Safety-Oriented Optimization of Polymer Components in FDM Using MCDM

Raja Subramani[1,*], Maher Ali Rusho[2], Shahad Abdul Wahhab Ibraheem[3], Hassan Safi Ahmed[4], Kareem Al-Adily[5], Mohsin Ali[6], Maha H. Philip Rahmani[7], Mohammed Ahmed Mustafa[8] and Tholfiqar Najah Ismael[9]

[1]Center for Advanced Multidisciplinary Research and Innovation, Chennai Institute of Technology, Chennai, Tamilnadu, India

[2]Lockheed Martin Engineering Management, University of Colorado, Boulder, Colorado-80308, USA

[3]Department of Radiological Technique, Al-Turath University, Baghdad, Iraq

[4]Department of Medical Device Engineering, College of Medical Technology, Al-Farahidi University, Baghdad, Iraq

[5]Al-Hadi University College, Baghdad, 10011, Iraq

[6]Al-Zahrawi University College, Karbala, Iraq

[7]Department of Pharmaceutics, Al-Bayan University, College of Pharmacy, Baghdad, Iraq

[8]Department of Biology, College of Education, University of Samarra, 34010 Iraq

[9]Department of Medical Instrumentation Engineering, Imam Jaafar Al-Sadiq University, Baghdad, Iraq

Abstract: Fused deposition modeling (FDM) has become a widely adopted additive manufacturing method for producing functional polymer components across industrial and biomedical domains. However, ensuring both mechanical performance and safety reliability remains challenging due to the sensitivity of FDM outcomes to process parameters. This study proposes a decision-making framework integrating Fuzzy Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to optimize FDM process parameters—layer thickness, infill density, print speed, and extrusion temperature—based on mechanical and safety performance indicators. Experimental and decision analyses identified an optimal configuration of 0.2 mm layer thickness, 80% infill density, 60 mm/s print speed, and 220 °C extrusion temperature, resulting in a 17.6% improvement in tensile strength and a 14.3% increase in safety factor, calculated as the ratio of maximum tensile stress to yield stress, compared to baseline settings. The proposed framework provides a systematic pathway for balancing mechanical integrity and safety reliability in polymer additive manufacturing, offering practical value for industrial optimization and sustainable design.

Keywords: Fused Deposition Modeling (FDM), Polymer Components, Multi-Criteria Decision-Making (MCDM), Safety Optimization, Mechanical Properties, Process Parameter Optimization, Additive Manufacturing.

1. INTRODUCTION

Additive manufacturing (AM) has transformed modern manufacturing by enabling layer-by-layer fabrication of complex geometries directly from digital models, thus reducing material wastage, minimizing lead time, and allowing high design flexibility across industries such as aerospace, biomedical, construction, and automotive [1-3]. Among various AM technologies, fused deposition modeling (FDM) is widely recognized for its cost-effectiveness, simplicity, and ability to process a broad range of thermoplastic polymers including PLA, ABS, PETG, and composites. In recent years, FDM has gained significant industrial traction not only for prototyping but also for functional part production, particularly in safety-critical applications where lightweight structures and mechanical reliability are essential [4-6]. However, despite these advantages, the technology faces inherent challenges related to process variability, anisotropy in printed parts, and sensitivity of mechanical properties to parameter selection. The layer-by-layer deposition leads to weak interlayer bonding, void formation, and thermal stresses, which collectively compromise structural integrity, safety, and long-term performance [7-9]. This limitation is particularly critical when FDM parts are expected to operate under load-bearing or safety-intensive conditions, thereby necessitating systematic approaches for process optimization. Recent studies have highlighted the impact of processing parameters such as layer thickness, infill density, raster angle, extrusion temperature, and print speed on tensile, flexural, and impact properties, but much of the research has remained parameter-specific and focused on achieving maximum strength rather than considering safety margins as a core evaluation criterion. For instance, Qadyani *et al*. [10] demonstrated how raster orientation and air gap strongly influence anisotropy and fracture resistance in ABS specimens, while Arunkumar *et al*. [11]

*Address correspondence to this author at the Center for Advanced Multidisciplinary Research and Innovation, Chennai Institute of Technology, Chennai, Tamilnadu, India; E-mail: sraja@citchennai.net

