ADVANCED TECHNOLOGIES AND MATERIALS VOL. 49, NO.1 (2024), 25- 31
DOI: 10.24867/ATM-2024-1-004

1. Received: 12 March 2024
2. Revised: 10 April 2024
3. Accepted: 24 April 2024

Advanced Technologies & Materials

http://journal-atm.org
ISSN: 2620-0325 (print), ISSN: 2620-147X (online)

Original article

A Multi-Criteria Decision-Making Approach for Enhancing Mechanical Properties of FDM 3D-Printed Parts

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ABSTRACT

The quest for optimizing 3D printing processes to meet industrial demands for improved mechanical properties and dimensional stability is an ongoing challenge. This study delves into the task of determining the optimal 3D printing parameter (material and layer height) and annealing parameter (annealing time and annealing temperature) combinations for FDM 3D-printed parts through a systematic and objective approach. By utilizing Multi-Criteria Decision-Making (MCDM) methods, specifically the Analytic Hierarchy Process (AHP) for criteria weighting and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for ranking, the study endeavors to address this challenge effectively. The primary aim of this research is to identify the most suitable 3D printing and annealing parameter combination that maximizes tensile strength and Young's modulus of elasticity while minimizing change in width, change in thickness, and change in length of the specimen after annealing. To achieve this, a comprehensive dataset stemming from the experimental analysis of three distinct materials (Polylactic acid - PLA, Polyethylene terephthalate glycol - PETG, carbon fiber reinforced PETG - PETGCF), three layer heights (0.1 mm, 0.2 mm, 0.3 mm), five annealing temperatures (60°C, 70°C, 80°C, 90°C, 100°C), and three annealing times (30 minutes, 60 minutes, 90 minutes) is employed. These criteria were determined based on the requirements of a specific industrial case study, highlighting their relevance and significance in real-world applications. The results show that the best combinations are the ones from PETGCF material with 0,1 mm layer height, with long annealing times (90 minutes) and low to mid annealing temperatures (60 - 70°C). The worst alternatives are the ones annealed at high temperatures (90 - 100°C), and with PETG material, as the dimensional change of this material are significant at high temperatures.

Key words: *multi-criteria decision making; AHP; TOPSIS; FDM 3D printing; annealing.*

1. INTRODUCTION

3D printing, also known as additive manufacturing (AM), has transformed the landscape of modern industry, offering unmatched versatility and efficiency for crafting intricate parts. As industries increasingly adopt this technology, the need to optimize 3D printing processes becomes more vital than ever. Among the many challenges in this quest, two stand out: improving the mechanical performance of 3D-printed parts and achieving greater dimensional accuracy. The study takes on this dual challenge by systematically and objectively identifying the best combinations of printing parameters, with both goals in mind. To achieve this, the study uses well established Multi-Criteria Decision-Making (MCDM) methods, specifically the Analytic Hierarchy Process

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Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

(AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The widespread applicability and global significance of MCDM methods are underscored by their extensive utilization in resolving real-world challenges, as evidenced by numerous studies [1, 2, 3]. Furthermore, the adaptability of this approach to diverse problems is a testament to its flexibility in accommodating variations in criterion weights [4, 5]. The determination of weighting coefficients emerges as a pivotal element in the process of selecting the optimal alternative and ranking research findings, as evidenced by the studies conducted by [6] and [7]. Furthermore, the works of [8] and [9] underscore the significance of preserving subjective viewpoints when establishing initial weights, a practice that enhances the relevance of results and their applicability to specific scenarios. It is imperative to recognize that the assignment of criterion weights exerts a direct and profound influence on the research outcomes, thereby highlighting the inherent interplay between weight allocation and decision-making results. Extensive research within the domain of MCDM consistently advocates the adoption of robust models for the selection of optimal alternatives within the decision-making framework, aligning with the recommendations put forth by a majority of authors, including [10] and [7]. Because of this, the primary objective of the study is to introduce a robust and hybrid MCDM approach, which encompasses the assessment of the collective influence of printing and annealing parameters in the context of 3D printing.

