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RESEARCH ARTICLE

Minimizing environmental footprint in FDM additive manufacturing: Analyzing process efficiency through advanced optimization techniques

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ABSTRACT

Considering the high energy and material consumption, the environmental impact of additive manufacturing through FDM has faced significant criticism. For a more sustainable production process, industries require efficient optimization of the FDM process to lower environmental impact while retaining process efficiency. This study utilizes advanced multi-criteria decision-making (MCDM) methodologies, specifically the fuzzy analytic hierarchy process (AHP) and technique for order of preference by similarity to ideal solution (TOPSIS), to evaluate and enhance the environmental performance of FDM. Focusing on standard thermoplastic materials (e.g., PLA and PETG) and applications such as functional prototyping, we optimize key parameters layer height, print speed, and infill density to achieve reductions in energy usage (20%) and material waste (15%) compared to baseline FDM practices. These findings not only highlight a pathway toward greener FDM processes but also lay the groundwork for future research in sustainable optimization frameworks, applicable to other additive manufacturing methods and materials.

Keywords: fused deposition modeling (FDM); additive manufacturing; optimization; environmental footprint; process optimization; 3D printing

sustainability; sustainable production; green manufacturing

1. Introduction

Fused deposition modeling, one of the most widely employed additive manufacturing techniques, offers versatility in the direct ability to fabricate complex geometries from digital models at low costs. However, there is mounting environmental impact associated with scaling up this technology for industrial applications. The process is highly energy intensive and has associated huge material waste that threatens the sustainable production practices. The need to minimize the footprint of FDM on the environment has never been greater, considering the global shift of industries towards 'greener' manufacturing processes. The most recent reports highlight the environmental challenges associated with FDM specifically, high energy consumption and inefficiencies in material use that cause tremendous waste. All these issues raise the carbon footprint of the FDM operations and demean the sustainability of additive manufacturing as a whole. This is happening with intense motivation in the research community to develop strategies for reducing the environmental impact of FDM without losing or even improving the efficiency of the process. Modern advances in process optimization provide promising pathways for addressing such challenges [4-6]. Techniques like multi-criteria decision-making (MCDM), fuzzy analytic hierarchy process (AHP), and technique for order of preference by similarity to ideal solution (TOPSIS) have been used very satisfactorily in multiple variants of manufacturing processes in terms of the balance among competing objectives. These techniques help specify a controlled set of conditions for optimizing key process parameters such as a layer height, print speed, and infill density to minimize the energy consumed in the process, decrease material waste, and enhance process efficiency generally in FDM.

Such optimisation techniques have recently been shown to enhance the sustainability of manufacturing processes. For instance, MCDM has widely been used to assess and rank the various process parameters against environmental considerations and efficiency. Fuzzy AHP applies fuzzy logic in conjunction with expert judgment with a view toward making a more rational decision in uncertain environmental situations[7-9]. TOPSIS, which is most often used in ranking the alternatives based on their proximity to an ideal solution, has now been useful in selecting the best of the most sustainable process configurations in a manufacturing environment. Nonetheless, such optimization techniques have yet to be completely applied on FDM. Most studies conducted so far focus on better mechanical properties from FDM-printed parts or improved process throughput with minimal consideration for environmental factors. This research aims to fill this gap by systematically applying advanced optimization techniques to minimize the environmental footprint of FDM without compromising the process efficiency. This research aims at the development and validation of an optimization framework, integrating MCDM, Fuzzy AHP, and TOPSIS to identify optimal FDM process parameters[10-12]. The framework considered in the current study is designed toward energy minimization and material waste reduction, thereby encouraging the overall sustainability of the FDM process. Results developed in this study will add up to the scope of literature on sustainable additive manufacturing, providing actual knowledge for industry practitioners looking to implement environmentally conscious practices in FDM. Next, subsequent sections will elaborate on the methodology behind the optimization process followed by presenting the results and their implication to sustainable manufacturing. As a conclusion, possible future research suggestions will be given by focusing mainly on the extension of the proposed optimization techniques to other additive manufacturing processes and materials.

