Comparison of measurement techniques for evaluating the quality of 3D printed products using the analytic hierarchy process

Jacek Wojnowski[1*], Agnieszka Sawa[1]

[1] Maritime University of Szczecin, Wały Chrobrego 1-2, 70-500 Szczecin, Poland
* Corresponding author's e-mail: j.wojnowski@pm.szczecin.pl

ABSTRACT

The aim of this study is to demonstrate that popular measurement techniques – visual inspection, mechanical tools (digital calliper and steel linear ruler) and modern photogrammetry – can be used to detect shrinkage in 3D prints produced using fused deposition modeling (FDM) technology. The choice of the appropriate technique can be made objectively. Measurement techniques and their interrelationships have been the subject of much discussion and numerous scientific articles. They can be described using various criteria, which are often competitive and mutually exclusive. To avoid bias when selecting the measurement method, a multi-criteria decision-making tool – the analytic hierarchy process (AHP) was used. The results obtained in this study provide a quantitative decision-making framework for researchers selecting measurement methods in FDM quality control. The AHP analysis showed that decision-makers with the profile of a university researcher and lecturer tend to disregard visual inspection techniques and choose mechanical tools or photogrammetry, despite differences in the assessment of the importance of individual criteria characterising a given method. The key criteria for this profile of decision-makers were: measurement system precision (C2) and the overall ability of the technique to detect shrinkage (C8). The least important criteria were: the time-consumption of the measurement and the potential for automation of the measurement technique (C9). The analysis of weight aggregation (using a linear rule) and sensitivity analysis showed that decision-makers with the profile of a research and teaching staff can rely on the results presented in this study.

Keywords: management, quality, shrinkage, photogrammetry, additive manufacturing, analytic hierarchy process.

INTRODUCTION

Additive manufacturing

Additive manufacturing (AM) comprises the technologies that build components by adding material layer-by-layer, in contrast to subtractive methods that remove material to form the final shape. The key drivers of AM development include increasing confidence in the technology, the ability to produce personalised components with complex geometries, low material waste, efficient low-volume manufacturing, and advances in materials along with 3D and 4D printing processes [1]. The use of the AM technology offers many benefits for both the customer and the company providing services to the customer [2]. Among the

seven additive manufacturing technologies, the most widespread technology is fused deposition modelling (FDM), which is based on extruding material (filament) through a nozzle heated to its melting point [3]. FDM offers low equipment and material costs, a wide selection of thermoplastic filaments (both filled and unfilled), the option to recycle post-production waste, relatively low health risks, and high production flexibility. It also supports multi-material printing, serial production on printer 'farms' [4], and post-processing of printed parts [5].

Despite significant advances in the FDM 3D printing technology, decision-makers and 3D printing technologists still face various print defects. Print defects have been widely examined

in scientific studies [6, 7] and in online guides for 3D printer users [8]. A major defect in FDM printing is shrinkage, which occurs as thermoplastics soften during heating and contract during cooling [6, 9]. The products manufactured using the FDM technology may undergo significant shrinkage under certain print parameter settings [10]. The problem of shrinkage will continue to occur in the FDM technology due to the thermal plasticisation and cooling of the material from which the filament is made.

Measurement techniques

Visual inspection is the fastest, simplest, and least expensive non-destructive method, requiring no specialised tools or advanced operator training. However, it offers the lowest precision and cannot always clearly determine whether print shrinkage is present, especially more complex print geometries. The method cannot express results in SI units and is strongly affected by subjective judgement. Work [11] stated that the visual inspection method is used to detect defects in 3D prints, such as warping and delamination between individual layers. Publication [10] indicated that visual assessment is applied to detect and identify defects including overhangs, bridging (defects in the reproduction 'bridges' or unsupported elements), stringing, and warping. According to [12], it is possible to detect warping and assess print quality on a five-point scale. Publication [13] stated that a preliminary assessment of surface quality can be made for prints produced using three technologies: FDM, Selective Laser Sintering (SLS), and Material Jetting (MJ). As it was noted in [14], visual inspection supports preliminary identification of edge rounding, general deformation, and deviations from perpendicularity. Another aspect of visual inspection assessment is examining the surface quality of chemically treated ABS (in acetone vapour) [15]. A profilometer was also used to measure the roughness of PLA prints after chemical smoothing process [16].

Mechanical tools, such as digital callipers are widely used for quick dimensional checks of machine components and 3D-printed parts. They offer measuring ranges typically between 150 mm and 1000 mm, which allows assessment of features of various sizes. The choice of a specific calliper depends on the required accuracy and on the dimensions of the measured element. Another mechanical tool – a linear ruler, a simple

stainless-steel tool without moving parts – can also be used for preliminary detection of print shrinkage. Key advantages include short measurement time, results expressed in SI units, and low tool cost. The disadvantage is the high measurement uncertainty when measuring rounded external surfaces of the model. Measurements of print geometry elements, such as diameters [17] and distances between parallel print walls [18, 19], were successfully performed using a digital calliper with an accuracy of 0.01 mm. In publication [19], shrinkage was measured using a vernier calliper. Using vernier calliper, deviation in dimensional accuracy was measured [20].

Shrinkage was understood as a reduction in the volume of the printed element. Using a digital calliper, warping was also detected and measured [11, 21]. It is worth noting a study in which characteristic points were measured on a human bone, specially prepared and printed using the FDM technology [22]. However, the measurement was a subject to a large random error.

A rapidly developing and noteworthy technology, photogrammetry belongs to non-contact measurement techniques. It reconstructs geometry by matching features between the photographs taken from different camera positions and generating a dense point cloud describing the object surface. Photogrammetry operates in two measurement modes: Structure from motion (SfM) and multi-view stereo (MVS) [23]. This method makes it possible to recreate the three-dimensional structure of the measured object without physical contact with its surface. The advantages of this technique include relatively high accuracy for non-parallel surfaces and the ability to quickly compare results with a CAD reference model. The disadvantages are strong dependence on photo quality and environmental conditions, long acquisition time, and the need of computer-based photo processing.

Photogrammetry has been successfully applied to assess the dimensional accuracy of the objects manufactured using the FDM additive technology [24]. A study published in Metrology and Measurement Systems [23] showed that, with an appropriate depth of field and a sufficient number of images, an accuracy of 0.03 mm can be achieved on reference surfaces of a metrological-sized slot gauge reconstructed using the SfM and MVS methods [23]. According to [25, 26], photogrammetry is classified as a medium-accuracy technique, achieving typical accuracy in the range

of 0.10–0.50 mm for the objects sized 5–10 cm. It is widely used to obtain a complete representation of a model's surface geometry. It is the preferred method for evaluating geometric features (cylindricity, flatness, surface parallelism), analysing spatial deformations (warping, shrinkage), or comparing the printed part with its digital CAD model. Studies [24, 27] confirm the effectiveness of photogrammetry in the geometric analysis of the models produced using the FDM technology and show that, with a well-prepared photo set, an accuracy of 0.15–0.40 mm can be achieved. The measurement accuracy achieved with photogrammetric method should therefore be sufficient for quality and metrological inspection of most utility models, including FDM 3D prints.

Measurement techniques comparison

Scientific literature compares multiple measurement methods, including visual inspection, vernier callipers, and 3D scanners [11]. Each method evaluates a different aspect of the printed part. The presence of warping, cracks and edge deformation was identified visually. A calliper was used to determine the extent of warping, and a scanner was used to measure the volume of the printed product. Paper [28] presented the results of measurements performed using visual inspection, a calliper, and a 3D scanner. Visual assessment examined how well the print matched the STL model, the deformation of external surfaces, overall surface quality, and any layer displacement. A vernier calliper was used to verify the conformity of individual print dimensions. A scanner was used to assess print deviations relative to the digital model in GOM Inspect software.

Publication [10] presents the results of comparative analyses of non-destructive methods, such as visual inspection, measurement using a hole fitting, vernier calliper, and 3D laser scanners. Visual inspection was used to identify print defects such as overhangs, warping, and stringing between print elements. Hole fittings were used to determine the tolerance of print features, e.g. a hole and a solid of matching shape. A vernier callipers was used to measure defects such as stringing and bridging. A 3D scanner was used to assess deviations in flat print surfaces.

The photogrammetric technique has been compared with other measurement methods. Study [29] presents a comparison between photogrammetry and a vernier calliper in measuring human facial features. The research indicates that 7 out of 10 photogrammetric measurements provide results comparable to those obtained with the vernier calliper (difference of less than 1 mm). The authors also noted that photogrammetry should be complemented by an additional measurement method. Reference [30] presents comparative analyses of techniques, including a laser line scanner (LLS) with a calibrated rotary stage, a structured light scanner (SLS), a photogrammetric scanning system with a rotary table (PSSRT), and a portable measuring arm with laser line scanner (LSA). The results show that photogrammetry achieves accuracy comparable to SLS, with reported differences of ±0.01 mm.

Analytic hierarchy process method

The decision-making process consists of identifying the problem, analysing available options, and choosing the best alternative for the defined goal. Decision-makers, such as team or department managers, often face important choices that influence future development. These may include improving product quality, adopting new manufacturing technologies, or selecting appropriate research methods. Simple problems can be solved through experience or intuition, whereas complex ones, involving multiple or conflicting criteria, require structured decision tools. Selecting an appropriate measurement technique for detecting shrinkage requires a structured analytical method, such as AHP.

The field of knowledge that addresses the search for optimal solutions to the problems with multiple alternatives and criteria is known as multi-criteria decision analysis (MDCA) or multi-criteria decision making (MCDM). MCDM methods include [31]: AHP, TOPSIS, VIKOR, WASPAS, GTMA, PROMETHEE 2, GRA, MULTIMOORA, ARAS, COPRAS, developed between 1977 (AHP) and 2012 (WASPAS) and still being expanded today. The AHP method, developed by T.L. Saaty [32], belongs to a group of approaches based on classical and multi-attribute utility theory. To determine the decision-maker's preference, a utility function is defined, in which numerical values are assigned to decision variants, resulting in a ranking of the alternatives.

