

Analysing shrinkage compensation in additive manufacturing: a comparative study of reverse engineering and gauge-based methods

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Abstract

Additive Manufacturing has transformed modern manufacturing with its well-known advantages. However, shrinkage remains a critical challenge, causing dimensional inaccuracies that should be properly compensated to assure geometric fidelity. This study aims to assess the reliability of a Reverse Engineering (RE) technique for dimensional compensation. A gauge-based measurement approach has been used to validate the RE method. Results confirm that the RE method is promising, while highlighting the intrinsic errors of the RE technique, and suggesting ways to evaluate and prevent them.

Keywords: *design for additive manufacturing, reverse engineering, additive manufacturing, shrinkage compensation, scale factor*

1. Introduction

In the landscape of modern manufacturing, Additive Manufacturing (AM) represents a revolutionary departure from conventional subtractive and formative processes. It offers unparalleled freedom in design, reducing lead times, and facilitating the production of complex geometries that were previously infeasible (Attaran, 2017). The diverse AM techniques, encompassing Material Extrusion (MEX), Powder Bed Fusion (PBF), and Vat Photopolymerization (VPP), are pivotal in prototyping, tooling, and direct manufacturing of functional parts (Gibson et al., 2020).

Despite its potential, AM is not without limitations. Among the most significant of these is the issue of dimensional shrinkage, driven primarily by the thermal dynamics of materials as they transition from processing temperatures to ambient conditions (Xie et al., 2022). This contraction can vary unpredictably due to factors such as the thermal coefficient of the material, print orientation, layer height, and cooling rates, leading to dimensional inaccuracies in the final product (Fitzharris et al., 2018). The repercussions of shrinkage are multifaceted, influencing not only the geometric fidelity but also the mechanical performance and assembly compatibility of the parts (de Pastre et al., 2022). For industries where precision is not just a quality marker but a critical requirement (e.g., aerospace, biomedical implants, and precision engineering) the repercussions of shrinkage are not merely a limit but a barrier to application (Srivastava and Rathee, 2021).

Addressing the core issue of dimensional shrinkage, traditional compensation methods have relied on scaling initial geometries based on predictive and statistical models to ensure the fidelity of critical dimensions post-cooling (Rajamani et al., 2018). Empirical measurements with coordinate measuring machines (CMM) and numerical analyses lead to a significant reduction in dimensional errors (Thompson et al., 2021). Several studies have focused on shrinkage compensation on simple geometric shapes (such as holes, internal cavities, and squared shapes) using these traditional methods (Yaman, 2018; Bahnini et

al., 2020). Compensation is directly applied to geometric shapes to comprehend shrinkage behaviour. Numerical simulations play a crucial role in forecasting distortions and dimensional shrinkage in AM components. Considering that, Shaikh et al. (2021) explored the effectiveness of a computational simulation-based approach to predict and measure distortions. Similarly, Ait-Mansour et al. (2020) utilized a dimensional inspection tool, such as GOM Inspect, to assess the dimensions of additive manufactured objects. Additionally, the literature suggests an alternative approach wherein shrinkage compensation is implemented to enhance the STL files, which are used extensively in AM workflows, derived from a Reverse Engineering (RE) process (McConaha and Anand, 2020). The integrated application of AM and RE contributes significantly to the improvement of manufacturing processes and products optimization, also accelerating the development phase (Kumar et al., 2023). Indeed, the development of a procedure exclusively based on RE holds the promise of establishing a comprehensive digital process proficient in both estimating and compensating for dimensional shrinkage in AM processes. This transformative approach not only has the potential to enhance accuracy in predicting shrinkage effects, but also opens avenues for the automation of the entire manufacturing process. Compensation strategies could be implemented directly, reducing manual intervention, and improving overall operational efficiency.

The present study aims to assess the reliability of a RE technique in compensating for shrinkage phenomena in AM. To accomplish this, a RE method leveraging scanning techniques and digital modelling is used to quantify and rectify the observed shrinkage, alongside a direct gauge-based measurement approach used to compare and validate the scanned dimensions. Both the RE and gauge methods focus on the computation of a scale factor, a pivotal element in dimensional compensation, serving to align the printed models to their intended design specifications.