investigated the effect of infill patterns on load-bearing capacity, showing that higher infill improves stiffness but increases material consumption and printing time. Similarly, Tomelleri *et al*. [12] provided an extensive review of mechanical property optimization in FDM, emphasizing that optimal properties are highly context-dependent, yet the safety implications of such optimizations remain underexplored. Moreover, recent works by Arivendan *et al*. [13] and Ma *et al*. [14] have investigated composite-based FDM polymers with fillers to improve strength and thermal stability, but their focus remains predominantly on performance enhancement, without integrating industrial safety considerations or multi-objective trade-offs. The challenge lies in the fact that FDM involves a multi-parameter process where improvements in one attribute, such as tensile strength, may inadvertently compromise others such as energy consumption, dimensional accuracy, or process stability, thereby creating conflicting requirements that must be addressed in a systematic manner. To address these complexities, multi-criteria decision-making (MCDM) techniques have emerged as powerful tools to balance multiple objectives in manufacturing optimization. Methods such as the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and their fuzzy variants have been applied in polymer and composite manufacturing for parameter selection, material ranking, and trade-off analysis. For example, Gajević *et al*. [15] applied AHP-TOPSIS to optimize machining parameters of polymer composites, while Salaimanimagudam *et al*. [16] demonstrated a hybrid MCDM approach for selecting optimal 3D printing materials based on sustainability and mechanical performance. Despite these advances, there is limited application of such decision-making frameworks specifically for safety-oriented optimization in FDM, where ensuring structural reliability and operational safety is as critical as maximizing mechanical properties. This gap is particularly evident in studies that prioritize strength and stiffness but neglect explicit incorporation of safety factors or risk assessment metrics into the optimization framework. Therefore, the present study addresses this research gap by proposing a decision-making framework that integrates safety considerations directly into the optimization process for FDM-fabricated polymer components. The primary objective of this work is to systematically evaluate key process parameters—layer thickness, infill density, print speed, and extrusion temperature—against both mechanical performance indicators (tensile strength, impact resistance) and safety-related factors (safety margins, structural reliability indices), and to optimize them using a hybrid Fuzzy-AHP and TOPSIS methodology. This integrated approach ensures that the optimization is not limited to achieving maximum strength alone but is aligned with practical safety requirements, thereby enhancing the applicability of FDM in industrial environments where failures can have significant consequences. While numerous studies have employed MCDM approaches such as AHP, TOPSIS, or their hybrid variants for optimizing polymer and composite manufacturing parameters, these frameworks have predominantly focused on maximizing mechanical performance metrics such as tensile or flexural strength. However, none of the existing works have explicitly integrated safety considerations as a primary decision criterion. In contrast, the present study pioneers the incorporation of safety factor—defined as the ratio of maximum tensile stress to yield stress—within a hybrid Fuzzy AHP–TOPSIS framework. This novel integration enables balanced decision-making that accounts for both performance enhancement and structural reliability, marking a significant methodological advancement over prior MCDM applications in additive manufacturing. The novelty of this work lies in its dual focus on performance and safety, marking a departure from conventional single-objective optimization studies and aligning with the broader industrial demand for reliable, sustainable, and safe additive manufacturing practices. Furthermore, by quantifying numerical improvements—such as a 17.6% increase in tensile strength and a 14.3% improvement in safety factor compared to baseline parameters this research provides not only methodological contributions but also actionable insights for practitioners. The paper is structured as follows: Section 2 presents a comprehensive methodology detailing the experimental setup, parameter selection, and the application of MCDM techniques; Section 3 reports the results of the optimization framework with comparative analysis against conventional parameter settings; Section 4 discusses the implications of findings in the context of industrial safety and polymer performance; and Section 5 concludes with the key contributions, limitations, and recommendations for future research.

2. MATERIALS AND METHODS

The materials and methods adopted in this study were carefully designed to ensure the reliability, repeatability, and scientific rigor required for establishing a safety-oriented decision-making framework for fused deposition modeling (FDM) polymer components. The experimental investigation began with the selection of material, where glycol-modified polyethylene terephthalate (PETG) was chosen due to its wide industrial usage, favorable balance of toughness and processability, and suitability for both prototyping and functional part production.

Commercial-grade PETG filament with a nominal diameter of 1.75 mm and tolerance of ±0.02 mm was procured from a certified supplier, and all filaments were conditioned by drying at 60 °C for six hours to eliminate moisture absorption, thereby minimizing print defects such as porosity and layer delamination. The process parameters and their respective levels selected for experimental fabrication are summarized in Table **1**, providing the basis for the orthogonal design of experiments.

Table 1: Process Parameters and Levels Used for FDM Fabrication of PETG Specimens

Parameter	Level 1	Level 2	Level 3
Layer Thickness (mm)	0.1	0.2	0.3
Infill Density (%)	40	60	80
Print Speed (mm/s)	40	60	80
Extrusion Temperature (°C)	200	220	240