AHP represents the decision problem as a hierarchy that includes the goal, the criteria, and the alternatives. The criteria are then compared in pairs to assess which of the two criteria is more

important. The final stage produces a matrix of global and local preferences. AHP supports discrete decision problems with a limited number of criteria and alternatives, which do not need to be measurable. The advantages of AHP include the speed and simplicity of the decision-making process compared to other MCDM methods, easy-to-understand logic, a wide range of applications, and equal consideration of each criterion [31].

Background summary

On the basis of the information above, it was concluded that:

- the most popular and easily accessible testing techniques include: visual inspection, mechanical tools (calliper and linear ruler), scanners, and photogrammetry,
- shrinkage of the products obtained using FDM additive manufacturing technology from the ABS material can be easily detected using the following techniques: visual inspection, mechanical tools, and photogrammetry,
- the MCDM AHP method is a simple and effective tool for decision-making when there are several options/solutions that can be described using a list of criteria,
- there are no scientific studies comparing popular and easily accessible measurement techniques such as visual inspection, mechanical tools, and photogrammetry,
- the problem of selecting the best of the above-mentioned measurement techniques in terms of selected criteria is still insufficiently described in the literature.

The paper attempted to answer the following questions:

a) can the measurement techniques presented in this paper be used to detect shrinkage in products manufactured using the FDM technology?
b) can the presented measurement techniques be compared with each other in terms of selected criteria?
c) which of the presented measurement techniques will be chosen first by the decision-maker responsible for the profile of research and teaching staff?
d) which criteria for evaluating alternative measurement techniques should be considered most important for making the final decision?

Additive manufacturing still underutilises its potential, mainly due to the lack of unified standards, process understanding, and metrological consistency. As highlighted by Vora and Sanyal [33], AM parts often exhibit high geometric complexity but insufficient dimensional accuracy and repeatability. To address this metrological gap, the present study introduced an innovative AHP-based framework supporting the selection of measurement techniques, linking dimensional evaluation with structured decision-making to enhance the reliability and comparability of FDM inspection results.

The research aimed at reducing the level of shrinkage in FDM prints is beyond the scope of this publication and will not be considered.

MATERIALS AND METHODS

This study used a controlled setup with one FDM printer, one ABS material, three small-scale models, and three academic experts. The following assumptions were adopted for the research and analysis:

a) the prints were produced on a single FDM printer to avoid introducing random variability inherently associated with different printer models,
b) the prints were made from one material – ABS copolymer – using fixed technological parameters. Additional materials or process parameters were excluded, because they would greatly expand the scope of the study,
c) the printed parts were small (45 × 45 × 45 mm) but differed in geometry. This was intentional, allowing the assessment of how model complexity affects the capability of each measurement technique to detect shrinkage,
d) three experts were selected to balance the representativeness of AHP results with a reasonable duration of the evaluation process.

Such a focused scenario eliminates variability caused by process and material differences, enabling a clear comparison of measurement techniques (visual inspection, mechanical tools, and photogrammetry) under reproducible laboratory conditions.

3D printing – materials and 3D printer setup

The Pro3D acrylonitrile-butadiene-styrene (ABS) filament with a diameter of 1.75 mm was used for 3D printing. It offers good mechanical properties, high impact strength, and resistance to

temperatures up to 100 °C. The disadvantage of ABS is its high shrinkage [11]. ABS was selected due to its pronounced shrinkage, which highlights detection limits, and its widespread use as an engineering polymer. ABS is commonly used in: medicine (human organ models), space engineering (electromagnetic interference shielding), metrology (stress-strain sensors), energy (energy storing devices) [34], automotive (car parts), general and consumer applications (consumer goods and prototypes) [3]. Using standard ABS filament reduces variability and reflects typical research-lab practice while supporting quality control improvements in the FDM-based manufacturing. The authors intentionally selected the ABS filament to facilitate reliable detection of shrinkage in 3D-printed components.

The prints were produced using a MakerBot Replicator 2X 3D printer with default settings for standard-quality ABS filament prints (layer height 0.20 mm, build table temperature 100 °C, nozzle temperature 255 °C, infill printing speed 120 mm/s, outline printing speed 50 mm/s, infill density 30%).

3D models

For the purposes of this publication, three models were printed and tested using visual inspection, digital calliper, a linear ruler and photogrammetry. The models were classified into three geometric groups: simple, complex and highly complex geometry (Table 1, Figure 1).

For each print geometry, the largest linear dimension did not exceed 45 mm; in other words, each print could be placed in a cube of dimensions: 45 × 45 × 45 mm. The choice of print dimensions was dictated by the desire to obtain prints with visible shrinkage at a relatively short printing time (the maximum printing time is 1.5 hours). The models were designed using Free-CAD version 1.0 software.

Measurement techniques

The table below (Table 2) presents the measurement time results. For each technique, the measurement was carried out once any shrinkage was detected. Shrinkage was assessed visually using a two-state scale. Three separate observations were made for each model geometry.

The digital calliper time represents the average of three measurements taken at three heights of each model. However, for the model with highly complex geometry, the error was too large to be considered reliable, and the result was therefore marked as N/A (not available).

For the steel linear ruler, the tool was placed against the model wall to check whether shrinkage was visible.

For photogrammetry (Table 2, Table 4), the measurement time refers to the duration from placing the printed part on the turntable to obtaining the digital 3D model, including the deviation map generated against the reference CAD model (STL format). The measurement time was recorded once per each geometry.

Table 1. Features of the geometry of the 3D prints examined in this study

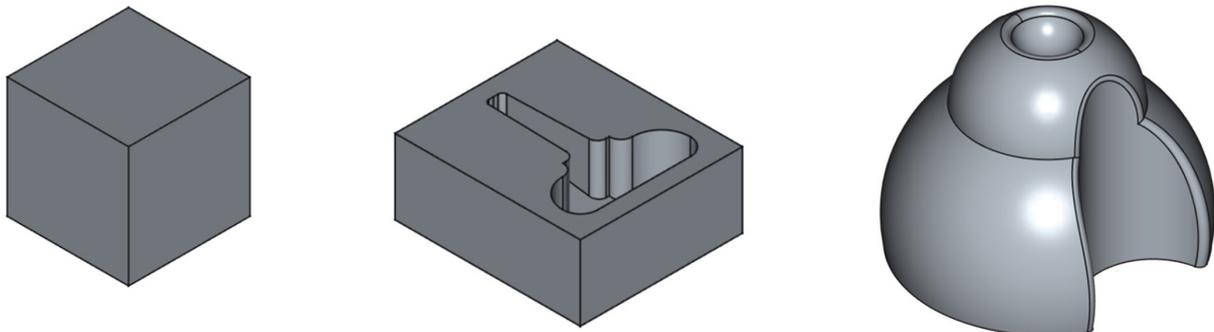| Characteristic features	Geometry		
	Simple	Complex	Highly complex
Flat surfaces	Yes	Yes	No
Holes/grooves	No	Yes	Yes
Complex (non-regular/flat) surfaces	No	Yes	Yes

Figure 1. CAD models used as reference geometries for FDM printing and subsequent dimensional and shrinkage analysis: from left, simple geometry, complex geometry, and highly complex geometry, all designed for fabrication in ABS

Table 2. Measurement time results. The mean value and standard deviation are given for each measurement technique

Print geometry	(AL1) Visual inspection	(AL2) Digital calliper and linear ruler	(AL3) Photogrammetry
Simple	5.16±0.77 s	5.89±1.31 s (linear ruler) 31.74±1.15 s (calliper)	81.30±8.51 min
Complex	5.51±1.33 s	5.60±0.63 s (linear ruler) 39.57±3.00 s (calliper)	81.30±8.51 min
Highly complex	N/A	N/A	81.30±8.51 min

For visual inspection, the uncertainty of straightness assessment was estimated at approximately 0.5 mm for 100 mm, according to ISO 16610-21:2011, reflecting human perception limits for small FDM features. Measurement with the digital calliper ensured an accuracy of ±0.02 mm, consistent with ISO 13385-1 and ASME B89.1.14. For photogrammetry, repeated extraction of identical dimensions from the reconstructed 3D model provided deviations below ±0.05 mm, depending on geometry and point selection, in accordance with the VDI/VDE 2634 guidelines.

It was assumed that the shrinkage detection threshold corresponds to the curvature of external surfaces: 0.5 mm for visual inspection, 0.04 mm for digital calliper, and 0.1 mm for photogrammetry (twice the precision of the technique).

Visual inspection was used as the first measurement technique to detect shrinkage in the printed parts. The inspection was carried out by a metrologist with normal vision, not requiring corrective glasses. No magnifying devices or microscopes were used during the evaluation. The measurement time reported in Table 2 represents the average duration required to examine each model and determine the presence or absence of shrinkage. The measurement time varied depending on the geometry of the printed part.

The photographs in Figure 2 show the inspected prints. A white background was used to improve visibility and facilitate the detection of shrinkage on the surfaces of the samples.

HOREX digital calliper with a measuring range of up to 150 mm and an accuracy of 0.01 mm were used for the measurements. In addition to the digital calliper, a steel linear ruler was also applied for mechanical assessment. Figure 3 illustrates how shrinkage was identified on the printed parts of simple and complex geometries using both the digital calliper and the linear ruler (Table 1).

Close-range photogrammetry was used in the study to obtain a three-dimensional representation of the geometry of a small object printed using the FDM technology.

The photogrammetric acquisition was performed using a Nikon Z5 camera placed on a tripod with a Nikkor Z 24–50 mm f/4–6.3 lens and a Meike 11 mm extension ring. The imaging parameters were: focal length 50 mm, aperture f/8, ISO 100, and a fixed distance of approximately 0.22 m from the object. The measurement photogrammetry system is shown in the figure below (Figure 4).

