Comparative analysis of 3D printing technologies (FDM and SLA) for the production of complex geometry parts

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Abstract— **This paper conducts a comparative analysis of 3D printing technologies, specifically Fused Deposition Modeling (FDM) and Stereolithography (SLA), in the production of complex geometric parts – spur gear. The research employs a multi-criteria analysis approach, specifically the Analytic Hierarchy Process (AHP) method. Two alternatives, FDM and SLA technologies, are developed and scrutinized. The assessment of these alternatives is based on six chosen criteria: the complexity of starting a 3D printer, printing time, dimensional stability, the complexity of the part geometry, mechanical properties of the printed part, and part postprocessing. The analysis results indicate that, based on the chosen criteria, Stereolithography (SLA) emerges as the optimal 3D printing technology for producing complex geometry parts.**

Keywords-additive manufacturing; 3D printing; AHP method; complex geometry parts.

I. Introduction

Additive manufacturing (AM), also known as 3D printing, is a digital fabrication process wherein materials are incrementally added layer by layer to create objects from computer-aided design models directly. Over the past two decades, 3D printing has garnered significant popularity, thanks to its numerous advantages, such as unlimited design flexibility and the ability to produce cost-effective and multifunctional objects featuring intricate and complex structures quickly. As a result, 3D printing has emerged as a viable manufacturing technique in rapid prototyping and various engineering domains, including mechanical engineering, civil engineering, aerospace, electronics, biomedical, and more [1]. Numerous AM methods exist to facilitate 3D printing across a diverse range of materials, including metals, polymers, polymer composites, ceramics, and cement.

The process of choosing suitable 3D printing technology is intricate, demanding, and multifaceted for those in search of technological solutions. Given that various 3D printing technologies have been developed so far, the choice of an adequate technology depends on numerous influencing factors. Selecting an adequate technology proves challenging due to the absence of benchmark standards and limited industry experience with many of these systems.

Previous efforts have been made to compare various 3D printing technologies through benchmarking studies conducted by either user companies or independent researchers [2]. Some authors focus on evaluating three distinct 3D printing technologies: Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Material Jetting (MJ). Each technology underwent testing, with a particular emphasis on assessing the accuracy and resolution of the printed elements [3]. Others compared 3D printing technologies to printed retainers' precision, trueness, and accuracy [4]. Also, research was conducted to identify the strengths and weaknesses of Fused Deposition Modeling (FDM) and Masked Stereolithography (MSLA) technologies, with a specific focus on assessing their appropriateness for unit and hobby production [5]. Certain authors undertake a comparison to assess whether mandibular models created through various established and readily accessible 3D printing technologies demonstrate comparable accuracy [6]. To compare and choose different 3d printing technologies, the authors used different decision-making tools [7]. Also, some authors have developed different models to choose 3d printing technology [8].

This paper conducts a comparative analysis of 3D printing technologies, specifically Fused Deposition Modeling (FDM) and Stereolithography (SLA), in producing complex geometric parts. The research employs a multi-criteria analysis approach, specifically the Analytic Hierarchy Process (AHP) method. Two alternatives, FDM and SLA technologies, are developed and scrutinized. The assessment of these alternatives is based on six chosen criteria: the complexity of starting a 3D printer, printing speed, dimensional stability, the complexity of the part geometry, mechanical properties of the printed part, and part postprocessing.

II. MATERIAL AND METHODS

A. 3D printing technologies

Various 3D printing technologies exist, differing in their processes for depositing materials to generate the desired 3D model. These technologies employ diverse methods, including melting materials, solidifying powders, or liquidizing substances. The fundamental processes encompass Material Extrusion, Powder Bed Fusion, Vat Photopolymerization, and Sheet Lamination.

Material Extrusion involves the additive manufacturing process of layer creation by mechanically extruding molten thermoplastic material onto a build platform. In Powder Bed Fusion, an electron beam melts the spread material on a powder bed. Vat Photopolymerization employs an ultraviolet laser to polymerize UV resins, forming a layer of solidified material. Sheet Lamination utilizes a controlled laser to cut coated material on a building platform [9]. The primary advantages of using these technologies over traditional manufacturing technologies lie in the capability to fabricate intricate, customized models with high precision. However, a notable drawback of 3D printing technologies is their limited potential to construct large-scale models [10].