Specifically, the focus of the current study is to delve into and address the following research question:

- What is the comparative reliability of reverse engineering techniques in compensating for dimensional shrinkage in additive manufacturing compared to direct measurement approach?

A comparative analysis of these methodologies is conducted to establish a validated process that not only demonstrates RE's potential within AM but also offers a dependable strategy for achieving dimensional accuracy in printed products for industry professionals.

Following this introduction, Section 2 delineates the methodology employed, outlining the essential steps for its implementation in AM. Subsequently, Section 3 presents a practical case study focused on the application of the methodology. The ensuing Section 4 engages in a thorough analysis of the results. The paper concludes with Section 5, which recapitulates the key findings, discusses their significance in the context of AM, and proposes directions for future research.

2. Methodology

In this section, a comprehensive methodology is presented for the evaluation of a dimensional scale factor of a generic AM technology, using a Reverse Engineering process. More specifically, the primary objective of this methodology is to validate whether a RE procedure can be valid to compensate for dimensional shrinkage caused by AM thermal effects.

The methodology, shown in Figure 1, presents several consecutive steps appropriately grouped into four main phases:

- a) *Preliminary phase*, representing the initial steps of the methodology.
- b) *RE method*, which is the procedure using reverse engineering techniques for dimensional compensation by defining a scale factor.
- c) *Gauge method*, serving as a technique for validating the outcomes obtained from the reverse method.
- d) *Validation phase*, that consist of assessing the reliability of the RE method.

The preliminary phase accuracy of the methodology greatly depends on how the geometry is defined. According to Noriega et al. (2013) in AM, the definition of a geometry is strictly dependent on the specific application and testing. In this context, the geometry should be as simple as possible. Complex shapes may require excessive support structures and longer printing times. Furthermore, elementary shapes are easier to measure than complex ones, and the measurement process represents a crucial aspect in the validation of the methodology.

The printing phase includes both the material's properties and the machine's used settings. Nonetheless, the methodology extends beyond the merely obtaining the optimal printing parameters. While these parameters are crucial for successful printing, they are considered already known within this approach. The RE method is based on consecutive steps, starting with the RE process. This initial step includes the RE technique, which remains consistent regardless of the technology employed. The subsequent step involves defining the entities to be measured through a dimensional inspection software, as suggested by the study of [Ait-Mansour et al. \(2020\)](#). In this way, a digital model of the initial geometry is obtained and measured using a purely digital procedure. After acquiring the characteristics of the scanned geometry, a direct comparison is made with the corresponding nominal values (RE measurement verification). The evaluation of the gap between nominal and measured values is the basis for the definition of the scale factor (Section 2.1) required for dimensional compensation. The reverse process output is a mesh-format representation of the scanned geometry, such as STL, OBJ, or PLY. Therefore, applying the scale factor within the slicing software is more straightforward as evidenced by [McConaha and Anand \(2020\)](#). Since AM processes consist of three main directions in which the component is made, three scale factors should be considered, one for each printing direction. Following the printing process of the scaled geometry, a direct comparison is made between the obtained entities and the nominal ones proceeding to the validation phase.

The gauge method has the same steps as the reverse method, with the key distinction being that the measurement procedure is performed directly on the manufactured object using a specific instrument. The choice of a direct method is based on having a benchmark metric for the entities measured digitally by the reverse process ([Yaman, 2018](#)). Indeed, the purpose of the gauge method is to verify the results of the reverse procedure, concluding in a final validation phase where the results are directly compared. In both methods, there is a validation step where measurements are conducted again on the geometry that has been appropriately scaled and manufactured. Subsequently, the outcomes derived from the RE method are directly compared with those from the gauge method, aiming to assess the suitability of only employing the RE procedure for a digital compensation of the initial geometry dimensions. This thorough evaluation seeks to establish whether the RE process is a reliable method for achieving accurate dimensional compensation merely using a digital technique.



