A Case Study on the Correlation Between Functional and Manufacturing Specifications for a Large Injection Moulded Part

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Abstract. Large parts produced by injection moulding are usually subjected to large deformations that may be reduced during assembly. The single parts manufacturing specification should refer to the as produced (free) state. On the other hand, the functional specification, derived from the assembly functional specification should address the "as assembled" state. Geometrical inspection, based on the functional specification requires dedicated fixtures to simulate the "as assembled" state. This contribution suggests a procedure, based on FEM simulation, to correlate the geometric specification at the "as assembled" state with the "as produced" (free) state, applied to an industrial case study. The result of the procedure are free state tolerance limits, e.g., manufacturing specification, that allows conformity of the part to the functional specification once assembled. The part may be inspected based on the manufacturing specification fixtureless during mass production. The result of the case study shows a significant reduction in position and orientation error due to the assembly process as it was expected.

Keywords: Geometrical Product Specification, Tolerancing, Deformable Assemblies, Compliant Assemblies, FEM simulation.

1 Introduction

Large parts are subject to large deformations when produced by injection moulding, but these deformations may be significantly reduced during assembly. Therefore, the functional specifications of the assembly should not be used to assess the conformity of the single sub-assembly parts, whose manufacturing specifications should refer to a free state condition (see ISO 10579 [1]).

The management of the relations among functional and manufacturing specifications is still an issue in industry. The different documents (functional, manufacturing and verification specifications) establish a multi-pole structure, driven by hierarchical relations, therefore imposing a rigorous correlation (see ISO/TS 21619:2018 [2]). For rigid parts and assemblies, the correlation may be achieved by tolerance stack-up analysis, an example may be given by the tolerance transfer method [3].

Finite Element Method (FEM) simulation-based approaches have been presented in the literature when dealing with deformable bodies. Many different approaches can be found in the literature for sheet metal parts that are widely used in the automotive and aerospace sector. Sellem and Rivière [4] proposed a mechanical approach based on the computation of influence coefficient matrices for tolerance computation of welded, bolted, glued or riveted sheet metal parts. Liu and Hu [5] present the offset finite element model as a mono-dimensional strategy to predict the assembly variability when plates are spot welded. Liu, Hu and Woo [6] investigated the difference between "series" and "parallel" assembly for deformable plates: the parallel assembly allow a smaller assembly variability compared to the variability of the single parts. A further development [7] presents the Method of Influence Coefficient in which a sensitivity matrix linking the spring-back of the assembly to the free-state condition is calculated and used to determine the "as assembled" configuration. This methodology has been further developed to integrate shape defects and contact surfaces [8, 9]. A review of these methods can also be found [10].

Stockinger et al. [11] presented an approach to combine the elastic deformation in tolerance stack-ups with sheet metal parts. The approach was validated with experimental results and compared to a commercial solution that integrates 3DCS™ (Dimensional Control Systems®) and CATIA V5™ workbench TAA™ (Tolerance Analysis of deformable Assemblies) (Dassault Systèmes®) that analyze the deviations impressed by the assembly processes based on FEM analysis.

Radvar-Esfahlan and Tahan [12] developed the Generalized numerical inspection fixture (GNIF) that allows performing freeform surfaces inspection on thin-walled nonrigid parts without using fixtures. The part deformation is considered isometric, as such the geodesic distance between two internal points remain the same allowing the determination of correspondent points between the CAD and the free-form dataset. This methodology was further developed improving the definition of the boundary conditions [13] and automated [14].

Raymauld et al. [15] proposed a methodology for performing virtual measurement in constrained state for a thin-walled plastic component.

Most of the contribution found in the literature deals with sheet metal and/or thin-walled parts. The methodologies are optimized for tolerance analysis or inspection purposes. For quality control, the methodologies are used as a post-processing operation during the measuring protocol: the analysis needs to be routine per each acquisition. Our aim is to suggest a procedure to correlate the geometric specification at "as assembled" state with the "as produced" (free) state, therefore, performing the activity at start-up of production and inspecting the part at free state during mass production.

The presented procedure is based on FEM simulation and uses the datum system and geometric tolerances definition given by the ISO-GPS (Geometrical Product Specification) standards. Furthermore, the procedure is intrinsically deterministic resulting in a straightforward possibility to simulate the result of each configuration without losing the effect of the statistical covariance of the inputs parameters.