The utilization of the Multi-Objective Optimization using Ratio Analysis (MOORA) method for optimizing 3D printing process parameters, accommodating diverse criteria, both quantitative and qualitative, and providing an accessible computational approach, is noteworthy [11]. This study's exploration of FDM 3D printer parameters, specifically layer thickness, build pattern, and fill pattern, with a focus on their impact on surface roughness and build time, adds valuable insights to the field. The study [12] contributes to understanding the influence of process parameters on the mechanical properties of FDM printed parts, with a focus on optimizing these parameters to achieve reduced surface roughness and maximum strength. The research employs diverse optimization techniques, including the TOPSIS, the response surface methodology (RSM), the Non-dominated Sorting Genetic Algorithm (NSGA-II), and Grey Relational Analysis (GRA), to identify the optimal FDM process parameters. The hybrid optimization approach, combining a genetic algorithm with RSM, demonstrates enhanced prediction accuracy. Notably, the study identifies the optimal parameters, including an infill density of 61.02%, a layer thickness of 0.26 mm, a print speed of 37.77 mm/s, and an extrusion temperature of 191.1 °C, for achieving the lowest surface roughness and maximum strengths in FDM parts. The study [13] presents an endeavour to discern the most suitable AM process with a focus on sustainability considerations. The research encompasses a comprehensive assessment of key dimensions within the realm of sustainable AM, encompassing aspects such as material and product quality, machine performance, market stability, total cost, and ecological values. To facilitate this decision-making process, a hybrid multi-criteria approach, combining stepwise weight assessment ratio analysis and complex proportional assessment methods, is applied. Among the four AM processes evaluated, namely FDM, laminated object manufacturing (LOM), stereolithography apparatus (SLA), and selective laser sintering (SLS), the study identifies FDM as the most favourable alternative. In the work [14], authors delve into the analysis of process parameters within the context of the FDM process, employing an integrated MCDM approach that combines modified fuzzy and Analytic Network Process (ANP) methods. The experimental investigation centres on three pivotal process parameters: layer height, shell thickness, and fill density, alongside their corresponding response parameters, encompassing ultimate tensile strength, dimensional accuracy, and manufacturing time. Subsequently, the research undertakes the optimization of FDM process parameters utilizing the proposed methodology. The results highlight that experiment recommend a configuration with a layer height of 0.08 mm, shell thickness of 2.0 mm, and fill density of 100%. This optimized setting not only enhances ultimate tensile strength but also improves dimensional accuracy while reducing manufacturing time, thereby enhancing the overall performance and efficiency of the FDM process. The article [15] introduces an efficient decision support system designed for the purpose of selecting the most suitable AM process. To achieve this, a novel hybrid MCDM technique is proposed, featuring the utilization of the Best Worst Method (BWM) to determine optimal criteria weights and the Proximity Indexed Value (PIV) method for ranking available AM processes. The study benchmarked the capabilities of four AM processes, including Vat Photopolymerization (VatPP), Material Extrusion (ME), Powder Bed Fusion (PBF), and Material Jetting (MJ), by fabricating a conceptual model of a spur gear. Key criteria under consideration encompassed dimensional accuracy, surface roughness, tensile strength, percentage elongation, heat deflection temperature, process cost, and build time. Sensitivity analysis was further conducted to validate the reliability of the results. The findings indicate that the Material Jetting (MJ) process consistently produces dimensionally accurate and high-quality parts, as corroborated by the ranking derived through the PIV method, which is noted for its reliability and consistency.

The literature review underscores the frequent and successful utilization of MCDM techniques within the additive manufacturing domain. However, it is worth noting that, to the best of the authors' knowledge, none have applied MCDM techniques to the context of FDM 3D printing in conjunction with an annealing process. Within the academic realm, this study contributes significantly to the ever-expanding body of knowledge surrounding additive manufacturing and the practical implementation of MCDM methodologies. It advances our comprehension of optimizing 3D printing, specifically addressing a pivotal challenge: the enhancement of both the strength and quality of 3D-printed components, through annealing process. Extending beyond academia, in today's fiercely competitive industrial landscape, where efficiency, product, and environmental considerations take precedence, the optimization of 3D printing processes assumes critical importance. The capacity to fabricate 3D-printed parts boasting superior mechanical properties without compromising precision holds far-reaching implications across diverse industries.

