoiding the PD determination. The proposed transfer allows directly the transposition of FR into MD and integrates the β values in the tolerance allocation. The Figure 2 elucidates the contribution of proposed UTDCC method. The DDC is clarified in details in [5]. The dimension tolerances are calculated in Table 1 according to Worst Case (WC) and Root Sum Square (RSS) methods; where t_i is the dimension tolerance, t_Y is the tolerance of the functional requirement, α_i is the influence coefficient and β_i is the difficulty coefficient.

Table 1 Tolerance formulas

Approaches	**Formulas**
WC	$t_i = \beta_i \times \frac{t_Y}{\sum_i \lvert\alpha_i\rvert \times \beta_i}$
RSS	$t_i = \beta_i \times \frac{t_Y}{\sqrt{\sum_i \alpha_i^2 \times \beta_i^2}}$

The DCC procedure is already described more attractively in [5] and the main steps are the flowing:

- Get manufacturing process of parts overview,
- Identify the difficult Manufacturing Operation (MO),
- Observe the failure effect in tolerance values,
- Draw Ishikawa diagram to determine failure causes,
- Calculate the Risk Priority Number (RPN) to Criticality specification,
- Quantify difficulty coefficient β
- Fill FMECA Worksheet.

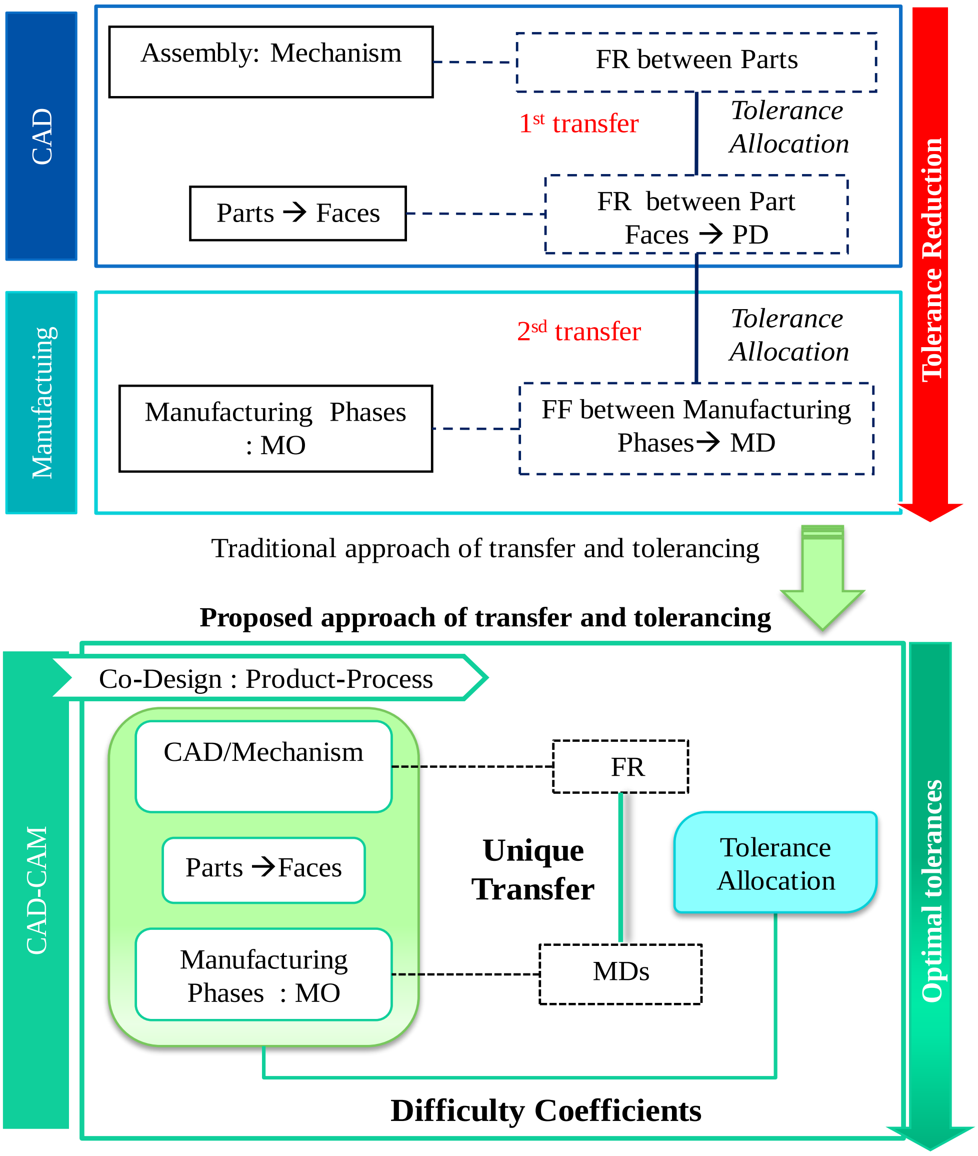


Figure 2 Whole comparison of traditional and proposed approach

2.2. Manufacturing cost model

The cost model of Sampath et al. [25, 26] is used to the comparative study. This model presents a mathematical relationship between cost and tolerance. The tolerance manufacturing cost (C_m) decreases when tolerance increases according to the following exponential relation: Eq.1.

$$C_m = C_0 \times \exp(-C_1 \times t) \tag{1}$$

The coefficients C_0 and C_1 of C_m are computed basing on a broad scope of the empirical data of all frequently used manufacturing processes [1]. Thus, the Total assembly Manufacturing Cost C_{Tm} can be expressed as the summation of the C_m of MD multiplied by difficulty cost. According to Ghali et al. [5], the β represents the difficulty cost. The equation 2 allows the C_{Tm} computation where βi is the difficulty cost of each MDs.