1.1 The Case Study

The present contribution aims to describe the preliminary activities that were performed to correlate the functional and the manufacturing specifications for an industrial case study. The assembly consists of three main parts: an inner core that will be considered as a rigid body and two outer deformable shells. The focus is on the two large external parts that are produced by plastic injection moulding. The single parts, at the end of the manufacturing process, show a deformation that is not compliant with the functional specification. The assembly process takes place through vibration welding, impressing a stable configuration to both parts. Consequently, part of the deformation that is present in the as-produced state is reduced.

For this reason, one of the main problems is the assessment of the tolerance limits in free state conditions coherent with functional requirements. The full activity has been preliminarily performed in one of the two moulded parts.

The first hypothesis is that during the welding process the deformation is impressed only in the welding plane, the other portions of the structure are free to deform accordingly. The second hypothesis is that at the end of the process the welding plane is perfectly planar, which is not realistic since the elasticity of both mating parts allows further deformation (spring back) after the welding is completed: the result is the best-case scenario, i.e., the maximum possible reduction.

2 Materials and methods

During a preliminary phase of the study, one single part was acquired using an articulated scan arm with a laser probe. The resulting mesh (STL file) was compared with the CAD nominal model to determine the most deformed areas and the overall range of deviations.

The part, at free state, is first acquired using a 3D articulated arm. A discrete point cloud is obtained for the datum features and the welding plane. The anti-deviations of the welding plane (i.e., the opposite value of the normal deviation), representing the constraints impressed by the assembly process, are then used as input for a FEM simulation. These constraints are applied to the nominal geometry assessing the “virtual deformation” of nominal features when an actual assembly deformation is imposed. The result of the simulation is then summed to the free state deformation to simulate the constrained state of the part, see Fig. 1.

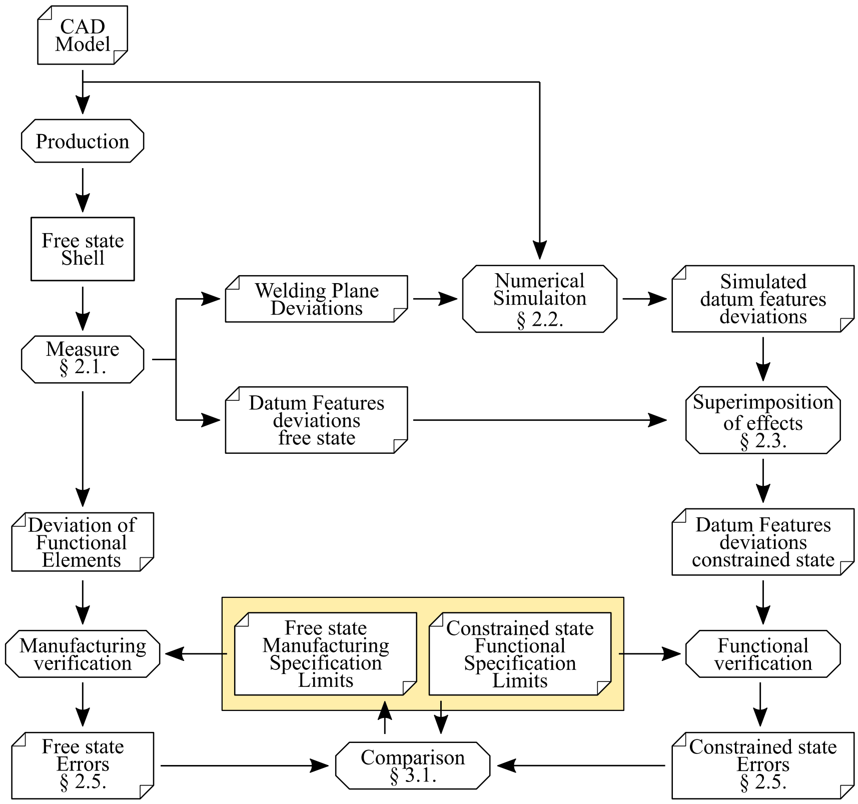

Fig. 1. Methodology workflow: the inputs are the "CAD Model", the "Free state shell" and the "Constrained State Functional Specification Limits", the output is the definition of "Free state "Manufacturing Specification Limits". Once defined, these limits are used in the "Manufacturing verification" to check for non-conformities.

