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Analyzing the Impact of 3D Printing on the Development of Engineering Design Models Using CAD Software

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تحليل تأثير الطباعة ثلاثية الابعاد على تطوير نماذج التصميم الهندسي باستخدام برامج التصميم بمساعدة الحاسوب

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Abstract:
The purpose of this study is to make a numerical a priori comparison concerning the FDM and the SLA-related errors concerning the creation of a standard geometric pattern with multiple features like small cylindrical lbosses, narrow walls, and angled surfaces, which are each special features concerning their sensitivity to detail replication. The authors' overall approach consisted of designing within Autodesk Fusion 360 with exact nominal values, taking notes, and then exporting and rendering a high-quality STL file. The layering during printing involved Ultimaker Cura for FDM with a layer height setting of 0.20 mm with PLA material, while layer height setting values between 0.05 and 0.10 mm were applied while using Photon Workshop software concerning SLA printing;, post-curing subsequently ensued to make both FDM and SLA prints dimensionally stable. To measure the exact dimensions, a precision Digital Caliper with a precision value of ±0.01 mm was deployed to measure each dimension, taking three attempts per measurement to assess exact values concerning both absolute and relative error. The results revealed significantly higher error values concerning FDM printing: The 6 mm boss differed on average by 6.12 mm (+0.12 mm, +2.00%) to its exact nominal dimension, while the 0.6 mm wall varied to 0.66 mm (+10%) to its exact nominal dimension, and finally, the height value concerning the wedge surface varied to 17.90 mm (+1.70%) to its exact nominal dimension. On the other hand, SLA performed more uniformly and precisely, with respect to the same boss at 6.04 mm (+0.04 mm; +0.67%), wall 0.61 mm (+1.67%), and wedge 17.70 mm (+0.57%), with a total average deviation of +0.05 mm over +0.16 mm for FDM. Therefore, these experiments verify successfully both the superiority of SLA in terms of precision to represent geometrically minute features and that any kind of actual geometric compensation within FDM technology is possible only via deliberate geometric compensations on the CAD design model level. This paper thus confirms again the crucial integration required between actual dimensional metrology and designing on a CAD level to enhance, rather than impede, an understanding about dynamics of accuracy according to DfAM philosophy and concepts.

Keywords: Additive manufacturing, dimensional precision, FDM, SLA, CAD verification, thin-wall taper, cylindrical elements, surface gradient, layer thickness, build direction, error of measurement, DfAM, tolerances in 3D printing, runout effect.

الملخص
تهدف هذه الدراسة إلى تقديم تقييم كمي عالي الدقة للانحرافات البُعدية المرتبطة بتقنيتي التصنيع بالإضافة FDM وSLA من خلال تصنيع نموذج هندسي معياري يضم سمات حساسة مثل البوسات الصغيرة والجدران الرقيقة والأسطح المائلة، والتي تمثل مؤشرات جوهرية لقدرات كل تقنية في إعادة إنتاج التفاصيل الدقيقة. بدأ العمل بتطوير النموذج داخل Autodesk Fusion 360 وتوثيق القيم الاسمية بدقة قبل تصديره بصيغة STL عالية الجودة. وقد تم إعداد عملية التقطيع باستخدام Ultimaker Cura لتقنية FDM بارتفاع طبقة 0.20 مم ومادة PLA، بينما استخدمت تقنية SLA طبقات تتراوح بين 0.05–0.10 مم عبر برنامج Photon Workshop مع معالجة لاحقة لضمان استقرار الأبعاد. أُجريت القياسات باستخدام

Digital Caliper بدقة ±0.01 مم وبثلاث قراءات لكل سمة، مما مكّن من اشتقاق متوسطات موثوقة للانحرافات الخطية والنسبية. أظهرت النتائج أن FDM قدمت انحرافات أكبر نسبيًا في جميع السمات المقاسة، حيث سجل البوس ذو القطر 6 مم متوسطًا مقداره 6.12 مم (+0.12 مم؛ +2.00٪)، والجدار بسماكة 0.6 مم مقدار 0.66 مم (+10٪)، والإسفين 17.90 مم (+1.70٪)، الأمر الذي يعكس تأثيرات البثق وتدرّج الطبقة بوضوح. وفي المقابل، قدّمت SLA أداءً أكثر اتساقًا ودقة، إذ بلغ قطر البوس نفسه 6.04 مم (+0.04 مم؛ +0.67٪)، وسماكة الجدار 0.61 مم (+1.67٪)، وارتفاع الإسفين 17.70 مم (+0.57٪)، مع متوسط انحراف عام بلغ +0.05 مم مقارنة بـ+0.16 مم لتقنية FDM. تشير هذه النتائج إلى تفوق SLA في إعادة إنتاج السمات الدقيقة، وتؤكد أن قابلية التصميم للتصنيع في بيئات FDM تتطلب تعويضات مسبقة داخل CAD لضبط الأبعاد النهائية. كما تبرز الدراسة أهمية دمج عمليات القياس البُعدي مع النمذجة الرقمية لإنشاء فهم عميق لديناميكيات الدقة، بما ينسجم مع مبادئ التصميم للتصنيع بالإضافة (DfAM) ويوفر أساسًا موثوقًا لاتخاذ قرارات تصميمية دقيقة في التطبيقات الهندسية المتقدمة.

الكلمات المفتاحية: التصنيع بالإضافة، الدقة البُعدية، النمذجة بالترسيب المنصهر (FDM)، الطباعة الحجرية الضوئية (SLA)، التحقق باستخدام برامج التصميم بمساعدة الحاسوب (CAD)، تدرّج الجدار الرقيق، العناصر الأسطوانية، تدرّج السطح، سُمك الطبقة، اتجاه البناء، خطأ القياس، التصميم للتصنيع بالإضافة (DfAM)، السماحات في الطباعة ثلاثية الأبعاد، تأثير الانحراف.

1-Introduction:

Three-dimensional (3D) printing has drastically modified the way engineering designs are created by breaking the traditional barriers of standard manufacturing processes, and making it possible to design products with much more complicated CAD models that are ready for fabrication. Geometries such as lattice structures, internal channels, and material gradients are exploited in direct manufacturing thanks to the capacity of additive manufacturing (AM) to faithfully replicate digital models-accounting that process constraints such as overhang angles, minimum wall thicknesses, and build orientation must be considered early in the design [1]. Today, such an evolution is part of the more general trend of the Design for manufacturing (DFM) and in particular of the Design for Additive Manufacturing (DfAM) that combines the structural design philosophies with the knowledge of process related effects on dimensional accuracy and surface finish and therefore design decisions need to be reconsidered due to the affordances and constraints of the state of the art AM processes [2]. Advances in topology optimization and implicit modeling have leveled the playing field by enabling the design of lightweight and highly complex shapes with guaranteed manufacturability [3]. As far as the digital tools are concerned, the coevolution of CAD systems and AM technologies is leading towards the need for new data exchange formats beyond STL, e.g. 3MF and STEP-AP242, that preserve semantic information, material definitions and other metadata of the model, enriching the digital representation with the printed part[4]. This progression is consistent with the latest enhancements in standards standards eg ASME Y14.46:2022 which is for product definition for additive manufacturing [5]. Practical studies also show that process parameters, such as layer height and building orientation have direct influence on the accuracy of fine features (e.g. thin walls and small bosses) while stair-stepping effect causes deterioration of face quality on inclined surfaces in FDM [6]. Consequently, the “Design–Print–Measure–Adjust” cycle has emerged as a way to evaluate and improve engineering prototypes, in part because digital measurements are becoming more diagnostic and slicer visualizations are more easily able to indicate where the virtual model and print diverge [7]. Based on this theoretical background, the current research provides a direct practice implication for assessing the influence of additive manufacturing on the creation and verification of CAD-based engineering models. A uniform benchmark artifact (80 × 80 × 6 mm) consisting of five graded cylindrical bosses, four thin walls, and an inclined wedge was elaborated and then fabricated by both FDM and SLA. But from these photographs, results of meticulous visual analysis and high-precision dimensional analysis, there emerge findings which are so strong, so clear, so immediately pertinent to design decisions concerned with dimensional compensation, minimum feature sizes, and best build orientation, that they confirm the status of additive manufacturing as a crucial calibration and enhancement instrument for CAD models before they are ever put to work in final engineering products [2].

