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From manufacturing tolerancing to adaptive manufacturing targets

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Abstract

The functional tolerancing process involves the allocation of the tolerance derived from each functional requirement, expressed at the assembly level, into multiple functional tolerances at the part level. For each part, the manufacturing tolerancing process transfers each functional tolerance into multiple manufacturing tolerances on the dimensions produced throughout the entire process. However, this transfer faces challenges when dealing with tight functional tolerances and constrained process capability.

This article proposes an innovative method for adaptively optimizing the production process to enhance its capabilities. Rather than relying on a static manufacturing transfer, this approach involves intermediate measurements of each workpiece during production, modelling its digital shadow. By dynamically adjusting the targets of the upcoming manufacturing dimensions, individual adjustments aim to maximize the likelihood of conformity. This adaptive strategy allows for the allocation of tighter functional tolerances while ensuring workpiece conformity and maintaining the same manufacturing process. Concurrent engineering is thereby facilitated.

Keywords: Tolerance charting, process planning, adaptive manufacturing, manufacturing tolerancing, concurrent engineering

1. Introduction

1.1. Industrial Context

In the context of manufacturing helicopter engine components, different high-value added parts entail elevated production costs due to their numerous tight-tolerance functional specifications. When a functional specification is achieved after the successive realization of multiple manufactured specifications, the functional tolerance is divided into multiple manufacturing tolerances. Throughout production, these manufacturing specifications are verified at each intermediate state of the workpiece. In case of non-conformity, analysis of acceptability, exploration of remanufacturing options, or consideration of scrapping are necessary. However, in an industrial context, such an approach results in significant cost and time implications.

1.2. The tolerancing process

Figure 1 presents an overview of the conventional tolerancing process. Initially, the designer specifies geometric constraints on the assembly, referred to as the **functional requirements** (Figure 1a). Following this, the design process moves to the stage of **functional tolerancing** (Figure 1b), which involves distributing the tolerance derived from each functional requirement, expressed at the assembly level, into multiple functional tolerances at the part level. At the end of this stage, the designer finalizes the **definition drawings** for each part (Figure 1c), incorporating the effective dimensions and tolerance values on every

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functional specification. This step ensures a traceability from the functional requirements to the specifications of each part.

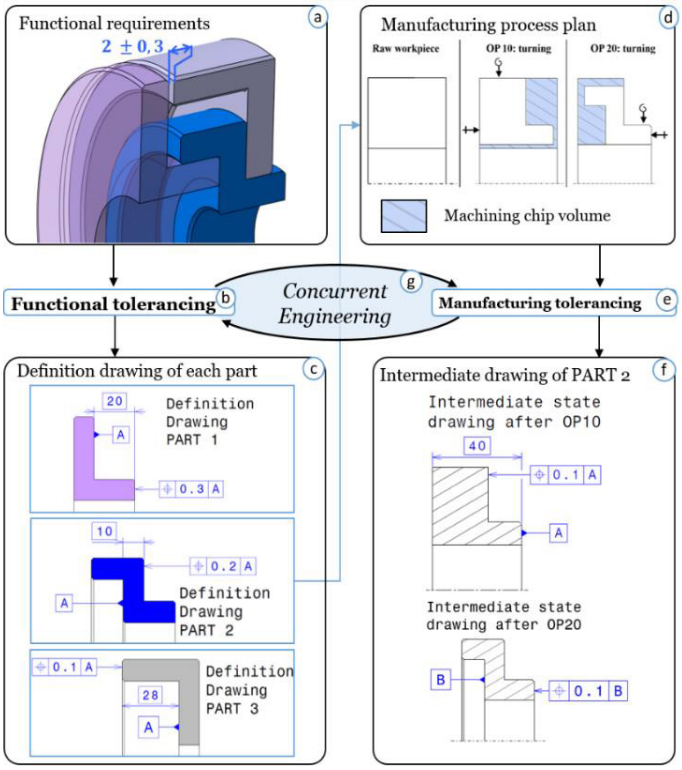

Figure 1: Overview of the tolerancing process

For each designed part, a proposed manufacturing **process plan** (Figure 1d) involves a detailed sequence of manufacturing steps. Each step outlines the manufactured surfaces, along with the positioning surfaces of the workpiece. The process planner also specifies manufacturability requirements, such as stock removal tolerances. **Manufacturing tolerancing** (Figure 1e), also referred to as **manufacturing transfer**, aims to determine the geometric characteristics requiring validation at each intermediate state of the part throughout the manufacturing process. It involves transferring each functional specification of the part into manufacturing specifications and distributing the functional tolerance among a set of manufacturing tolerances. At the end of this stage, the manufacturer finalizes the **intermediate state drawings** of the workpiece (Figure 1f), which include specifications to be verified between each manufacturing step.