Figure 1. Methodology for validating dimensional shrinkage compensation in AM processes using RE method and Gauge method (benchmark method)

2.1. Scale factor definition

The purpose of the scale factor is to compensate for the dimensions of a generic geometry by accounting for the variations between the measured entities and the nominal ones. In the context of AM, which involves three distinct printing directions, it becomes possible to discern three different scale factors, each corresponding to one of these printing directions. The scale factor relates the dimensions measured after the printing process to the expected nominal dimensions. Equation 1 enables the derivation of scale factors by considering the j -th selected dimensions for each i -th printing direction. Consequently, a distinct scale factor will be calculated for each dimension corresponding to the specific printing direction (i.e., X, Y, and Z).

$$SF_{j,i} = \frac{N_{j,i}}{M_{j,i}} \quad (1)$$

$M_{j,i}$: j -th measured dimension relative to i -th axis

$N_{j,i}$: j -th nominal dimension relative to i -th axis

Once the scale factors $SF_{j,i}$ for the j -th dimensions and i -th printing directions have been determined, the calculation of the scale factors for the i -th axis becomes a straightforward process through the Equation 2. This yields three distinct scale factors, one for each axis.

$$SF_i = \frac{\sum_{j=1}^n SF_{j,i}}{n} \quad (2)$$

n : analysed dimensions

The number of dimensions n depend entirely on the user of the methodology, tailored to the specific context. Scale factors are not influenced by the number of dimensions analysed, but only by their value. Therefore, there is no limitation on the number of dimensions that can be examined, making the methodology even more flexible.

The evaluation of the dimensional compensation after applying the scale factor can be determined by considering the deviation between the acquired dimensions and the nominal ones using Equation 3. Meanwhile, Equation 4 provides the deviation in percentage terms.

$$\delta_j = M_j - N_j \quad (3)$$

$$\% \text{ of } \delta_j = \frac{\delta_j}{N_j} \cdot 100 \quad (4)$$

3. Methodology testing: A MEX case study

With the methodology for dimensional compensation through a RE method in AM processes established in Section 2, this section pivots toward its practical application. The primary objective here is to delve into the practical implications of the methodology, with a particular emphasis placed on a specific case study. More specifically, the manufacturing of specimens will be performed with MEX technology for its suitability in creating prototypes, cost effectiveness, and ease of use (Kumaresan et al., 2022). Structured light scanning technology will be used for the RE method for its accuracy and non-contact nature (Geng and Bidanda, 2017). The purpose of case study is to validate the methodology and assess its applicability in real-world scenarios. The inherent versatility of the methodology permits its adoption across various AM technological contexts. Indeed, beyond the specific technology adopted in additive processes, the materials used undergo a different shrinkage phenomenon due to thermal effects (Turner and Gold, 2015).

In this section, the methodology application is presented in a structured manner. Section 3.1 delineates the process of defining the geometry for the specific case study, offering insights into the criteria for selection and definition. Section 3.2 provides a comprehensive overview of the experimental setup, emphasizing the equipment, materials, and procedures to enhance the transparency and replicability. Section 3.3 explores the key factors that impact the effectiveness of the RE method in AM. Lastly, Section 3.4 presents an analysis of the results obtained by applying the methodology.

3.1. Geometry definition

The successful execution of measurement steps depends primarily on the precise definition of the geometry. The first step in defining geometry is to have independence between the entities that are to be evaluated during the measurement phases. Indeed, having independent entities means that each entity can be measured and assessed without any interference on another entity. This ensures that any anomalies identified on one entity do not affect the measurements of other entities minimizing the potential biases that might arise from an over-reliance on specific types of measurements. Furthermore, selecting a geometry that includes entities of different sizes is crucial. This approach offers a comprehensive analysis, considering multiple aspects rather than focusing solely on a single dimension. In essence, by choosing a geometry with these features, the measurement process becomes more robust and reliable. Figure 2 shows the defined geometry based on the above criteria. The geometry is composed of simple entities to simplify its evaluation during the next steps. To highlight regions where the printing process could yield unexpected outcomes, the geometry also includes internal geometric shapes (such as cylinders, cuboids, and grooves).