$$C_{Tm} = \sum_{i=1}^{n} \beta_i C_m(t_i) \tag{2}$$

The proposed cost computation is extended by the addition of quality loss (QL) cost. The QL, introduced by Taguchi [27], is a quadratic expression for the evaluation of the target value derivation. This is a loss function, in monetary terms, due to a product failure expressing consumer dissatisfaction. Consequently, the total tolerance cost (C_T) is calculated as the sum of total C_m (C_{Tm}) and QL as Eq. 3.

$$C_T = C_{Tm} + QL \tag{3}$$

The QL is obtained according to Noorul et al. [28] as Eq. 4.

$$QL = \frac{A}{t_{FR}^2} \sum_{i=1}^{n} \sigma_i^2 \tag{4}$$

With tolerances equals to six sigma ($\sigma_i = \frac{t_i}{6}$), the equation Eq. 4 is rewritten as Eq. 5.

$$QL = \frac{A}{36 t_{FR}^2} \sum_{i=1}^{n} t_i^2 \tag{5}$$

Where t_{FR} is the FR tolerance, t_i is MD tolerance and A is the QL coefficient.

3 Case study

In this paper, the case study is a rotor key base assembly. The mechanism is chosen to use the cost model of tolerances proposed by Sampath et al. [25, 26]. The rotor key base is composed by two parts *a* and *b* as shown in Figure.3. The contact between components is established thought the faces *a2* and *b1* of *a* and *b* respectively as illustrate in Fig. 1. The above contact is defined using the assumption that the axes *a3* and *b2* are supposed coincident (*a3*=*b2*) in assembly nominal configuration. This choice completes here Sampath article that does not indicate these contact conditions. The FR of this mechanism is between the faces *a3* and *b5*: FR=a3b5. A tolerance of 1.016mm is required: ta3b5=1.016mm.

The tolerance cost model parameters of rotor key base assembly is given in Table 2.