Using the principles above, various 3D printing technologies have been developed which are the most common used explained below:

Stereolithography (SLA) employs an ultraviolet (UV) laser focused on the top surface of the resin, causing precise hardening at the laser's impact points. The advantages of this technology are a less time-consuming process, customized coloring, detailed large prints, high quality, and fine resolution of parts. Their disadvantages are limitations in materials usage, possible brittle components, expensive processes, and requiring support structures for parts with overhangs.

Fused Deposition Modeling (FDM) utilizes a continuous filament of thermoplastic material, constructing a part by heating and extruding the filament through a moving, heated extrusion print head, one layer at a time. The advantages of this technology usage are the possibility of making parts of different materials various colors, simplicity, and high speed. Their disadvantages are: require supports for complex structures, weak mechanical properties, limited resolution, and poor surface finish.

Selective Laser Sintering (SLS) uses a high-power laser to sinter small parts of powdered material at specific points across a powder bed. Advantages of this technology usage are the possibility of making large part sizes, the possibility of making parts of different materials, fast procedure, high strength, and stiffness. Their disadvantages are: require post-processing and expensive process.

Digital Light Processing (DLP) involves a digital projector screen flashing a single image of each layer across the entire platform simultaneously. The advantages of this technology usage are high accuracy, fine resolution, the possibility of making parts of different materials, and a fast process. Their disadvantages are expensive processes and require post-processing.

B. The Analytic Hierarchy Process (AHP)

For the comparison of 3D printing technologies for the production of parts of complex geometry, the method of multi-criteria analysis Analytic Hierarchy Process (AHP) was used. The AHP is a method for making decisions in situations involving multiple criteria. It is commonly applied to address complex decision-making challenges across various fields, including manufacturing, environmental management, power and energy, transportation, and construction. Some authors also used the AHP method for the selection of low-cost 3D printers [11], as well as one of the decision-making tools when applying FDM 3D printing technology [12].

The hierarchical structure of AHP provides decision-makers with a clear understanding of problems by organizing them into relevant criteria and sub-criteria. This comparison facilitates the effective evaluation of optimal solutions. The AHP decision-making process consists of four steps: 1) defining the problem and identifying the desired knowledge; 2) structuring the decision hierarchy based on the decision goal; 3) creating a set of pair-wise comparison matrices; 4) using the priorities derived from these comparisons to weigh priorities at the next level.

III. EXPERIMENTAL RESEARCH

The comparison of 3D printing technologies of parts with complex geometry was performed on the example of a spur gear with module 1.75, which is shown in Figure 1.

Figure 1. Spur gear

A. Alternative Description

To compare 3D printing technologies for the production of parts of complex geometry, two technologies (alternatives) were used:

Alternative 1 – FDM 3D printing technology on printer Sindoh DP200, machine calibration is automatic, nozzle diameter 0.4 mm. Printing material is PLA. Process parameters are layer thickness 0.2 mm, extrusion width 0.4 mm, infill 70%, bed temperature 50 ^{o}C, nozzle temperature 220 ^{o}C, and printing time 1 h 17 min (Figure 2).

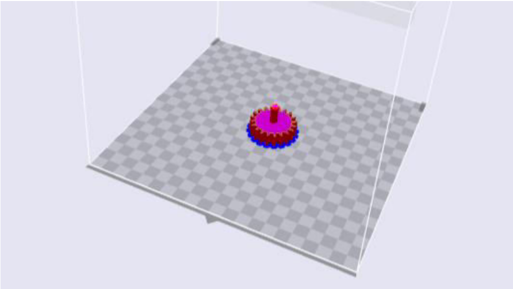


Figure 2. Position of the printed part in FDM printer

Alternative 2 – SLA 3D printing technology on printer Enycubic MONO X. The printing material is resin. Process parameters are: fill cure depth 70%, layer thickness 0.2 mm, layer width 0.05 mm, post-curing 5 min, printing time 47 min (Figure 3).

