Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 128 (2024) 327–332

www.elsevier.com/locate/procedia

34th CIRP Design Conference

Alignment through bolted Connections: a Comparative Investigation Among different Geometric Specifications

Mattia Maltauro[ab*], Roberto Meneghello[a], Gianmaria Concheri[b]

[a] *Department of Management and Engineering, University of Padova, Stradella San Nicola 3, 36100 Vicenza, ITALY*
[b] *Laboratory of Design Methods and Tools in Industrial Engineering, Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Venezia 1, 35131 Padova, ITALY*

* Corresponding author. Tel.: +39 049 827 6734; *E-mail address:* mattia.maltauro@unipd.it

Abstract

One commonly overlooked design rule advises against relying on bolts to ensure alignment between parts. Bolted connections often require a significant nominal size difference between screws and holes to avoid interference during assembly. Using the boundary condition design criterion, it is possible to define dimensional and location tolerances for this purpose, but it typically results in clearance being expected, thus accurate alignment cannot be assured. Despite this, many industrial practices still utilize bolted connections (or more broadly, shaft-hole connections) to align different parts. While automated assembly lines might resolve alignment issues through robotic arms, such designs lack robustness, especially when viewed from a design-for-maintenance perspective. During service or maintenance, correctly reassembling bolted parts can become a challenging task.
This paper aims to address these issues by applying tolerance stack-up analysis to various possible geometric specifications. The study will explore the impact of a dedicated alignment feature and analyze the influence of material conditions on the geometric specification quantifying rejection rates. To accomplish this, a straightforward assembly involving two parts bolted together will be examined. The study will assess the effects of different specifications, encompassing both functional specification (representing assembly conditions) and non-functional specification (based on fiducial features).

Keywords: Bolted connections; Geometric Specification, Design methodology, tools and technologies.

1. Introduction

One commonly forgotten design rule advises against using bolts to guarantee alignment between parts. Bolted connections often rely on a large difference in nominal size between the screw and the holes to avoid interference during assembly. The boundary condition design criterion can be used to define dimensional and location tolerances for this purpose [1]; the obvious result is that clearance is always expected, therefore accurate alignment cannot be guaranteed [2]. Despite the simplicity of this explanation, many industrial practices continue to use bolted connections (or shaft-hole connections, more generally) to align different parts. While automated assembly lines may solve the alignment problem using robotic arms [3], the design still lacks robustness, especially from a design-for-disassembly and design-for-maintenance perspective [4]. The product may be assembled on the automated line, but during service or maintenance, it becomes challenging to reassemble it correctly.

Tolerance stack-up can be used to evaluate such design decisions: whether to use a dedicated alignment feature or not.

10.1016/j.procir.2024.04.007

The simulation outcome suggests whether both solutions are viable or not.

Another significant design question concerns material conditions [5]. Designers are often told that Maximum Material Condition (MMC) should always be used to describe the assemblability requirements in shaft-hole connections [6]. In [7], it is also advised not to use MMC if the feature is used to guarantee alignment. However, no real rationale (metric) behind this statement is provided.

This paper aims to address all these questions. The impact of a dedicated alignment feature will be explored, and the effect of material conditions will be analyzed. To achieve this, a simple assembly between two parts, bolted together, will be considered. The effect of different specifications, both functional and non-functional will be assessed.

1.1. Functional VS Non-Functional Geometric specifications

The existence of different types of geometric specifications is postulated by ISO/TS 21619:2018 [8], where a classification among Functional, Manufacturing, and Verification specification is stated. The interrelation between these types of geometric specifications is described in [9]. For what concern this work the important distinction is between Functional and Non-Functional geometric specification. Functionality pertain to the final assembly [9,10] consequently, Functional Geometric Specifications address the part in its "as-assembled" state [11] therefore describing the assembly condition of the part in the final product. The Datum System describes the assembly features considering the assembly order. Other end-features are controlled in position and orientation from the Datum System. Any Geometric specification not following these guidelines is hereinafter considered as Non-Functional.