During production, if all specifications of an intermediate state are compliant, the manufacturing process proceeds. Otherwise, the manufacturer rejects the workpiece before completion due to the risk of non-conformity on the final obtained part. This proactive approach aims to prevent time and resource wastage. The overall tolerancing process takes place within the framework of **concurrent engineering** (Figure 1g). It is an iterative process where the distribution of functional tolerances determines the capabilities of the complete manufacturing processes for each part, which subsequently serve as inputs for the functional tolerancing cost optimization step. Multiple iterations are required until a compromise is reached.

1.3. Towards an alternative to manufacturing transfer

The main innovation of this article is the introduction of a manufacturing approach that diverges from the conventional process relying on manufacturing tolerancing. The primary motivation behind this shift is to automatically adjust manufacturing dimension targets based on measured deviations on each individual part as the process progresses.

For that, the section 2 provides a concise overview of the state-of-the-art in manufacturing tolerancing. A classical manufacturing approach is then applied to an illustrative part to provide a support. Following this, section 3 presents the methodology for adapting the manufacturing parameters of each individual part within the process plan of the part. Section 4 showcases simulation results derived from implementing this method on the example, demonstrating how this approach can facilitate concurrent engineering.

2. State of the art on manufacturing tolerancing

Nomenclature

S_i	Surface i of the workpiece
Y_k	Blueprint dimension k of the workpiece
tol_{Y_k}	Functional tolerance value associated to Y_k (mm)
X_{ij}	Working dimension between surfaces S_i and S_j
$tol_{X_{ij}}$	Manufacturing tolerance value associated to X_{ij} (mm)
σ_{ij}	Standard deviation on the working dimension X_{ij}
$Y_{k_{th}}$	Theoretical dimension Y_k (mm)
$X_{ij_{th}}$	Theoretical dimension of X_{ij} (mm)
X_{ij_c}	Recentered machining target on X_{ij} (mm)
$X_{ij_{mes}}$	Measured value of X_{ij} on the workpiece (mm)
Δ_{ij}	Adjustment parameter on the machining of X_{ij} (mm)
Δ	Adjustment parameter vector containing the Δ_{ij}
$target_{X_{ij}}(\Delta)$	Machining target of X_{ij} depending on the Δ values
$target_{Y_k}(\Delta)$	Resulting target of Y_k depending on the Δ values, and measured dimensions (mm)

2.1. Input data

The manufacturing transfer activity mainly requires three input data:

- The definition drawing (blueprint), shown in Figure 2, preferably expressed using ISO – GPS standards.
- The process plan, illustrated in Figure 3.
- A capability estimation on each working dimension, depending on the machine characteristics, tooling and positioning of each operation.

For the sake of simplicity, only functional specifications belonging to the $\vec{x}$ direction are considered. The manufacturing process plan, depicted in Figure 3, includes three successive machining operations. The manufacturing conditions M1 and M2 are related to the required chip thickness (stock removal). While these conditions are critical for the manufacturability of the workpiece, they will not be addressed in the following example.