2. METHODOLOGY

The objective of this study is to identify the optimal combinations of 3D printing and annealing parameters that maximize mechanical properties (e.g., tensile strength and Young's modulus of elasticity) while minimizing dimensional changes (width, thickness, and length after annealing). To achieve this objective, a two-step approach was adopted. Firstly, the Analytic Hierarchy Process (AHP) method was employed to establish objective weights for the evaluation criteria, considering the relative importance of mechanical properties and dimensional changes. Subsequently, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method was applied to rank the optimized parameter combinations based on their performance across the defined criteria. This comprehensive methodology enables a systematic and efficient evaluation of parameter combinations, facilitating well-informed decision-making in the context of 3D printing and annealing processes. The best solutions (based on the MCDM analysis) are then used for real world case study.

2.1 AHP method

The Analytic Hierarchy Process (AHP) method, developed by Saaty [16, 17], is a robust tool widely employed in MCDM to establish objective weights for evaluating criteria. AHP provides a structured approach to decision-making by breaking down complex problems into a hierarchical structure comprising a goal, criteria, and alternatives. In the context of the study, the goal is to optimize 3D printing and annealing parameters for enhancing mechanical properties and minimizing dimensional change after annealing. The criteria include factors such as tensile strength, Young's modulus of elasticity, and dimensional changes after annealing process (width, thickness, and length after annealing). AHP employs pairwise comparisons to assess the relative importance of these criteria. These pairwise comparison matrices can be established using expert opinions or data-driven techniques. To quantify preferences, Saaty's scale (refer to Table 1) was utilized to populate the matrices with numerical values. Subsequently, through the calculation of eigenvectors and eigenvalues, the weights for each criterion were derived, indicating their relative importance in the parameter optimization process.

To maintain the robustness of the analysis, evaluation of the consistency of pairwise comparisons using the consistency ratio (CR) was employed. A CR value close to 0 signifies a high level of consistency, while higher CR values prompt a reassessment and adjustment of the comparisons. The flexibility of the AHP method permits its application across diverse processes, as the CR ensures the consistency of criteria weights. This adaptability makes the hybrid approach, which combines AHP with TOPSIS method, a robust and dependable decision-making tool for optimizing 3D printing and annealing parameters to achieve the research objectives.

Table 1 *Saaty's scale*

Saaty's scale	Meaning
1	Equally preferred
3	Moderate preference of one over the other
5	Strong preference of one over the other
7	Very strong preference of one over the other
9	Extreme preference of one over the other
2, 4, 6, 8	Intermediate values, indicating the degree of preference between adjacent values

2.2 TOPSIS method

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, a widely recognized MCDM method, plays a pivotal role in the study, facilitating the ranking of optimized alternatives for 3D printing and annealing operations. TOPSIS is a distance-based method that assesses alternatives based on their proximity to the ideal and anti-ideal solutions. In this context, the ideal solution represents the optimal achievement of desired criteria (e.g., maximum tensile strength, maximum Young's modulus of elasticity, minimum dimensional changes) while the anti-ideal solution represents the least favorable scenario.

To compute the TOPSIS rankings, one first represents the alternatives as a decision matrix. Each row in the matrix corresponds to an alternative, while each column corresponds to a specific criterion. To ensure fairness in the evaluation, normalizing the decision matrix to eliminate the influence of scale differences among the criteria is needed. Subsequently, the ideal and anti-ideal solutions are identified based on the maximum and minimum values for each criterion, respectively. After that, distance metrics are employed (such as the Euclidean distance or other suitable measures), to gauge the proximity of each alternative to these reference solutions. The relative closeness of each alternative to the ideal solution is quantified using relative closeness coefficients. Finally, the alternatives are ranked based on these coefficients. The TOPSIS method offers a robust and intuitively comprehensible approach to prioritize the alternatives, facilitating the selection of the most promising combination of 3D printing and annealing parameters.