Table 2 Cost model parameters

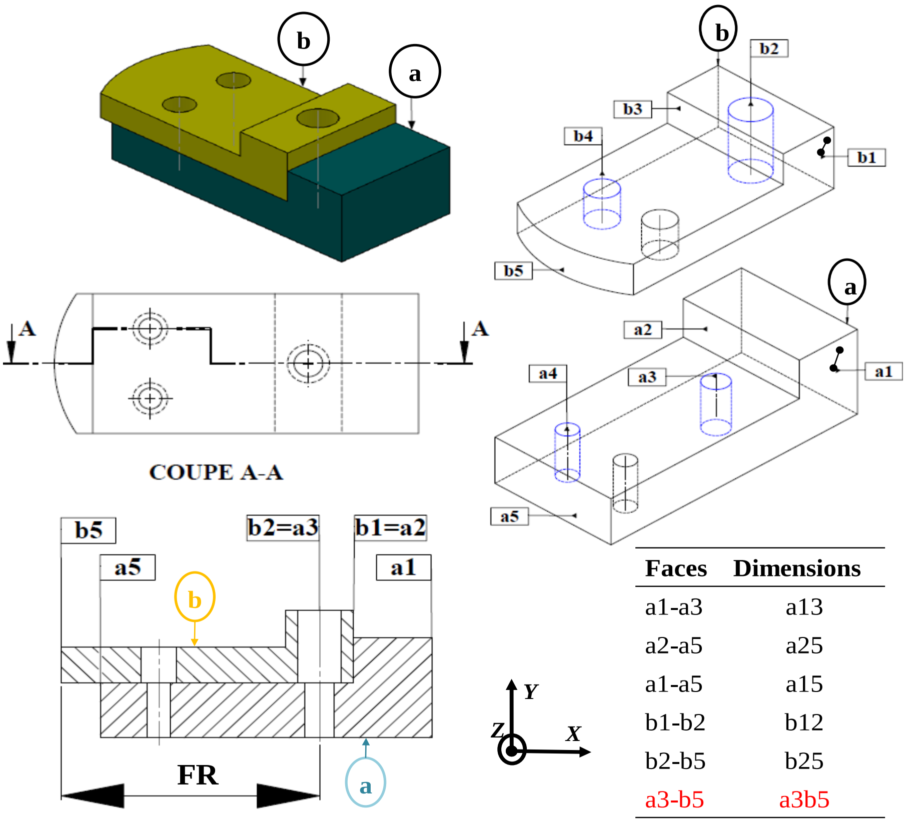
Cost model	t_{a13}	t_{a15}	t_{a25}	t_{b12}	t_{b25}
C_0	27.84	431.5	431.5	27.84	66.43
C_1	3.661	17.64	17.64	3.661	2.738

For the rotor key base example, the C_{Tm} is given in Eq. 6.

$$C_{Tm} = \beta_{a13}C_{13}(t_{a13}) + \beta_{a15}C_{15}(t_{a15}) + \beta_{a25}C_{25}(t_{a25}) + \beta_{b12}C_{12}(t_{b12}) + \beta_{a25}C_{25}(t_{b25}) \tag{6}$$

Thus, the QL of this case study is given as Eq.7.

$$QL = \frac{A}{36{t_{a3b5}}^2}\left({t_{a13}}^2 + {t_{a15}}^2 + {t_{a25}}^2 + {t_{b12}}^2 + {t_{b25}}^2\right) \tag{7}$$



Faces	Dimensions
a1-a3	a13
a2-a5	a25
a1-a5	a15
b1-b2	b12
b2-b5	b25
a3-b5	a3b5

Figure 3 Rotor key base assembly

The MDs are closely linked to the manufacturing process. In this paper, the manufacturing process of Rotor key base parts is chosen according to MD proposed by Sampath et al. [25, 26]. For this, the Wade method is adopted.