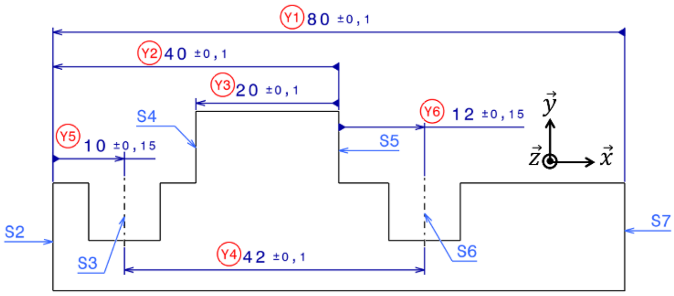

Figure 2: Unidirectional representation of the studied specifications

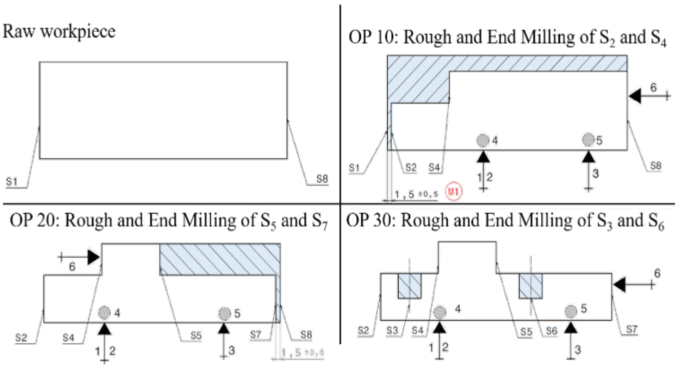

Figure 3: Manufacturing process plan

The manufacturer's experience often provides reasonably accurate estimates of expected dispersions on each working dimension X_{ij} . Thus, conducting a pre-series with an adequate number of workpieces enables a more accurate estimation of these dispersions. The pre-series also helps in assessing the mean offsets of the working dimensions and then adjusting manufacturing parameters.

2.2. Unidimensional manufacturing transfer methods

Current manufacturing transfer methods are mainly used for unidirectional study, rooted in the development of tolerance charting since the 1950s. Tolerance charting involves vectorial representation of the process plan in a graph, allocating manufacturing tolerances to working dimensions satisfying both design and manufacturability conditions. The contributions by Eary and Johnson [1] as well as Wade [2] establish the foundations of manual tolerance charting. In [3], Ji employs a tree representation of the manufacturing transfer, coupled with the tolerance chart, ensuring traceability in case of blueprint dimension modifications [4]. Ngoi and Kuan, in [5], present numerous approaches to computer-aided tolerance charting, automating the determination of working dimensions and enhancing tolerance allocation (balancing process).

Multiple methods enable the allocation of the manufacturing tolerances $tol_{X_{ij}}$. The Δl method, introduced by Bourdet in 1973 [6], facilitates a nuanced manufacturing transfer that takes into account dispersions shared across multiple working dimensions. This initial tolerancing method was improved by Anselmetti [7] through further refines in the principles established by the Δl tolerance method. In this approach, it is crucial to acknowledge that the resulting dispersions on each working dimensions can be interdependent, particularly when obtained within the same operation.

2.3. Application on the studied example

The tolerance chart in Figure 4 synthetizes the manufacturing transfer applied to the studied example using the method proposed by Anselmetti [8]. The working dimensions chains are conducted to ensure, for each blueprint dimension Y_k:

$$tol_{Y_k} \geq \sum tol_{X_{ij}} \quad (1)$$

The distribution of the working dimension tolerances is commonly referred to the "balancing process". This process aims to optimize the widening of the $tol_{X_{ij}}$, while considering the estimated capabilities of each working dimension. The scattered dispersions of a working dimension can be considered equal to $6.\sigma_{ij}$, with the choice of 6σ being a widely accepted standard [5]. The first step of the balancing process involves verifying, for each working dimension chain that:

$$tol_{Y_k} \geq \sum 6.\sigma_{ij} \quad (2)$$

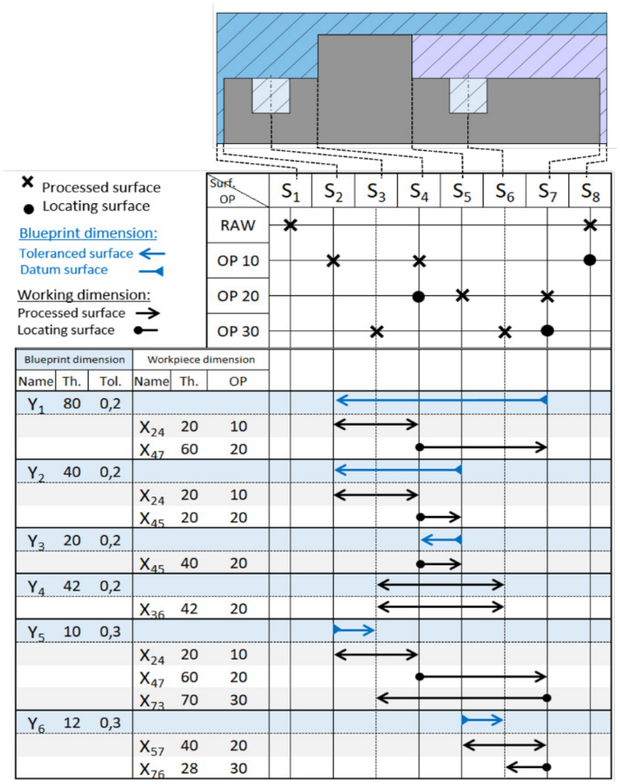

Figure 4: Tolerance chart of the studied example

If (2) is verified, there is a positive residual tolerance $\mathrm{tol_{res}}$, such as:

$$\mathrm{tol}_{\mathrm{Y_k}} = \sum 6.\sigma_{\mathrm{ij}} + \mathrm{tol}_{\mathrm{res_k}} \quad (3)$$

This residual tolerance could be evenly distributed over each of the n $tol_{X_{ij}}$ of the dimension chain, such that

$$\mathrm{tol}_{\mathrm{X_{ij}}} = 6.\sigma_{\mathrm{ij}} + \frac{\mathrm{tol}_{\mathrm{res_k}}}{\mathrm{n}} \qquad (4)$$

In the studied case depicted in Figure 4, a more advisable approach would lead to distribute $\mathrm{tol}_{\mathrm{res_k}}$ proportionally to each σ_{ij}, as detailed below in (5):

$$\mathrm{tol}_{\mathrm{X_{ij}}} = \alpha_k * 6.\sigma_{\mathrm{ij}} \;\; \text{With} \;\; \alpha_k = \frac{\mathrm{tol}_{\mathrm{Y_k}}}{\sum 6.\sigma_{ij}} \qquad (5)$$

The balancing table, available in Table 1, enables the determination of the coefficient α_k for each working dimension chain, using (5). A previously conducted pre-series led to quantify the standard deviations σ_{ij} for all working dimensions.

	Tol	$6.\sigma_{24}$	$6.\sigma_{47}$	$6.\sigma_{45}$	$6.\sigma_{36}$	$6.\sigma_{73}$	$6.\sigma_{57}$	$6.\sigma_{76}$	$\sum 6.\sigma ij$	$\mathrm{tol_{res}}$	α_k
Y_1	0,2	0,06	0,12						**0,18**	**0,02**	**1,11**
Y_2	0,2	0,06		0,12					**0,18**	**0,02**	**1,11**
Y_3	0,2			0,12					**0,12**	**0,08**	**1,67**
Y_4	0,2				0,06				**0,06**	**0,14**	**3,33**
Y_5	0,3	0,06	0,12			0,10			**0,28**	**0,02**	**1,07**
Y_6	0,3						0,06	0,10	**0,16**	**0,14**	**1,88**

Table 1: Proportional balancing table – first iteration

	X24	X47	X45	X36	X73	X57	X76
$\alpha_1 * 6.\sigma_{ij}$	0,067	0,133					
$\alpha_2 * 6.\sigma_{ij}$	0,067		0,133				
$\alpha_3 * 6.\sigma_{ij}$			0,200				
$\alpha_4 * 6.\sigma_{ij}$				0,200			
$\alpha_5 * 6.\sigma_{ij}$	0,064	0,129			0,107		
$\alpha_6 * 6.\sigma_{ij}$						0,11	0,19

Table 2: Deduction of the working dimension tolerances after first iteration

The widened tolerances $\mathrm{tol}_{\mathrm{X_{ij}}}$ resulting from the application of (5) are listed in Table 2. Some X_{ij} are part of several dimension chains. Thereby, tolerances should be systematically assigned, prioritizing dimension chains with the lowest $\mathrm{tol_{res}}$. This results in the quantification of the following tolerances:

- X_{36} only appears in the Y_3 chain: $\mathrm{tol}_{X_{36}}$ is set to 0.2.
- X_{57} only appears in the Y_6 chain: $\mathrm{tol}_{X_{57}}$ is set to 0.11.
- X_{76} only appears in the Y_6 chain: $\mathrm{tol}_{X_{76}}$ is set to 0.19.
- X_{73} only appears in the Y_5 chain: $\mathrm{tol}_{X_{73}}$ is set to 0.107.
- With k_5 being the smallest coefficient, the Y_5 chain's working dimensions are thereby constrained to: $\mathrm{tol}_{X_{24}} = 0.064$ and $\mathrm{tol}_{X_{47}} = 0.129$

In the subsequent iteration, the only remaining unknown is $\mathrm{tol}_{X_{45}}$. Since it only appears in the Y_2 dimension chain, one can write:

$$\mathrm{tol}_{Y_2} \geq \mathrm{tol}_{X_{24}} + \mathrm{tol}_{X_{45}}$$
$$\Leftrightarrow \mathrm{tol}_{X_{45}} \leq \mathrm{tol}_{Y_2} - \mathrm{tol}_{X_{24}}$$
$$\Leftrightarrow \mathrm{tol}_{X_{45}} \leq 0.2 - 0.064 = 0.126$$

After the determination the working dimension tolerances, the process planner can create the intermediate state drawings, outlining the manufacturing specifications to be verified on the workpiece between each operation.

2.4. 3D Manufacturing transfer methods and approaches

Many industrial parts encompass numerous functional specifications expressed in various analysis directions. Tolerancing the deviations in orientation and position, particularly on complex surfaces, accurately capture the functional requirements. Although mastery of manufacturing transfers for these three-dimensional specifications is uncommon, several transfer approaches for such cases are identified in the literature. Most methods mentioned below use the small displacement torsor [9] in order to include the orientation deviations propagated trough the successive manufacturing operations. Anselmetti and Louati [10] propose a method for determining the types of manufacturing specifications expressed with ISO standards. Following this, Royer [11] uses the analysis lines method to express the deviations resulting from the accumulation of variations throughout the manufacturing process. Additionally, the Model of Manufactured Part [12] by Villeneuve and Vignat allows for the three-dimensional simulation of the worst-case part resulting from the process, propagating orientation and position dispersions.

3. Method of manufacturing target adaptation

3.1. From series to individualized adjustments

Manufacturers usually optimize the part production, by adjusting manufacturing parameters to rectify systematic offsets and variations over time. This series-wide adjustment process often involves the use of Statistical Process Control (SPC) techniques, with Shewart's control charts [13] laying down a fundamental framework. In the studied example shown in Section 2, the machining targets of the working dimensions X_{ij} are initially set to their theoretical mean values $X_{ij_{th}}$. However, if a systematic offset δ is observed over time on a particular working dimension X_{ij}, the manufacturer can counteract it by establishing a recentered machining target $X_{ij_c} = X_{ij_{th}} - \delta$.

In the context of the tight tolerances resulting from the manufacturing transfer discussed in section 2, conventional practices would typically result in the rejection of a non-conforming workpiece at an intermediate state of the process. Nevertheless, there is an opportunity to prevent scrapping by modifying the dimension targets of the subsequent operations. This optimized adjustment involves intermediate measurements, which can be taken on the positioned workpiece using in-situ probing, or using external devices such as a coordinate-measuring machine.

It is then proposed to introduce an automated method for determining the future manufacturing targets for each individual workpiece, adjusting parameters to maximize the probability of conformity. Throughout the manufacturing process, a digital shadow of the semi-finished workpiece is updated based on intermediate measurements, modelling the its deviations. Before each manufacturing operation, the challenge is to select the best adjustment values set for the future operations targets that will ensure the overall conformity of the finished part.

3.2. Assessing the adjustment values Δ

In the following example, one can consider that the current state of the workpiece corresponds to the intermediate state of the workpiece after OP10, illustrated in Figure 5. The representation of the actual workpiece is referred to as the **digital shadow** post OP10.