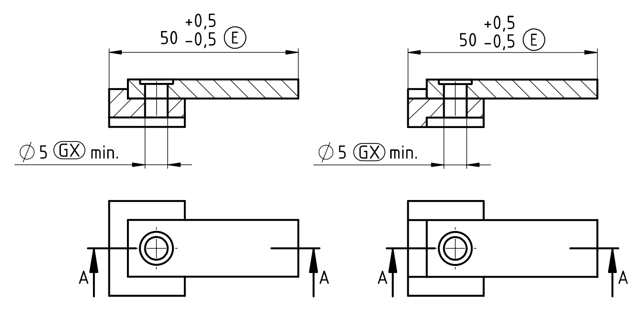
2. Tolerance Stack-Up tool

To perform tolerance stack-up an updated version of the model presented by Fischer [7] is implemented in MS Excel. A brief description of the tool is given in a previous work [2].

A preliminary strategy to deal with unequally disposed tolerance zone (UZ modifier) is implemented. In the vector loop scheme (see Fig. 4 for a graphical reference), in the vertical lines corresponding to a surface specified with a surface profile along an UZ modifier, the "out of the material" side (+) and "into the material" side (-) are marked. A new vertical line is traced on the "out of the material" side. This new vertical line represents the Offset Theoretical Feature, the original line the Theoretically Exact Feature (Nominal Feature) according to ISO 1101:2017 [12]. At this point the vector loop can be created according to the rules in [7]. The verse of vector connecting the two aforementioned lines give the sign to use before the UZ value (to be considered with its value).

3. Functional requirements and geometric specifications

The functional requirements for the case study, and both assembly conditions, are shown in Fig. 1. The assembly needs to have a total length of $50 \pm 0.5\,mm$, and a M5 bolt is required for assembly. The first requirement is simply stated using a size dimension on the total length. The second one asks for a perfect cylinder of diameter 5 mm to pass through, so a size dimension is specified using the global maximum inscribed feature. The requirement is considered respected with both Cp and Cpk greater than one using the Root Sum of Square (RSS) computation method. The Key Characteristics (KC) studied through tolerance stack-up is the total length of the assembly.



a) Explicit alignment feature b) Alignment through the bolt

Fig. 1. Case study functional requirements.

3.1. Geometric specifications

For the case study four different geometric specifications are studied. The first one is the functional geometric specification pertaining to the use of a specific alignment feature, as in Fig. 1.a), see Fig. 2. The datum system of both parts describes the assembly features. Both the version with material condition and without material condition applied to the through holes are considered.

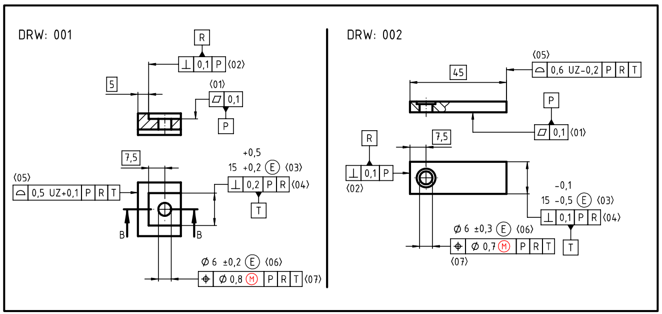


Fig. 2: Functional specification for both parts considering the explicit alignment feature.

The second one is the functional geometric specification in case the bolted connection is used for alignment, as in Fig. 1.b), see Fig. 3. Therefore the hole is considered as a datum feature. Also in this case both the version with material condition and without material conditions applied to the through holes are considered.

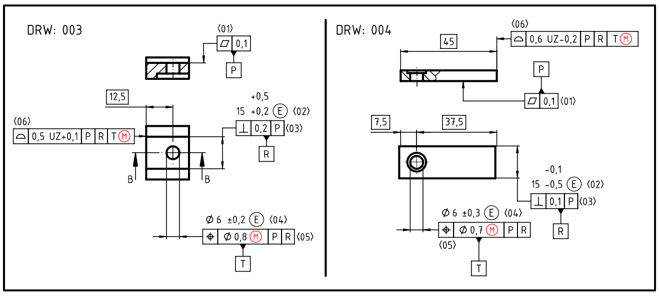


Fig. 3: Functional specification for both parts considering the alignment through the bolt.