4 Results and discussion

4.1. Transfer and Tolerance results

Using Traditional Transfer (TT), the diagram of double transfer and tolerance relationships are shown in Fig. 4 and Table3 respectively. In addition, the new UT results are clarified in Figure 4 and Table3 in order to establish comparative study. According to Figure 4, the dimension chain and tolerance allocation results of TT and UT approaches are resumed in Table 4 and Table5

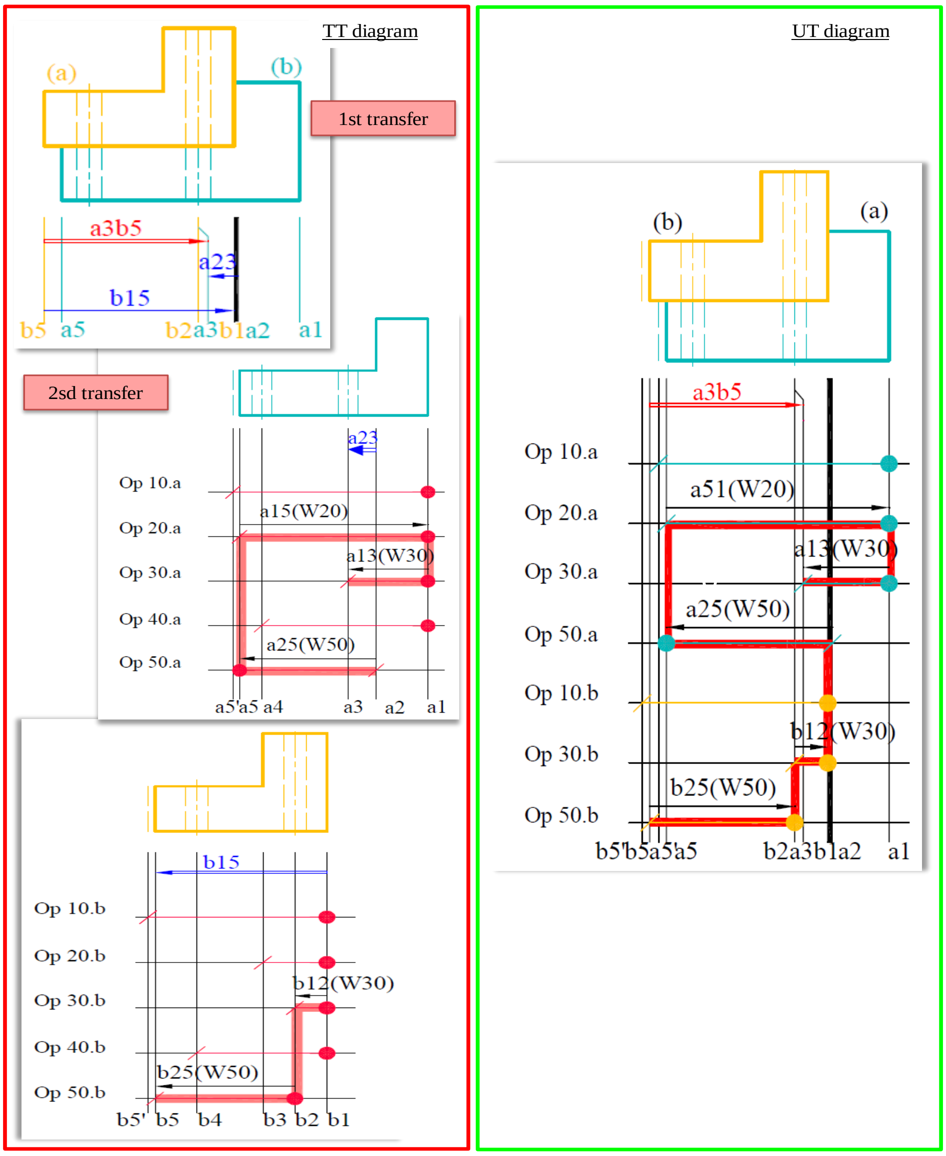


Figure 4 Comparison of diagram transfer results

Table 3 Dimension and tolerance chains results

Traditional transfer(TT)	Unique transfer(UT)
$a3b5 = -a23 + b15$ $t_{a23} = t_{b15} = \frac{1.016}{2} = 0.508mm$ $a23 = a13^{W30} - a15^{W20} + a25^{W50}$ $b15 = b12^{W30} + b25^{W50}$ $t_{a13^{W30}} = t_{a15^{W20}} = t_{a25^{W50}} = \frac{0.508}{3} = 0.169mm$ $t_{b12^{W30}} = t_{b25^{W50}} = \frac{0.508}{2} = 0.254mm$	$a3b5 =$ $-a13^{W30} + a15^{W20} - a25^{W50} + b12^{W30} + b25^{W50}$ $t_{a13^{W30}} = t_{a15^{W20}} = t_{a25^{W50}} = t_{b12^{W30}} = t_{b25^{W50}} =$ $\frac{1.016}{5} = 0.203mm$