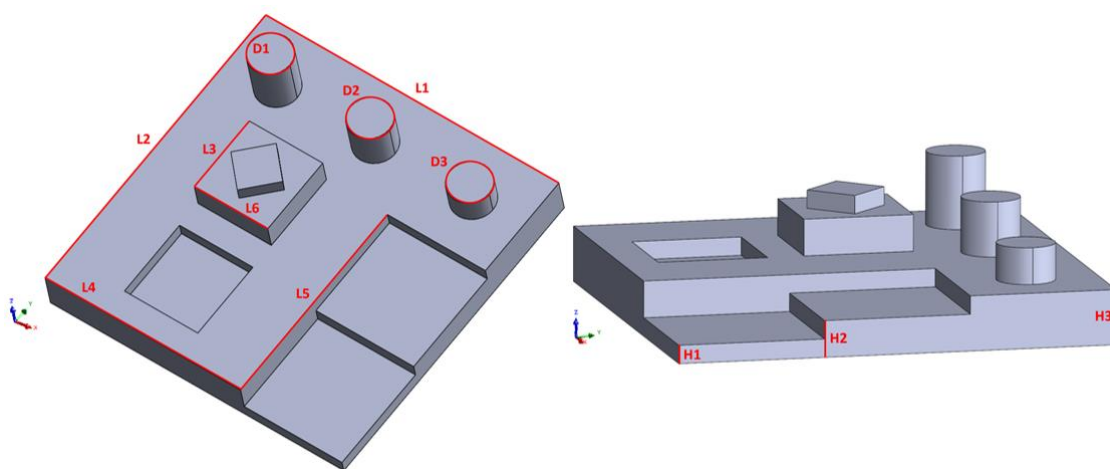


Figure 2. Geometry used for case study

3.2. Experimental setup

The geometry was created and converted to STL format with SolidWorks modelling software. Although some research has proposed the use of alternative formats like STEP and AMF (Pei et al., 2019; Xiao et al., 2017), the STL format is considered a 'de facto' standard for storing design data (Martínez-García et al., 2021). The chosen printing technology was MEX, and the specimens were produced using the Raise3D Pro 2, a professional MEX 3D printer with dual extrusion block. PLA was selected as the printing material due to its moderate extrusion temperature and higher surface finish compared to other materials (Aida et al., 2021). Tests were carried out to determine the optimal printing parameters for the chosen material. As a result, the extrusion temperature was set at 210°C, with a layer height of 0.2 mm and an infill percentage of 20%. Ideamaker was selected as the slicing software since it is associated with the printer's manufacturer. Three specimens were manufactured using the same printing parameters, and subsequently measured with both the RE and gauge methods to compute the relevant scale factors.

The RE method detailed in Section 2 consists of employing a reverse engineering approach to acquire geometries. In this specific case study, structured light scanning technology was adopted, specifically with the RangeVision Spectrum scanner model. Its 3D resolution is equal to 0.15 mm and its accuracy is up to 0.06 mm. During the scanning process, the geometry registration was fully automated using the provided turntable and markers to reduce potential errors from manual surface registrations. The scans were processed for each specimen using the dedicated software (ScanCenter) provided by the scanner's manufacturer. Moreover, the digital measurement step was conducted using a dimensional inspection software, and this process was entirely automated. Upon importing the scanning geometry in STL format, specific dimensions were derived through an advanced entity recognition feature, eliminating

the need for manual selection. This automated approach enhances accuracy, efficiency, and consistency in the measurement process, minimizing the potential for human error and ensuring a reliable standardized outcome. The experimental configuration for the RE method is shown in Figure 3, which provides a detailed depiction of the equipment, tools, and arrangements employed in the execution of the RE procedure.

The gauge method serves to validate the dimensional values acquired digitally through the reverse engineering process. Measurements were performed on each specimen using a Mitutoyo 150 mm centesimal calliper, with a resolution of 0.01 mm. The measurement procedure followed the standard established by ISO 13385-1:2019, which define the functional and metrological requirements for digital callipers. Moreover, each test specimen will be measured five times to increase the reliability of the direct measurements.

Furthermore, following the application of the scale factors, three specimens will be printed again applying the scale factors derived from the RE method, and another three specimens using the scale factors from the gauge method. Printed specimens will be evaluated using the relevant methods.