4. Alignment trough alignment feature

In this section, the tolerance stack-up considering the assembly condition relying on the explicit alignment feature is presented. The vector loop considering the geometric specification presented in Fig. 2 is depicted in Fig. 4.

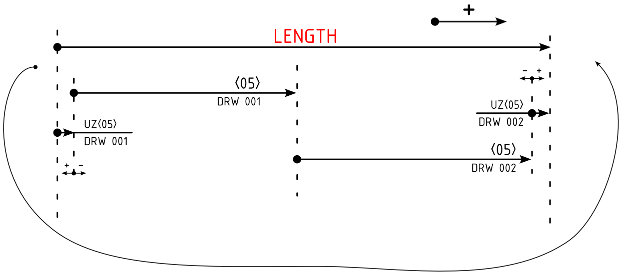
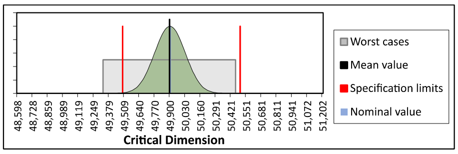


Fig. 4: Total length stack-up scheme using an explicit alignment feature.

Since a functional specification is considered, the stack-up scheme results short and direct. Furthermore, it can be seen that no feature of size are considered in the stack-up scheme. Therefore, the material condition gives no effect and only one result is obtained, see Fig. 5.



	RSS	Adjusted RSS
$C_p=(USL-LSL)/(2\cdot 3\sigma)$	1,28	0,85
$C_{pk_u}=(ULS-\mu)/(3\sigma)$	1,54	1,02
$C_{pk_l}=(\mu-LSL)/(3\sigma)$	1,02	0,68
$C_{pk}=\min[C_{pk_u};C_{pk_l}]$	1,02	0,68

	RSS	Adjusted RSS
	PPM	
Above USL probability	2	1060
Below LSL robability	1060	20251
Out of tolerance probability	1062	21311

Fig. 5: Extract from the input and output for the total length tolerance stack-up.

It can be noted that with the proposed specification, the KC (total length) is well within requirements if we look for both Cp and Cpk greater or equal to 1 with the RSS computation method. The upper limit is not reached even with the worst-case analysis.

5. Alignment trough bolted connection

In this section, the tolerance stack-up considering the assembly condition relying on the bolted connection for alignment is presented. Both a functional geometric specification considering this assembly conditions, Fig. 3, and a non-functional geometric specification that consider the previous assembly condition, Fig. 2, are considered in the following sub-paragraphs.

5.1. Using a functional geometric specification

Considering the functional geometric specification for this case, as in Fig. 3, the vector loop scheme is presented in Fig. 6.

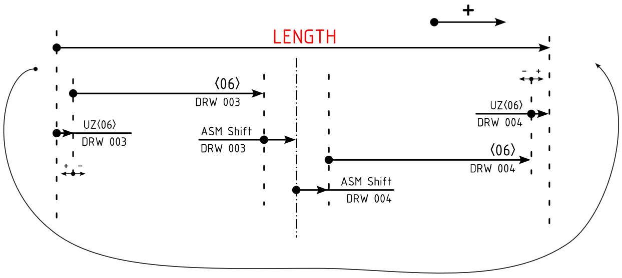


Fig. 6: Total length stack-up scheme using the bolt as alignment with functional specification.

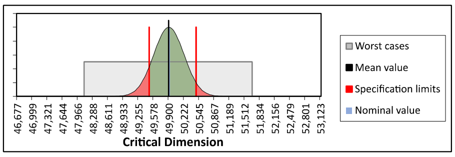
The stack-up scheme, when compared to the previous case, see Fig. 4, has two further contributions given by the assembly shift describing the possible relative movement between each of the two parts and the bolt. The assembly shift is defined by the following equation [7]:

$$ASM_{Shift}=\pm(HOLE_{LMC}-SHAFT_{LMC})/2 \tag{1}$$

In this case the size variability for the bolt can be neglected.