The object was placed on a turntable against a black background. Lighting was provided by a lamp with constant, natural, cool white light, without the use of flash, which ensured evenly lit
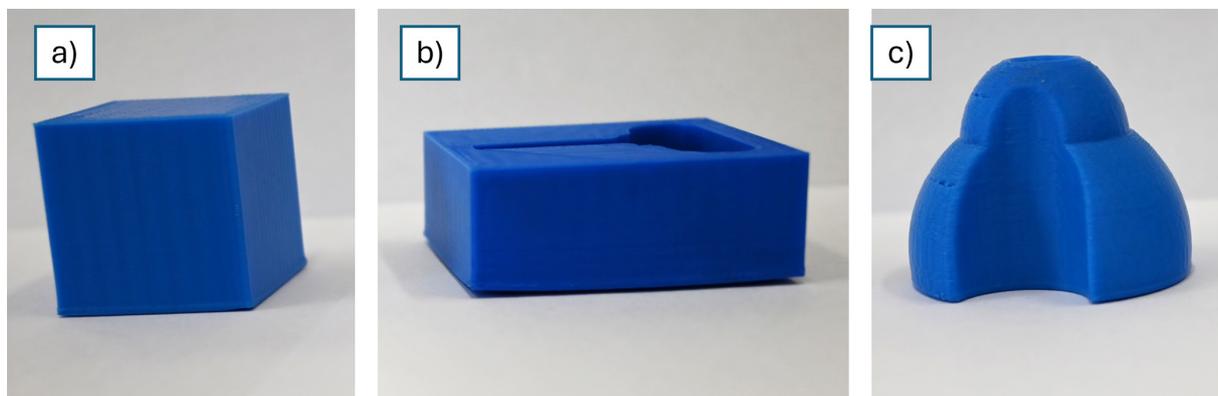

Figure 2. Visual inspection of printed ABS parts: (a) simple geometry, (b) complex geometry, (c) highly complex geometry. Surface shrinkage and deformation effects are visible under uniform white background illumination
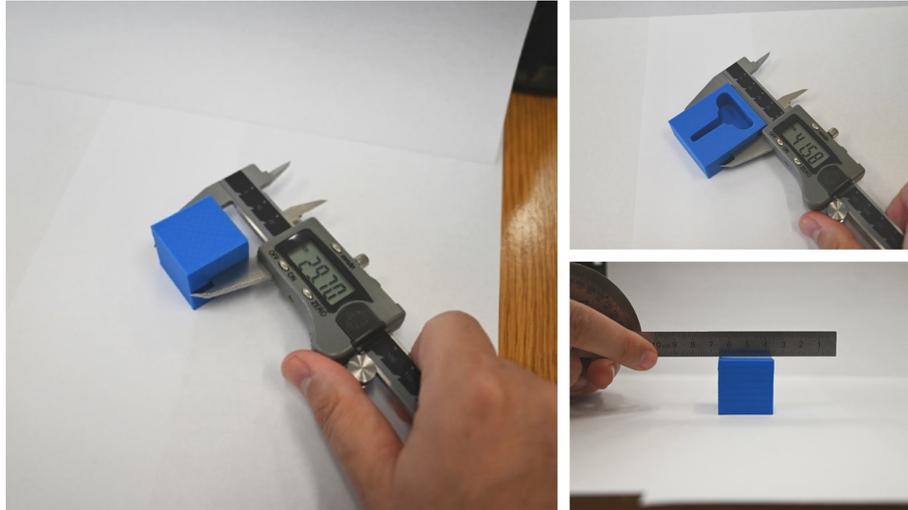
Figure 3. Example of dimensional measurements performed using digital calliper and a linear ruler on FDM-printed ABS parts for shrinkage and dimensional accuracy assessment
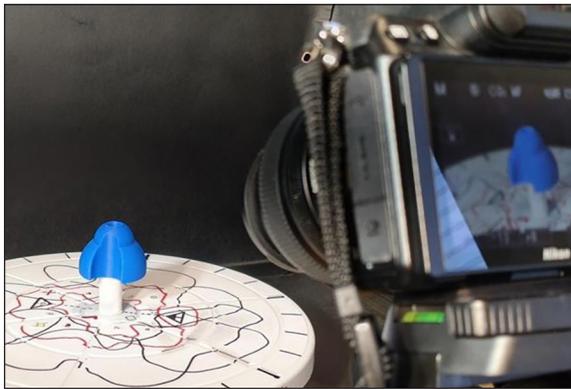

Figure 4. Photogrammetry setup used for 3D reconstruction of FDM-printed ABS models, showing camera position on a tripod and turntable arrangement against a black background for capturing overlapping images from multiple angles

shots without overexposure or reflections. Each model was photographed from three height levels at 30°, 45°, and 55–60°, with images taken every 15° around the object, providing approximately 96% overlap between consecutive photos. The total number of images was 74, 100, and 82 for the three models, respectively.

The photographs were processed in Meshroom 2025.1.0 using algorithms default SfM/MVS parameters [35, 36]. The meshing step generated dense point clouds (~3.0 M points) and final meshes containing between 0.35 M and 0.74 M faces (average ≈ 0.49 M).

The meshes were edited and scaled in MeshLab [35, 36], using a reference line of 7.82 mm visible on the turntable. The resulting model

in.STL format was then imported into GOM Inspect, where a best-fit alignment to the CAD reference was applied, and a Compare Mesh analysis was performed.

Colour-deviation maps were created with tolerance thresholds of ± 0.75 mm. Deviations within this range were classified as no shrinkage (light green), values below – 0.10 mm as shrinkage present (blue), and values above + 0.10 mm as material accumulation (red).

The models prepared for photogrammetric measurements and the results from the GOM Inspect software are shown in Figure 5.

Other measurement systems, such as coordinate measuring machines (CMMs) or structured-light and laser scanners, were not included in this study due to their limited availability as well as high acquisition and calibration costs in typical laboratories or production companies [37].

The focus was intentionally placed on accessible and low-cost techniques, commonly used for educational and research purposes, aligning with the scope of the study and decision-maker profile.

Decision-maker profile

In the field of additive manufacturing, three main decision-maker profiles can be distinguished:
1. Single-person business owner, amateur, or hobbyist,
2. Medium-sized enterprise (MES) owner with a fleet of 3D printers,
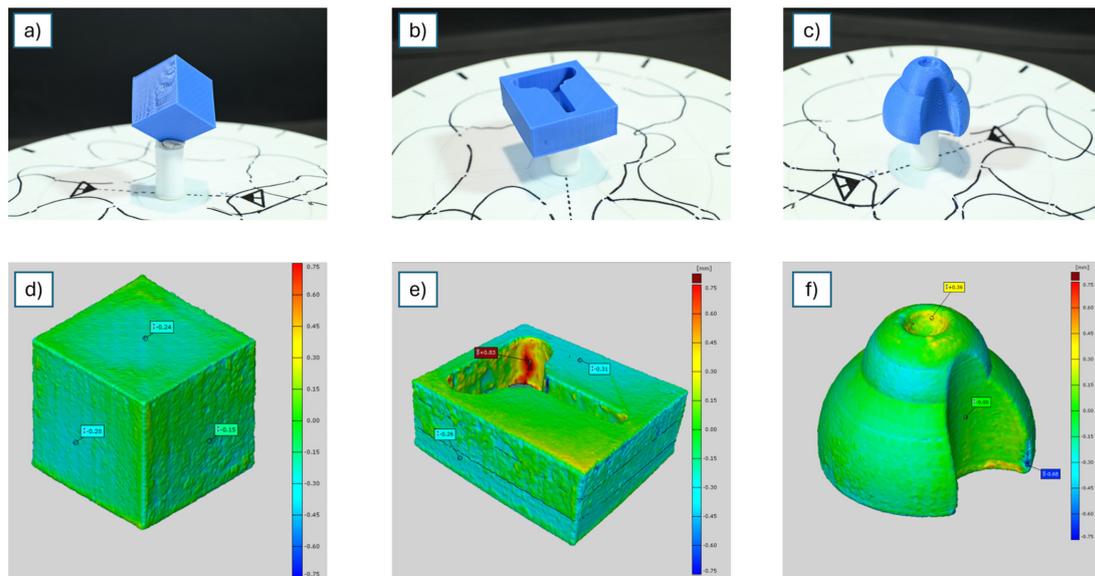3. Research and teaching staff.

Figure 5. Measurement workflow using photogrammetry and GOM Inspect: (a–c) printed ABS parts prepared for photogrammetric capture; (d–f) corresponding GOM Inspect deviation maps for simple, complex, and highly complex geometries

Each decision-maker can be characterised by a combination of attributes, including professional experience, soft and technical skills, competencies, and motivations.

Table 3 presents the profiles of decision-makers involved in additive manufacturing and their relevance to the selection of measurement systems for evaluating printed parts.

The independence of expert judgments, their profiles, and the selection of specific individuals are crucial elements in AHP analyses.

All experts in this study were employees of the same university and faculty, selected intentionally due to their proven experience in additive manufacturing and measurement technologies. This ensured that the evaluations were made by qualified professionals familiar with both 3D printing processes and metrological assessment methods. To maintain independence, each expert worked individually and was unaware of the identities of the other participants.

Each of the three experts represented a different professional background:
- Expert 1 – a practitioner specialising in 3D printing and measurement techniques,
- Expert 2 – a theoretician and lecturer involved in production management, additive manufacturing, and familiar with MDCM and metrology,
- Expert 3 – a theoretician and lecturer focused mainly on optical metrology and modern manufacturing technologies.

No prior training or calibration session was conducted before the pairwise comparison process. The academic research and teaching staff profile is primarily characterised by the need for high measurement reliability and precision, as well as the responsibility for delivering accurate knowledge to students and fellow researchers. However, academic staff may not always possess in-depth practical experience with all measurement techniques, such as digital calliper, photogrammetry, structured light or laser scanning, or CMM systems, which often necessitates forming interdisciplinary research teams. Unlike other profiles, academic decision-makers are typically not constrained by equipment cost, as research tools are usually funded through institutional or public sources. In contrast, single-person businesses, hobbyists, and MES owners are mainly limited by cost and available time, and their choice of measurement technique is often subjective, sometimes requiring the support of a metrologist or external measurement service provider.