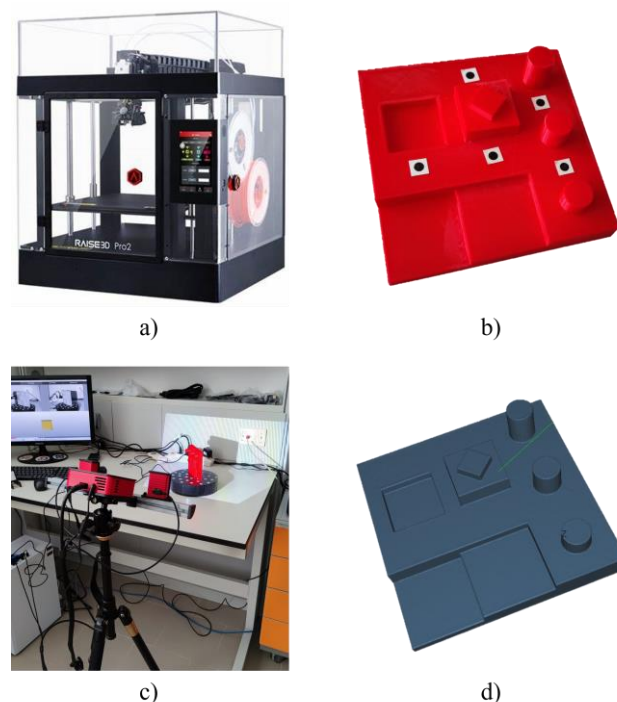


Figure 3. Experimental setup for RE method: a) MEX 3D printer ([Raise3D](#), n.d.); b) Printed specimen with marker applied; c) Structured light scanning process; d) Reconstruction with ScanCenter

3.3. Factors affecting the RE method

The reliability and accuracy of the RE method are influenced by various factors that must be carefully considered and addressed ([Vukašinović and Duhovnik, 2019](#)). Exploring the key factors that influence the effectiveness of the RE method highlights the challenges and considerations inherent in its application for dimensional compensation.

The main factors affecting the RE method are:

- *Accuracy of the 3D scanner*, which affects the precision of the scanned of the scaled model.
- *Resolution of the 3D scanner*, that determines the level of detail captured in the scanned model.
- *Calibration of the 3D scanner* ensures that the scanner accurately captures dimensions and shapes without distortion.
- *Measurement technique*, used in the inspection software to measure the converted part.

- *Mesh quality*, generated from the scanned data and can impact the accuracy of the measurements.
- *Environmental conditions*, such as temperature and humidity can influence the dimensional stability of the printed component.

By addressing the mentioned factors, proactive measures could likely be taken to minimize errors and improve the overall reliability of the RE method in compensating for dimensional shrinkage in AM. Indeed, the scanner used has an accuracy of 0.06 mm, indicating its ability to capture dimensions with a high level of precision. Additionally, the scanner's resolution of 0.15 mm suggests it can accurately capture fine details. Moreover, a full calibration of the scanner in the same lighting conditions as the scanning environment has been performed, ensuring accurate capture of dimensions and shapes without distortion. This step minimizes errors in the scanning process.

Regarding the measurement technique, automated features within the inspection software for measurement after importing scanned components helps standardize the measurement process and reduce human error, enhancing the accuracy and repeatability of measurements. The quality of the mesh significantly impacts the accuracy of measurements taken on scanned components; thus, it was set to high for optimal precision. Lastly, to enhance the scanning process effectiveness, the components were scanned under minimally altered environmental conditions.

After addressing the main factors influencing the reverse engineering process, the remaining factors typically relate to the printing process, where dimensional shrinkage becomes evident. Once factors like machine calibration and printing parameters have been managed, dimensional shrinkage primarily depends on material properties and thermal effects. These factors play a crucial role in determining the accuracy of the final printed product compared to the CAD model.