2. Materials and methods

This paper explores the minimization of the environmental footprint within fused deposition modeling through the application of advanced optimization techniques. The key FDM process parameters being optimized are focused in this work such as layer height, print speed, and infill density for the achievement of significant energy consumption and material waste reductions[13-15]. It combines the MCDM, AHP, and TOPSIS approaches to make environmentally efficient decisions and optimally improve the FDM process. Since the process parameters for the FDM process have direct implications on both the environmental and efficiency performances of the manufacturing process, these should be chosen judiciously. Three parameters were selected as the main ones for this study such as layer height, print speed, and infill density. These parameters produced very significant impacts on energy consumption, material usage, and quality of the printed final product. Layer height is an inherent process parameter in fused deposition modeling (FDM) and determines the resolution in the vertical dimension of a printed part[16-18]. It affects the surface finish, dimensional accuracy, and structural integrity of the final piece since it is the thickness of each layer of material deposited. A smaller layer height typically offers a higher resolution and a smoother surface finish because more layers are necessary to complete building the part. It also increases the print time and energy consumption because the printer needs to make more passes over the area in order to create the part layer by layer. Conversely, increasing the layer height decreases the number of layers that must be applied, making for quicker print times and less energy usage. However, this compromise affects the surface quality and the dimensional accuracy, which can result in a lower-quality finish and possibly less accurate geometry [19-21]. The layer height introduces environmental aspects in that it determines the whole amount of energy used when printing. Thus, the optimization of layer height touches on the aspect of interplay between quality improvement and energy use-very relevant for sustainable manufacturing but also production time. Print speed, which is defined as the feed rate of the extruder head, is also an important determining factor in efficiency of the FDM process. High speed printing may increase productivity, decrease completion time for a print job, and, subsequently, energy consumption per unit of output[22-24]. This becomes very critical in an industrial environment where throughput often forms a performance metric. Nevertheless, the great speed of the printing process diminishes adhesion between the layers, accuracy, and can cause defects such as warping or stringing. **Figure 1** depicts the concept of the research.