Table 4 MD tolerance of TT and UT

$t._{MD}$	**TT**	**UT**
t_{a13}	0.169	0.203
t_{a15}	0.169	0.203
t_{a25}	0.169	0.203
t_{b12}	0.254	0.203
t_{b25}	0.254	0.203

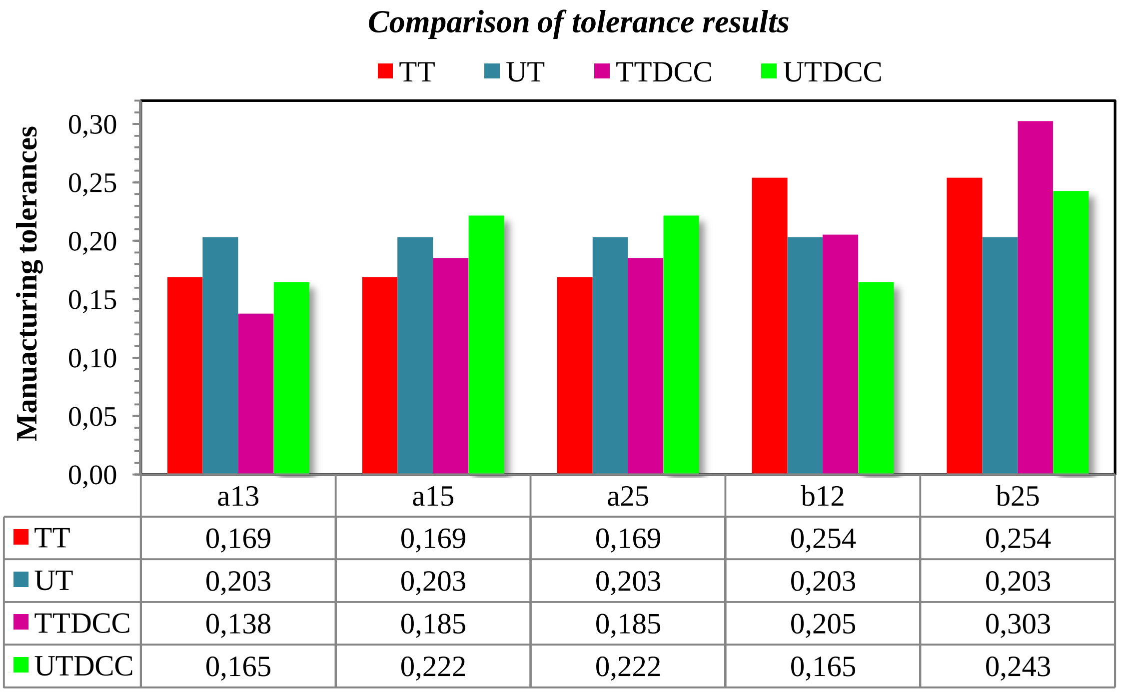
4.2. DCC and tolerance results

After achieving DCC procedure steps and completing FMECA worksheet of MO affecting MD of FR dimension chain, the β values are obtained. The Table 5 recapitulates influencing MO and related β of each MDs. The tolerance results according to different compared approaches are illustrated in Figure 5, where TTDCC method is TT using DCC.

Based on allocated tolerance analysis, the proposed UTDCC method leads to obtain the most suitable tolerances by winding tolerance of difficult MDs. For example a15, which has β_{a15} = 1.48, is more difficult than a13 which has β_{a13} =1.10. Thus, the new obtained t_{a15} is upper than t_{a13} (t_{a15} = 0. 222 mm> t_{a13} = 0.165 mm) as illustrated in the Table 5. This fact guarantees absolutely optimal quality and cost. Hence, the comparison of tolerance and related β variation is shown in Figure 6. In this respect, the UTDCC method represents tolerance fluctuation perfectly proportional to β variation compared to TT, UT and TTDCC approaches.