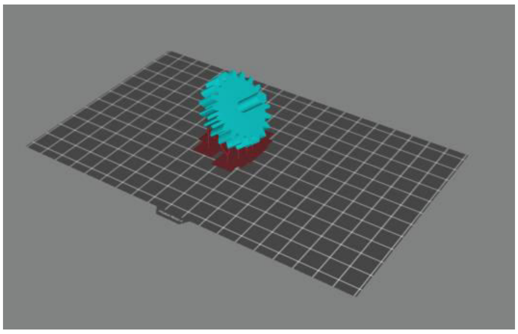


Figure 3. Position of printed part in SLA printer

B. *Criteria Selection and Determination of Values*

The following were chosen as criteria based on which 3D printing technologies were compared: the complexity of starting a 3D printer, printing time, dimensional stability, the complexity of the part geometry, mechanical properties of the printed part, and part postprocessing.

The complexity of starting a 3D printer – It involves importing CAD models, slicing, placing supports, and setting printing parameters.

Printing time – Represents the total printing time.

Dimensional stability – Implies the tolerance of shape, position, and dimensions to the CAD model. The measurement and comparison of characteristic gear diameters, thickness, and modulus with the nominal values was carried out.

The complexity of the part geometry – Represents freedom of forms and freedom of materials.

Mechanical properties of the printed part – Two mechanical properties of printed parts are assessed, including strength and stiffness. The measurements conform to relevant standards and are conducted using calibrated devices. The results obtained from these mechanical property assessments are consolidated into a single criterion. A 5-level scale, ranging from 1 (indicating the worst) to 5 (representing the best), is employed to evaluate this criterion.

Part postprocessing – It includes removing of printing bed, removing the support, and finishing printed surfaces. The time required for the previously mentioned activities was measured and compared.

The assessment of criteria was conducted by measuring, taking into account the printing time, dimensional stability, and mechanical properties of the printed part. Additionally, practical experience, encompassing factors such as the complexity of starting a 3D printer, the complexity of the part geometry, and part postprocessing played a pivotal role in the evaluation of criteria. The details of the criterion evaluation are outlined in Table 1.

TABLE I. CRITERIA VALUES

Criteria	Alternative 1	Alternative 2
The complexity of starting a 3D printer	50%	100%
Printing time	1 h 17 min	42 min
Dimensional stability	50%	100%
The complexity of the part geometry	60%	100%
Mechanical properties of the printed part	5	2
Part postprocessing	25%	75%

IV. RESULTS AND DISCUSSION

The criteria prioritization was carried out by experts dealing with 3D printing, based on which a pair-wise comparison was made, and criteria weight, was obtained (Figure 4).

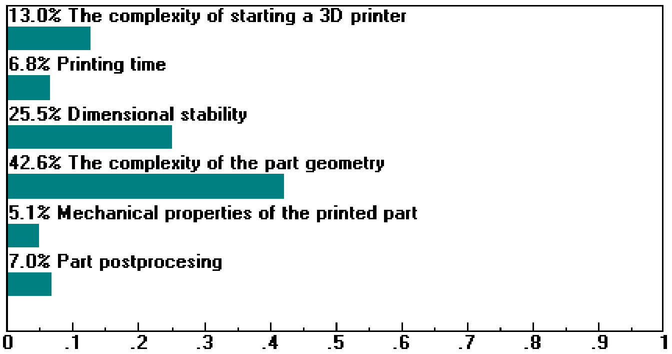


Figure 4. Criteria priorities concerning the goal

Based on the criteria weights, an alternative ranking was conducted which is illustrated in Fig. 5.

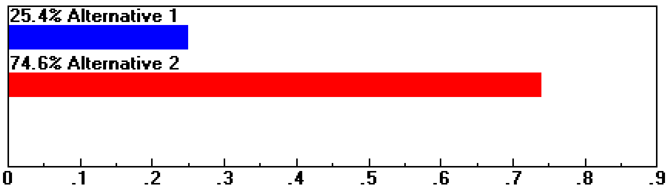


Figure 5. Ranking of alternatives

Given that one of the most significant characteristics of additive technologies is freedom of form, i.e. the easy creation of complex geometric forms, the highest priority was given to the criterion of the complexity of the part geometry. Therefore, it is expected that SLA technology according to this criterion will be dominant. It follows from this that dimensional stability is much better with SLA technology, because the part is obtained by polymerization excited by a laser beam, and not by a predefined nozzle diameter.