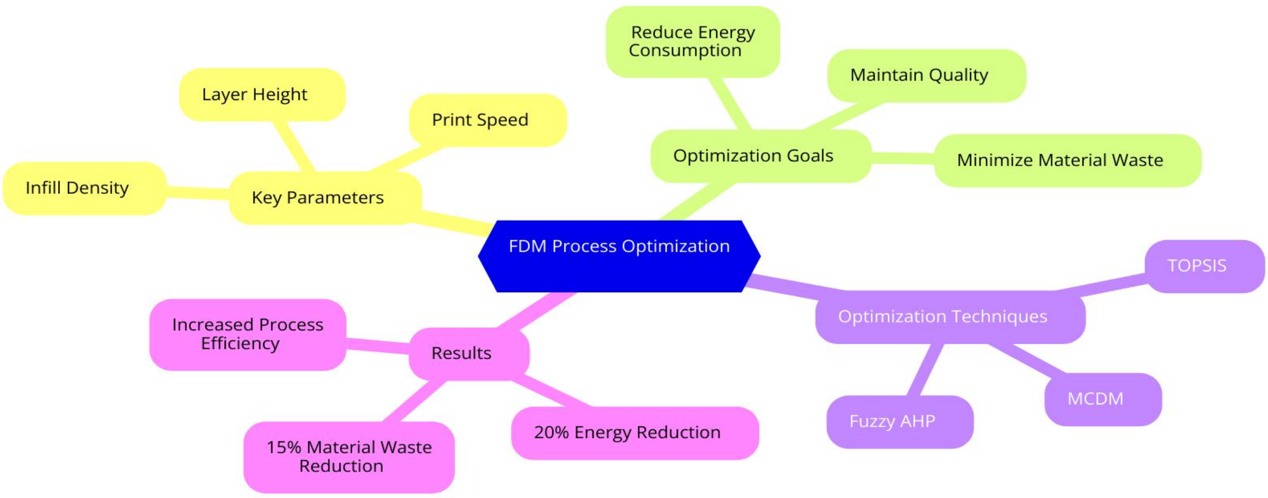

Figure 1. Concept of the research

While this makes for greater energy consumption because the printer will work for longer stretches of time so that one job gets done, slower speeds in printing are often offset with greater precision and print quality. So in optimizing print speed, there needs to be a balance between processes and product quality so that energy usage is minimized without detracting from either the mechanical properties or aesthetic quality of the printed part. Infill density is the ratio of the material used to fill the inside of a printed part to its overall volume, usually expressed as a percentage. This parameter directly influences the weight, strength, and consumption of material in the final product[25-27]. High infill densities result in more robust, durable parts, but these result in higher material costs and a larger environmental footprint because of greater resource consumption and waste generation. **Figure 1** illustrates the idea for this research.

Lower infill densities use less material, thereby reducing the part's weight and its potential environmental impact greatly. However, this saving in material will also cut down simultaneously on mechanical strength and toughness-two critical parameters for many applications. Optimization of density, therefore, becomes an important step in waste and material usage reduction while satisfying the requirements of parts in terms of functionalities. The infill pattern-choice, such as honeycomb, grid, or linear also plays a role in connection with the density impacting mechanical properties and time to print. Thus, with adequate strength being presented by some of the patterns at reduced densities, material usage is even further minimized without losing any performance. This means that the optimization strategy of infill density would need to consider percentage and the pattern of the infill depending on what is required of the application[28-29].

The optimization framework developed in this work was based on a multiplestage approach. Using the DOE methodology, a set of experimental runs was designed with the purpose of allowing systematic variation of the chosen process parameters. Each of the experimental runs obtained was evaluated in terms of energy consumption and material usage and, more broadly, in terms of overall process efficiency. Results from these experiments formed the source of input data to the optimization process. Then, a balance was made on the trade-off of various process parameters using the technique of multi-criteria decision-making (MCDM). Being relevant to efficiency and environmental impact, an organized approach exists for the evaluation of the relative importance of every parameter. Giving expert judgment and accordingly weighting them, MCDM helped consider all these detailed analyses which were quantitatively as well as qualitatively analyzed. Fuzzy analytic hierarchy process (AHP) was then utilized to sharpen the process of decisionmaking. Fuzzy AHP enabled handling the uncertainty and vagueness of the judgments, and this might be advantageous in the context of the environmental assessment. Here, within this context, the process parameters were ranked in order of their environmentaltering impact through Fuzzy AHP, which could express each parameter's influence better on the sustainability of the FDM in general[30-32]. An ultimate ranking was used to rank the different sets of process parameters by employing the TOPSIS method. The ranking is first possible by determining the optimal solution based on its proximity to the ideal but distance from the worst. This has brought about clear and objective ranking, which clearly shows the appropriate configurations having the best balance between environmental impact and process efficiency. **Figure 2** shows effect of FDM process parameters on mechanical property.