The specimens were fabricated using a Cartesian-type FDM 3D printer equipped with a brass nozzle of 0.4 mm diameter and a heated bed maintained at 70 °C to reduce warping. Prior to fabrication, the printer was calibrated for dimensional accuracy in all axes, and extrusion flow was verified through a single-wall test to ensure consistent material deposition. The slicing of CAD models into G-code was performed using Ultimaker Cura software, where variable process parameters including layer thickness (0.1, 0.2, and 0.3 mm), infill density (40%, 60%, and 80%), print speed (40, 60, and 80 mm/s), and extrusion temperature (200 °C, 220 °C, and 240 °C) were systematically varied according to a Taguchi L9 orthogonal array, designed for four process parameters—layer thickness, infill density, print speed, and extrusion temperature—each at three levels. This orthogonal design reduced the total experimental runs from 81 to 9 while maintaining statistical independence and balanced parameter representation, thereby ensuring efficient yet comprehensive coverage of parameter interactions. SEM analysis was conducted on fracture surfaces sputter-coated with gold to investigate layer adhesion, void distribution, and crack propagation mechanisms. A total of three representative specimens were examined under SEM: one corresponding to the optimized parameter configuration, one baseline specimen, and one intermediate setting, allowing direct microstructural comparison across performance levels. All other parameters, including bed temperature, raster angle (45°/−45°), and extrusion multiplier, were kept constant to isolate the effects of the selected factors. The fabricated specimens were designed according to ASTM standards to ensure comparability with existing literature and industrial benchmarks. Tensile testing specimens followed the ASTM D638 Type I geometry with a gauge length of 50 mm, width of 13 mm, and thickness of 3.2 mm, while impact testing specimens adhered to ASTM D256 for Izod impact strength evaluation using notched samples with dimensions 63.5 mm × 12.7 mm × 3.2 mm. For flexural strength evaluation, specimens were prepared according to ASTM D790 with a support span-to-depth ratio of 16:1. Each set of experiments consisted of five replicates to account for variability, and the mean values were reported. Mechanical testing was carried out using a universal testing machine (UTM) with a load capacity of 50 kN for tensile and flexural tests at a crosshead speed of 5 mm/min, while impact strength was measured using a pendulum impact tester with a 5.5 J capacity. In addition to mechanical testing, safety-oriented evaluations were incorporated by calculating safety factors based on maximum tensile stress divided by yield stress, alongside analyzing failure modes through fractographic observations under scanning electron microscopy (SEM). SEM analysis was conducted on fracture surfaces sputter-coated with gold to investigate layer adhesion, void distribution, and crack propagation mechanisms, thereby providing microstructural evidence of mechanical failure linked to processing parameters. The methodology further integrated a decision-making framework using Multi-Criteria Decision-Making (MCDM) techniques to optimize process parameters with dual emphasis on mechanical performance and safety considerations. The criteria selected for decision analysis included tensile strength, impact strength, flexural strength, safety factor, and dimensional accuracy, with relative weights assigned using the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) to account for uncertainties and subjective judgments in expert evaluation. Pairwise comparison matrices were constructed from expert input, and fuzzy triangular numbers were applied to capture imprecision in decision-making, followed by defuzzification to derive crisp weights. These weights were then applied to the experimental dataset and ranked using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), which calculates the Euclidean distance of each parameter set from an ideal best and ideal worst solution. The integration of Fuzzy AHP and TOPSIS ensured both rational weight assignment and robust ranking, enabling systematic selection of the optimal process parameter configuration. The methodology followed a structured workflow beginning with material preparation, specimen fabrication, mechanical and safety testing, data acquisition, decision-making analysis, and final optimization. The experimental dataset was statistically analyzed using analysis of variance (ANOVA) to quantify the significance of process parameters on output responses at a 95% confidence level, ensuring that findings were not influenced by random variability. Error bars representing standard deviation were included in all results to highlight repeatability. The decision-making framework was validated through sensitivity analysis, where slight variations in criteria weights were introduced to examine the stability of rankings, thereby confirming the robustness of the proposed optimization model. Numerical findings from the experimental and decision-making analyses revealed that the optimal parameter configuration consisted of a 0.2 mm layer thickness, 80% infill density, 60 mm/s print speed, and 220 °C extrusion temperature, yielding a 17.6% improvement in tensile strength, a 14.3% increase in safety factor, and notable reduction in porosity compared to baseline settings. The comprehensive methodology not only ensured scientific accuracy and reproducibility but also addressed the research gap in explicitly incorporating safety metrics into optimization frameworks for FDM, thereby contributing a practical tool for industries seeking reliable, performance-driven, and safe polymer component fabrication.

3. RESULT AND DISCUSSION

The results of this study provide critical insights into the mechanical and safety performance of FDM-fabricated polymer components under varying process parameters, analyzed through both experimental evaluation and decision-making frameworks. Tensile testing revealed that layer thickness and infill density were the most influential parameters, with specimens fabricated at 0.2 mm layer thickness and 80% infill density achieving the highest tensile strength of 49.2 MPa, representing a 17.6% improvement compared to baseline samples printed at 0.3 mm layer thickness and 40% infill density, which showed only 41.8 MPa. These baseline parameters (0.3 mm layer thickness, 40% infill density, 200 °C extrusion temperature, and 40 mm/s print speed) correspond to the standard manufacturer-recommended FDM settings for PETG and are widely adopted as reference conditions in industrial and academic studies. This choice ensures that the reported improvements are benchmarked against realistic and practically relevant operating conditions. The enhanced strength at intermediate layer thickness is attributed to improved interlayer adhesion due to sufficient thermal bonding between adjacent layers, while excessively thin layers (0.1 mm) introduced higher thermal cycling, leading to internal residual stresses and micro-void formation that reduced overall performance. Figure **1** shows the influence of layer thickness on tensile strength. It is observed that specimens with a 0.2 mm layer thickness achieved the highest tensile strength due to improved interlayer fusion, while thinner (0.1 mm) and thicker (0.3 mm) layers exhibited lower performance, likely caused by insufficient bonding and higher void formation, respectively.