Analytic hierarchy process method – stages and detailed description

SuperDecisions software by TL Saaty and his team, version 2.8.0, was used for calculations and analyses – judgement matrices for criteria and alternatives in relation to criteria, global priorities

Table 3. Profiles of decision-makers in additive manufacturing and their relation to print measurement techniques

Parameter	Single-person business/amateur/hobbyist	A medium-sized enterprise (MES) owner with a fleet of 3D printers	Research and teaching staff
Position and role	The individual directly decides which measurement tools and systems to use. In most cases, this profile values ease of use and low cost of the measurement system.	The owner of a medium-sized enterprise may not always personally decide which measurement systems are used in quality control.	A university research and teaching staff member directly selects the measurement system for experimental studies. Although not involved in business operations, their responsibility is to provide reliable and reproducible research results.
Experience in additive manufacturing and print metrology	Typically based on practical knowledge and problem-solving experience in 3D printing. The main challenge is choosing a measurement system suited to the produced parts.	May come from a background in 3D printing or management; may or may not have hands-on experience but usually understands the requirements of production measurement systems.	Combines both practical and theoretical understanding of 3D printing processes. This profile often involves in-depth knowledge of quality control and metrological techniques.
Soft skills	Creativity and the ability to find quick, practical solutions.	Decisiveness, problem-solving under pressure, and a focus on practical outcomes.	Logical reasoning, creativity, and the ability to solve complex analytical problems
Technical skills related to measurement systems	Basic or limited knowledge of additive manufacturing and measurement systems.	High measurement competence when the person comes from a metrology or 3D printing background.	Very high familiarity with various measurement systems and related analytical concepts.
Decision-making process (criteria)	Preference for the simplest and lowest-cost measurement systems.	Selection of systems that meet accuracy standards or customer requirements.	Priority is given to precision and measurement reliability. Cost is of secondary importance, as equipment is often financed by institutional budgets.
Motivation to solve problems	Low for amateurs/hobbyists; high for single-person business owners motivated by market survival.	High motivation, as measurement time directly affects company profits.	Focused on scientific innovation and advancement of research.
Limitations	Low accuracy and limited reliability of measurement results.	The MES owner may not always have sufficient technical insight to assess which measurement technique ensures the expected performance.	The need to conduct reliable studies and provide credible data to practitioners and other researchers; it may not always be feasible to master every measurement method in depth.

for each expert, consistency ratio (CR), aggregated priorities, sensitivity analysis.

In the AHP method, decisions are made on the basis of established and transparent criteria, which do not necessarily have to be measurable. The decision-making process according to the AHP method consists of the following stages [32]:

Structuring the decision problem

This stage involves breaking down the decision problem into its constituent elements, such as the goal, criteria and alternatives. The hierarchy of the decision problem is usually represented using a value tree (Figure 6).

Goal – selection of the best measurement technique for detecting print shrinkage, assuming that the decision-maker is a research and teaching staff member at a technical university. The selection criteria (C1-C9) for measurement techniques (AL1-AL3) are presented in the table

below (Table 4). The selection criteria (C1-C9) for the research methods and their number were chosen top-down and based on preliminary tests and analyses by the authors. By the name of the criterion the direction of evaluation of a given variant is presented, e.g. lower better means that a lower value in the row corresponds to a more favourable option.

Redundancy refers to strong overlap between criteria. To avoid it, the study applied the MECE principle (Mutually Exclusive and Collectively Exhaustive). The criteria compared in pairs were designed so that none could be directly interchanged – each belongs to a separate category and represents a distinct physical concept (mutually exclusive). For example, the criterion describing the measurement accuracy of a technique (C2) is fundamentally different from the cost of the measurement system (C6).

The selected criteria adequately and comprehensively describe the problem of choosing a
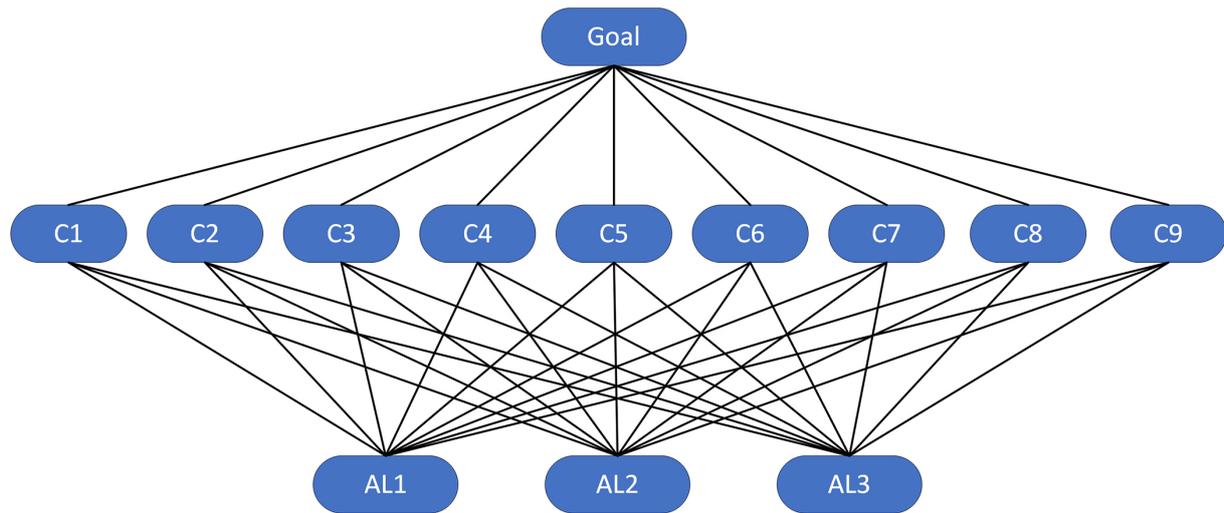
Figure 6. Value tree representing the hierarchical structure of the AHP decision model, showing the main goal, criteria (C1–C9), and evaluated measurement alternatives

measurement technique for shrinkage detection (collectively exhaustive). Ultimately, nine uncorrelated criteria were selected to identify the advantages, limitations, and applicability of the proposed AHP-based approach. Table 4 summarises the nine criteria used to evaluate and compare the measurement techniques for detecting shrinkage in FDM prints, along with the corresponding method alternatives analysed in the study.

Conducting pairwise comparisons of decision alternatives and criteria.

Not all elements (criteria or alternatives) are equally important, so pairs of elements should be assigned appropriate weights according to the nine-point scale proposed by TL Saaty [32]. When comparing two criteria, the question is: "Is element 1 (column) more important than element

Table 4. Selection criteria and testing method alternatives

Criterion	(AL1) Visual inspection	(AL2) Digital calliper and linear ruler	(AL3) Photogrammetry
(C1) Measurement time-consumption (lower better)	Low (for detailed information see Table 2)	Low (linear ruler), medium (digital calliper) (for detailed information see Table 2)	High (for detailed information see Table 2)
(C2) Measurement system precision (lower better)	0.3–0.5 mm [a]	Up to 0.02 mm [b]	Up to 0.05 mm [c]
(C3) Human factor (lower better)	High	Medium	High
(C4) Measurement difficulty (lower better)	Low	Medium	High
(C5) Required experience and knowledge of a metrologist (lower better)	Low	Medium	Low (at the stage of image processing and analysis in the GOM Inspect software) Medium (for close range photogrammetry measurement)
(C6) Measurement system cost (lower better)	0 EUR	Medium-grade digital calliper: 40 EUR Steel linear ruler: 55 EUR	Camera, peripheral devices and software cost: 1000 EUR
(C7) Geometry complexity (higher better)	Simple	Simple and complex	Simple, complex and highly complex
(C8) Overall ability of the technique to detect a shrinkage (higher better)	Low	Medium	High
(C9) Potential for measurement automation (higher better)	Low	Medium	High

Note: [a] see ISO 16610-21:2011 standard, [b] see ISO 13385-1 standard, [c] see VDI/VDE 2634 guidelines.

2 (row), and how important is it for achieving the goal?". A scale from 1 (equal importance) to 9 (extreme importance) was used for the evaluation.

The following relationships apply to the assessment of the importance of elements: $a_{ij} = 1 / a_{ji}$ and for $i = j$, $a_{ij} = 1$.

The judgement matrix for the decision maker - a research and teaching staff member involved in 3D printing research, is presented in Tables 5, 6 and 7. Three experts in additive manufacturing technologies employed at the University participated in the study. The judgement matrix for criteria C1-C9 was prepared separately for each of the three decision-makers (experts) based on the information provided.

In order to avoid repeating the time-consuming process of evaluating criteria in pairs – for such a large number of criteria – it was decided to use the following methodology:

a) The first step in the paired criteria assessment was to establish a hierarchy of criteria importance, assuming that no criteria could have the same rating (ex aequo); each criterion was assigned a rating from 1 to 9,

b) Secondly, individual criteria were compared in pairs and the score was calculated using Equation 1 and Equation 2:

$$\text{Criteria pairwise comparison score} = |CX – CY| + 1, \text{ for } CX > CY \quad (1)$$

$$\text{Criteria pairwise comparison score} = 1/(|CX – CY| + 1), \text{ for } CX < CY \quad (2)$$

where: *CX* – first (column) criterion hierarchy importance, *CY* – second (row) criterion hierarchy importance.

For example. Using Equation 1, for 1st criterion hierarchy importance equal 7 and 2nd criterion hierarchy importance equal 3 (CX > CY), we obtain:

$$\text{Criteria pairwise comparison score} = |7\text{-}3|+1 = |4|+1 = 5 \quad (3)$$

In the case where CX < CY, for example CX equals 3 and CY equals 7, we use Equation 2 and calculate the pairwise comparison score as:

$$\text{Criteria pairwise comparison score} = 1/(|3\text{-}7|+1) = 1/5 = 0.20 \quad (4)$$

Therefore, the values 5 and 0.20 will be placed in Tables 5, 6 and 7, of the judgement matrices in the appropriate place.