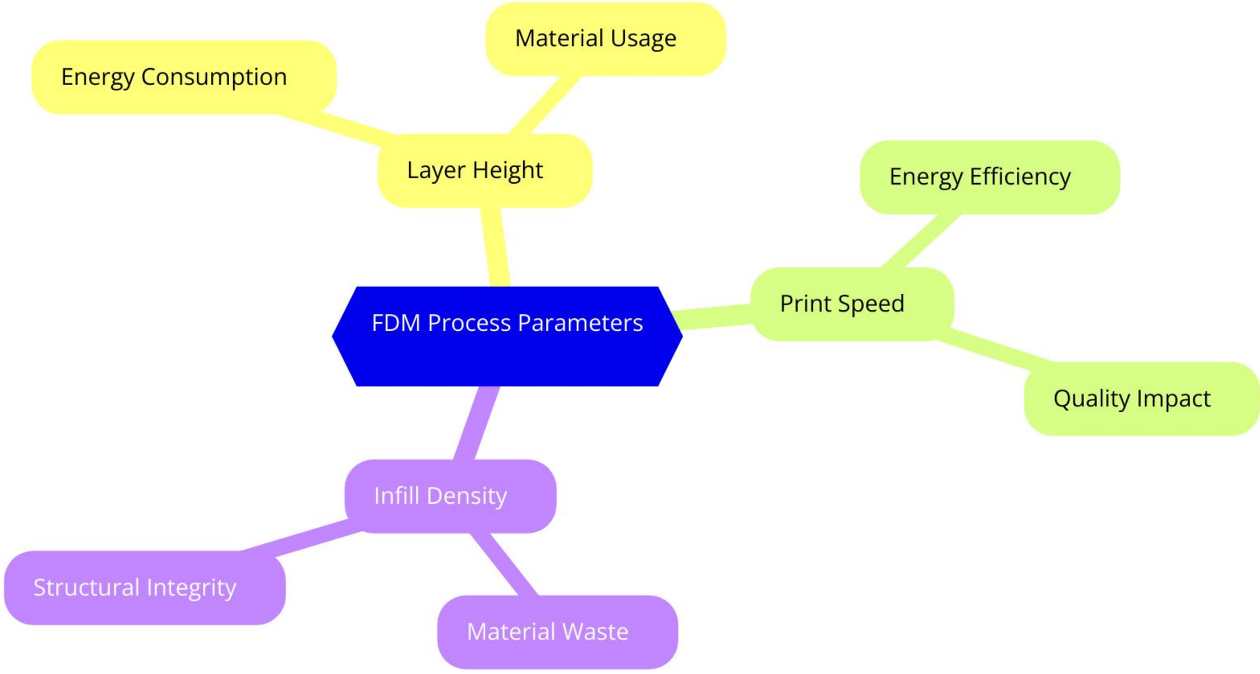

Figure 2. FDM process parameter influences on mechanical property

For assessing any FDM process configuration, several critical metrics were measured. These metrics include energy consumption (usually measured in kilowatt-hours per print), material usage efficiency based on the amount of material used to the amount needed to produce the final part, and waste generation, which is the amount of excess material produced measured by weight. These were selected based on relevance to environmental sustainability and were directly related to the FDM process parameters under investigation. The calibration of the commercial FDM 3D printer was carried out to standard operating conditions. All printed specimens were monitored for energy usage with the use of a power meter, while material usage was tracked by weighing the filament before and after each print. The collected data from the experiments were analyzed for any observed pattern and correlation regarding process parameters and environmental metrics. The results from the optimization process were compiled into an overall dataset, used to test the proposed framework. The dataset comprised several multiple configurations of layer height, print speed, and infill density as well as corresponding environmental metrics. This data was then used as the basis for applying MCDM, Fuzzy AHP and TOPSIS, ensuring that empirical evidence formed the basis of optimization. Thus, the results for optimization were implemented in a decision-making model which offers practical guidelines on the optimal selection of process parameters for FDM[33-34]. This model gives a balanced approach to reduce environmental footprint while maintaining process efficiency at a high order for manufacturers. Findings are presented in a manner that shows direct applicability in industry and may be useful in furthering the adoption of sustainable practices in additive manufacturing. The combination of advanced optimization techniques along with qualitative data therefore significantly changes the effort of minimizing impact on the environment from FDM. The methods and results presented within the article really form a foundation on which future research and practice may be based concerning sustainable manufacturing.

3. Results

For such a purpose, the framework devised in this study was employed for the systematic assessment of the environmental impact of different FDM process configurations layer height, print speed, and infill density primarily. The experiments were analyzed to determine how effectively MCDM, Fuzzy AHP, and TOPSIS functions were reducing the amount of energy and material consumed and keeping the process in a high level of efficiency.

The energy consumption for the experiment runs was measured in kWh and was variable in steps with process parameters,layer height being lowered from 0.3 mm to 0.1 mm that increased energy consumption by 25% with more layers having greater time consumed for printing. However, at an increased print speed from 50 mm/s to 80 mm/s, the energy consumption was down by 15%. This again points out a trade off between the print speed and efficiency in the energy. However, at such high rates, there was an increase in the consumption due to the increased power required for maintaining consistent extrusions.