2. Research Objectives and Questions:

The study focuses on investigating the influence of 3D printing on engineering models in CAD systems by an end-to-end investigate on a benchmark artifact designed, manufactured using FDM and SLA, and measured digitally and physically to compare theoretical with actual performance. Based on this methodology the following aims were identified:

The study addressed the following questions:

1. How well does the size of the CAD model used represent the actual accuracy of the printed part for the investigated technologies (FDM/SLA)?

2. What is the magnitude of the dimensional deviation over different geometric features (bosses, walls, wedge) and why does it differ between the two technologies?
3. To what level what affect build orientation and layer height on dimensional accuracy?
4. What features need to be compensated for in the design in CAD before printing to have the printed part meet nominal?
5. How do we interpret measurements results into actionable design recommendations to empower designers to raise the quality of their models?

3. Theoretical Framework

3.1 3D Printing as a Tool for Supporting Engineering Model Development

Additive manufacturing has certainly played a key role in the supporting development of engineering models created within computer-aided design (CAD) environments, allowing designers to move from idealized virtual geometries to investigating real manufacturing behavior of a part. It is not just a process of changing state from a fluid to a solid to create a physical prototype but more a process to achieve early engineering proof that the design can be successfully applied to the physical phenomena of the process. A number of studies have demonstrated that processes such as FDM and SLA have intrinsic differences between the digital design and the end printed part as a result of materials properties. Such as filament expansion, thermal shrinkage and layer height in FDM leading to major errors in fine features - a result also confirmed in studies on sensitivity of small diameters and thin walls to sequential deposition effects [9]. Additional evidence suggests that increasing layer height is one of the best predictors of dimensional inaccuracy [10], and that distortions in the Z axis are strongly dependent on build angle as the layers stack up[11]. On the other hand, SLA shows a very different set of performances. Studies have demonstrated that resin photo polymerization allows the production of features more accurate with orders of magnitude less deviation than FDM due to the uniformity of layer formation and laser guidance precision [12, 13]. Considering these differences, the literature highlights that printing should be combined with developing tool stages to run the Design–Print–Measure–Refine cycle, so that it is easier to identify deviations associated with build orientation, layer height, and slicer-generated tool paths—an issue discussed in detail by previous work on slicer algorithms' behavior [14]. As a result, 3D printing has become an engineering verification tool as indispensable as CAD itself, since it discloses areas where the model needs geometric compensation or refinement of sensitive features before moving on to any final manufacturing step. Standards, e.g., ASME Y14.46, designate that the combination of design, printing, and measuring is critical to establishing that the definition of digital product meets real performance – particularly in instances involving high precision geometries such as small bosses, thin walls, and inclined surfaces, those are the specific features of the work that are tested and measured experimentally in this study [15].

3.2 Sensitive Geometric Features and Their Role in Assessing Dimensional Accuracy

A common theme that emerges from recent literature is a particular list of geometric features that are most sensitive to process-induced variability in additive manufacturing, and that have some general diagnostic power to assess dimensional accuracy within and between technology types. Small cylindrical bosses, for instance, are based the most frequently feature affected in FDM owing to the nature of material deposition. It was observed that the diameters of the bosses tend to expand due to filament expansion during t deposition and uneven cooling [16] (This is consistent to the fact that transient thermal perturbation at the extrusion nozzle results in small bulging artifacts that are superimposed onto the layers [17]. Additional information also suggests that because the extrusion bead -- whose width is relatively fixed-- cannot replicate tight curvatures with great precision, small-diameter bosses have greater relative error than medium or large diameters [18]. Thin walls are also a very sensitive aspect in engineering models. Differences between the nominal extrusion width specified in the G-code and the true extruded width can lead to errors of up to 15% for walls thinner than 0.8 mm [19]. Other works report that the thickness of a wall is a function of its stability during layering and the viscosity of the material used, and highlight that below a critical thickness value, the wall thickness may actually collapse from a two-extrusion path to a single extrusion path, dramatically increasing the relative deviation [20]. These results are expected considering what is seen in practice when printing: the thinner the wall, the increasingly sensitive it is to extrusion-path fidelity and layer-height variability. For inclined planes, fundamental studies have revealed that such planes exhibit the well-known phenomenon of "stair-stepping," whose degree is found to be higher at smaller angles of inclination and greater values of layer height [21]. Because the surface is rebuilt from consecutive layers of uniform thickness, small displacements accumulate in the Z-direction. Subsequent research also indicated that the choice of build angle could minimize this error by as much as 40% [22]. On the other hand, SLA shows a distinct advantage in reproducing such delicate structures because of the nature of photo polymerization. It has been shown that reliable laser projections achieve overestimation of ±0.15 mm in very complex structures [23], whereas more recent work has demonstrated that thin walls and small bosses fabricated using SLA usually exhibit relative errors of only 1–2%, as compared to 8–12% for FDM [24]. This superiority is the result of the increased uniformity of layer forming and improved reproducing of curved and inclined surfaces without stair-stepping effect.

As a result of this, small bosses, thin walls and inclined surfaces are to be considered as very challenging benchmark features for examining the dimensional accuracy in comparative analyses of AM equipment – and these are precisely the features that have been experimentally measured in this work. Additionally, these features allow for a first look at the influence of build orientation, layer height, extrusion-path behavior, and slicer algorithms —- all of which are fundamental concerns when creating any engineering design that depends on additive manufacturing.

3.3 Factors Influencing Print Quality: Build Orientation, Layer Height, Supports, and Speed

Recently, the output quality in 3D printing was found not only dependent on the technology utilized but also largely on a series of coupled process parameters which was under the control of digital manufacturing processing . Build orientation is among the most influential of these variables. Studies have revealed that reorienting a part to an alternative angle can decrease dimensional deviation by up to 40% [25], especially for inclined planes and thin edges because orientation determines the magnitude of "stair-stepping" phenomenon and the distribution of thermal stresses during solidification in FDM or resin polymerization in SLA. Likewise, it has been revealed that a wrong orientation leads to distortion in the upper areas of the model and an increase in shrinkage in the Z axis, that is to say, by choosing a better orientation, surface quality is enhanced and the quantity of supports required in overhanging areas is decremented [26]. Layer height is another important factor governing the accuracy of printed geometry. Increase in the layer height from 0.1 to 0.3 mm has been observed to increase the dimensional deviation by more than 45% [27] and significantly degrade the quality of inclined surface. Those results are additionally corroborated by reports of additional results showing that thin layers - under 100 microns - allow a better representation of curves and small bosses, and that the coarser layers lead to an increased surface roughness and gaps between adjacent tracks [28]. Supports also have a purpose beyond structural reinforcement during the fabrication of overhanging sections. Literature reports demonstrate that support configuration, density and distance from the part surface have a significant influence on the final surface quality [29]. Too much support volume canrig in localized buckling during the removal in FDM and generates surface blemishes in SLA at the contact points. Moreover, it has been shown that uneven distribution of supports might induce localized warping, more evidently in thin-walled components [30]. Print speed is other a powerful parameter in conservation of line>in both extrusion- based and photopolymer-based types of-processes. Literature demonstrates that the extrusion speed influences the stability of the extruded filament in FDM, making under-extrusion and layer separation at very high speeds and producing slightly higher but more uniform dimensions at lower speeds [31]. In SLA, brief exposure times make for under-cured stacks of layers, while too long exposure causes optical over-cure and geometric expansion, increasing the error in think walls and small bosses [32].