By incorporating the TOPSIS method into the hybrid MCDM framework, one can enhance the overall decision-making process, rendering it more comprehensive and effective in optimizing 3D printing and annealing operations for superior mechanical performance and dimensional stability.

3. CASE STUDY

The case study presented in the paper centers on the fabrication of a camera holder for mounting on a simple drone design. This camera mount production was undertaken using FDM 3D printing, as part of a Do-It-Yourself (DIY) drone project (Fig. 1). To meet the specific requirement of keeping the camera mount as lightweight as possible, but also to have exceptional mechanical properties, unconventional approaches were explored. One approach involved the production of the camera mount with minimal dimensions and weight through 3D printing, followed by a subsequent annealing process to enhance its mechanical properties. Because of this, the need for determining the best combination of printing parameters and annealing parameters was born. In addition, because the material of the camera mount was not specifically determined, different materials could also be tested, which just added more depth to the research.

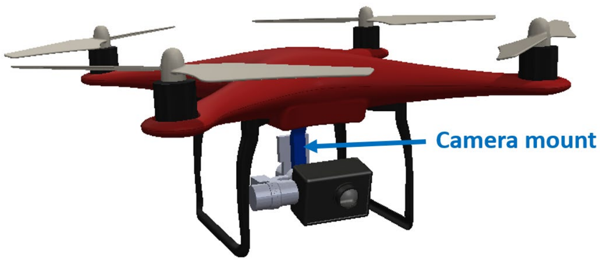

Fig. 1 *DIY drone design with the camera mount.*

The data employed in this study originates from a prior research investigation conducted by the authors, as documented in a previous research paper [18]. In that study, the primary focus was to explore the effects of annealing time, temperature, and layer height on the tensile strength, modulus of elasticity and dimensional change characteristics of three distinct 3D printing materials, namely PLA, PETG, and carbon fiber-reinforced PETG. A comprehensive series of experiments was executed, involving variations in layer heights (0.1 mm, 0.2 mm, and 0.3 mm) and annealing processes conducted within a temperature range of 60–100 °C, spanning time intervals of 30, 60, and 90 minutes. The utilization of data from the prior research paper is justified by the specific requirements and constraints associated with the camera mount's design and function. The camera mount, due to its position and structural characteristics, is primarily subjected to tensile forces resulting from the weight of the camera it supports. Consequently, the tensile strength and modulus of elasticity of the chosen material for the camera mount emerge as paramount considerations. Furthermore, beyond its mechanical attributes, it is essential for the camera mount to exhibit a reasonable degree of dimensional accuracy. While exacting tolerances are not obligatory for this application, the avoidance of significant warping or substantial dimensional variations is crucial. In this context, the utilization of FDM 3D printing, complemented by annealing processes, offers an effective means to strike a balance between mechanical integrity and dimensional stability.

By leveraging the previously discussed dataset and considering the case study involving the camera mount, we encounter a MCDM challenge as follows:

A total of 144 alternative combinations have been formulated, each encompassing distinct attributes related to 3D printing layer height, material type, annealing time, and temperature [18]. The objective is to discern the optimal combination from this vast array of possibilities, guided by a set of well-defined criteria. The criteria identified for evaluation encompass maximal tensile strength, maximal modulus of elasticity, minimal dimensional changes in terms of thickness, minimal dimensional changes in terms of width, and minimal dimensional changes in terms of length of the specimen. These criteria form the foundation for determining the most favorable combination amidst the multitude of choices, aligning with the overarching aim of enhancing the camera mount's mechanical properties and dimensional accuracy after annealing process.

The AHP method was used to determine the weight coefficients. The pairwise comparison matrix was formulated to establish the relative importance of the criteria. In this case, the matrix indicates that tensile strength (TS) was considered two times more important than Youngs modulus of elasticity (YM), six times as important as dimensional change in terms of width (ΔWc) and thickness (ΔT), and four time as important as dimensional change in terms of length (ΔL0), as can be seen in Table 2.