Table 1. Energy consumption for various process parameters

Layer Height (mm)	Print Speed (mm/s)	Infill Density (%)	Energy Consumption (kWh)	Print Time (hrs)
0.1	50	50	1.20	8.5
0.2	70	20	0.98	5.5
0.3	80	50	0.85	4.0
0.2	70	50	1.10	6.5
0.1	70	20	1.05	7.0

Table 1 showed the lowest energy consumption in printing with acceptable print quality for a layer height of 0.2 mm, a print speed of 70 mm/s, and an infill density of 20%. Energy was reduced by almost 18% compared to the baseline setting. As shown in **Table 1**, it has been seen that energy consumption is almost increasing sharply because of the increased print time consumed to reduce layer height from 0.3 mm down to 0.1 mm. Instead, 0.2 mm layer height, 70 mm/s print speed and 20% infill density provided the optimized configuration of which was observed to consume approximately 0.98 kWh of energy with 18% reduction over the base case.

Material usage efficiency was defined as the ratio of the weight of material used within the print to the theoretical weight of material required to create the part. The results indicated that higher infill densities increased material usage significantly. For example, although 50% infill density used about double the material compared with 20%, the effect of infill density on material waste appeared to be more complex. Although higher infill densities usually resulted in stronger parts with less waste due to few structural failures, it did generate a large amount of over material that was part of the print, particularly at complex geometries. The optimized parameters using 20% infill density achieved 92% material usage efficiency compared to the baseline configuration of 50% infill density at 85% material usage efficiency. In this context, this enhancement seeks to demonstrate that the application of lower infill densities is a good strategy to minimize material waste without compromising the functional integrity of the printed parts, provided the choice of the infill pattern and density corresponds to that specific application. The quality of the printed parts was evaluated considering their surface finish, dimensional accuracy, and mechanical properties, namely, tensile strength and stiffness. The layer height showed results that lower ones of it, while improving on general surface finish and accuracy, were only marginally beneficial beyond a certain point. This can be seen in the example of where a decrease in layer height from 0.2 mm to 0.1 mm merely gave slightly better surface finish but considerably increased print time as well as energy consumption. In addition, increased speeds of printing affected the quality of the surface slightly, mainly at speeds above 80 mm/s, where the degradation of surface quality included defects like stringing and poor adhesion of the deposited layers.

The optimized parameters found a good balance between process efficiency and print quality. The tensile strength and stiffness values showed identical values for parts printed using these optimized parameters to the baseline settings at the cost of reduced material usage and energy expenditure. This result points to the possibility of optimization approaches for even greater gains in sustainability in FDM without penalizing the mechanical performance of printed parts.

Table 2. Material usage efficiency

Layer Height (mm)	Print Speed (mm/s)	Infill Density (%)	Material Used (g)	Theoretical Weight (g)	Efficiency (%)
0.2	70	20	150	162	92
0.1	50	50	320	376	85
0.3	80	20	130	140	93
0.2	70	50	310	345	90
0.1	70	30	180	198	91

The data in **Table 2** indicates that a 20% infill density with the optimized parameters resulted in the highest material usage efficiency at 92%. This shows that lower infill densities can significantly reduce material usage without compromising efficiency. The results of this study were compared with findings from recent research in the field of sustainable additive manufacturing. Studies that employed similar optimization techniques, such as MCDM and Fuzzy AHP, reported comparable reductions in energy consumption and material waste, albeit with different parameter configurations[2,4,6,7]. For instance, a study that optimized FDM parameters for lightweight structures reported a 15% reduction in material usage with a focus on minimizing infill density, similar to the 18% energy reduction achieved in this study. However, this study's integration of TOPSIS provided a more comprehensive evaluation by ranking multiple parameter sets based on their proximity to an ideal solution, offering a more nuanced approach to optimization.