The number of pairwise comparisons for a matrix of order n is given by the binomial coefficient: $\binom{n}{2} = \binom{9}{2} = 36$. Publication [38] stated that each element of the judgement matrix of criteria was calculated based on the ratio of scores obtained from the established hierarchy of criteria importance, for example, criterion C1 ranked 7th and C2 ranked 2nd yield a matrix element value of 3.5. A limitation of this approach can occur when determining elements of the judgement matrix for alternatives. In some cases, it is not possible to establish a strict ranking order for the alternatives. For example, for criterion C3 in this study, where AL1 and AL3 were equally rated but less important than AL2.

According to T.L. Saaty, two criteria (or alternatives) are compared pairwise, and a subjective judgment is made indicating which of the two is more important. When the consistency ratio (CR) > 0.10 the pairwise judgments should be revised. However, in high-order matrices, it is not always clear whether to increase or decrease a given value or by how much, which can increase subjectivity in the evaluation.

The approach proposed in this study allows for a flexible construction of the pairwise comparison matrix for alternatives. It eliminates the drawback of time-consuming repetitions required when inconsistencies occur in traditional pairwise assessments (CR > 0.10). The authors' approach enables the determination of matrix element values in such a way that the consistency ratio (CR) for a 9 × 9 matrix remains constant at 0.035.

This approach also introduces a rule that, in comparisons of criterion C1 against criteria C1–C9, no two ratings are equal (ex aequo); each appears only once.

The strengths of the proposed approach are as follows:
- high repeatability,
- resistance to generating inconsistent comparison matrices,
- clarity and simplicity of the evaluation process,
- requires specifying only one ranking of criteria at the beginning of the analysis.

In turn, the weaknesses of the proposed approach are the following:
- by design, the method is limited to analyses involving nine criteria,
- the need to provide a single ranking of criteria may lead to conflicts or inaccuracies when two criteria have nearly equal importance,

- results may be inconsistent compared to reference methods in the literature.

Calculation of local weights and verification of the consistency of the comparison matrix

This stage was based on the calculations and results from the Super Decisions software. Local weights for individual criteria and alternatives are then determined. In addition, each time a comparison matrix is created, the consistency of the assessments presented in it must be checked. The consistency of the comparison matrix is determined using the consistency ratio (CR). If the CR for the comparison matrix is greater than 0.10, return to stage two and re-evaluate the criteria. $CR \leq 0.10$ means that the decision-maker's assessments between individual elements are consistent [32], and therefore the analysis can be continued without the need to re-evaluate the importance of the criteria.

Criterion weight aggregation and sensitivity analysis

At this stage of the AHP analysis, the criteria weights are aggregated, i.e. ranked from most to least important. This is done based on an appropriate utility function. In this publication, an additive (linear) rule was selected for this purpose, which allows correct results to be obtained quickly [39]. It should be noted that this rule assumes linear relationships and full independence between criteria. In practice, small changes in weights or partial correlations between criteria may slightly affect the final ranking, although the overall hierarchy of alternatives remained stable in this study.

In this study, other aggregation rules were also considered, including multiplicative and outranking approaches. The choice of the additive rule was supported by several arguments:

- transparent methodology and simplicity of calculations,
- susceptibility of the calculation process to automation,
- compatibility with the 1–9 scale proposed by Saaty et al., which also made it possible to test the authors' proposed method for calculating values in the experts' judgment matrices,
- high popularity and ease of interpretation among decision-makers.

However, certain limitations were also recognised:

- possibility of obtaining unrealistic or overly compensatory results,

- a linear model that ignores interactions and synergies between criteria,
- sensitivity of results to small weight changes, which may cause so-called rank reversal.

The simplicity and transparency of the additive rule, its controllability at each stage of the AHP analysis, low resource intensity, high level of automation, and compatibility with the Saaty scale make it a strong starting point for further comparative studies of multi-criteria analysis methods.

On the basis of these considerations, the multiplicative and outranking rules were excluded due to their more complex interpretation, low transparency, and incompatibility with the Saaty scale. During the methodological design phase, the authors reviewed alternative aggregation rules, yet they did not conduct numerical experiments with them; therefore, the study applies only the additive rule and describes it in detail.

The purpose of sensitivity analysis is to answer the question: 'How will the solution change if the decision-maker's preferences or assessments change?' As a result, the outcome of the analysis may change, and consequently, the decision to choose a particular measurement method. It was decided to examine the impact of a change in the weight (global priorities) of the decisive criteria (ranked 1st, 2nd and 3rd) in the event of a 25% increase in the global weight of a given criterion [40].

Figure 7 presents a schematic flow of the AHP used in this study, outlining the main stages from defining the goal and criteria to deriving final priorities of alternatives.

RESULTS AND DISCUSSION

Visual inspection, calliper and photogrammetry

In this study, the visual inspection technique was used to detect shrinkage in the parts produced by the FDM process. The analysis focused on shrinkage on the side and top surfaces of the prints. Warping of the base was also observed in the simple and complex geometry models [10–12]. Similar to the findings reported in [14], the visual inspection method also revealed additional phenomena, such as edge rounding of printed models and overall geometric deformation.

For simple and complex geometries, visual inspection allows a preliminary assessment of

AHP workflow for selecting a measurement technique for FDM parts

EXPERIMENTAL SCOPE
One FDM printer, ABS, three small models; Meshroom/MeshLab; CAD-to-mesh comparison in GOM Inspect.

DECISION GOAL
Select the best technique to detect shrinkage / verify dimensions of FDM prints in an academic setting.

CRITERIA (C1-C9)
Measurement time (C1), Accuracy (C2), Repeatability (C3), Simplicity (C4), Experience (C5), Cost (C6), Geometry complexity (C7), Shrinkage detection (C8), Automation (C9).

EXPERT PANEL & INPUTS
Three independent academic experts; pairwise comparisons on Saaty scale; SuperDecisions v2.8.0.

PAIRWISE + CONSISTENCY
Judgement matrices for criteria & alternatives; CR < 0.10 for all matrices (Table 5).

WEIGHT DERIVATION
Global priorities of criteria per expert: C2 & C8 highest, C9 & C1 lowest (Table 12).

ALTERNATIVES
AL1: Visual inspection, AL2: Mechanical tools (digital caliper / ruler), AL3: Photogrammetry.

AHP SYNTHESIS (per expert)
Local→global weights computed; sensitivity→checked.

FINAL RANKING (per expert)
Expert 1: AL3 > AL2 > AL1 (photogrammetry preferred).
Experts 2 & 3: AL2 > AL3 > AL1 (mechanical tools preferred).
Visual inspection least preferred for all.

Figure 7. Schematic flow of the analytic hierarchy process (AHP) used in this study

shrinkage. However, this method cannot quantify shrinkage in SI units such as % or mm. It is not possible to measure the shrinkage of a print with very complex geometry, where there are mainly surfaces with high curvature, without the use of a specialised fittings (Table 1). The digital calliper played a significant role in assessing shrinkage, which was indirectly observed by measuring the distances between opposite walls of the printed models [18, 19]. The use of a steel linear ruler enabled a quick identification of deviations from flatness on specific surfaces of the prints.

Mechanical tools, such as a digital calliper and a linear ruler can assess the presence and degree of shrinkage in simple and complex geometries (Table 1). In these cases, shrinkage can be expressed as a percentage or a linear dimension. Assessment of shrinkage in the models with highly complex geometry using mechanical tools is practically impossible due to the error caused by applying the jaws to 'rounded' surfaces. If it is possible, it is subject to very large measurement error and very low measurement repeatability.

Photogrammetry – consistent with studies [23, 24] – was used to evaluate the geometric accuracy of the printed models relative to their CAD references. References [24, 27] indicate that photogrammetry is highly effective for the geometric assessment of 3D-printed parts, which is confirmed by the results of this study. With the chosen setup and software, dimensional fidelity could be determined within approximately 90 minutes, regardless of geometry complexity.

Photogrammetry allows shrinkage to be measured and expressed in units of length or percentage for each geometry. Holes and grooves with limited visibility are difficult or impossible to map. It also offers high accuracy for varied shapes and complex geometries, but low accuracy for shaded elements, grooves, openings and light-reflecting structures. The photogrammetric method is the most complex of the methods analysed in this study. Reliability depends on operator experience, including planning image acquisition and adapting conditions to the object's geometry.

Studies [10, 11, 28] show that visual inspection, callipers, and 3D scanning are used for preliminary quality assessment, dimensional evaluation, and measurement of deviations relative to the digital reference. The present study provides results and analyses that do not contradict these findings. Instead, they offer a new perspective on measurement techniques — visual inspection, calliper with a linear ruler, and photogrammetry — as versatile and complementary tools for assessing the quality of FDM prints.

Photogrammetry and mechanical tools were identified as the most balanced alternatives for dimensional verification of FDM prints under academic laboratory conditions. This result indicates that both techniques offer a practical compromise between accuracy, cost, and ease of use. Photogrammetry provided sub-0.05 mm repeatability and proved effective in detecting shrinkage and geometric deviations, while mechanical tools maintained acceptable precision for simple geometries at a much lower operational cost.

Vora and Sanyal [33] emphasised that mechanical and optical instruments remain the most frequently used in AM laboratories, but that their selection is typically based on operator experience rather than a formalised decision model. Mietliński et al. [41] further highlighted that the choice of measurement technique should depend on part geometry and feature accessibility—contact tools being preferred for simple external dimensions, and optical methods for complex or curved surfaces. Liu et al. [42] demonstrated that CMM and XCT complement each other depending on part complexity, yet their cost and calibration effort restrict their application in everyday research practice.

Analytic hierarchy process results

Table 5 presents the CR values for the judgment matrices included in this study. The Consistency Ratio of the experts' judgment matrices (Table 6, 7 and 8), equal to 0.035, indicates that the experts' assessments were consistent and that no re-evaluation of pairwise comparisons was required. The CR values of the judgment matrices for the alternatives (see: Table 9, 10 and 11) range from 0.005 to 0.068, which are all below the commonly accepted threshold of 0.10, confirming a high level of consistency and reliability of the presented pairwise comparison results.