Table 2 *Pairwise comparison matrix*

	TS	YM	ΔWc	ΔT	ΔL_0
TS	1	2	6	6	4
YM	0.5	1	3	3	2
ΔWc	0.16667	0.333	1	1	0.6667
ΔT	0.16667	0.333	1	1	0.6667
ΔL_0	0.25	0.5	1.499925	1.499925	1

The weight coefficients obtained as the result of the AHP analysis are as follows:

1. w1 (weight coefficient for TS) = 0.480000384
2. w2 (weight coefficient for YM) = 0.240000192
3. w3 (weight coefficient for ΔWc) = 0.080000864
4. w4 (weight coefficient for ΔT) = 0.080000864
5. w5 (weight coefficient for ΔL0) = 0.119997696

Furthermore, the consistency of criterion importance was verified, confirming that the criteria were adequately compared in terms of importance, with a consistency ratio (CR) of 0.0000000000892812.

Following the assessment of MCDM rankings, the two top-ranked alternatives were selected to produce the camera mount. The 3D printing process was executed using the Wanhao Duplicator i3 Plus 3D printer (Fig. 2a), while the annealing process was conducted within an industrial-grade oven (Fig. 2b). Subsequently, a tensile strength analysis was performed on these two camera mounts, in comparison with the base camera mount which did not undergo the annealing process. The evaluation was conducted utilizing the Shimadzu Table-top AGS-X 10kN universal testing machine (Fig. 3). It's important to note that the camera mount does not conform to a standardized shape for testing, thus the results may not be considered entirely precise or universally applicable. However, the consistency in testing methodology across all camera mounts allows for meaningful comparisons and serves as a reference point to assessing if any potential improvements in mechanical properties were achieved, and if the presented MCDM method was successful.

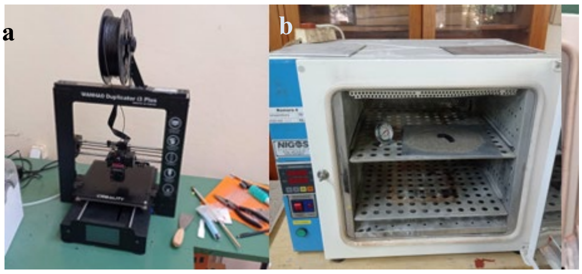

Fig. 2 *presentations of (a) Wanhao Duplicator i3 Plus 3D printer; (b) industrial-grade oven*

Fig. 3 *Shimadzu Table-top AGS-X 10kN universal testing machine*

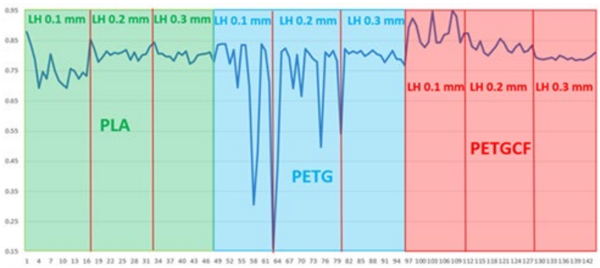

Fig. 4 *Results of TOPSIS analysis with LH depicting layer height of the alternative*

4. RESULTS AND DISCUSSION

Identifying the optimal combination of 3D printing and annealing parameters based on the criteria of minimizing dimensional changes, maximizing tensile strength and modulus of elasticity is inherently a multi-criteria decision-making challenge. Within this context, the criteria encompass minimizing changes in width, thickness, and length (dimensional stability), while maximizing tensile strength and modulus of elasticity (mechanical performance). The outcomes of this investigation yield valuable insights into the recommendations put forth by the TOPSIS method. Upon examining Fig. 4, a notable trend emerges: PETG material consistently exhibits inferior rankings among the various alternatives, with the exceptions being those employing a 0.3 mm layer height, which demonstrate comparably good results when compared to the other materials with the same layer height. In contrast, PLA material showcases a remarkable level of consistency across different parameter combinations, with only the variants featuring a 0.1 mm layer height marginally deviating from the otherwise stable performance. As for PETGCF, the outcomes are notably favourable, with the alternatives employing a 0.1 mm layer height showcasing significantly superior performance in comparison to other parameter combinations.