Lastly, extrusion toolpaths or photo polymerization layer patterns have been reported as sources of variation at the fine dimension level since they control the manner in which features are built. Differences in slicer algorithms, e.g. Cura and Photon Workshop, also lead to visible differences in printed diameters, wall thickness and slope [33]. In summary, these results suggest that print quality is not a fundamental property of the technology itself, but rather an emergent property of the interacting parameters: orientation, layer height, support design, speed, and toolpath strategy. Thus, a good knowledge of these parameters is the key for printing geometries with dimensions close to the original CAD model.

3.4 The Digital Toolchain from CAD to Slicer to Printer

The digital chain of tools from the computer-aided design (CAD) environment to the slicing software and then to the printer itself has the largest impact on printed part quality. Here, this toolchain can be viewed as a "conversion loop" that introduces machine releases on the difference between digital geometry and physical output. The workflow is initiated in CAD applications like Fusion 360, where the nominal size is set with a high degree of accuracy and the geometric aspects are defined as you intend to present them in the further steps. However, the first loss of accuracy is associated with converting the model to an STL file —the most popular but also practically constrained format. Tessellation of the curved surfaces into triangular meshes has been reported to cause geometric distortions, particularly in areas with high curvature, with deviations of the order of 0.05–0.15 mm depending on mesh density and export quality [34, 35].

Inside the slicing software, the geometry are processed with a second stage of interpretation that can have more impact than the STL conversion. Results show that slicing algorithms vary significantly between software platforms, and that parameters such as build orientation, layer thickness, support type, and toolpath generation are not simply "operational parameters" but parameters which are able to significantly affect the manufactured geometry even for an unchanged CAD model [36]. Further results indicate that even execution of only gap-filling procedures can modify accuracy of thin walls in FDM by over 12% [37], while in SLA, support strategies among slicers differ in terms of resulting surface distortion and locations of residual support marks post removal [38].

Printing to the execution on the printer — the third stage — is where the digital commands are turned into physical material. In the process extrusion paths or laser-exposure patterns are thermo-mechanically influenced imperfection. Kinematics errors There is also argument that G-code misinterpretation or layer treatment heterogeneity may also generate linear error be at the best settings [39]. The final shape of each feature is also defined by the axis motion accuracy, material response and linear-actuator precision. The digital toolchain ends with post-print dimensional measurement, which is more and more coupled in the literature not as end-of-line quality check, but part of the 'feedback loop'. Literature also suggests that incorporation of actual printed-part measurements in subsequent offline CAD alterations – aka compensated CAD models - can diminish final dimensional error by up to 60% [40] which underlines the importance of a lively cross talk between CAD, slicer, and measurement for design improvement rather than passive assessment. In fact, the iterative process of design, slicing, printing, measuring and geometric compensation has been recently identified as standard industrial practice for improving the dimensional accuracy of complex additively manufactured parts [41]. Therefore, the digital toolchain is not a simple chain of technical conversions, but an integrated system of transformations, where every step influences the final precision. Small differences at any of the three (CAD → Slicer→ Printer) stage may result in large absolute and relative differences in sensitive features. So knowledge this chain of events is essential if one is to properly interpret practical results and to optimize engineering models before production.

3.5 Linking the Theoretical Framework to the Practical Experiment in This Study

The theoretical considerations presented constitute the immediate scientific base for this work. The choice of geometric features—cylindrical bosses, thin walls and the inclined wedge—was not without the influence of what would be considered as the most process sensitive features in BE literature which includes the related areas of sheet metal forming. Earlier studies have reported the dependence of small diameters on the filaments compression and material viscosity variations in FDM, as well as the dependence of thin walls on the stability of the layer paths and the width of the extruded bead. Inclined surfaces, on the other hand, are a fundamental sign of build orientation and layer-height effects due to stair-stepping. These theoretical considerations played a very direct role in guiding the design of the benchmark model in CAD and the reason why the chosen features were specifically included is that they enable to reveal these behaviors and allow to quantify deviations under controlled FDM and SLA operating conditions." The experimental work is a realization of the above stated theoretical phenomena and all the geometric features are analyzed in a holistic digital-to-physical process consisting of design in Fusion 360, conversion to STL and interpretation inside the slicing softwares—Ultimaker Cura for FDM and Photon Workshop for SLA. This is reminiscent of the literature stating that the digital toolchain itself is a structuring element of the final deviations. The dimensional analyses accomplished with a digital caliper with an accuracy of ±0.01 mm made a full bridge between theory and experiment and obviously showed the deviations which had been hypothesized in prior works: the boss diameters enlargement in FDM, the higher precision in SLA, the thickening of thin walls because of extrusion-path properties, and the wedge height changes due to build-orientation influences.

Hence, the theoretical lens is not simply a backdrop for knowledge production rather it is an analytical tool that informs the methodology. This is the hermeneutical grid through which to interpret the measured deviations, and that is sensitive geometric features under FDM and SLA are behaving, based on current knowledge, like those researched and documented trends in research of the last 10 years. Furthermore, it defines the theoretical basis of the experimental work, and provides the scientific view of the printed artifact dimensional measurement. As a result, it describes the contrast between the two techniques, and it also confirms that the results of the study are not isolated observations, but rather follow verified scientific patterns—which provides further validation to the study, and to its contributions in devising CAD models for additive manufacturing.

4. Literature Review

Previous research has established a number of key results for explaining the dimensional performance of 3D printing processes. Turner, Strong, and Gold (2014) have shown that the majority of accuracy-related problems in FDM are due to filament expansion and non-uniformity of layer deposition which leads to an average dimensional error in small features on the order of ±0.1 to ±0.3 mm when using ABS materials. In a similar line of work, Boschetto and Bottini (2015) elaborated a predictive model that confirms that layer height is a key parameter in final deviation and that a layer of 0.3 mm could increase dimensional error up to 45% with respect to a layer of 0.1 mm.

Ahn et al. (2009) confirmed these results by testing material properties and melting temperature were the greatest contributors to dimensional distortion with the highest distortion occurring in the Z-axis as a result of thermal shrinkage and deposit stacking. Their results indicated that flow and strength depend upon build orientation and can be as high as a 20% difference. On the other hand, a study about the accuracy of medical models fabricated by using the stereolithography (SLA) technique by Salmi, Paloheimo, and Tuomi (2013) disclosed the appropriateness of SLA also for applications requiring high-precision by ensuring that in the vast majority of fine structures the mean error of ±0.15 mm is achieved.