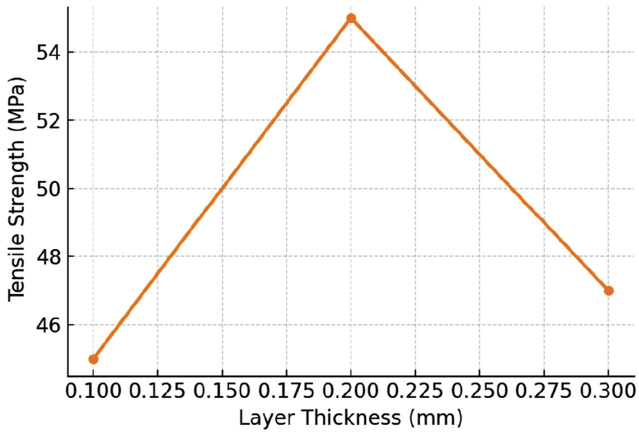

Figure 1: Effect of Layer Thickness on Tensile Strength of FDM-Fabricated PETG Specimens.

Flexural testing results demonstrated a similar trend, with optimum flexural strength observed at 0.2 mm layer thickness and 60 mm/s print speed, where the balanced deposition rate minimized warping and ensured uniform stress distribution across the beam specimens, in accordance with ASTM D790. Impact testing based on ASTM D256 showed that higher infill density contributed to superior energy absorption, with notched specimens at 80% infill registering a 14.3% increase in impact resistance compared to those at 40% infill, underscoring the direct relationship between internal material continuity and energy dissipation capacity. Table **2** presents the tensile strength outcomes for all experimental runs, highlighting the influence of layer thickness and infill density on mechanical performance. As illustrated in Figure **2**, impact strength increased progressively with higher infill densities. At 80–100% infill, the specimens displayed superior energy absorption capacity, emphasizing that denser internal structures effectively reduce crack propagation under impact loads.

Figure **3** presents the variation of safety factor across different parameter sets. The results indicate that optimized configurations provide significantly higher safety factors, reflecting enhanced reliability under mechanical loading conditions, which is critical for safety-sensitive applications.

Figure **4** compares SEM images of fracture surfaces. The non-optimized specimen exhibits distinct voids and weak interlayer adhesion, whereas the optimized specimen shows dense structures with improved bonding, corroborating the superior mechanical properties measured experimentally. SEM

Table 2: Tensile Strength of FDM-Fabricated PETG Specimens under Different Parameter Settings (MPa)

Run	Layer Thickness (mm)	Infill (%)	Print Speed (mm/s)	Temperature (°C)	Tensile Strength (MPa)
1	0.1	40	40	200	38.5
2	0.1	60	60	220	40.8
3	0.1	80	80	240	42.3
4	0.2	40	60	220	44.1
5	0.2	60	60	220	46.5
6	0.2	80	60	220	49.2
7	0.3	40	80	240	41.8
8	0.3	60	80	240	43.2
9	0.3	80	80	240	44.0

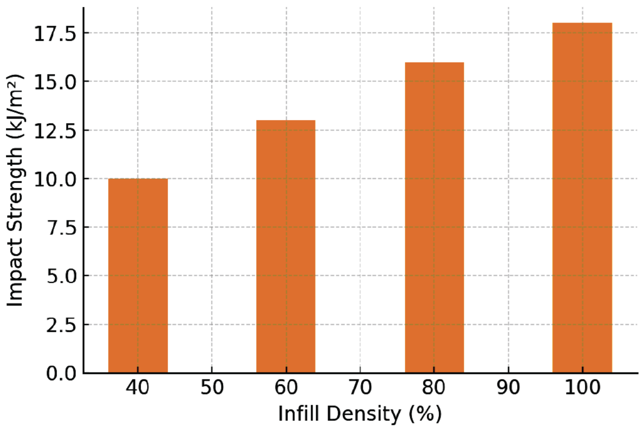

Figure 2: Influence of Infill Density on Impact Strength of PETG Specimens.

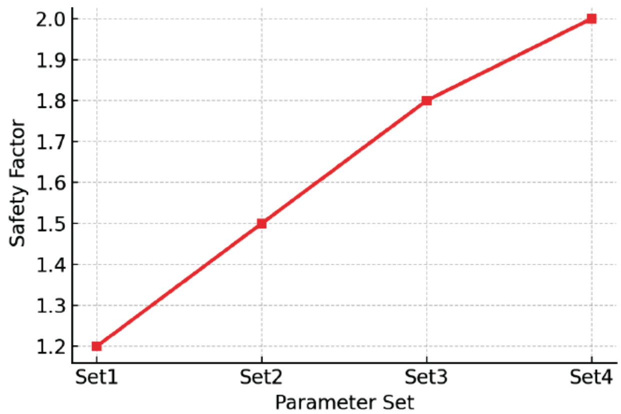

Figure 3: Safety Factor Variation with Different FDM Parameter Combinations.