3.4. Results

Table 1 provides a comprehensive display of the measurements obtained using both the gauge and RE methods, which collectively played a crucial role in determining the corresponding scale factors. To streamline the measurement process, three distinct dimensions were carefully selected to represent each axis. Notably, diameters were intentionally excluded from the scale factor definition, as their variations will be examined subsequently, post the application of the scale factor, to assess its reliability. This systematic approach ensures a comprehensive examination of the chosen dimensions and their impact on the overall scale factor determination. Consequently, it enhances the methodological transparency of the study by providing a clear understanding of the entities considered in the scale factors definition process.

Table 1. Scale factors derived from selected dimensions using Gauge and RE methods

Entity	Nominal Dimension [mm]	Gauge Dimension [mm]	Gauge Std. Dev.	RE Dimension [mm]	RE Std. Dev.	Gauge Method		RE Method	
						SF _{j,i}	SF _i	SF _{j,i}	SF _i
L1 [X]	120	119.58	0.03	119.38	0.09	1.003	1.0009	1.005	1.0069
L4 [X]	80	79.78	0.01	79.50	0.09	1.003		1.006	
L6 [X]	30	30.11	0.01	29.73	0.12	0.996		1.009	
L2 [Y]	120	119.61	0.03	119.32	0.07	1.003	1.0009	1.006	1.0087
L3 [Y]	30	30.11	0.01	29.61	0.11	0.996		1.013	
L5 [Y]	80	79.77	0.05	79.43	0.11	1.003		1.007	
H1 [Z]	5.05	5.09	0.05	4.99	0.22	0.993	0.9962	1.010	1.0140
H2 [Z]	10.05	10.08	0.05	9.92	0.14	0.997		1.014	
H3 [Z]	15.05	15.07	0.06	14.78	0.06	0.999		1.018	

Table 2 details the measurements obtained after applying scale factors from both gauge and RE method. Additionally, the deviation and percentage of deviation from the nominal values for each chosen entity were defined using Equation 3 and 4.

Table 2. Results of measurements after scale factor application using Gauge and RE methods

Entity	Nominal Dimension [mm]	Gauge Dimension [mm]	Gauge Std. Dev.	Gauge δ [mm]	Gauge % of δ	RE Dimension [mm]	RE Std. Dev.	RE δ [mm]	RE % of δ
L1 [X]	120	119.71	0.02	-0.29	-0.24%	120.05	0.19	0.05	0.04%
L4 [X]	80	79.82	0.13	-0.18	-0.23%	79.87	0.11	-0.13	-0.13%
L6 [X]	30	29.96	0.04	-0.05	-0.15%	29.80	0.02	-0.20	-0.67%
L2 [Y]	120	119.70	0.06	-0.30	-0.25%	120.17	0.23	0.17	0.14%
L3 [Y]	30	29.95	0.01	-0.05	-0.18%	29.79	0.09	-0.21	-0.71%
L5 [Y]	80	79.88	0.04	-0.12	-0.15%	79.88	0.20	-0.12	-0.15%
H1 [Z]	5.05	5.04	0.01	-0.01	-0.16%	4.78	0.14	-0.27	-5.40%
H2 [Z]	10.05	10.04	0.01	-0.01	-0.07%	9.75	0.13	-0.30	-2.99%
H3 [Z]	15.05	15.04	0.02	-0.01	-0.07%	14.75	0.16	-0.30	-1.97%
D1	Ø16	Ø15.81	0.02	-0.09	-0.56%	Ø15.72	0.28	-0.28	-1.75%
D2	Ø16	Ø15.99	0.03	-0.01	-0.06%	Ø15.73	0.27	-0.27	-1.69%
D3	Ø16	Ø15.93	0.01	-0.07	-0.44%	Ø15.73	0.28	-0.27	-1.69%

4. Discussion

The results presented in the previous section offer a substantial evaluation of the methodology, focusing on the accuracy of the methods employed and the scale factors applied that are pivotal for dimensional compensation. As expected, the measurements values obtained from the gauge and RE methods are typically less than the nominal dimensions due to the shrinkage effects commonly associated with AM processes. Initial observations (Table 1) point to a slight disparity in the consistency of measurements between the gauge and RE methods. The standard deviation values are crucial indicators here, shedding light on the repeatability of each method. Particularly, the low standard deviation values observed in the gauge method results suggest a reasonably high level of reliability, which supports its suitability as a validation method. Conversely, the RE method demonstrates higher standard deviation values when compared to the gauge method. This becomes particularly pronounced in the Z-direction measurements, where the RE method exhibits a notable increment in variability. Moreover, similar behaviour can be appreciated for diameters, which exhibit modest deviations.