Judgement matrices of decision-makers

The tables below (Table 6, 7 and 8) present the results of the criteria assessments by individual experts. Each of the matrices below is unique.

Judgement matrices for alternatives

Tables 9, 10 and 11 show the ratings of alternatives for each criterion (C1-C9). The tables were prepared based on the data from Table 4. Each table is designed to answer the question of which measurement technique is the most advantageous in light of a given criterion.

For example, in the case of the time-consumption criterion (C1), the most preferred option is visual inspection (AL1), followed by assessment with mechanical tools (AL2) and, in last place, photogrammetric technique (AL3).

Table 5. Consistency ratios for judgement and alternatives matrices; CR higher or equal to 0.10 marked in green

Position number	Group	Description	CR
1.	Decision-makers judgement matrices	Judgement matrix for 1st expert	0.035
2.		Judgement matrix for 2nd expert	0.035
3.		Judgement matrix for 3rd expert	0.035
4.	Judgement matrices of alternatives	Judgement matrix with respect to criterion C1	0.035
5.		Judgement matrix with respect to criterion C2	0.028
6.		Judgement matrix with respect to criterion C3	0.005
7.		Judgement matrix with respect to criterion C4	0.005
8.		Judgement matrix with respect to criterion C5	0.068
9.		Judgement matrix with respect to criterion C6	0.068
10.		Judgement matrix with respect to criterion C7	0.068
11.		Judgement matrix with respect to criterion C8	0.068
12.		Judgement matrix with respect to criterion C9	0.068

Table 6. Judgement matrix of 1st expert

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1.00	0.17	0.25	0.50	0.33	2.00	0.20	0.14	3.00
C2	6.00	1.00	3.00	5.00	4.00	7.00	2.00	0.50	8.00
C3	4.00	0.33	1.00	3.00	2.00	5.00	0.50	0.25	6.00
C4	2.00	0.20	0.33	1.00	0.50	3.00	0.25	0.17	4.00
C5	3.00	0.25	0.50	2.00	1.00	4.00	0.33	0.20	5.00
C6	0.50	0.14	0.20	0.33	0.25	1.00	0.17	0.13	2.00
C7	5.00	0.50	2.00	4.00	3.00	6.00	1.00	0.33	7.00
C8	7.00	2.00	4.00	6.00	5.00	8.00	3.00	1.00	9.00
C9	0.33	0.13	0.17	0.25	0.20	0.50	0.14	0.11	1.00

Table 7. Judgement matrix of 2nd expert

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1.00	0.20	0.50	2.00	4.00	3.00	0.33	0.25	5.00
C2	5.00	1.00	4.00	6.00	8.00	7.00	3.00	2.00	9.00
C3	2.00	0.25	1.00	3.00	5.00	4.00	0.50	0.33	6.00
C4	0.50	0.17	0.33	1.00	3.00	2.00	0.25	0.20	4.00
C5	0.25	0.13	0.20	0.33	1.00	0.50	0.17	0.14	2.00
C6	0.33	0.14	0.25	0.50	2.00	1.00	0.20	0.17	3.00
C7	3.00	0.33	2.00	4.00	6.00	5.00	1.00	0.50	7.00
C8	4.00	0.50	3.00	5.00	7.00	6.00	2.00	1.00	8.00
C9	0.20	0.11	0.17	0.25	0.50	0.33	0.14	0.13	1.00

Global priorities of criteria and synthesised priorities for alternatives

Table 12 summarises the results of the analyses obtained in the Super Decisions software. Global priorities were assigned to individual criteria and experts (1st = most important, 9th = least important). The bottom part of the table shows the ranking of criteria. The highest priority criteria were C2 and C8 for each of the three experts. This means that the experts were primarily guided by the accuracy of the measurement system (C2) or the overall ability to detect contraction. For experts 1 and 2, the criterion of the degree of complexity of the

Table 8. Judgement matrix of 3rd expert

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1.00	0.11	0.17	0.50	0.14	0.20	0.25	0.13	0.33
C2	9.00	1.00	4.00	8.00	3.00	5.00	6.00	2.00	7.00
C3	6.00	0.25	1.00	5.00	0.50	2.00	3.00	0.33	4.00
C4	2.00	0.13	0.20	1.00	0.17	0.25	0.33	0.14	0.50
C5	7.00	0.33	2.00	6.00	1.00	3.00	4.00	0.50	5.00
C6	5.00	0.20	0.50	4.00	0.33	1.00	2.00	0.25	3.00
C7	4.00	0.17	0.33	3.00	0.25	0.50	1.00	0.20	2.00
C8	8.00	0.50	3.00	7.00	2.00	4.00	5.00	1.00	6.00
C9	3.00	0.14	0.25	2.00	0.20	0.33	0.50	0.17	1.00

Table 9. Judgement matrices for alternatives with respect to criterion C1, C2 and C3

C1	AL1	AL2	AL3	Weight	C2	AL1	AL2	AL3	Weight	C3	AL1	AL2	AL3	Weight
AL1	1.00	4.00	9.00	0.713	AL1	1.00	0.11	0.33	0.071	AL1	1.00	0.20	1.00	0.149
AL2	0.25	1.00	4.00	0.220	AL2	9.00	1.00	5.00	0.748	AL2	5.00	1.00	4.00	0.690
AL3	0.11	0.25	1.00	0.067	AL3	3.00	0.20	1.00	0.180	AL3	1.00	0.25	1.00	0.161

Table 10. Judgement matrices for alternatives with respect to criterion C4, C5 and C6

C4	AL1	AL2	AL3	Weight	C5	AL1	AL2	AL3	Weight	C6	AL1	AL2	AL3	Weight
AL1	1.00	4.00	8.00	0.701	AL1	1.00	5.00	9.00	0.735	AL1	1.00	5.00	9.00	0.735
AL2	0.25	1.00	4.00	0.227	AL2	0.20	1.00	4.00	0.199	AL2	0.20	1.00	4.00	0.199
AL3	0.13	0.25	1.00	0.072	AL3	0.11	0.25	1.00	0.065	AL3	0.11	0.25	1.00	0.065

Table 11. Judgement matrices for alternatives with respect to criterion C7, C8 and C9

C7	AL1	AL2	AL3	Weight	C8	AL1	AL2	AL3	Weight	C9	AL1	AL2	AL3	Weight
AL1	1.00	0.20	0.11	0.062	AL1	1.00	0.20	0.11	0.062	AL1	1.00	0.20	0.11	0.062
AL2	5.00	1.00	0.25	0.236	AL2	5.00	1.00	0.25	0.236	AL2	5.00	1.00	0.25	0.236
AL3	9.00	4.00	1.00	0.701	AL3	9.00	4.00	1.00	0.701	AL3	9.00	4.00	1.00	0.701

measured geometry (C7) was less important (third place in the ranking). For expert 3, the criterion of the required knowledge and experience of the metrologist performing the measurement ranked third.

The criterion of a metrologist's experience and knowledge ranks only 8th in the ranking, which may seem counterintuitive. This ranking reflects that a decision-maker, such as a manager, aims to achieve the best possible results from the metrologist while minimising costs, including training expenses. Therefore, the low ranking of C5 aligns with practical considerations.

Aggregation of local priorities

The global priorities of alternatives determined using the linear rule for each expert are presented in the chart below (Figure 8). The largest bar in the chart indicates that the expert will be inclined to choose a given measurement technique to detect shrinkage in 3D prints. Expert 1 will choose the third measurement technique, i.e. photogrammetry, while Experts 2 and 3 will be inclined to use mechanical tools, i.e. a digital calliper or a linear ruler. It is worth noting that the decision-maker working at a university as a

Table 12. Global priorities and ranking of criteria C1–C9 for each expert

Parameter	Criteria								
	C1	C2	C3	C4	C5	C6	C7	C8	C9
Expert 1	0.035	0.222	0.107	0.051	0.074	0.025	0.155	0.312	0.018
Expert 2	0.074	0.312	0.107	0.051	0.025	0.035	0.155	0.222	0.018
Expert 3	0.018	0.312	0.107	0.025	0.155	0.074	0.051	0.222	0.035
Priorities rank for Expert 1	7th	2nd	4th	6th	5th	8th	3rd	1st	9th
Priorities rank for Expert 2	5th	1st	4th	6th	8th	7th	3rd	2nd	9th
Priorities rank for Expert 3	9th	1st	4th	8th	3rd	5th	6th	2nd	7th

Note: shading highlights the three highest-priority criteria for each expert to allow a clear visual comparison of their decision preferences. A lower numerical rank indicates a higher priority.

research and teaching staff member is the least likely to use visual assessment to detect shrinkage in 3D prints.

University research and teaching staff are least likely to choose visual inspection for detecting shrinkage in 3D prints.

Sensitivity analysis

The relative importance assigned to two criteria and/or changes in their ranking hierarchy directly affect the global priorities of alternatives. In practice, this means that the decision regarding the selection of a measurement technique may shift in favour of one option over another. The data presented in the table below (Table 13) show whether increasing the weight of one of the three most significant criteria for a given expert by 25% results in a change of preference from one alternative to another. This threshold is referred to as the Rank Reversal Point (RRP) — the point at which both alternatives become equivalent in terms of their overall priority.