Table 5 Influencing MO and related β

MD	**MO**	**β notation**	**β values**
a13	Drilling	β_{a13}	1.10
a15	Face milling	β_{a15}	1.48
a25	Face milling	β_{a25}	1.48
b12	Drilling	β_{b12}	1.10
b25	Turning	β_{b25}	1.62



	a13	a15	a25	b12	b25
🟥 TT	0,169	0,169	0,169	0,254	0,254
🟦 UT	0,203	0,203	0,203	0,203	0,203
🟪 TTDCC	0,138	0,185	0,185	0,205	0,303
🟩 UTDCC	0,165	0,222	0,222	0,165	0,243

Figure 5 Comparison of manufacturing tolerance results

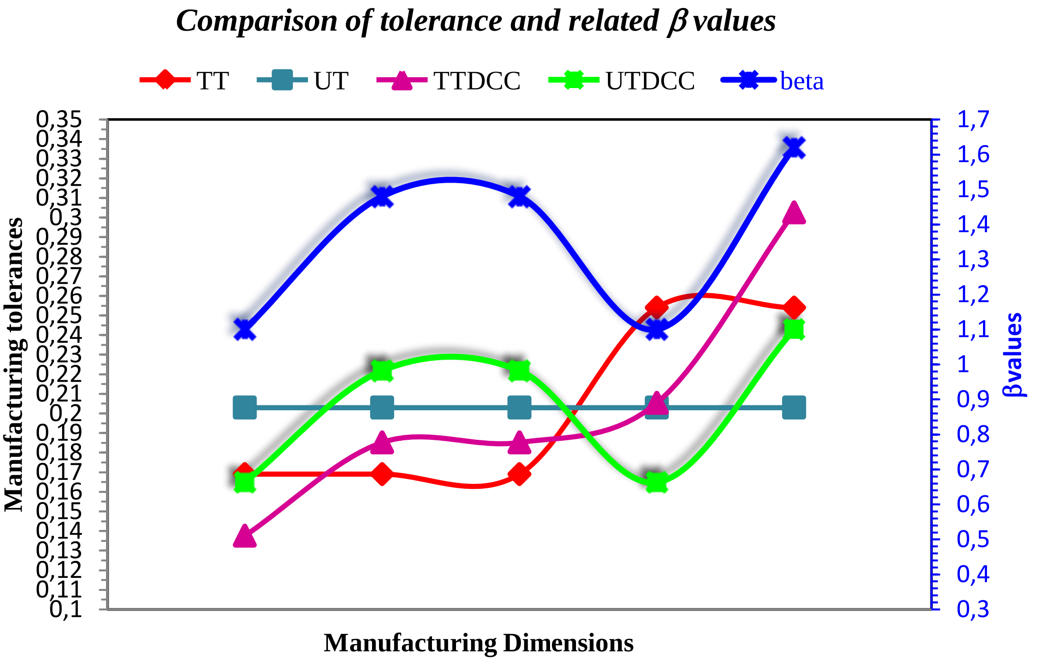


Figure 6 Comparison of manufacturing tolerances and related βs fluctuations

4.3. Cost results

In order to clarify the assembly total cost computation, the Table 6 summarizes the allocated tolerances as well as the assembly total cost in the cases of TT, UT, TTDCC and the proposed UTDCC approaches. According to Table 6, UTDCC is the most economical method.