2.1 Free state acquisition

A total of nine parts, from two different pre-production batches (5+4), are acquired using a 3D articulated arm (FARO® ScanArm 2) with a touching probe controlled through Autodesk® PowerInspect®.

The datum features, namely two cylinders [A-B] (i.e., bearing seats), one plane [C] (i.e., external bearing shoulder), and one point [D] (i.e., one point in one of the shotted holes used for alignment during the welding) are acquired and used for the alignment of the CAD and the functional datum system definition [A-B|C|D]. The welding plane is acquired through 24 discrete points, Fig. 2, that are sampled five times per part. To guarantee that the same points were acquired each time a template was used. The normal deviation of each point is the average among the five repetitions.

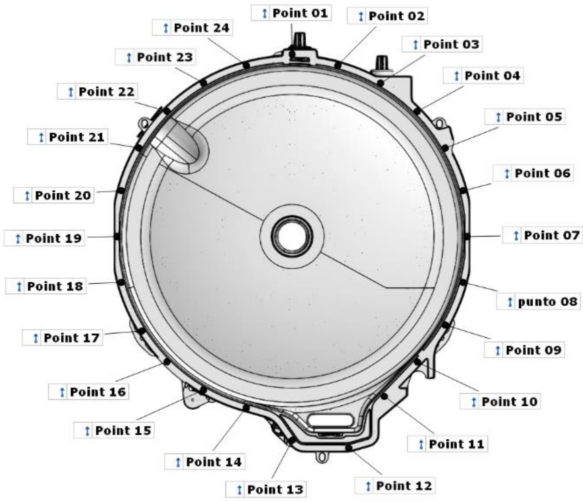

Fig. 2. Measuring points for the welding plane

The actual cartesian coordinate, based on the functional reference system [A-B|C|D], are exported in CSV format.

A gage R&R (crossed) study is performed in Minitab® to assess the repeatability of the measuring process for the welding plane deviations. Each point in each part is considered as a different item, the operator term is not assigned.

2.2 Numerical Simulation

The FEM simulation is performed in SolidWorks® (Dassault Systèmes SolidWorks Corporation) using the “SolidWorks® Simulation” plug-in. The software allows the application of boundary conditions only along edges or surfaces of the CAD body.

There are no external forces applied to the body. The displacements in the welding plane are locked all over the perimeter of the part and the displacements normal to the welding plane are applied on small circular areas (Ø 8 mm) based on the free state measure.

The body is meshed with linear tetrahedral solid elements with a minimum dimension of 2mm and a maximum dimension of 10mm.

The analysis is launched and the coordinate of the mesh nodes of the edges of the Datum features [A], [B] and [C], in deformed states, are exported and elaborated in Rhinoceros® 6 (Robert McNeel & Associates) to extrapolate the derived geometry in a format compatible with the free state measure.

2.3 Superimposition of the effects

If small deviations from nominal and linear constitutive relations are considered, the superposition principle can be used to find the deviation from the nominal of the real geometry in the constrained state by summing the two contributions.

The free state acquisition assesses the deviations of the real part from the nominal geometry due to the manufacturing: injection moulding. The simulation outputs represent the deviations of an ideal part (nominal geometry) after the application of the assembly constraints quantified on a real part.

The result is a discrete cloud of points simulating the deviations of the part in the constrained, as assembled, state.

2.4 Approach validation

To validate the overall approach two "simulated" welding plane deformations, from which the resulting deformation of the axis [A-B] is known, were tested, Fig. 3. The first configuration (a) is an axisymmetric deformation that according to the hypothesis should not influence the final orientation of the axis [A-B]. The second configuration (b) is an angular rotation of the welding plane, in this case, a rigid rotation of the axis [A-B] in the opposite direction is expected.