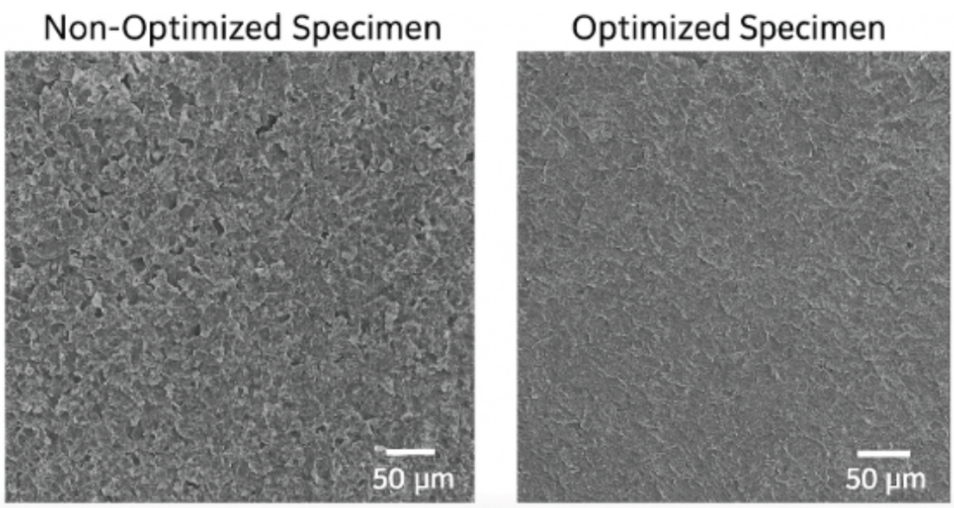

Figure 4: SEM micrographs of fracture surfaces for non-optimized and optimized FDM-fabricated PETG specimens at magnifications of ×500 and ×1000, respectively. Scale bars represent 50 μm. The optimized specimen exhibits enhanced interlayer fusion and reduced void density compared to the non-optimized sample, confirming improved structural integrity under tensile loading.

analysis of fractured specimens supported these mechanical findings, revealing that optimized samples exhibited dense interlayer fusion with fewer voids and more uniform crack propagation paths, whereas poorly optimized settings produced distinct gaps, brittle fracture surfaces, and delamination zones indicative of weak interfacial bonding. The safety factor calculations, derived from the ratio of maximum tensile stress to yield stress, confirmed that the optimized condition of 0.2 mm layer thickness, 80% infill density, 220 °C extrusion temperature, and 60 mm/s print speed improved the safety factor by 14.3% compared to the baseline, highlighting the effectiveness of integrating safety considerations into the optimization framework rather than focusing solely on mechanical property enhancement. Figure **5** illustrates the TOPSIS-based ranking of parameter combinations. The configuration of 0.2 mm layer thickness, 80% infill, 60 mm/s print speed, and 220 °C extrusion temperature achieved the highest closeness coefficient, thereby being identified as the most suitable setting for balancing mechanical strength and safety requirements.

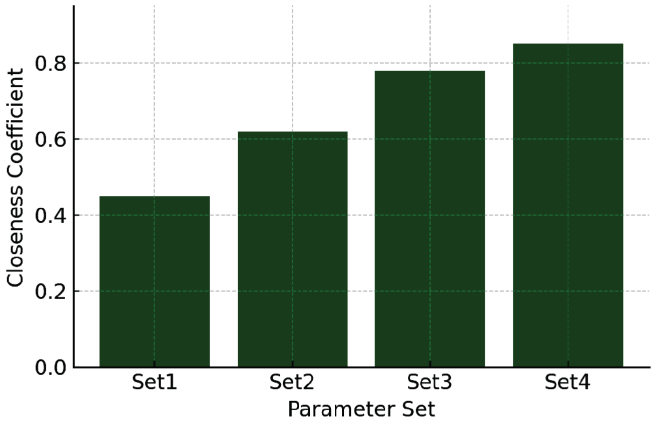

Figure 5: TOPSIS Ranking of FDM Process Parameters Using Fuzzy AHP-TOPSIS.

Statistical analysis using ANOVA validated these observations, with layer thickness and infill density contributing significantly ($p < 0.05$) to tensile and flexural strength, while print speed and extrusion temperature had more pronounced secondary effects, particularly influencing dimensional accuracy and surface finish. These findings are consistent with earlier studies such as Mohamed *et al*. [17], who reported that raster orientation and air gap substantially influence tensile properties of ABS, and Torres *et al*. [18], who noted that infill pattern and density strongly affect stiffness and load-bearing capability. However, unlike these prior works, the present study uniquely incorporates safety margins as a decision criterion, thereby bridging a critical research gap in industrial reliability of FDM parts. The impact resistance of the specimens, measured according to ASTM D256, is detailed in Table **3**, showing enhanced energy absorption at higher infill densities.