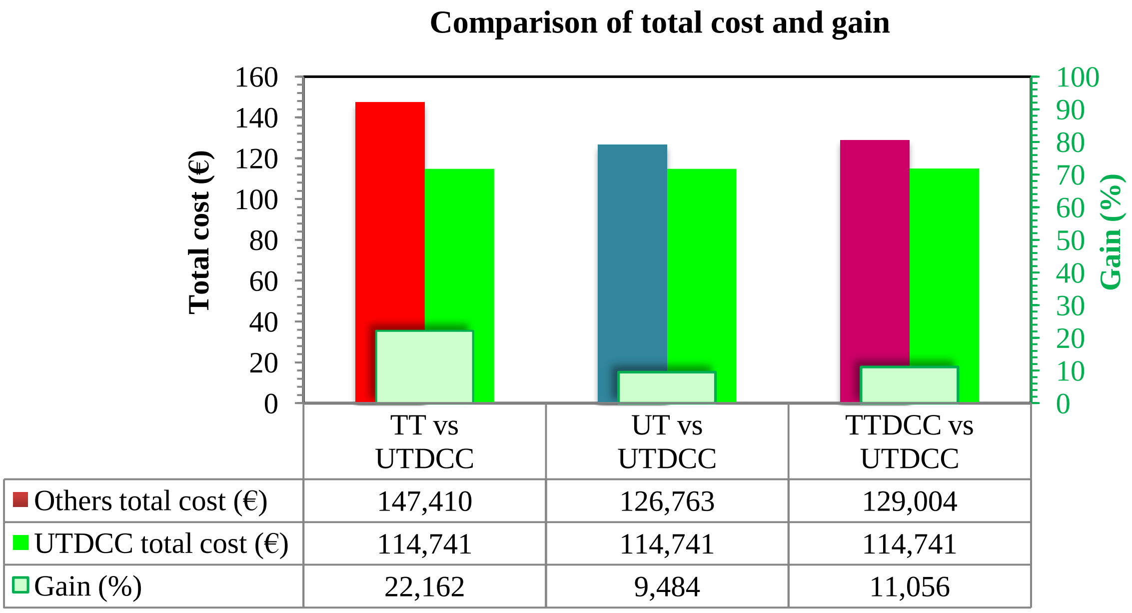
Table 6 Comparison of assembly allocated tolerance and total cost

Approach	a13	a15	a25	b12	b25	Total cost (€)
TT	0,169	0,169	0,169	0,254	0,254	147,410
UT	0,203	0,203	0,203	0,203	0,203	126,763
TTDCC	0,138	0,185	0,185	0,205	0,303	129,004
UTDCC	0,165	0,222	0,222	0,165	0,243	114.741

Moreover, the Figure 7 embellishes the total cost and obtained gain compared to TT, UT and TTDCC approaches. Indeed, the proposed approach UTDCC based on UT and DCC promotes a Monetary Gain (MG):

- MG= (147.410- 114,741) ×100/ 147.410 = 22.162% per assembly compared to TT,
- MG= (126.763- 114,741) ×100/ 126.763= 9.484% per assembly compared to UT,
- MG= (129.004- 114,741) ×100/ 129.004= 11.056% per assembly compared to TTDCC.

Therefore, the result analysis confirm that the proposed method generates an economical cost achievement and grants privileges to concurrent engineering environment by coupling of the DCC and UT approaches.


Comparison of total cost and gain

	TT vs UTDCC	UT vs UTDCC	TTDCC vs UTDCC
🟥 Others total cost (€)	147,410	126,763	129,004
🟩 UTDCC total cost (€)	114,741	114,741	114,741
☐ Gain (%)	22,162	9,484	11,056

Figure 7 Comparison of total cost and gain

5 Conclusion

This paper presents a new approach for tolerance allocation and dimension transfer based simultaneous on DCC and UT procedures. The proposed UTDCC solves the tolerance allocation problems by quantifying manufacturing dimension difficulty and minimizing the tolerance cost. Moreover, DFA and DFM are involved while respecting functional requirements. This fact enhances consequently the co-design environment: Product- Process.

A case study shows that the proposed methodology leads to the allocation of tolerances proportionally to manufacturing difficulty. As a result, the tolerance allocation, using proposed UTDCC method, reduces the total assembly cost considering manufacturing cost and quality loss. Thus, the proposed method is both economical and successful compared to TT, UT and TTDCC approaches. Future works will focus on the consideration for an optimization algorithm and geometrical tolerances. In addition, the implementation of the proposed approach in different industrial manufactories is also among the desired outlooks.

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