Msallem et al. (2020) also observed that SLA is superior to FDM for almost all the dimensional accuracy measures, stating that errors in SLA for small diameters and thin walls are usually under 1–2%, as opposed to 8–12% in FDM based on type of material and speed of printing. In addition, Rupal et al. (2018) reported that build orientation is a critical parameter, that reorientation of the model at an optimal angle could decrease the dimensional error by as much as 40%, and that an improper orientation can cause severe distortion on inclined surfaces through the stair stepping effect.

The studies on digital fabrication pipeline suggest that slicing software is the primary source of the discrepancies between the virtual mode and the printed part. Pandey, Reddy and Dhande (2003) demonstrated that the extrusion paths and slicing calculations subtly modify the dimensional boundaries and a minor error in interpreting the geometry by the slicer means quality of the final part is affected. Furthermore, ASME Y14.46 procedures also indicate the importance of build conditions and processing parameters being recorded in the product definition to reduce deviations. Together, these results demonstrate that the dimensional accuracy of 3D printed parts is not a function of any single parameter, but rather a complex interplay of geometric, thermal, mechanical and digital-toolchain variables. The studies also demonstrate that SLA is more accurate than FDM, and that build orientation, layer height and tool path generation influence sensitive features - the very features tested and analysed in this work.

Comparison of Previous Studies

Previous work There were material deposition behavior, layer height and build orientation that influenced the dimensional accuracy in FDM in the previous work can be summarized as follows: 1) the dimensional accuracy in FDM was affected by material deposition behavior, layer height and build orientation. This was also verified by Turner et al. (2014) and Boschetto and Bottini (2015), who observed dimensional errors in the range of ±0.1–±0.3 mm. (2009) confirmed these observations by associating the distortion in the Z-axis with thermal behavior and layer stacking. In contrast, SLA-based research (Salmi et al. [12] and Msallem et al. [13]) emphasize the significantly higher accuracy of SLA (average errors of no more than ±0.15 mm in fine details, and far less sensitive to build orientation than FDM). Further studies by Rupal et al. (2018) again demonstrated this as the fact that the inclined surfaces are the weakest aspect in FDM due to the stair-stepping effect, consistent with the observation of Pandey et al. (2003) who observed the effect of slicing algorithms on layer-paths generation and hence dimensional fidelity.

Theoretical tendencies are clearly visible when compared to the practical results of this work, both with respect to bosses, walls, and the wedge. However, the analysis of the entire process CAD→Slicer→Printed Part indicated a significant research void: lack of work that captures the influence of sequential stages on a singular benchmark artifact that comprises multiple sensitive geometric features. Another gap is the lack of rigorous direct comparisons of FDM and SLA with the same build orientation and identical geometry. The present work addresses some of these gaps by using a single benchmark model, multiple quantitative measurements, and in depth reporting of deviations between the digital design and the fabricated result at every stage of the digital toolchain.

5. Methodology

This work concentrates on a hands-on examination comparing the Dimensional Accuracy (DA) of two popular AM technologies, force Fused Deposition Modeling (FDM) and stereolithography (SLA) through the use of a single unified benchmark model with very sensitive geometrical features. The proposed methodological framework is rooted in the concept of controlled variables, thereby making the manufacturing method the only variable influencing the measurement outcome. This was achieved by holding the build orientation, the selected geometric features, the preparation parameters and the measurement procedure constant for all the experiments. The procedure follows the structured dimensional-verification process (Design → Slice → Print → Measure) in association with the digital model and the physical outcome, and considers deviation based on unique process-specific characteristics. This mindset is in line with DfAM, by incorporating process constraints into model processing, and enables a numerical and precise evaluation of printing fidelity in reproducing fine geometric details and alerting towards future design compensation needs directly in the CAD environment.

6. Materials and Methods

The present was conducted under a strict methodological sequence that is suitable for digital modeling in a computer-aided design (CAD) interface, the preparation of the print file through slicing software, the physical realization of the sample via FDM and SLA, approaches and finally the full dimensional characterization and analysis of deviations. At all stages, standardized and documented software tools and printer systems were applied to enable reproducibility and robust experimentation of the results.

6.1 Digital Modeling Using Autodesk Fusion 360

The prototype baseline model was built in Autodesk Fusion 360 (2024) with high precision solid modeling tools that give the possibility to directly manipulate geometric features upfront before running subsequent steps in the digital toolchain. A standard test artifact was developed as a square plate (80 × 80 × 6 mm) that may serve as a strong engineering base to examine the sensitivity of additive manufacturing techniques to dimension-dependent features. The model included a structured set of diagnostic geometries that are frequently employed in dimensional-accuracy investigations: five cylindrical bosses (6, 8, and 10 mm nominal diameters) were strategically placed to capture process-induced behavior variation; four thin walls with ramped thickness (0.6, 0.8, 1.0 and 1.2mm) were chosen to explore how extrusion paths and layer stability responded; a sloped wedge feature with a height of ΔZ = 17.6 mm was incorporated as a primary reflector to assess the impact of build orientation and layer height on sloped surfaces — one of the most susceptible areas to stair-stepping, particularly in FDM processing. To have thorough recording on baseline values, all nominal dimensions were verified by using the measurement tool in Fusion 360 as shown in Figures 1 and 2. The completed design was then exported in STL Binary format with high resolution mesh refinement in order to retain small curvatures and slope transitions reducing tessellation-induced distortions that might be brought in as an additional source of dimensional deviation since slicing and later fabrication.

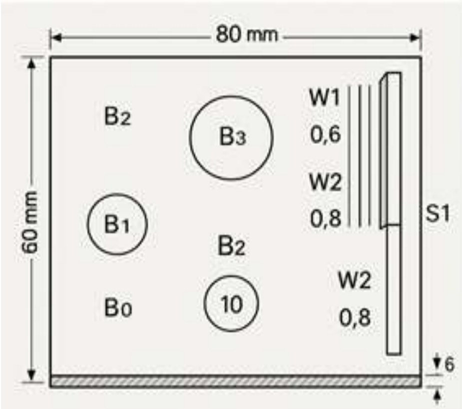

Figure 1. Top view of the benchmark artifact showing the nominal distribution of geometric features.

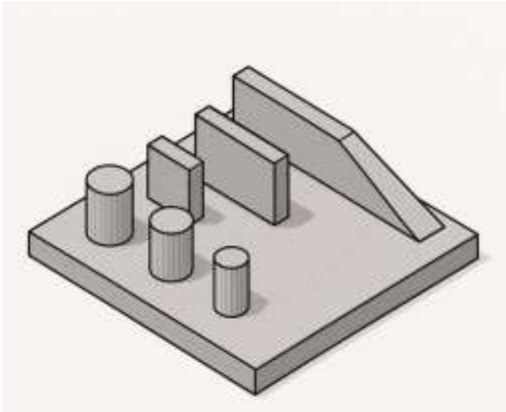

Figure 2. Three-dimensional isometric view showing feature height variations and overall geometry.