As the SLA technology is based on the laser polymerization process, the resin printer slicer software requires much more data and a great deal of operator experience when setting it up, compared to the FDM printer slicer software, where most of the parameters are automatically set for the types of materials, it is expected that according to the complexity criterion of starting a 3D printer has the advantage of FDM technology.

When it comes to the criterion of mechanical properties, FDM technology has a significant advantage, because the material is continuously applied, while with SLA technology it is point-wise, which affects the mechanical properties. This is why FDM technology is slower than SLA technology.

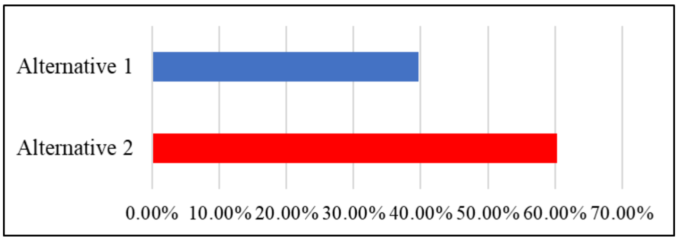
To assess the influence of prioritizing criteria weights on alternative rankings, a sensitivity analysis is conducted. This analysis involves exploring various scenarios where criteria weighting priorities are altered. If consistent rankings are achieved across most scenarios, the outcome is deemed robust. In this study, the following scenarios were examined:

Scenario 1: All criteria are assigned an equal weighting factor of 16.67%.

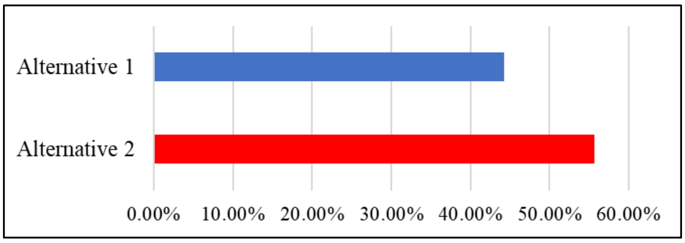
Scenario 2: The criteria Dimensional stability and Mechanical properties of the printed part each receive a weighting factor of 30%, totaling 60%, while the remaining criteria are assigned a combined weighting factor of 40%.

Scenario 3: The criteria The complexity of starting a 3D printer, Printing time, and Part postprocessing each receive a weighting factor of 23.33%, totaling 70%, whereas the other criteria collectively hold a weighting factor of 30%, with each of them having a weighting factor of 10%.

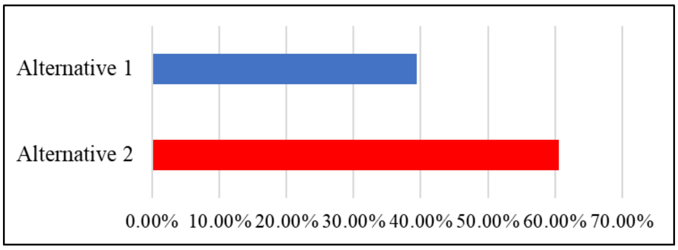
The results obtained from the sensitivity analysis are shown in Figure 6.



a)



b)



c)

Figure 6. Sensitivity analysis: a) Scenario 1, b) Scenario 2, c) Scenario 3

The results obtained from the sensitivity analysis show that in all scenarios Alternative 2, that is, the SLA technology of 3D printing is ranked first, which means that the SLA technology is better than the FDM technology to the considered criteria.

V. Conclusions

To compare 3D printing technologies, specifically Fused Deposition Modeling (FDM) and Stereolithography (SLA), in producing complex geometric parts – spur gear, a multi-criteria analysis, specifically the Analytic Hierarchy Process, was employed. The criteria considered for comparing these two technologies include the complexity of starting a 3D printer, printing time, dimensional stability, the complexity of the part geometry, mechanical properties of the printed part, and part postprocessing.

The results indicate that the SLA technology of 3D printing is ranked first, which means that the SLA technology is better than the FDM technology to the considered criteria. Additionally, a sensitivity analysis corroborated the consistent top ranking of SLA technology.

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