Since the features of size contribute to the stack-up, the material condition influences the results in this case. The results obtained without material condition are presented in Fig. 7. The results pertaining to the application of the material conditions are presented in Fig. 8. In this last case, being the Datum specified with the MMC the Datum Feature shift needs to be considered too. The Datum Feature Shift is given by the following equation [7]:

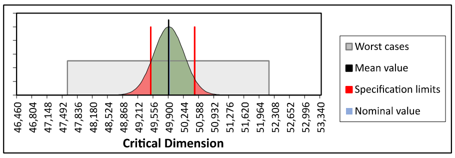
$$DFS=\pm|(FEATURE_{LMC}-FEATURE_{MMC})/2| \tag{2}$$



	RSS	Adjusted RSS
C_p=(USL-LSL)/(2·3σ)	0,52	0,34
C_{pk_u}=(ULS-μ)/(3σ)	0,62	0,41
C_{pk_l}=(μ-LSL)/(3σ)	0,41	0,28
C_{pk}=min[C_{pk_u};C_{pk_l}]	0,41	0,28

	RSS	Adjusted RSS
	PPM	
Above USL probability	31336	107301
Below LSL robability	107301	204022
Out of tolerance probability	138637	311323

Fig. 7: Extract from the outputs for the total length stack-up using the bolt as alignment without material condition and functional specification.



	RSS	Adjusted RSS
C_p=(USL-LSL)/(2·3σ)	0,48	0,32
C_{pk_u}=(ULS-μ)/(3σ)	0,58	0,39
C_{pk_l}=(μ-LSL)/(3σ)	0,39	0,26
C_{pk}=min[C_{pk_u};C_{pk_l}]	0,39	0,26

	RSS	Adjusted RSS
	PPM	
Above USL probability	40562	122455
Below LSL robability	122455	219110
Out of tolerance probability	163016	341565

Fig. 8: Extract from the outputs for the total length stack-up using the bolt as alignment with material condition and functional specification.

5.2. Using a non-functional specification

Now a non-functional specification is considered. The geometric specification defined for the explicit alignment feature, see Fig. 2, is used. The resulting vector loop scheme is presented in Fig. 9.

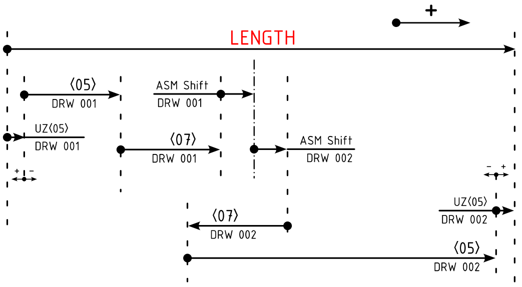
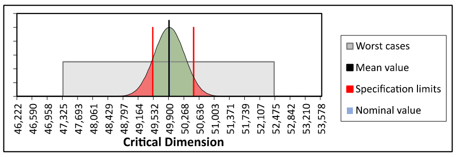


Fig. 9: Total length stack-up scheme using the bolt as alignment with non-functional specification.

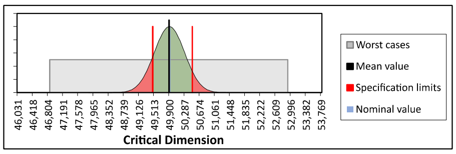
Here, a direct relation between the assembly feature and the controlled feature cannot be found, and a “double jump” needs to be made, passing through the datum features. Furthermore, the assembly shift is still present and need to be considered. As result, the stack-up scheme becomes “longer” with respect to both previous cases. The result from the tolerance stack-up without considering the material condition can be seen in Fig. 10. The results obtained considering the material condition are depicted in Fig. 11.



	RSS	Adjusted RSS
C_p=(USL-LSL)/(2·3σ)	0,45	0,30
C_{pk_u}=(ULS-μ)/(3σ)	0,54	0,36
C_{pk_l}=(μ-LSL)/(3σ)	0,36	0,24
C_{pk}=min[C_{pk_u};C_{pk_l}]	0,36	0,24

	RSS	Adjusted RSS
	PPM	
Above USL probability	51412	138398
Below LSL robability	138398	234217
Out of tolerance probability	189810	372615

Fig. 10: Extract from the output for the total length stack-up using the bolt as alignment without material condition and non-functional specification.