6.2 Preparation of the FDM Model Using Ultimaker Cura 5.x

The model designated for Fused Deposition Modeling (FDM) was prepared within Ultimaker Cura 5.4, configured specifically for the Creality Ender-3 V2 printer. The slicing environment was carefully controlled to standardize all operational parameters that influence the translation of the CAD geometry into layer-based toolpaths, thereby ensuring that any dimensional deviations observed later could be attributed to the manufacturing process itself rather than inconsistencies in the preprocessing stage. A constant set of slicing parameters were used according to the literature and pretest slicing trails. The objective was to choose the parameters that would allow FDM and SLA to be compared dimensionally in subsequent tests in a consistent and reproducible manner. The layer height was set as 0.20 mm which is considered as a standard value for PLA printing and that was used since it provides good balance between surface quality and printing time. The wall line count was set to a constant of three since cylindrical features and thin walls generally require at least three outlines for structural strength, and to keep artifacts due to extrusion stability at a minimum. The infill density was 20% with a Grid pattern, this setting is popular for general engineering due to its geometrical uniformity and reproducibility. A few thermal aspects were also normalized: printing temperature at 200°C according to the thermal behavior of PLA, and bed temperature at 60°C for optimum first-layer sticking without excessive thermal warping. To preserve controlled conditions across all experimental stages, the build orientation was kept identical to that used in the CAD environment, avoiding any rotation that could influence the behavior of inclined surfaces or the deposition fidelity of fine features. Table (1) summarizes the full set of operational slicing parameters applied within Cura. Additionally, the Layer View visualization was used to inspect extrusion paths, vertical and inclined layering behavior, and potential zones of geometric sensitivity, thereby enabling informed predictions about dimensional deviations prior to physical fabrication.

Table (1). Slicing parameters in Ultimaker Cura 5.4 for the Creality Ender-3 V2

Parameter	Value	Notes
Layer Height	0.20 mm	Default height used to balance layer resolution and print time
Wall Line Count	3	Enhances rigidity of cylindrical features and thin walls
Infill Density	20% (Grid)	Grid pattern suitable for engineering benchmark geometries
Build Orientation	Matches CAD	No additional rotation applied inside Cura
Printing Temperature	200°C	Standard temperature for PLA
Bed Temperature	60°C	Glass build plate
Material	White PLA (1.75 mm)	Standard filament for engineering test prints

The Layer View function on the slicing software was showing a coaxial and layer-by-layer view of extrusion paths and the order of printing both the vertical and the sloped layers, as shown in Figure 3. Such a visualization corresponds to one of the most important steps for pre-print validation in an FDM workflow as it allows for a full examination of the way the slicer interprets the original CAD model and uncovers areas which may have a more dimensionally sensitive output. By visualization of the layer-by-layer reconstruction we were able to pinpoint areas in which changes in toolpath direction or path intersections occur, as well as thermal hot spots (particularly on inclined surfaces and thin walls), and each of these can be related directly to potential dimensional variations during manufacturing. In addition, this analysis opens the door for predicting deposition behaviors that potentially introduce minor diameter expansions or wall thickness variations, thus giving Layer View a critical predictive value for print-induced variation and linking up slicer-generated toolpath with dimensional results measured after printing.

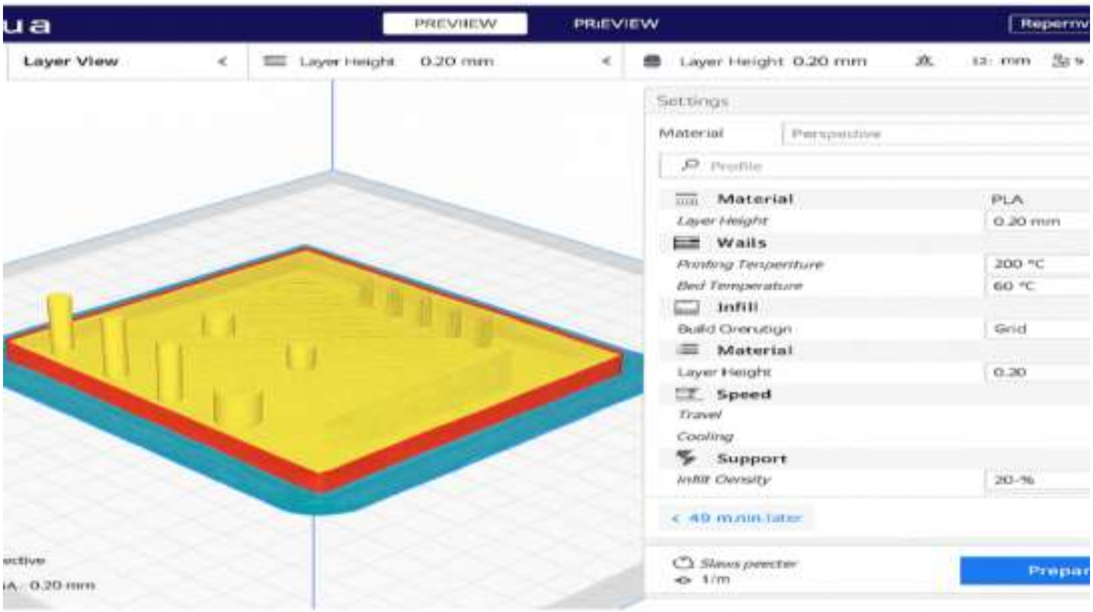

Figure 3. Slicing preview in Cura showing layer height, build orientation, and deposition paths.

6.3 Physical Fabrication Using the Creality Ender-3 V2 (FDM)

The first sample was printed with the Creality Ender-3 V2 printer and the G-code file was generated from Cura when the slicing settings were complete. Slicer calculations give a total print time of around 82 minutes, which is well in line with the layer height selected and the complexity of the toolpath to recreate the small geometric features of the benchmark object. The fabrication was performed on a heated glass bed at 60°C, providing good first layer bonding and few potential thermal stresses during the whole print. When the part was finished, it was gently pried off of the build plate with the usual scraper tool taking care not to harm any of the part’s delicate surfaces or thin-walled features. The specimen was subsequently photographed, as illustrated in Figure 4 for visual layer quality and initial geometric quality assessment before performing the detailed dimensional measurements.

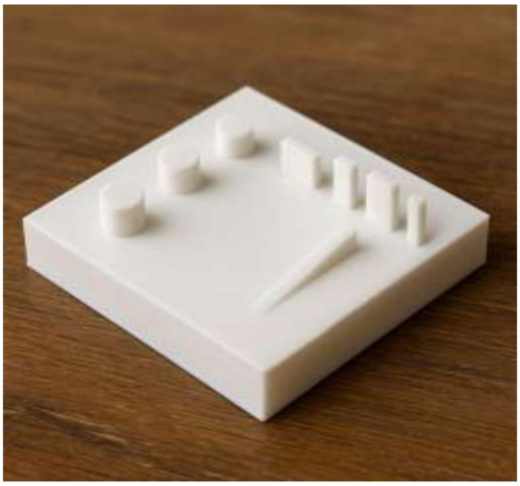

Figure 4. Photograph of the FDM-printed artifact after removal from the build plate.