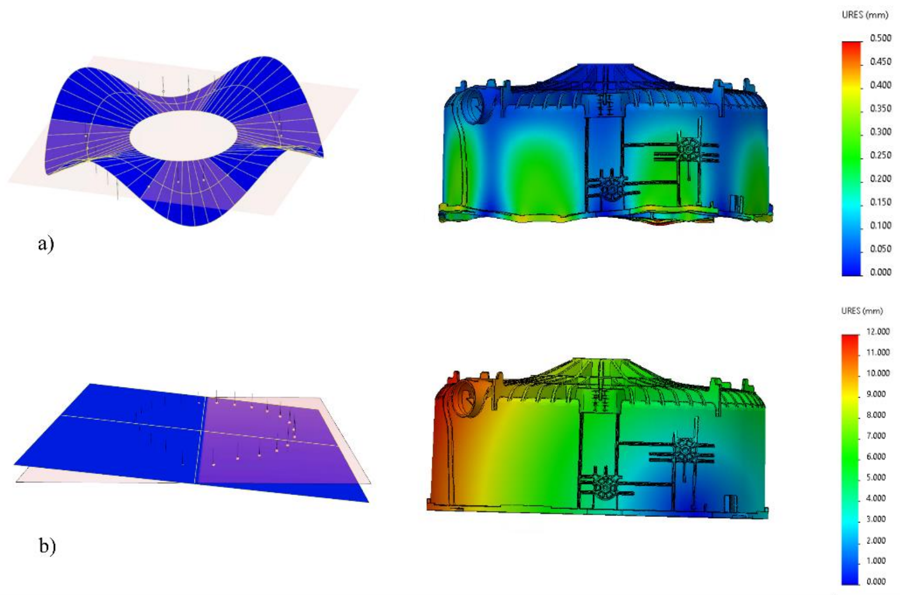

Fig. 3. The case studies used to validate the approach: a) Axisymmetric deformation; b) Rigid rotation.

2.5 Comparison

To compare and correlate the result of the free state measure with the simulated constrained state it is necessary to obtain a comparable metric between the two configurations. It is chosen to use orientation and position errors expressed in mm. The orientation error is the distance between two planes parallel to the nominal one, or, in other words, perpendicular to the primary datum [A-B], that strictly contains the measured points. The position error is the distance between two planes parallel and symmetrical to the nominal one that strictly contains the acquired data. The definition of errors is given according to ISO 1101:2017 [16].

For the free state measure, the welding plane deviations are exported in the direction parallel to the primary datum [A-B]: the orientation error coincides with the range of the deviations; the position error coincides with double the maximum deviation in absolute value Fig. 4.

The constrained state is known from a reference system centered in the welding plane: the deviations of the welding plane are null. It is necessary to change the reference system to express the state of the welding plane from the functional datum system. The orientation error is found as the product between the diametral dimension and the tangent of the angle of the axes [A-B] with respect to the welding plane (α). The position error is found accordingly considering the deviation of the plane [C], Fig. 5.

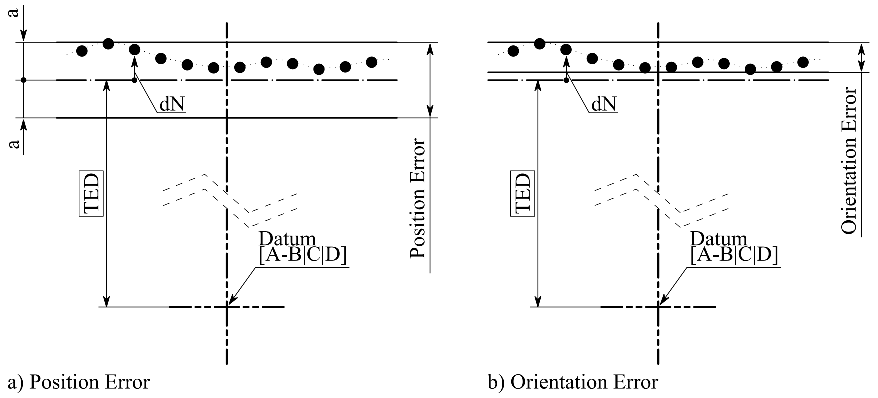

Fig. 4. Position and orientation error interpretation at free state

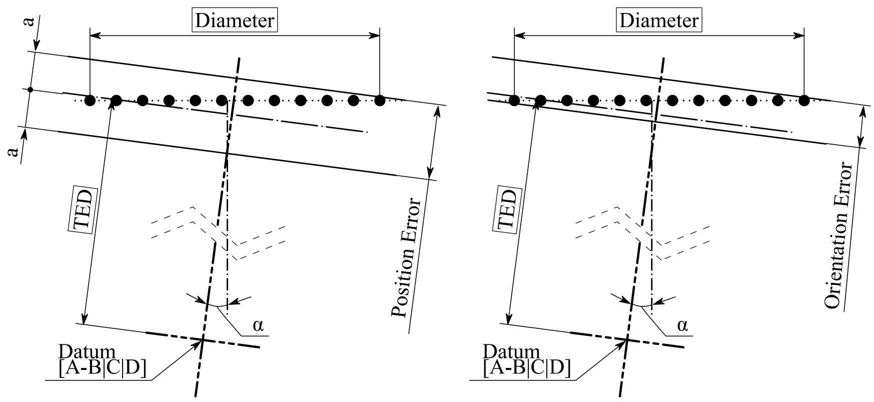

Fig. 5. Position and orientation error interpretation at constrained state

3 Results and discussion

The Gage R&R study showed that the measuring procedure has a repeatability one order of magnitude less than the normal deviation range. Therefore, it can be considered sufficient to evaluate the deformation of the welding plane given its deviation range.