	RSS	Adjusted RSS
C_p=(USL-LSL)/(2·3σ)	0,43	0,29
C_{pk_u}=(ULS-μ)/(3σ)	0,52	0,34
C_{pk_l}=(μ-LSL)/(3σ)	0,34	0,23
C_{pk}=min[C_{pk_u};C_{pk_l}]	0,34	0,23

	RSS	Adjusted RSS
	PPM	
Above USL probability	60495	150626
Below LSL robability	150626	245359
Out of tolerance probability	211121	395984

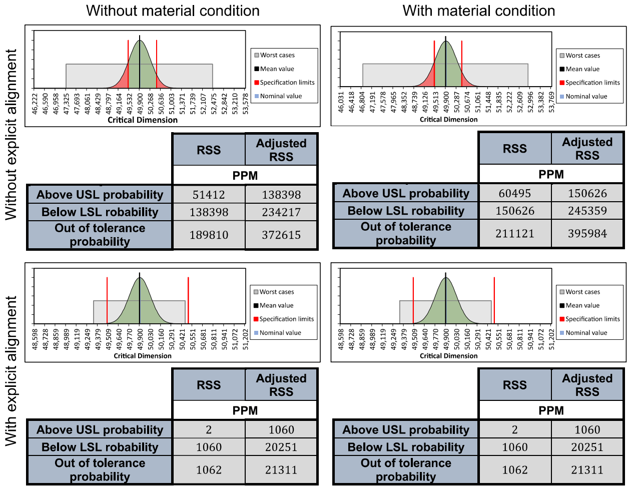
Fig. 11: Extract from the output for the total length stack-up using the bolt as alignment with material condition and non-functional specification.

6. Comparison and discussions

The first comparison addresses the differences coming from different design options: which feature to use for alignment. The same geometric specification is used independently from the assembly condition. The second comparison, assuming the alignment relies on the bolt, addressed the effect of material condition and a properly defined functional specification.

6.1. Design option influence

The comparison between different assembly conditions using the same geometric specification is shown in Fig. 12. The first obvious difference is that while the explicit alignment feature ensures that the output statistical distribution is well within specification limits (both Cp and Cpk greater than one), using the bolt as alignment results in a much larger output statistical distribution and a significant increase in the number of scraps (by a factor of 10^3). It should be highlighted that the output statistical distribution for the alignment through the bolt represents a best-case scenario. According to our model, statistical distributions are considered as normal [2,7]. However, the assembly shift distribution may not conform well to a normal distribution since it comes from a free play in the assembly prior to the bolt being fastened. A better statistical distribution for this case would be a uniform distribution or a “U shape” distribution. The first option assumes that there is no bias during assembly, while the second one assumes that during assembly, the components will stop in a position where they both touch the screw. The actual statistical distribution depends on the specific assembly procedure and may be influenced by the operator's actions. The Gaussian distribution may represent the outcome from an automated assembly line. Nonetheless, the impact of any of the aforementioned distributions, when compared to the Gaussian one, is that the output variability increases. Therefore, using a Gaussian distribution for the assembly shift represents a best-case scenario.



	RSS	Adjusted RSS
	PPM	
Above USL probability	51412	138398
Below LSL robability	138398	234217
Out of tolerance probability	189810	372615

	RSS	Adjusted RSS
	PPM	
Above USL probability	60495	150626
Below LSL robability	150626	245359
Out of tolerance probability	211121	395984

	RSS	Adjusted RSS
	PPM	
Above USL probability	2	1060
Below LSL robability	1060	20251
Out of tolerance probability	1062	21311

	RSS	Adjusted RSS
	PPM	
Above USL probability	2	1060
Below LSL robability	1060	20251
Out of tolerance probability	1062	21311

Fig. 12: Comparison between the result obtained with the same geometric specification changing the assembly condition.

Since the tolerance values are the same for these specifications and the topology is almost the same, the production cost can be considered comparable (or even the same). The result is that at the same production cost, choosing to base the alignment on the bolt gives a far worse result compared to the use of an explicit alignment feature.