For Expert 1, the most important criteria are C8, C2, and C7 (Table 12). When the weight of criterion C8 increases up to the threshold value of 25.0%, the decision to select mechanical measurement tools remains unchanged. Raising the
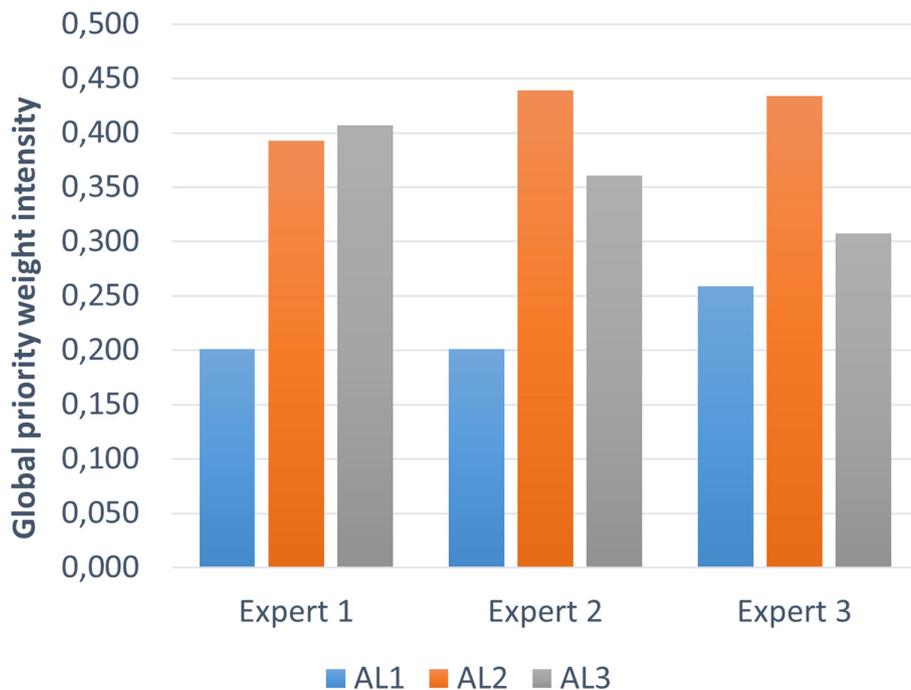

Figure 8. Global priorities of measurement alternatives for decision-makers. The intensity values represent normalised global priority weights (0–1 scale) calculated from the AHP model. AL1 – visual inspection, AL2 – mechanical tools, AL3 – photogrammetry

importance of criterion C2 to 25.0% does not alter the choice of measurement technique; at this level, mechanical tools and photogrammetry become equivalent. However, when the weight of criterion C7 increases by 11.0%, a RRP occurs – below this value, Expert 1 prefers mechanical tools, while above it, photogrammetry becomes the favoured technique. For Expert 2, the key criteria are C2, C8, and C7 (Table 12).

An increase in the weight of C2 to 21.0 % leads to an RRP, shifting the decision from photogrammetry to mechanical tools. For criteria C8 and C7, increasing their weights does not affect the final decision — the preferred technique remains unchanged. For Expert 3, the most important criteria are C2, C8, and C5 (Table 12).

An increase in the weight of C2 results in a recommendation to change the preferred technique from photogrammetry to mechanical tools. Rising weights of C8 and C5 do not cause any change in the measurement method selection.

Possible real scenarios

Scenario No. 1 (Expert 1 – photogrammetry). The scenario involves detecting print shrinkage using photogrammetry, where the key criteria are C8, C2 and C7 (Table 12). The least important criteria are C9, C6 and C1. The scenario assumes that the research is conducted by a university researcher and teaching staff member. In this

scenario, both maximum accuracy and the ability of the measurement technique to detect shrinkage in the most complex 3D print geometries are important. This would lead to obtaining general information and relationships between print shrinkage and 3D printer parameters and the complexity of the measured prints. The potential for automation, the cost of the measurement system and the measurement time in scientific research is irrelevant.

Scenario No. 2 (Experts 2 and 3 – mechanical tools). In this case, the scenario assumes that the measurements are also carried out by a university researcher and teaching staff member, but the most important criteria are C2 and C8, while the least important are C9 and C1 (Table 12). The scenario may be applicable in the research on 3D print shrinkage, where measurement accuracy is important (detection of the smallest signs of shrinkage), a high overall ability of the technique to detect shrinkage is required, and the ability of the selected measurement technique to provide correct results even for very complex geometries is important. In this scenario, implementation of the measurement technique into the production line is not important, nor is the cost of the measuring tool relevant in the case of scientific or basic research conducted by a researcher. It should also be noted here that the measurement will be performed using mechanical tools, the accuracy of

Table 13. Sensitivity of measurement - alternative rankings for each expert

Expert	Criterion rank	Key criterion	Rank reversal point	Final ranking of measurement alternatives
Expert 1	1st	C8 Shrinkage detection	-	AL2 > AL3 > AL1
	2nd	C2 Accuracy	-	C2 = 25.0% AL2 = AL3 > AL1
	3rd	C7 Geometry complexity	11.0%	For C7 < 11.0% AL2>AL3>AL1 For C7 > 11.0% AL3>AL2>AL1
Expert 2	1st	C2 Accuracy	21.0%	For C2 < 21.0% AL3>AL2>AL1 For C2 > 21.0% AL2>AL3>AL1
	2nd	C8 Shrinkage detection	-	AL2 > AL3 > AL1
	3rd	C7 Geometry complexity	-	AL2 > AL3 > AL1
Expert 3	1st	C2 Accuracy	11.8%	For C2<11.8% AL3>AL2>AL1 For C2>11.8% AL2>AL3>AL1
	2nd	C8 Shrinkage detection	-	AL2 > AL3 > AL1
	3rd	C5 Experience	-	AL2 > AL3 > AL1

Note: The table summarises the influence of changes in each expert's key criteria on the ranking of measurement alternatives. "Rank reversal point" indicates the threshold at which the preferred alternative changes.AL1 – visual inspection, AL2 – mechanical tools, AL3 – photogrammetry.

which decreases with increasing complexity of the 3D print geometry.

Practical applications

Each of the measurement techniques discussed in this study can be applied both in industrial quality assurance departments and in research and development (R&D) laboratories.

For laboratories operating within academic institutions, the use of photogrammetry is the most justified, as it enables detailed geometric analysis and visualisation of shrinkage effects under controlled conditions.

In contrast, industry, which is inherently focused on efficiency and maintaining high product quality, can achieve the best results using mechanical tools. By applying digital calliper and linear rulers, it is possible to identify the presence of shrinkage in prints with relatively simple geometries. In industrial environments, additional value can be achieved through the use of custom reference gauges and templates manufactured within appropriate tolerance limits.

CONCLUSIONS

The novelty of this work lies in integrating Analytic Hierarchy Process with experimental evaluation of FDM dimensional accuracy, focusing on the selection of measurement techniques rather than process parameters. To the authors' knowledge, this is the first study to systematically compare photogrammetry, mechanical tools, and visual inspection within a unified analytic hierarchy process framework for additive manufacturing metrology.

The measurement techniques presented in this publication – visual assessment, mechanical tools (digital calliper and a linear ruler) and photogrammetry – can be successfully used to detect shrinkage in prints with various geometries. However, the prints with complex and highly complex geometries may pose a problem.

The measurement techniques presented in the publication can be successfully compared with each other in terms of predefined criteria. The criteria for selecting a measurement technique often prove to be competitive, e.g. the lower the cost of the measurement system, the lower the accuracy. Decision-makers usually want low costs and maximum measurement accuracy.

It was shown that the research-and-teaching staff profile does not always lead to selecting the same measurement technique for detecting shrinkage in 3D prints. Expert 1, according to the ranking of criteria indirectly presented in the judgement matrix, will be inclined to choose the photogrammetric measurement technique. Experts 2 and 3, despite holding the same position at a university, will be inclined to choose a digital calliper and a linear ruler to detect shrinkage in 3D prints over photogrammetric techniques and visual assessment.

The key criteria used by all Experts include C2 (precision of the measurement technique) and C8 (overall shrinkage detection capability), which rank 1st and 2nd in the criteria ranking.

The aggregation of local weights and the sensitivity analysis showed that decision-makers (Experts 1, 2 and 3) can have a high level of confidence in the results.

Future work should extend the analytic hierarchy process – based comparison to different materials, printer types, and expert profiles, and test automated or AI-assisted photogrammetry to make measurements more reliable and less dependent on the operator, especially in academic research environments, where improving measurement consistency can support better training and validation of metrological methods.

During the preparation of this scientific publication, numerous questions arose that remained unanswered. The authors of this publication see this as an opportunity for further research and analysis. In particular, the following should be analysed:

- different profiles of decision-makers and their impact on the decision-making process; for example: profiles of a single-person business/amateur hobbyist and a medium-sized enterprise (MES) owner with a fleet of 3D printers and a need for product quality management,
- the use of other, more advanced measurement techniques, e.g. coordinate measuring machines, structured light or laser scanners,
- verification of the ability of measurement techniques to produce 3D prints with much more complex geometry and made of filament with different shrinkage,
- consistency in the decision to select the appropriate measurement technique among a larger number of experts,
- the impact of the research results presented in this publication on changes in product flow chains within the company and its development.

REFERENCES

1. Additive Manufacturing Market Report 2025. Research and Markets, 2025. https://www.researchandmarkets.com/reports/5807051/additive-manufacturing-market-report (Accessed: 10.10.2025).

2. Budzik G., Woźniak J., Przeszłowski Ł., Druk 3D jako element Przemysłu Przyszłości. Analiza rynku i tendencje rozwoju. 1st Edition. Rzeszów, Poland: Oficyna Wydawnicza Politechniki Rzeszowskiej; 2022 (in Polish).

3. Kantaros A., Katsantoni M., Ganetsos T., Petrescu N. The evolution of thermoplastic raw materials in high-speed FFF/FDM 3D printing era: Challenges and opportunities. Materials 2025; 18: 1–26. https://doi.org/ 10.3390/ma18061220

4. Wojnowski J., Iwańkowicz R. Identyfikacja warunków uruchomienia produkcji masowej wyrobów elastomerowych przy użyciu technologii przyrostowych. Management and Quality. 2024; 6(3): 248–262 (in Polish).