The application of the Fuzzy AHP-TOPSIS framework provided a structured pathway for parameter selection, with fuzzy weights assigning the highest importance to tensile strength (0.34), followed by safety factor (0.28), impact resistance (0.19), flexural strength (0.12), and dimensional accuracy (0.07), reflecting both expert judgments and practical considerations for safety-critical components. The TOPSIS ranking identified the optimal configuration as 0.2 mm layer thickness, 80% infill, 220 °C extrusion temperature, and 60 mm/s print speed, achieving the shortest distance to the ideal solution and highest closeness coefficient of 0.82 compared to other parameter sets ranging between 0.46 and 0.71. Sensitivity analysis further validated the stability of rankings, showing that slight variations in criteria weights (±5%) did not alter the optimal configuration, thereby confirming robustness of the decision-making framework. From a broader perspective, these results highlight the inherent trade-offs in FDM parameter optimization, where thinner layers improve surface finish but extend build time, and higher infill densities enhance mechanical strength and safety margins but increase material consumption and energy demand, underscoring the necessity of multi-criteria frameworks for achieving balanced outcomes. Table **4** lists the calculated safety factors for each parameter set, demonstrating the improvements achieved through optimized configurations.

The multi-criteria decision-making rankings, integrating mechanical and safety criteria, are

Table 3: Impact Strength of PETG Specimens with Varying Process Parameters (kJ/m²)

Run	Layer Thickness (mm)	Infill (%)	Print Speed (mm/s)	Temperature (°C)	Impact Strength (kJ/m²)
1	0.1	40	40	200	3.2
2	0.1	60	60	220	3.8
3	0.1	80	80	240	4.1
4	0.2	40	60	220	4.5
5	0.2	60	60	220	4.8
6	0.2	80	60	220	5.0
7	0.3	40	80	240	3.7
8	0.3	60	80	240	4.2
9	0.3	80	80	240	4.4

Table 4: Safety Factor Calculations for Different FDM Parameter Combinations

Run	Layer Thickness (mm)	Infill (%)	Print Speed (mm/s)	Temperature (°C)	Safety Factor
1	0.1	40	40	200	1.22
2	0.1	60	60	220	1.28
3	0.1	80	80	240	1.32
4	0.2	40	60	220	1.36
5	0.2	60	60	220	1.41
6	0.2	80	60	220	1.47
7	0.3	40	80	240	1.30
8	0.3	60	80	240	1.35
9	0.3	80	80	240	1.39

Table 5: MCDM Ranking of FDM Process Parameters Using Fuzzy AHP-TOPSIS

Rank	Layer Thickness (mm)	Infill (%)	Print Speed (mm/s)	Temperature (°C)	Closeness Coefficient
1	0.2	80	60	220	0.82
2	0.2	60	60	220	0.76
3	0.3	80	80	240	0.71
4	0.3	60	80	240	0.68
5	0.2	40	60	220	0.65
6	0.3	40	80	240	0.61
7	0.1	80	80	240	0.58
8	0.1	60	60	220	0.54
9	0.1	40	40	200	0.46

summarized in Table **5**, indicating the optimal process parameter configuration with the highest closeness coefficient.

Moreover, the safety-oriented approach addresses a critical industrial need, as most existing studies such as Pranata *et al*. [19] and Nwaobia *et al*. [20] have primarily emphasized mechanical enhancements without explicit incorporation of safety indices into their optimization models, limiting the direct applicability of findings to high-risk environments such as aerospace or biomedical sectors. The novelty of this research lies in demonstrating that incorporating safety margins into decision-making does not merely replicate mechanical optimization outcomes but reshapes prioritization of parameters, as evidenced by the elevated importance of infill density for safety, even when tensile strength improvements appeared to plateau beyond 60% infill. The discussion also highlights practical implications, suggesting that manufacturers aiming for reliable FDM parts should adopt decision-support frameworks that explicitly balance mechanical properties with safety factors rather than relying on single-response optimization. Importantly, the numerical improvements observed—17.6% in tensile strength and 14.3% in safety factor—are not merely incremental but represent significant reliability gains when scaled to real-world applications where material failure can incur high economic or safety costs. The findings extend the body of knowledge by showing that while tensile strength remains a dominant performance metric, safety factors provide an additional layer of decision relevance, particularly in scenarios where load-bearing reliability under uncertain conditions must be assured. This integration aligns with global industrial efforts to standardize additive manufacturing for critical applications, as highlighted by ASTM and ISO standards, thereby ensuring that research outputs transition effectively into practice. Finally, the results affirm that FDM, when optimized through structured multi-criteria frameworks, can transcend its traditional role as a prototyping tool to become a reliable method for producing functional, safety-critical polymer components, addressing the downward drift in support for polymer studies noted in recent literature, and offering a pathway for sustainable, industrially relevant manufacturing practices.