Regarding scale factors, the RE method has identified values exceeding one for all printing directions. This suggests that the measured values are smaller than the nominal dimensions and need to be scaled up. Furthermore, it is worth emphasizing that the scale factors derived from the RE method for the X- and Y- directions are slightly different between them, unlike the gauge method where they are the same. The scale factors of the Z-axis, which corresponds to the direction of the specimen's printing, exhibit divergent values between the two methods. Indeed, the scale factor derived from gauge method falls below unity, indicating an expansion in layer height along Z-direction (Baturynska, 2018).

The application of scale factors derived from gauge and RE methods for compensating dimensional shrinkage in AM presents a multifaceted insight into the efficacy of the method. Upon application of the scale factors derived from the RE method (Table 2), the measured values exhibit a slight convergence towards the nominal dimensions for the X and Y axes, yet this adjustment does not fully rectify the dimensional shrinkage observed. For the Z axis, the values remain notably distant from their nominal counterparts, underscoring that the scale factor adjustment is insufficient in overcoming the shrinkage phenomena in this orientation. Conversely, the gauge method demonstrates a slight but noticeable convergence towards the nominal dimensions.

Further analysing the results in Table 2, the RE method, while generally consistent, shows greater variability in its measurements, as indicated by higher standard deviations. This variability is especially pronounced in the Z-axis, suggesting a potential area for methodological improvement. Considering the standard deviations, the gauge method has a higher degree of consistency which could be attributed to its direct measurement approach. On the other hand, the RE method, being computationally intensive, might introduce errors through multiple stages of processing. Indeed, the measurements obtained with

the gauge method have the only errors due to the manual measurement process, which were minimized as much as possible by following the guidelines of ISO 13385-1:2019.

The measurements recorded by the RE method reflect not only the inherent inaccuracies of the RE technology employed but also the errors introduced during the conversion of scanned geometries into the STL format. Hence, an assessment of these errors should be conducted to the aim of consolidating them into a unified RE coefficient. To evaluate this coefficient effectively, cross-measurement of the specimens could be undertaken, where those produced by the gauge method are measured using the RE approach and vice versa. Such a methodology might illuminate the consistent occurrence of errors within the RE workflow, facilitating their quantification within a singular coefficient.

5. Conclusion and future developments

The current paper aims to evaluate a RE-based method for compensating dimensional shrinkage of AM parts, also using a gauge-based approach for the validation. The comparative analysis between gauge and RE methods in the measurement of additively manufactured components has underscored several key findings. The gauge method, characterized by lower standard deviation values, has demonstrated a high degree of precision and consistency, affirming its utility as a reliable measurement approach for validation within the AM process. Meanwhile, the RE method has revealed variability in its measurements, particularly along the Z-axis, highlighting the susceptibility of computationally based methods to a series of potential errors at different stages of the measurement and model reconstruction process. However, the application of scale factors to compensate for the inherent shrinkage observed in AM processes has been partially successful. While the RE method's scale factors slightly brought the X and Y axis measurements closer to nominal dimensions, they fell short of fully rectifying the shrinkage, and the Z-axis discrepancies remain challenging. In conclusion, the RE-based method presents a highly promising avenue for the compensation of dimensional shrinkage in AM processes.

Despite the intrinsic errors associated with the RE procedures, the approach holds considerable potential for improving dimensional accuracy and mitigating the discrepancies introduced during the manufacturing process. Indeed, future research could investigate the aggregation of these errors into a unified RE coefficient, which could be integrated into the RE scale factors to account for the systematic error impacts stemming from the RE process. Additionally, assuming the isotropic condition of dimensional shrinkage, a universal scale factor could be defined and applied for all directions, probably mitigating the discrepancies that arose using different scale factors.

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