The approach validation shows a residual error, for the axis [A-B] orientation, of $7.1 \cdot 10^{-4}$ [deg] for the first configuration tested, and $8.1 \cdot 10^{-3}$ [deg] for the second configuration. Although the difference is negligible in both cases, it can be interpreted as due to the imperfect application of the boundary condition on the welding plane, furthermore, in the first case, the part stiffness is non-axisymmetric. The approach is successfully validated.

The two batches are analysed separately. The results are presented as the ratio between the actual value and the maximum value. One sample of the first batch (4 parts) shows a different trend compared to the others, this sample is considered an outlier, see Fig. 6. The remaining three samples show a maximum normal deviation of 0.724, a minimum deviation of 0.061, a range of 0.786, and an average deviation of 0.505. The second batch (5 parts) shows a maximum deviation of 1.000, a minimum deviation of -0.250, a range of 1.250, and an average deviation is 0.562, see Fig. 7.

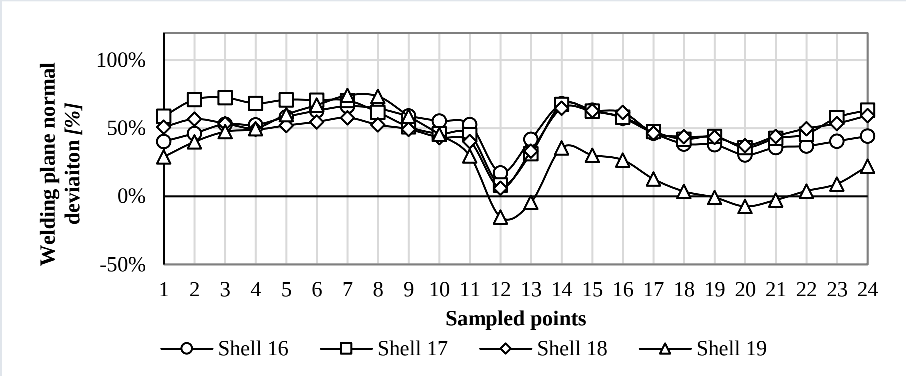

Fig. 6. First batch sampling: Welding plane normal deviations

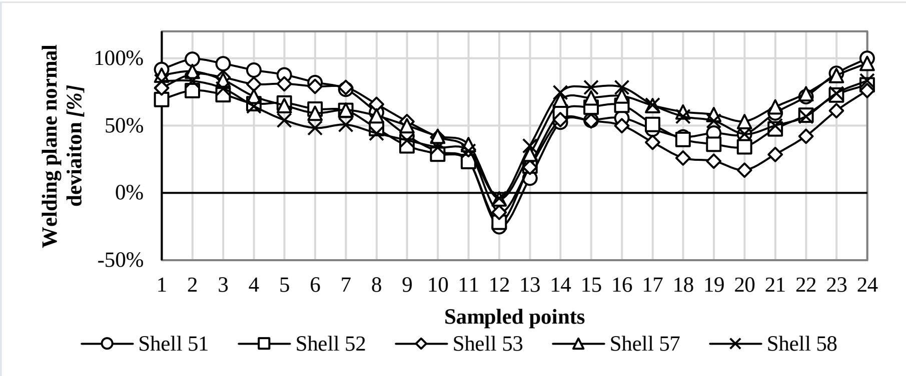

Fig. 7. Second batch sampling: Welding plane normal deviations.

The average deviation, point by point, of the two batches, as can be seen in Fig. 8, both have the same general behaviour, but the values of the deviations differ.