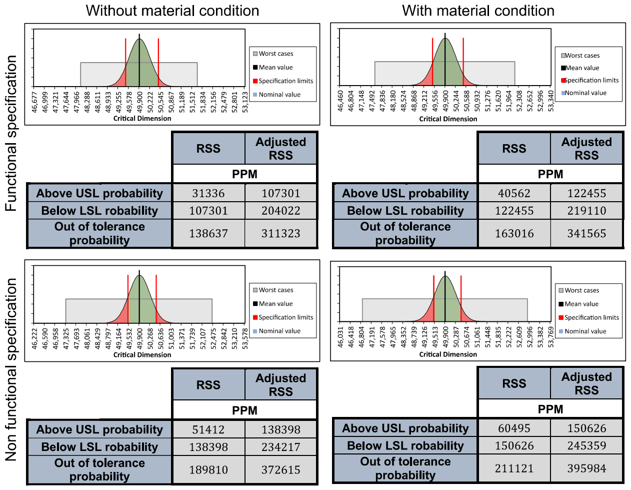
This proves that bolted connections should never be used to guarantee alignment if the requirement is critical. It might be noted that if a pattern of bolts is used, the effect of the assembly shift might be mitigated and, therefore, help with the alignment. The precise computation of the effect is still difficult and, so far, may be achieved only with Monte Carlo simulation [2].

If the stack-up is used for tolerance synthesis according to a pre-defined metric (e.g., Cp and Cpk greater or equal to one) using the bolt as alignment will inevitably lead to tighter tolerance values, and therefore, higher manufacturing costs.

These considerations do not apply if the alignment is guaranteed with dowel pins since, in this case, the clearance is minimal by design.

6.2. *Material Requirements influence*

The comparison between different specifications for the same assembly condition is shown in Fig. 13. In this case, the alignment is given by the bolt. It has already been discussed that this is not the most efficient way of managing the assembly. Nonetheless, in industry, this situation often occurs, and it is important to find solutions that can help to mitigate the effect of the assembly shift.



	RSS	Adjusted RSS
	PPM	
Above USL probability	31336	107301
Below LSL robability	107301	204022
Out of tolerance probability	138637	311323

	RSS	Adjusted RSS
	PPM	
Above USL probability	40562	122455
Below LSL robability	122455	219110
Out of tolerance probability	163016	341565

	RSS	Adjusted RSS
	PPM	
Above USL probability	51412	138398
Below LSL robability	138398	234217
Out of tolerance probability	189810	372615

	RSS	Adjusted RSS
	PPM	
Above USL probability	60495	150626
Below LSL robability	150626	245359
Out of tolerance probability	211121	395984

Fig. 13: Comparison between the result obtained with different geometric specifications with the same assembly condition.

With the given tolerance values, it can be seen that none of the proposed specifications fulfills the functional requirements. Nonetheless, significant differences can be seen when comparing the different cases.

Considering the functional specification, the application of the material requirements increases the number of estimated scraps by 17.58 %, while considering the non-functional specification, the number of scraps increases by 11.23 %. Therefore, in both cases, the application of the material condition decreases the quality of the assembly and it is not a good solution. A definitive answer shall be derived by computing the cost of the scrap compared to the savings coming from the application of the material requirement. The tolerance stack-up gives the possibility to economically evaluate the solution, allowing sound decisions. Such considerations shall be addressed in future development creating a design tool for the designer to make informed decision. Also in this case, if the stack-up is used for tolerance synthesis starting from a worst solution will inevitably lead to tighter tolerance values, and therefore, higher manufacturing costs.

6.3. *Functional VS Non-Functional Specification influence*

Considering the differences between the use of a functional specification versus a non-functional one, it can be seen that a non-functional specification always estimates a larger number of scraps. If the case without material condition is considered, the non-functional specification results in 36.91 % more scraps; considering the case with material condition, it leads to 29.51 % more scraps. Inevitably, using a non-functional specification during tolerance synthesis induces having tighter tolerances than actually needed. Indeed, the higher number of scraps derives from a tolerance stack-up that does not represent the assembly conditions. Since the functional specification, as defined in this work, describes the assembly conditions, the stack-up that can be created is the “shortest” possible, meaning that it has the least contribution possible. The result is that a tolerance synthesis based on a functional specification allows larger tolerances when compared to other possible geometric specifications that do not consider the assembly conditions.