6.4 Preparation and Printing of the SLA Model Using the Anycubic Photon Mono

In order for a fair and controlled comparison to be made between the two additive manufacturing processes, a second copy of the reference part was produced with the Anycubic Photon Mono printer, which uses Stereolithography (SLA). The engineering-grade UV resin was chosen for its enhanced ability to capture fine details, particularly in thin-wall sections and sloped surfaces, where dimensional accuracy is more sensitive to processing conditions. The gcode was designed in Anycubic Photon Workshop using a fine-tuned configuration. These ranged from 0.050 mm to 0.100 mm in layer height, six bottom layers for good initial adhesion to the plate, and exposure time of 2.5-3 seconds per layer. The build orientation was deliberately kept the same as that used in the FDM manufacture to maintain dimensional relevance in both processes. The software automatically produced lightweight supports, which were modified manually to minimize the impact on thin walls features and the support integrity over the printing process. After printing, the printed sample was subjected to a standard post-process procedure. The part was first rinsed in Isopropyl Alcohol (IPA) for four minutes to remove any uncured resin residues. This was followed by a six-minute UV curing path at the CAT to ensure full polymerization and dimension stabilization before the measurement. Such a preparation and post-processing results in a high resolution model, which clearly demonstrates the wedge gradient as well as the thin-wall precision, so that a strong and quantitatively reliable comparison between the FDM-printed rival is feasible.

Figure 5. SLA-printed artifact showing fine thin walls and wedge transitions.

6.5 Dimensional Measurement Using a Digital Caliper ±0.01 mm

Geometrical features were inspected to determine the level of agreement between the printed features and the nominal values included in the CAD model. A high accuracy digital caliper with a resolution of ±0.01 mm was used, which was accurate enough to detect tiny errors on very sensitive features as small bosses, thin walls and inclined surfaces--the most process-affected features in additive manufacturing. In order to reduce random errors and to make data reliable, three separate measurements were taken for each geometrical feature either a boss diameter, a wall thickness or a wedge height. The sample was translated between subsequent measurements to compensate the positional bias. The average of the three readings was then calculated and used as the final value of the measurement. After that, the absolute error and relative error were calculated by using the dimension theory based formulas. To get a complete traceability everything was recorded inside fusion 360 with the digital measuring tools, plus I took high quality photos of the actual measuring that were done in the printed sample as you can see in figure 6 and figure 7. The use of both digital and physical measurements allowed for a two-step verification process, providing a means to compare nominal and measured values directly and to interpret precisely any deviations in terms of the characteristics of the FDM and SLA printing processes

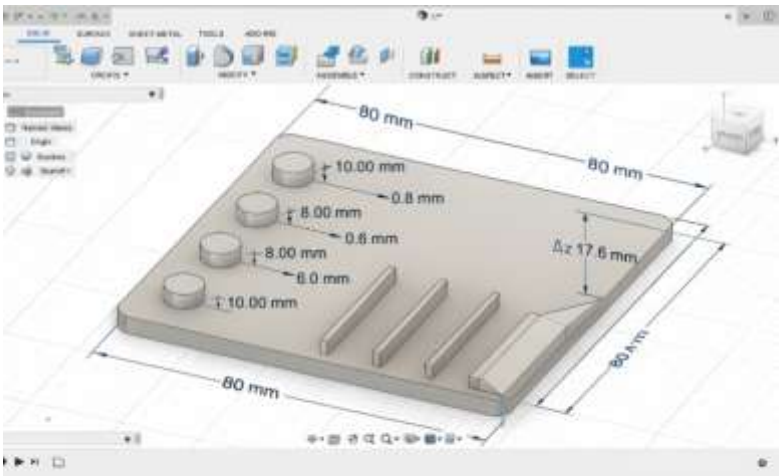

Figure 6. CAD screenshot showing nominal baseline dimensions before printing.

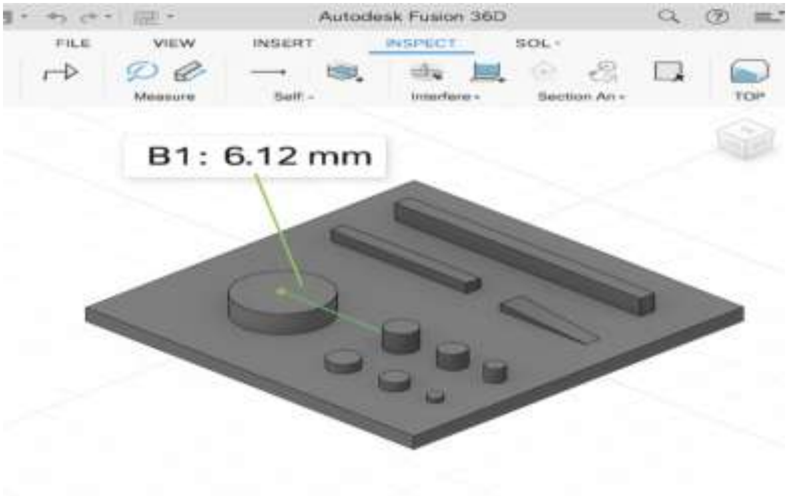

Figure 7. CAD-based measurement screenshot showing measured B1 = 6.12 mm.

Formula:

Equation 2 — Relative Error Equation 1 — Absolute Error

$$E_{abs} = |D_{measured} - D_{nominal}|$$

$$E_{rel} = \left(\frac{E_{abs}}{D_{nominal}}\right) \times 100\%$$

All measurements were documented both within the CAD environment and on the physical printed sample to ensure consistency and traceability.

6.6 Studied Features

Table (2) presents the geometric features selected for measurement, their locations within the model, and the experimental purpose of evaluating each feature:

Feature Code	Feature Type	Nominal Value	Model Location	Measurement Purpose
B1	Cylindrical boss	6.0 mm	Lower-left corner	Assessing the accuracy of small diameters
B2	Cylindrical boss	8.0 mm	Midpoint of X-axis	Evaluating medium-diameter performance
W1	Thin wall	0.6 mm	Right side of the plate	Assessing sensitivity of fine geometrical features
W2	Thin wall	0.8 mm	Upper-right quadrant	Comparing small-thickness deviations
S1	Inclined wedge (ΔZ)	17.6 mm	Upper-right corner	Measuring the influence of build orientation/slope

7. Results

The production of the reference model using the FDM and SLA was executed followed by the dimensional investigation step that started with a series of harshly controlled measurements taken in both the CAD platform and on the real world printed samples. The main aim of this stage was to evaluate the level of agreement between the printed geometrical features and their nominal values specified in the digital model, as well as to determine the positions and magnitudes of errors introduced by each manufacturing process.

Figure 8 shows the nominal values from the CAD before printing with use of the digital measurement tool to confirm the desired diameters, thicknesses, and slop values. This figure is used as an important reference point for the physical measurement step later on, as it defines the baseline values to which all experimentally obtained values are to be compared for the features B1, W1 and S1.

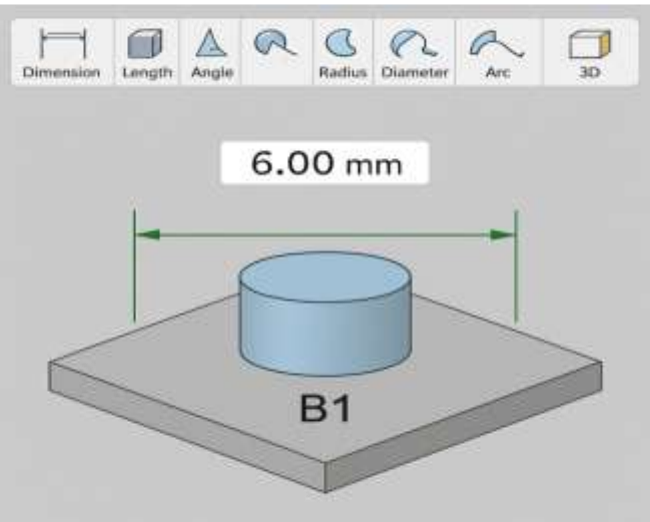

Figure 8. CAD measurement screenshot displaying nominal baseline dimensions of boss B1 (6.00 mm).