Based on the findings derived from the TOPSIS analysis, the optimal methods predominantly originate from the PETGCF material, evident in the top four alternatives that emerge as the highest-ranked (as presented in Table 3). Additionally, a preference for lower layer heights is discernible, as they appear to yield superior tensile strength, likely attributed to enhanced interlayer bonding. Furthermore, with respect to annealing parameters, lower temperatures are favoured (60°C and 70°C), primarily due to their tendency to induce lesser dimensional changes in the specimens, as well as longer annealing times (60 and 90 minutes).

Conversely, the least favorable alternatives tend to be associated with the PETG material, particularly those involving extended annealing times and higher temperatures (90°C and 100°C), as indicated in Table 4. This observation can be attributed to PETG's suboptimal mechanical properties following annealing, along with its pronounced dimensional instability.

Table 3 *Best alternatives according to TOPSIS method*

#	Material	Layer Height (mm)	Annealing time (min)	Annealing temperature (°C)
108	PETGCF	0.1	90	60
103	PETGCF	0.1	60	60
109	PETGCF	0.1	90	70
98	PETGCF	0.1	30	60

Following the analysis of MCDM results, two of the highest-rated alternatives were selected to produce camera mounts, enabling subsequent testing and comparison with the base camera mount (which underwent no annealing process). The base camera mount model, printed with a 0.1 mm layer height but without annealing, exhibited a maximum strain force of 253 N, roughly equivalent to a tensile strength of 5 MPa. In contrast, the model printed with a 0.1 mm layer height and annealed at 60°C for 60 minutes achieved a force of 266 N, approximately corresponding to a tensile strength of 5.3 MPa. Lastly, the model printed with a 0.1 mm layer height and annealed at 60°C for 90 minutes resulted in a force of 270 N, representing an estimated tensile strength of 5.4 MPa. Again, it should be noted that the testing method was not standard, and one cannot be certain about the results of the testing, nor should the results be used for universal comparison. However, due to the experiments being done in the same way every time, the results can be compared with each other, and it can be concluded that by following the recommendations from presented MCDM method, the enhancement of mechanical properties of the camera mount was achieved.

Table 4 *Worst alternatives according to TOPSIS method*

#	Material	Layer Height (mm)	Annealing time (min)	Annealing temperature (°C)
63	PETG	0.1	90	90
58	PETG	0.1	60	90
75	PETG	0.2	60	100
80	PETG	0.2	90	100

5. CONCLUSION

This paper explores the application of established MCDM methods to determine the optimal parameter combinations for enhancing the mechanical properties of FDM 3D-printed parts and minimizing dimensional changes following the annealing process. MCDM methods offer valuable insights, particularly when dealing with extensive databases and numerous alternative combinations. The combined use of AHP and TOPSIS methods provides a comprehensive and robust analytical framework adaptable to various applications. According to the analysis, the most favourable alternatives in the presented case study are those produced with PETGCF material, with low layer heights (0.1 mm), low annealing temperatures (60 and 70°C), and long annealing times (60 and 90 minutes). Conversely, the least favourable alternatives tend to originate from PETG material, annealed at higher temperatures (90 - 100°C) and for longer durations (60 – 90 minutes).

Camera mounts were fabricated for the DIY drone using the top two alternatives identified through the MCDM analysis. These mounts were subsequently compared with the base mount, which had not undergone the annealing process. The results indicated a notable improvement in achieved tensile force, ranging from 13 to 22 N.

ACKNOWLEDGEMENTS

This research was financially supported by the Ministry of Science, Techno-548 logical Development and Innovation of the Republic of Serbia (Contract No. 451-03-47/2023-01/ 549 200109).

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NOTE

This paper is based on the paper presented at 39th International Conference on production Engineering of Serbia – ICPES 2023, organized by University of Novi Sad, Faculty of technical sciences, 6 - 27. October 2023, Novi Sad, Serbia.