7. Conclusions

The aim of this paper was to demonstrate the potential of tolerance stack-up as a design tool, both for validating design assumptions on the nominal model and for evaluating alternatives in geometric specifications. Tolerance stack-up is a valuable tool for comparing different design options by analyzing output metrics such as Cp, Cpk, or scraps number.

In the case study presented, the old design rule that advises against using bolted connections for guaranteed alignment was investigated. The evidence from the tolerance stack-up confirms the validity of this empirical rule, providing yet another proof.

The effect of material condition was also analyzed statistically, confirming that the MMC shall be avoided when precise alignment is needed.

Furthermore, the impact of a functional specification versus a non-functional one was studied. As previously postulated [9], it was proven that a functional specification that accurately describes the assembly conditions allows the creation of "shorter" tolerance stack-ups, which, in turn, permits larger tolerances to be assigned during the tolerance synthesis phase.

Future development to this work shall consider tolerance to cost optimization allowing the designer a more comprehensive understanding of his design impact. Other aspects, such as stress concentration, fatigue life, and ease of assembly and/or disassembly might be also integrated for an even more comprehensive design evaluation. It will be also interesting to compare the theoretical results describe in this paper with the results coming from actual measurement on physical prototypes. Theoretical results coming from a tolerance stack-up where actual distributions coming from the prototypes might also be considered. In this last case, the use of actual statistical distribution shall be treated with care as presented in [13].

In conclusion, tolerance stack-up represents a powerful tool in the hands of designers to validate design assumptions and optimize their designs when used wisely. By leveraging tolerance stack-up analyses, designers can make informed decisions and improve the overall quality of their designs.

References

[1] ASME: ASME Y14.5 - 2018 - Dimensioning and Tolerancing, (2019).

[2] Maltauro M., Meneghello R., Concheri G. (2023). Conformity Rate Estimation for Shaft-Hole Pattern Fit Not Compliant with the Boundary Condition Design Criterion. In: Gerbino, S., Lanzotti, A., Martorelli, M., Mirálbes Buil, R., Rizzi, C., and Roucoules, L. (eds.) Advances on Mechanics, Design Engineering and Manufacturing IV - Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing, JCM 2022, June 1-3, 2022, Ischia, Italy. Springer International Publishing. p. 1256–1267.

[3] Kim J.Y., Kim W.S., Cho H.S. (2005). Misalignment estimation and compensation for robotic assembly with uncertainty. Robotica. 23, p. 355–364.

[4] Desai A., Mital A. (2006). Design for maintenance: basic concepts and review of literature. International Journal of Product Development 3, p. 77-121.

[5] ISO 2692:2021 - Geometrical product specifications (GPS). Geometrical tolerancing. Maximum material requirement (MMR), least material requirement (LMR) and reciprocity requirement (RPR), (2021).

[6] Pierre L., Anselmetti B., Anwer N. (2018). On the usage of least material requirement for functional tolerancing. Procedia CIRP 75. p. 179–184.

[7] Fischer B.R. (2004). Mechanical Tolerance Stackup and Analysis. CRC Press.

[8] ISO/TS 21619:2018 - Geometrical product specifications (GPS) - Types of documents with GPS, (2018).

[9] Maltauro M., Meneghello R., Concheri G. (2024) Tolerance Specifications Management Integrated into the Product Development Cycle. Machines. 12,147.

[10] Whitney D. (2004). Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development. Oxford University Press.

[11] Maltauro M., Passarotto G., Concheri G., Meneghello R. (2023). Bridging the gap between design and manufacturing specifications for non-rigid parts using the influence coefficient method. The International Journal of Advanced Manufacturing Technology 127. p. 579–597.

[12] ISO 1101:2017 - Geometrical product specifications (GPS). Geometrical tolerancing. Tolerances of form, orientation, location and run-out, (2017).

[13] Maltauro M., Meneghello R., Concheri G. (2024) A second-order tolerance analysis approach to statistical virtual assembly for rigid parts. The International Journal of Advanced Manufacturing Technology 131. p. 437–446.