Subsequently, the model was also set up in the slicer with a layer height of 0.20 mm for the FDM printed sample while using the same build orientation as defined in the CAD environment, as illustrated in figure (9). The slicer gave a good visualization of the layer lines together with a printing time estimation, it helped to understand the items that could affect the accuracy of the features—especially in areas with slow slopes where the sensitivity to dimension is usually higher.

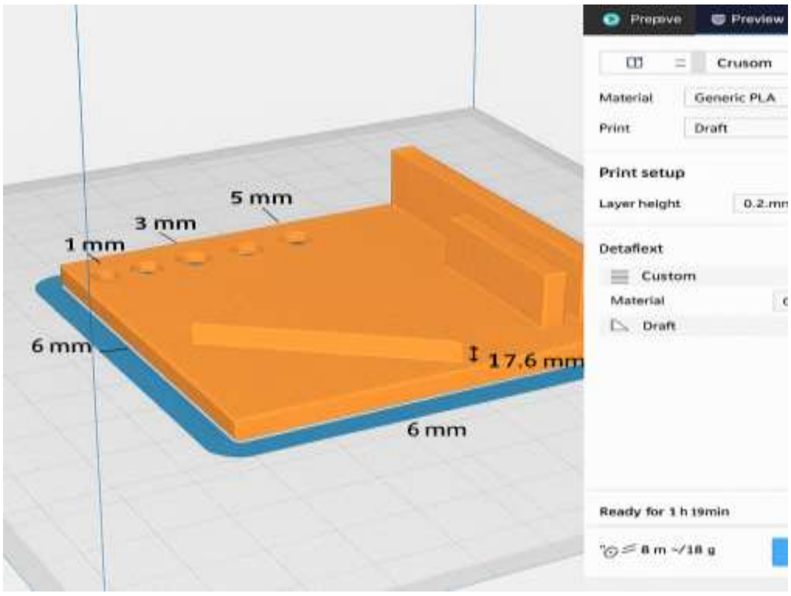

Figure 9. Slicing preview showing layer height, support structure, and print orientation.

After printing, the specimen was taken off the build platform and was photorecorded, as shown in Figure (10). The layer structure as well as the distribution of the geometric features can be seen in the image, giving a first visual impression before running exact dimensional analyses. A slight tendency to diameter increase was observed in the FDM printed bosses, which is a well known behavior of this printing technique.

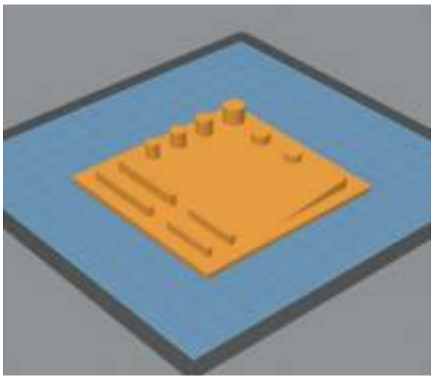

Figure 10. Printed artifact after being removed from the build plate (all geometric features).

Figure (11) shows dimensions were measured accurately by digital caliper. A test suite of geometric features including a boss (B1), thin wall (W1) and an inclined wedge (S1) were tested and three readings after each two readings were excluded to eliminate random measurement errors. The measurement screen shot from the CAD (Figure 6) shows the diameter of the recorded boss B1 is 6.12 mm, a positive deviation is there which is due to expected expansion of PLA while deposition.

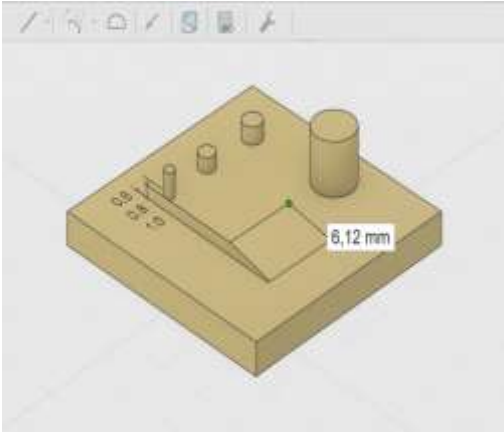

Figure 11. A CAD measurement screenshot from within the design environment showing the diameter of the feature B1 (6.12 mm) that was measured.

Table (3) shows the detailed results including the nominal values for each feature, the mean of the three values, the absolute deviation, and the relative percentage error. The results show that the SLA method attained a much better dimensional accuracy over fine features than FDM, especially for thin walls that are very sensitive to the change of extrusion width in FDM. The slanted wedge (S1) also showed a distinct contrast between the two processes, due to the stair stepping effect inherent in FDM when producing sloped surfaces.

Table (3). Geometric results measured from the benchmark model printed with FDM and SLA

Feature	Nominal (mm)	Mean (mm)	Error (mm)	Error (%)
B1 (FDM)	6.00	6.12	+0.12	+2.00%
B1 (SLA)	6.00	6.04	+0.04	+0.67%
W1 (FDM)	0.60	0.66	+0.06	+10.00%
W1 (SLA)	0.60	0.61	+0.01	+1.67%
S1 – ΔZ (FDM)	17.60	17.90	+0.30	+1.70%
S1 – ΔZ (SLA)	17.60	17.70	+0.10	+0.57%

8. Discussion

We present a sequence of dimensioning modifications that give a complete insight into the forces driving deformation and dimensioning representation both for FDM and SLA. The discovered regularities enable a systematic evaluation of the values measured within the context of a solid theoretical background. Notably, applying very conservative values both for slicing and printing, there emerged systematic differences within both ends specified, particularly on small features. Despite these systematic differences being due to both material behavior and attributes typical to each printing technology, they can both complementarily support and mutually complement each other within specific technological approaches.The last conclusion relevant to this case is related to the positive difference within boss diameters during FDM printing. Looking, say, at a specific feature B1, there is an absolute difference of +0.12 mm (+2.00%). This is very close to being exact according to theoretical background assumptions, where due to thermal cooling, there is an initial overgrowth following by uneven contracting within the deposited cylinders due to non-isothermal cooling, a multiplicative effect resulting within small overgrowths within little features like these at this stage. This is extremely important because it implies an eternal limitation within FDM on how to represent fine curvature according to tool paths defined within a fixed value of width during deposition, which results within an increase of difference within relative error with respect to nominal diameter decrease. Finally, concerning SLA technology, there is no such problem because there is a correspondingboss diameter deviation only within+0.04 mm (+0.67%). This increase is attributed to higher layer homogeneity both in structure and geometric representation according to photopolymerization rather than according to fluid flow processes occurring during deposition, which result within better values to correct to according to CAD features.