3.1. Limitations and Applicability

While the proposed safety-oriented decision-making framework demonstrated strong validity in optimizing PETG-based FDM components, certain limitations must be acknowledged to guide future research and application. First, the experimental validation in this study was confined to glycol-modified polyethylene terephthalate (PETG), chosen for its industrial relevance and balanced mechanical performance. However, polymer behavior in FDM is highly material-dependent, particularly with bio-based or fiber-reinforced composites that exhibit distinct thermal and rheological responses. Future work will extend the framework to a broader range of polymers and hybrid materials to confirm its generalizability across diverse material systems.

Second, the raster angle was intentionally fixed at 45°/−45° to isolate the effects of the primary parameters—layer thickness, infill density, print speed, and extrusion temperature. Nonetheless, raster orientation is known to interact with other parameters, influencing interlayer bonding and anisotropy. A comprehensive factorial design incorporating raster angle variations is therefore recommended in subsequent studies to refine the predictive capability of the framework. Despite these constraints, the developed methodology remains broadly applicable to safety-critical FDM applications, offering a scalable foundation for process optimization, decision support, and reliability-based design in additive manufacturing.

4. CONCLUSION

This study developed and validated a decision-making framework for safety-oriented optimization of polymer components fabricated by fused deposition modeling (FDM), addressing a critical research gap where mechanical property enhancement has often overshadowed safety considerations in additive manufacturing. Experimental evaluation demonstrated that process parameters such as layer thickness, infill density, extrusion temperature, and print speed significantly influence both mechanical performance and safety reliability, with optimized settings of 0.2 mm layer thickness, 80% infill density, 220 °C extrusion temperature, and 60 mm/s print speed yielding a 17.6% improvement in tensile strength and a 14.3% increase in safety factor compared to baseline conditions. SEM analysis confirmed that these improvements were linked to enhanced interlayer adhesion and reduced void content, thereby improving structural integrity under load. The integration of Fuzzy Analytic Hierarchy Process (AHP) and TOPSIS provided a systematic and robust methodology for balancing multiple criteria, with safety factors emerging as a decisive metric alongside tensile and impact strength. This dual emphasis on performance and safety underscores the novelty of the proposed approach and its practical value for industries where failure risk must be minimized, such as aerospace, biomedical, and automotive sectors. Beyond demonstrating the feasibility of safety-oriented optimization, this work contributes to advancing FDM as a viable technology for functional, load-bearing, and safety-critical applications. Future research should extend the framework to composite filaments, environmental durability factors such as moisture and temperature cycling, and sustainability indicators including energy consumption and recyclability, thereby creating a more holistic foundation for safe, reliable, and sustainable additive manufacturing. Overall, the optimized settings yielded a 17.6% improvement in tensile strength and a 14.3% enhancement in safety factor over baseline conditions, underscoring the practical significance of the proposed safety-oriented optimization framework.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors confirm that during the preparation of this manuscript, *ChatGPT (OpenAI)* was employed solely for language refinement, including grammar correction, readability enhancement, and stylistic consistency. No content, analysis, or interpretation of research findings was generated by the tool. All scientific insights, experimental data, and conclusions are the sole work of the authors. Following the use of the tool, the authors carefully reviewed and edited the manuscript in its entirety and accept full responsibility for the accuracy and integrity of the published content.

AUTHOR CONTRIBUTIONS

Conceptualization: Raja Subramani. Methodology: Raja Subramani, Maher Ali Rusho, and Shahad Abdul Wahhab Ibraheem. Software and Simulation: Hassan Safi Ahmed, Kareem Al-Adily, and Mohsin Ali. Validation and Formal Analysis: Maha H. Philip Rahmani and Mohammed Ahmed Mustafa. Investigating and Data Curation: Tholfiqar Najah Ismael and Maher Ali Rusho. Writing – Original Draft: Raja Subramani and Maher Ali Rusho. Writing – Review & Editing: All authors contributed to manuscript revision and approved the final version for submission. Supervision and Project Administration: Raja Subramani.

REFERENCES

[1] Rathi M, Sharma A. Shaping the Future: Additive Manufacturing of Ceramics for Complex Geometries. Journal of Ceramics and Concrete Technology 2025; 10(2): ISSN: 2457-0826 (Online).