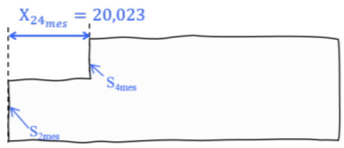

Figure 5: Digital shadow post OP10: modelling of the real workpiece

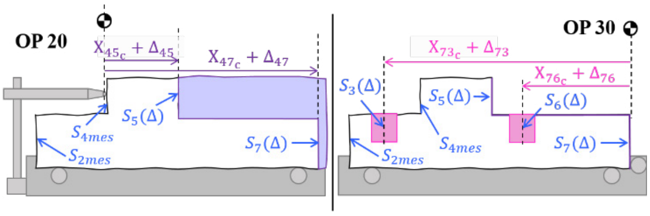

Figure 6: Digital shadows anticipating OP20 and OP30

Following this, a simulation of the upcoming manufacturing operation, OP20, can be carried out. The target values of the working dimensions X_{45_c} and X_{47_c} can be adjusted using two variable parameters: Δ_{45} and Δ_{47}. The digital shadow anticipating OP20, shown in Figure 6, incorporates a modelling of the already manufactured surfaces $S_{2_{mes}}$ and $S_{4_{mes}}$, as well as the anticipated future surfaces $S_5(\Delta)$, and $S_7(\Delta)$, which are dependent on the vector $\Delta = \{\Delta_{45}, \Delta_{47}\}$. It is then possible to perform a simulation of the last manufacturing operation, OP30, while considering that the working dimensions targets X_{73_c} and X_{76_c} can be adjusted using the two variable parameters: Δ_{73} and Δ_{76}. The anticipating digital shadow of the OP30 completes the previous digital shadow incorporating the anticipated future surfaces $S_3(\Delta)$ and $S_6(\Delta)$ depending on the vector $\Delta = \{\Delta_{45}, \Delta_{47}, \Delta_{73}, \Delta_{76}\}$.

Given that the current state of the workpiece corresponds to its intermediate state after OP10, the variable parameters for future operations are Δ_{45}, Δ_{47}, Δ_{73}, and Δ_{76}. These values will dynamically adjust the target dimensions X_{45_c}, X_{47_c}, X_{73_c} and X_{76_c} for the next operations. Therefore, the adjustment values to be optimized are encompassed in the parameter vector $\Delta = \{\Delta_{45}, \Delta_{47}, \Delta_{73}, \Delta_{76}\}$. However, the optimal Δ values remain undetermined at this stage. A relevant indicator must be defined to quantify the quality of a given set of adjustment Δ values. For any set of Δ values, a simulation of the expected finished workpiece can be performed, as shown in **Erreur ! Source du renvoi introuvable.**. This enables to evaluate the expected margins over each blueprint dimension Y_k corresponding to the given parameter vector Δ, as shown in Figure 7.

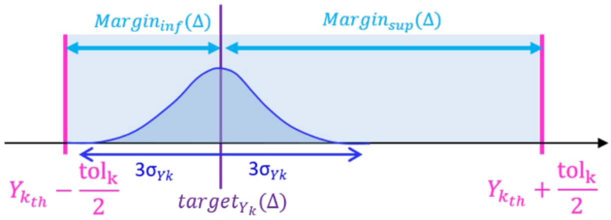

Figure 7: Simulated target for the blueprint dimension Y_k

From these simulated margins, the indicator suggesting the quality of the Δ values can be defined as follows, for each blueprint dimension Y_k:

$$Score_{Y_k}(\Delta) = \frac{\min(Margin_{inf}(\Delta), Margin_{sup}(\Delta))}{3\,\sigma_{Yk}} \quad (6)$$

With $\sigma_{Y_k} = \sqrt{\sum_i^n \sigma^2{}_{Y_{k_i}}}$, the resulting standard deviation on the blueprint dimension target, taking into account machining dispersions and measurement uncertainty. For example, the corresponding scores for the proposed set of Δ values outlined below would be:

$$\Delta = \begin{Bmatrix} \Delta_{45} = 0.01 \\ \Delta_{47} = 0.012 \\ \Delta_{73} = 0.008 \\ \Delta_{76} = -0.015 \end{Bmatrix} \rightarrow \begin{Bmatrix} Score_{Y1}(\Delta) \simeq 0.97 \\ Score_{Y2}(\Delta) \simeq 1 \\ Score_{Y3}(\Delta) \simeq 1.5 \\ Score_{Y4}(\Delta) \simeq 2.23 \\ Score_{Y5}(\Delta) \simeq 1.25 \\ Score_{Y6}(\Delta) \simeq 2.4 \end{Bmatrix}$$

For this particular set of adjustment values Δ, the functional specification exhibiting the smallest score is Y_1. This indicates that it has the lowest probability of being satisfied using these specific Δ values. Considering a different set of Δ values, the critical functional specification may not necessarily be Y_1. With the ability to assess the blueprint dimension scores for any set of Δ, it becomes possible to optimize these adjustment values.