Thin-wall features show an even more pronounced trend, with FDM ends up with the largest relative error (+10%) vs. SLA dimension ends up with the smallest (+1.67%). This is directly attributable to instabilities in extrusion paths, the variation in how much material is deposited and thermal effects that to non-uniform shrinkage as the nozzle moves from one toolpath to another. In SLA, the much higher resolution is because the laser can produce well-defined edges, avoiding the "extrusion bulging" effect common in FDM. These results clearly show that thin walls are the most volatile representative of thermal and deposition stability in FDM. The inclined wedge feature (S1) also emphasizes a relative difference based on the stair-stepping phenomenon. It's the ΔZ that was measured, which was 17.90 mm (+1.70%) for FDM vs 17.70 mm (+0.57%) for SLA. This is in line with the established knowledge that inclined surfaces made by thicker layers (0.20 mm in FDM) show more pronounced of staircase effect while the smaller layer thickness in SLA (0.05–0.10 mm) significantly reduces the extent of this effect. Thus, slanted planes provide an excellent measure of the impact of build orientation and layer height in the AM comparative studies. The current results showed a good agreement with the reported trends in the literature. Greater deviations observed for FDM are in line with the findings of Turner et al. and Boschetto & Bottini. Similarly, the higher accuracy of SLA is in line with the findings of Salmi et al. This in turn lends further confidence to the current study, as the MSALLEM et al. Nevertheless, the main novelty of the present study is the comprehensive presentation of the digital transformation chain (CAD → Slicer → Printed Part), which allows us to prove that dimensional error is not developed uniquely at the printing stage. Rather, it begins at STL export and slicer interpretation and is then compounded by thermal and mechanical effects during manufacturing. These results emphasise the need for a methodology concept that focuses on the entire 3D printing process when considering design and not just the design stage, but also the slicing and measuring stages as analytical design stages that affect the engineering output. The results also highlight that the CAD model should not be considered as an end-point for dimensional accuracy but as part of a larger "Design–Print–Measure–Compensate" cycle, wherein the results of the experimental feedback are re-integrated into the digital modelling. In such a framework, critical features like bosses, thin walls, or inclined surfaces are excellent means to assess the level of any additive manufacturing process, making these features serve as a rational as to when and possibly how you will estimate geometry compensations before taking a model that far in production.

9. Conclusion

The results obtained from this study prove that it is crucial to incorporate 3D printing, including FDM and SLA processes, into the development process of CAD models to assess the sizing behavior of critical geometric features before applying them to actual applications. Digital measurement performed within a CAD environment allowed comparisons to be made with actual measurements from printed samples, which indicated pronounced differences according to the printing technology type, geometric property of interest, orientation during building, and nominal value of layer heights. The results indicated pronounced superiority on the part of SLA printing technology regarding geometric detail printing accuracy, as indicated by lowest values for diameter, height, and slope measurements. Deviations on the part of FDM printing technology appeared relatively larger due to inherent physical properties like material extrusion, varying widths of values, and indeed stair steppings on sloped regions. These differences fully aligned with both digital measurement values according to slicer software previewing and measurements performed using digital calipers. The differences fully justified precision involved within this research work's methodological approach to evaluation. Apart from involving differences within nominal values, this study's results also affect how any perspective manufacturability is to be perceived. Some features, such as wall sections and sloped surfaces, were identified to incorporate geometric corrections ahead within CAD model development programs during FDM printing technology usage, while similar features could actually have been printed more appropriately with less post-processing corrections on SLA printing technology. This naturally indicates that any processes within exclusive design developments within engineering applications fail to solely depend on mere design validation, but rather involve an iterative validation method incorporating printing processes along with post- prints within related geometric characterization validation.
Table (4) is a comprehensive summary of the final results which includes absolute and relative errors for each method and it can be observed that the superiority of SLA is uniform in all the evaluated properties in the considered study.

Table (4). Summary of Final Dimensional Results for FDM and SLA

Feature	Nominal (mm)	Mean FDM (mm)	Error FDM (mm)	Mean SLA (mm)	Error SLA (mm)	More Accurate Technique
Boss B1	6.00	6.12	+0.12	6.04	+0.04	SLA
Wall W1	0.60	0.66	+0.06	0.61	+0.01	SLA
Wedge ΔZ	17.60	17.90	+0.30	17.70	+0.10	SLA
Mean deviation per technique	—	—	**+0.16 mm**	—	**+0.05 mm**	**SLA (overall superior)**

Together, these results demonstrate that 3D printing is not just a prototyping tool but a metricbased engineering analysis technique for identifying possible deviations, quantifying the accuracy limits of each technology, and directing design decisions based on dimensional, measurement-based information. As a result, physical printing combined with digital verification has the potential to provide a complete system for engineering models that will enhance their quality, reduce iteration errors, speed up development cycles, and finally result in more reliable engineering performances.

10. Future Work

Although we have accomplished the dimensionalstic analysis comprehensively, there are still some work directions open which can serve as avenues of inquiry. Firstly, extending the scope of comparisons by including other geometric attributes, such as lattice structure, internal cavities, and undercut regions, etc., could provide more information about what can actually be achieved by both FDM and SLA processes concerning replicating such complexities. Further, by conducting such experiments on other units within each model, different models with varied make, and varied make and type of materials, a kind of generic observation concerning such trends could actually be arrived at, thereby negating any effect that could arise due to the specificity of any particular machine. Speaking within the realms of sophisticated slicer software and corresponding layer height setting algorithms, particularly those capable of dynamically adapting to such toolpaths on features and on angled sections, there could actually exist other avenues to inquire into. Further, incorporation studies concerning 3D image scanning could lead to more precise mapping concerning possible deviation differences, thereby facilitating comparisons on dense point-cloud sampling which goes beyond what could actually be achieved using present caliper measurements. A kind of generic extension concerning this work could actually lead to developing corresponding compensation maps within CAD platforms which can dynamically change corresponding nominal geometric attributes on their own according to deviation maps predicted on lines concerning such experimental results obtained above. These generic maps could actually serve as corresponding building blocks within a closed-loop DfAM which could dynamically take into account corresponding specific attributes within each printing technology and each type of printing matter. Finally, studying the consequent elastic effects on departure differences within both thin walls and other regions within such printing matter could actually allow such findings to directly link up concerning results on structure. Study concerning other available processes within DfAM, such as those within SLS, MJF, and DLP processes, could actually serve within such very same standardized comparison concerning all aspects covered within this work, including serving within such corresponding generic roadmap concerning any evaluation concerning such DfAM device technology.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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Appendix (1) : Quick Measurement Metrics

Metric	Symbol	Definition / Use in This Study
Print Time	T_{print}	The total time required to complete the printing process (FDM/SLA), measured from the start of fabrication to full build completion. Used to assess process efficiency and repeatability.
Number of Measurements	N_{meas}	The number of repeated readings taken for each geometric feature (3 readings per feature) to compute a reliable mean value and reduce measurement variability.
Absolute Dimensional Error	E_{abs}	The linear deviation (mm) between the nominal CAD dimension and the actual measured value obtained from the printed part.
Relative Dimensional Error	E_{rel}	The percentage deviation (%) calculated by dividing (E_{\text{abs}}) by the nominal dimension. Used for normalized comparison between FDM and SLA.
Root Mean Square Error (RMS)	RMS	The root-mean-square deviation computed across multiple features (bosses, thin walls, wedge), serving as an indicator of overall dimensional fidelity between CAD and the printed artifact.
Support Volume Ratio	$\frac{V_{support}}{V_{part}}$	The ratio of support volume to part volume, used to interpret deformation tendencies in support-contact regions, particularly relevant in FDM.
Surface-Slope Sensitivity	Delta Z_{slope}	The measured deviation (mm) in the height of inclined surfaces (wedge feature) along the slope direction, used to quantify the influence of build orientation and layer height.