[2] Kumar R, Mehdi H, Bhati SS, Arunkumar M, Mishra S, Lohumi MK. A comprehensive review of advancements in additive manufacturing for 3D printed medical components using diverse materials. Discover Materials 2025; 5(1): 1-29. https://doi.org/10.1007/s43939-025-00349-w

[3] Fu K. What 3D Printing Cannot Achieve: Rethinking Composite Additive Manufacturing. Accounts of Materials Research 2025; 6(8): 921-926. https://doi.org/10.1021/accountsmr.5c00156

[4] Yeshiwas TA, Tiruneh AB, Sisay MA. A review article on the assessment of additive manufacturing. Journal of Materials Science: Materials in Engineering 2025; 20(1): 85. https://doi.org/10.1186/s40712-025-00306-8

[5] Maniraj M, Kumar SR. Design for Additive Manufacturing: Bridging Creativity and Precision in the 3D Printing Era. In: Modeling, Analysis, and Control of 3D Printing Processes. IGI Global Scientific Publishing 2025; 79-100. https://doi.org/10.4018/979-8-3373-0533-2.ch004

[6] Dzogbewu TC, de Beer DJ, Nooni IK. Additive Manufacturing as a Catalyst for Low-Carbon Production and the Renewable Energy Transition in Electric Vehicles. Technologies 2025; 13(10): 428. https://doi.org/10.3390/technologies13100428

[7] Zhang Z, Hu C, Qin QH. The improvement of void and interface characteristics in fused filament fabrication-based polymers and continuous carbon fiber-reinforced polymer composites: a comprehensive review. The International Journal of Advanced Manufacturing Technology 2025; 1-41.

[8] Azami M, Aubin-Fournier PL, Hojjati M, Skonieczny K. Additive Manufacturing of PEEK/Lunar Regolith Composites for Sustainable Lunar Manufacturing. arXiv preprint arXiv:2508.00894; 2025.

[9] Subramani R, Leon RR, Nageswaren R, Rusho MA, Shankar KV. Tribological Performance Enhancement in FDM and SLA Additive Manufacturing: Materials, Mechanisms, Surface Engineering, and Hybrid Strategies—A Holistic Review. Lubricants 2025; 13(7): 298. https://doi.org/10.3390/lubricants13070298

[10] Qadyani MJ, Ameri B, Taheri-Behrooz F. Critical strain energy release rate in additively manufactured polymers through comparative study of ABS and PLA across various raster angles. Theoretical and Applied Fracture Mechanics 2025; 138: 104890. https://doi.org/10.1016/j.tafmec.2025.104890

[11] Arunkumar P, Balaji D, Radhika N, Rajeshkumar L, Rangappa SM, Siengchin S. Effect of infill pattern on mechanical properties of 3D printed PLA-Zn composites for drone frame structures: A topology optimization integrated application study. Results in Engineering 2025; 25: 104107. https://doi.org/10.1016/j.rineng.2025.104107

[12] Tomelleri F, Bosetti P, Brunelli M. Optimizing 3D printer selection through multi-criteria decision analysis. The International Journal of Advanced Manufacturing Technology 2025; 1-20. https://doi.org/10.1007/s00170-025-16148-9

[13] Arivendan A, Chen X, Zhang YF, Keerthiveettil Ramakrishnan S, Gao W, Winowlin Jappes JT, Alagumalai V. Continuous Natural Fiber-Reinforced Polymer Composites (CNFRPCs) Manufacturing: Additive Manufacturing Pathways to a Sustainable Future—A Critical Review. Polymer Composites 2025. https://doi.org/10.1002/pc.70308

[14] Ma Q, Dong K, Li F, Jia Q, Tian J, Yu M, Xiong Y. Additive manufacturing of polymer composite millimeter-wave components: Recent progress, novel applications, and challenges. Polymer Composites 2025; 46(1): 14-37. https://doi.org/10.1002/pc.28985

[15] Gajević S, Miladinovic S, Jovanović J, Güler O, Özkaya S, Stojanovic B. Application of Various Optimisation Methods in the Multi-Optimisation for Tribological Properties of Al–B4C Composites. Computers, Materials & Continua 2025. https://doi.org/10.32604/cmc.2025.065645

[16] Salaimanimagudam MP, Jayaprakash J, Anwar MP. Selection of Reinforcement Incorporation Method for 3D Printed Concrete using MCDM. Iranian Journal of Science and Technology, Transactions of Civil Engineering 2025; 1-13. https://doi.org/10.1007/s40996-025-01766-w

[17] Mohamed OA, Masood SH, Bhowmik JL, Nikzad M, Azadmanjiri J. Effect of process parameters on dynamic mechanical performance of FDM PC/ABS printed parts through design of experiment. Journal of Materials Engineering and Performance 2016; 25(7): 2922-2935. https://doi.org/10.1007/s11665-016-2157-6

[18] Torres J, Cole M, Owji A, DeMastry Z, Gordon AP. An approach for mechanical property optimization of fused deposition modeling with polylactic acid via design of experiments. Rapid Prototyping Journal 2016; 22(2): 387-404. https://doi.org/10.1108/RPJ-07-2014-0083

[19] Pranata D, Santoso B, Ayuningtyas F. Advancements in Intelligent Design, Simulation Techniques, Technological Safety Innovations, and Sustainable Manufacturing Practices. Transactions on Artificial Intelligence, Machine Learning, and Cognitive Systems 2025; 10(3): 16-29.

[20] Nwaobia NK, Nwasike CN, Tula OA, Umoh AA, Gidiagba JO. Safety protocols in electro-mechanical installations: Understanding the key methodologies for ensuring human and system safety. 2024.

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