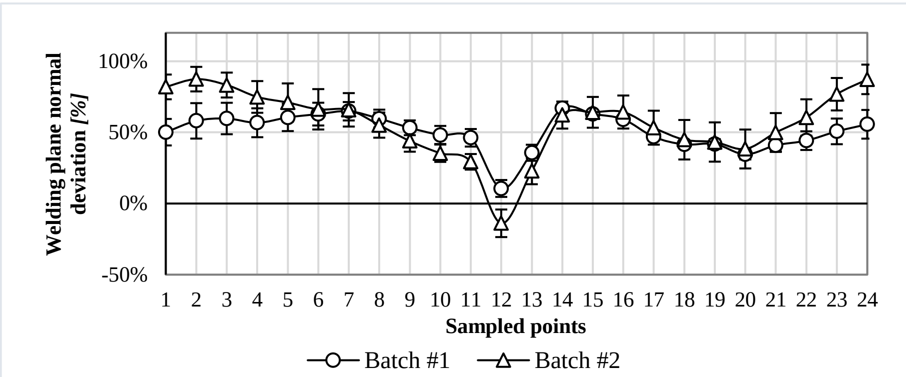

Fig. 8. Comparison among two available production batches

The methodology workflow (see Fig. 1) has been applied only to the second batch of five parts. The deviation of the points of the welding plane converted in orientation and position error, expressed as the ratio between its value and the maximum, can be found in Table 1. The mean orientation error is 0.516, and the average position error is 0.893.

Table 1. Position and orientation error for the welding plane at free state.

	Shell 51	Shell 52	Shell 53	Shell 57	Shell 58	Average
	[mm/mm]					
Orientation Error	0.625	0.511	0.513	0.504	0.436	0.516
Position Error	1.000	0.804	0.883	0.964	0.834	0.893

The orientation and position error derived from the constrained state can be seen in Table 2. The mean orientation error is 0.368, and the mean position error is 0.708.

Table 2. Position and orientation error for the welding plane at free state.

	Shell 51	Shell 52	Shell 53	Shell 57	Shell 58	Average
	[mm/mm]					
Orientation Error	0.459	0.360	0.281	0.391	0.350	0.368
Position Error	0.829	0.648	0.585	0.783	0.693	0.708

3.1 Comparison

By comparing the average error for the free state and the simulated constrained state a general reduction of both errors can be seen. For the five parts tested a 28.6% reduction for the orientation error and a 20.8% reduction for the position error can be seen, Table 3.

Table 3. Error reduction due to the simulated assembly process.

	Shell 51	Shell 52	Shell 53	Shell 57	Shell 58	Average
	[%]					
Orientation Error	26.5	29.57	45.1	22.5	19.8	28.6
Position Error	17.1	19.4	33.8	18.7	16.9	20.8

As a preliminary consideration, the manufacturing tolerances, applied to the welding plane, may be increased by a factor of 28.6% for the orientation and 20.8% for the position with respect to the functional values that are assigned considering the as assembled state and may be validated through tolerance stack-up analysis.

It is noteworthy to highlight that these are preliminary results obtained from a small test batch produced during the product development; once the first production batch will be available, the procedure may be run with a larger sample thus resulting in a higher statistical significance.

4 Conclusions

In this paper, a case study on the correlation between functional and manufacturing specifications has been presented considering a large injection moulded part.

The proposed procedure uses a FEM approach to simulate the constrained (as assembled) state starting from the free state acquisition as input. The comparison between the two states is based on the datum system and geometric tolerances definitions in ISO-GPS standards. The average location and orientation error reduction for a planar feature is determined and used as a preliminary scaling factor for the manufacturing tolerance limits applied to the feature.

In the early stages of product development, the use of injection moulding CAE software may also be added to the loop to simulate actual geometries due to different process parameters, instead of performing actual measurements, aiming to determine a possible range of process settings. The industrial experience shows that in the field of large, and massive parts, the injection moulding simulation still may not consider variables that may have a significant impact on the final, pre-assembly, geometry such as stoking and transportation.

The overall methodology may be further improved. First, a statistical correlation model between free state and constrained state may be developed to replace the scaling factor. A sensitivity matrix, considering only inputs and outputs that are needed for the correlation, may be created allowing to speed up the simulation process: once the matrix is defined no more FEM simulations are required. The use of a sensibility matrix may be integrated into the Influence Coefficient Method to evaluate the spring back of the assembly.

Even though each step should be experimentally validated, a simulation approach may allow testing free state initial deformations that are not available in the production batch exploring out-of-the-envelope configurations.

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