3.3. Optimizing the set of Δ values

The Δ values are optimized by the mean of an objective function, *f*, aiming at maximizing the minimum scores obtained across the functional specification with Δ:

$$Maximize\ f(\Delta) = \min\left(Scores_{Y_k}(\Delta)\right)$$

To summarize, the goal is to automatically determine the values of a set of manufacturing parameters $\Delta = \{\Delta_{45}, \Delta_{47}, \dots\}$ to increase the likelihood that each individual workpiece complies fully at the end of its manufacturing process. The algorithm operates through iterations on Δ:

- Simulate the expected workpiece, considering both the measured features and the target surfaces.
- Calculate the scores for each functional specification.
- Subsequently, the algorithm converges towards the Δ_{opt} solution that maximizes $f(\Delta)$. The machining program targets are then adjusted with the Δ_{opt} values.

When large deviations are measured, a low value of the optimum $f(\Delta_{opt})$ indicates a significant risk of non-conformity. The manufacturer must therefore define a risk threshold below which one will choose to halt the process of the current workpiece.

4. Simulation results

The objective of the presented simulation is to compare the expected conformity rates using either the classical manufacturing transfer method outlined in section 2 or the manufacturing dimension targets adaptation method presented in section 3.

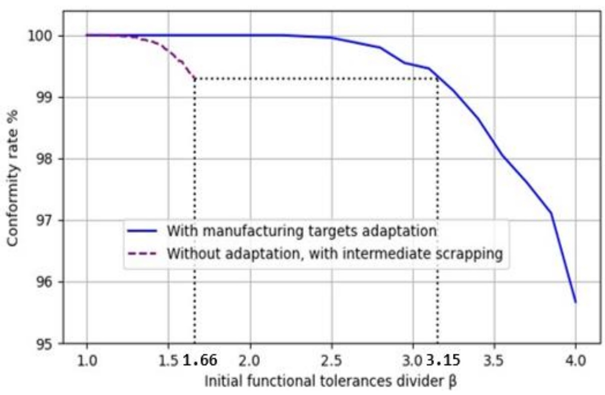

Figure 8: Simulation results with or without target adaptation

The dispersions over the working dimensions $\mathbf{X_{ij}}$ are assumed the same than in the previous section. Subsequently, a stochastic simulation of the production of various workpieces is conducted, employing both strategies. The initial functional tolerance set (β =1) is:

$$\mathbf{tol_{Y1} = 0.4; tol_{Y2} = 0.4; tol_{Y3} = 0.4;}$$
$$\mathbf{tol_{Y4} = 0.4; tol_{Y5} = 0.6; tol_{Y6} = 0.6}$$

These functional tolerances will be gradually decreased by simultaneously dividing them by a coefficient β. The dashed curve shows that the classical manufacturing transfer is no longer possible for a coefficient β > 1.66. A conformity rate of 99.3% is obtained for this limit value. The solid curve shows that with the adaptive manufacturing method, the same conformity rate is obtained for β = 3.15. This implies that all functional tolerances may be significantly tighter without affecting the conformity rate.

5. Conclusion and future work

In the context of production within Industry 4.0, where manufacturing and measurements tools are interconnected, a novel approach of manufacturing is enabled. Rather than relying on traditional manufacturing transfer methods, the use of an individualized adaptive manufacturing process must enhance the overall process capability. Consequently, with the same manufacturing cost, functional tolerances can be tightened, providing more design margins and enabling diverse tolerance allocations. Such flexibility can facilitate concurrent engineering, elevate product performance by refining requirement tolerances, or decrease manufacturing costs by preventing non-conformities. For instance, Safran Helicopter Engines' turboshaft engines could benefit from reduced clearances between rotating and stationary parts, improving performance and efficiency. Future research will focus on applying the approach to complex components with 3D specifications, extending its applicability in diverse manufacturing contexts.

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