5. Sola A. Materials requirements in fused filament fabrication: A framework for the design of next-generation 3D printable thermoplastics and composites. Macromol. Mater. Eng. 2022; 307(10): 1–40. https://doi.org/10.1002/mame.202200197

6. Sani A.R., Zolfagharian A., Kouzani A.Z. Artificial intelligence-augmented additive manufacturing: insights on closed-loop 3D printing. Adv. Intell. Syst. 2024; 6: 1–19. https://doi.org/10.1002/aisy.202400102

7. He H., Zhu Z., Zhang Y., Zhang Z., Famakinwa T., Yang R. Machine condition monitoring for defect detection in fused deposition modelling process: a review. Int. J. Adv. Manuf. Technol. 2024; 132(7–8): 3149–3178. https://doi.org/10.1007/s00170-024-13630-8

8. RepRap. https://reprap.org/wiki/Print_Troubleshooting_Pictorial_Guide (Accessed: 10.10.2025).

9. Koers T., Magyar B. Compensation of the shrinkage behavior occurring in cylindrical components in the FDM process. Macromol Symp. 2023; 411(1): 1–3. https://doi.org/10.1002/masy.202200185

10. He H., Zhu Z., Zhang Y., Zhang Z., Famakinwa T., Yang R. (Chunhui). Development of an integrated testing and calibration approach for fused filament fabrication of polylactic acid. Polym Test. 2025; 148: 1–18. https://doi.org/10.1016/j.polymertesting.2025.108834

11. Ramian J., Ramian J., Dziob D. Thermal deformations of thermoplast during 3D printing: Warping in the case of ABS. Materials. 2021; 14(22): 1–16. https://doi.org/10.3390/ma14227070

12. Frank D., Chandra R.L., Schmitt R. An investigation of cause-and-effect relationships within a 3d-printing system and the applicability of optimum printing parameters from experimental models to different printing jobs. 3D Print Addit Manuf. 2015; 2(3): 131–139. https://doi.org/10.1089/3dp.2015.0010

13. Minetola P., Calignano F., Galati M. Comparing geometric tolerance capabilities of additive manufacturing systems for polymers. Addit Manuf. 2020; 32: 1–10. https://doi.org/10.1016/j.addma.2020.101103

14. De Bruijn A.C., Gómez-Gras G., Pérez M.A. A comparative analysis of chemical, thermal, and mechanical post-process of fused filament fabricated polyetherimide parts for surface quality enhancement. Materials. 2021; 14(19): 1–14. https://doi.org/10.3390/ma14195880

15. Riva L., Fiorentino A., Ceretti E. Characterization of chemical surface finishing with hot acetone vapours on ABS parts fabricated by FFF. Prog. Addit. Manuf. 2022; 7(4): 785–796. https://doi.org/10.1007/s40964-022-00265-y

16. Abdulridha H.H., Abbas T.F., Bedan A.S. Investigate the effect of chemical post processing on the surface roughness of fused deposition modeling printed parts. Adv. Sci. Technol. Res. J. 2024; 18(2): 47–60. https://doi.org/10.12913/22998624/183528

17. Bermudo Gamboa C., Martín Béjar S., Trujillo Vilches F.J., Sevilla Hurtado L. Geometrical analysis in material extrusion process with polylactic acid (PLA)+carbon fiber. Rapid Prototyp J. 2022; 29(11): 21–39. https://doi.org/10.1108/RPJ-09-2022-0294

18. Aljazara A., Tuhaimer N.A., Alawwad A., Hani K.B., Qusef A.D., Alsalhi N.R., Quality of 3D printed objects using fused deposition modeling (FDM) technology in terms of dimensional accuracy. Int. j. online biomed. eng. 2023; 19(14): 45–62. https://doi.org/10.3991/ijoe.v19i14.43761

19. Ullah I., Wasif M., Tufail M. Analysis of shrinkage and dimensional accuracy of additively manufactured tooling for the composite manufacturing. Int. J. Interact. Des. Manuf. 2024; 18(2): 673–684. https://doi.org/10.1007/s12008-023-01640-x

20. Abdulridha H.H., Obaeed N.H., Jaber A.S. Optimization of fused deposition modeling parameters for polyethylene terephthalate glycol flexural strength and dimensional accuracy. Adv. Sci. Technol. Res. J. 2025; 19(4): 50–64. https://doi.org/10.12913/22998624/200088

21. Mittal Y.G., Patil Y., Kamble P.P., Gote G.D., Mehta A.K., Karunakaran K.P. Warpage control in thermoplastic ABS parts produced through material extrusion (MEX)-based fused deposition modeling (FDM). Rapid Prototyp J. 2024; 1–14. https://doi.org/10.1108/RPJ-01-2024-0023

22. Reddy M.V., Eachempati K, Gurava Reddy A.V., Mugalur A. Error analysis: How precise is fused deposition modeling in fabrication of bone models in comparison to the parent bones? Indian J Orthop.

2018; 52(2): 196–201. https://doi.org/10.4103/or-tho.IJOrtho_312_16

23. Guerra M.G., Galantucci L.M., Lavecchia F., De Chiffre L. Reconstruction of small components using photogrammetry: A quantitative analysis of the depth of field influence using a miniature step gauge. Metrol. Meas. Syst. 2021; 28(2): 323–342. https://doi.org/10.24425/mms.2021.136610

24. Lužanin O., Puškarević I. Investigation of the accuracy of close-range photogrammetry – a 3D printing case study. J. Graph. Eng. Des. 2015; 6(2): 13–18. https://doi.org/10.24867/JGED-2015-2-013

25. Pirlo R., Guerra M.G., Lavecchia F., Galantucci L.M. Evaluation of a photogrammetry-based scanner for measuring small-sized features in an additive manufacturing repair process chain. Int. J. Adv. Manuf. Technol. 2025; 136(11): 5581–5598. https://doi.org/10.1007/s00170-025-15153-2

26. Zheng F., Wackrow R., Meng F.R., Lobb D., Li S. Assessing the accuracy and feasibility of using close-range photogrammetry to measure channelized erosion with a consumer-grade camera. Remote Sens (Basel). 2020; 12(11): 1–21. https://doi.org/10.3390/rs12111706

27. Enesi I., Kuqi A. Measurement Accuracy of 3D Reconstruction for Small Objects. J Comput Eng Inf Technol. 2023; 12(2): 1-6. https://doi.org/10.4172/2324-9307.1000259

28. Budzik G., Woźniak J., Paszkiewicz.A, Przeszłowski Ł., Dziubek T., Dębski M. Methodology for the quality control process of additive manufacturing products made of polymer materials. Materials. 2021; 14(9): 1–19. https://doi.org/10.3390/ma14092202

29. Lim Y.C., Abdul Shakor A.S., Shaharudin R. Reliability and Accuracy of 2D Photogrammetry: A Comparison With Direct Measurement. Front Public Health. 2022; 9: 1–9. https://doi.org/10.3389/fpubh.2021.813058

30. Guerra M.G., Lavecchia F., Maggipinto G., Galantucci L.M., Longo G.A. Measuring techniques suitable for verification and repairing of industrial components: A comparison among optical systems. CIRP J Manuf Sci Technol. 2019; 27: 114–123. https://doi.org/10.1016/j.cirpj.2019.09.003

31. Aydin F., Gümüş B. Comparative analysis of multi-criteria decision making methods for the assessment of optimal SVC location. Bull. Pol. Acad. Sci.: Tech. Sci. 2022; 70(2): 1–11. https://doi.org/10.24425/bpasts.2022.140555

32. Saaty T.L., Katz J.M. How to make a decision: The analytic hierarchy process. Eur.

J. Oper. Res. 1990; 48: 9–26. https://doi.org/10.1016/0377-2217(90)90057-I

33. Vora H.D., Sanyal S. A comprehensive review: metrology in additive manufacturing and 3D printing technology. Prog. Addit. Manuf. 2020; 5(4): 319–353. https://doi.org/10.1007/s40964-020-00142-6

34. Pazhamannil R.V., Jishnu Namboodiri V.N., Govindan P., Edacherian A. Property enhancement approaches of fused filament fabrication technology: A review. Polym. Eng. Sci. 2022; 62: 1356–1376. https://doi.org/10.1002/pen.25948

35. Enesi I., Kuqi A. Performance Analysis for 3D reconstruction objects in meshroom and agisoft—A comparative study. Int. j. online biomed. eng. 2023; 19(5): 22–41. https://doi.org/10.3991/ijoe.v19i05.37257

36. Enesi I., Kuqi A., Zanaj E. Quality of 3D reconstruction based on photogrammetry for small objects, a case study. IOP Conf Ser Mater Sci Eng. 2022; 1254(1): 012039. https://doi.org/10.1088/1757-899X/1254/1/012039

37. Verykokou S., Ioannidis C. An overview on image-based and scanner-based 3D modeling technologies. Sensors (Basel). 2023; 23(2): 1–22. https://doi.org/10.3390/s23020596

38. Cremades L.V., Ponsich A. Simple and objective determination of criteria weights for evaluating alternatives when using the Analytic Hierarchy Process. Int. j. anal. hierarchy process. 2024; 16(3): 1–23. https://doi.org/10.13033/ijahp.v16i3.1177

39. Abdelaal O., Aldahash S.A. Realization of impression evidence with reverse engineering and additive manufacturing. Appl. Sci. (Switz.). 2024; 14(13): 1–29. https://doi.org/10.3390/app14135444

40. Maletič D., Maletič M., Lovrenčić V., Al-Najjar B., Gomišček B. An Application of Analytic Hierarchy Process (AHP) and Sensitivity Analysis for Maintenance Policy Selection. Organizacija. 2014; 47(3): 177–188. https://doi.org/10.2478/orga-2014-0016

41. Mietliński P., Gapiński B., Krolczyk J.B., Niesłony P., Bogdan-Chudy M., Trych-Wildner A. Review of surface metrology artifacts for additive manufacturing. Bull. Pol. Acad. Sci. 2024; 72(6): 1–10. https://doi.org/10.24425/bpasts.2024.151380

42. Liu W.D., Chen X., Zeng, W.H., Sun W.J., Gorman D., Wilson A., Qi Q.F., Scott, P., Jiang X.Q., Lou S., Dimensional measurements of additive manufacturing parts: A comparison of X-ray computed tomography and coordinate-measuring system using physical and simulation approaches. Meas. 2024; 229: 1–4. https://doi.org/10.1016/j.measurement.2024.114414