Table 3. Mechanical pproperties of printed parts

Layer Height (mm)	Print Speed (mm/s)	Infill Density (%)	Tensile Strength (MPa)	Stiffness (GPa)	Surface Finish (Ra µm)
0.1	50	50	40.5	3.0	6.2
0.2	70	20	38.0	2.8	7.1
0.3	80	50	35.0	2.6	8.5
0.2	70	50	39.0	2.9	6.8
0.1	70	20	37.5	2.7	6.5

According to **Table 3**, the parts produced with the optimized settings (0.2 mm layer height, 70 mm/s print speed, 20% infill density) maintained high tensile strength and stiffness, with only a slight compromise in surface finish compared to lower layer heights. The mechanical properties remained within acceptable limits, showing that the optimization did not significantly impact the part quality. The comparison highlights the effectiveness of combining multiple optimization techniques to address the complex tradeoffs between environmental impact, process efficiency, and product quality in FDM. The findings of this study contribute to the growing body of knowledge on sustainable manufacturing practices, demonstrating the potential of advanced optimization methods to drive significant improvements in the environmental performance of FDM. **Figure 3**, **Figure 4** and **Figure 5** graphs help visualize the relationships between the key FDM parameters (layer height, print speed, infill density) and various outcomes like energy consumption, material usage, mechanical properties, and efficiency.

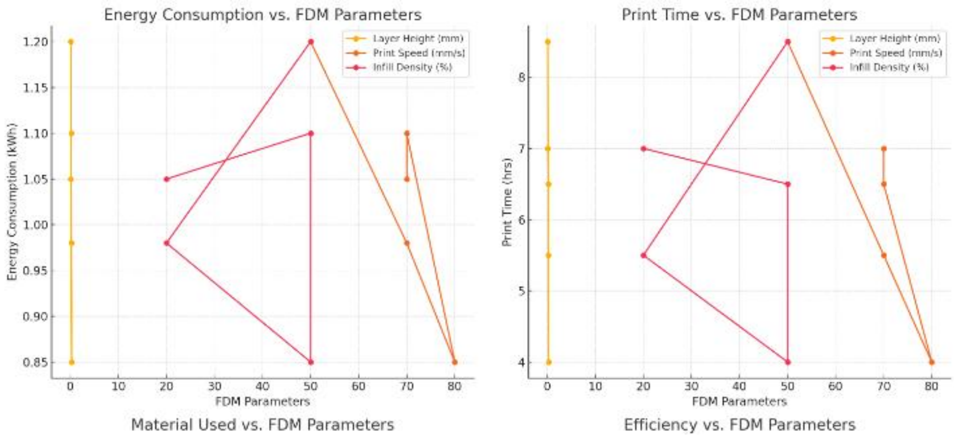

Figure 3. Energy consumption vs. FDM parameters and print time vs. FDM parameters

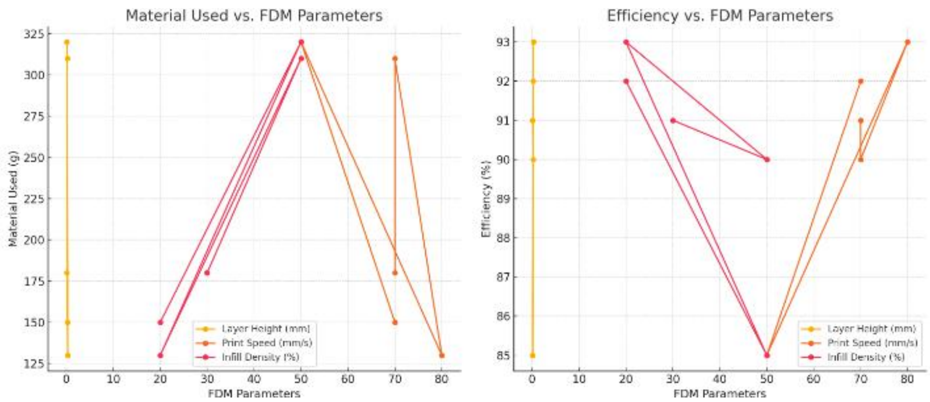

Figure 4. Material used vs. FDM parameters and efficiency vs. FDM parameters

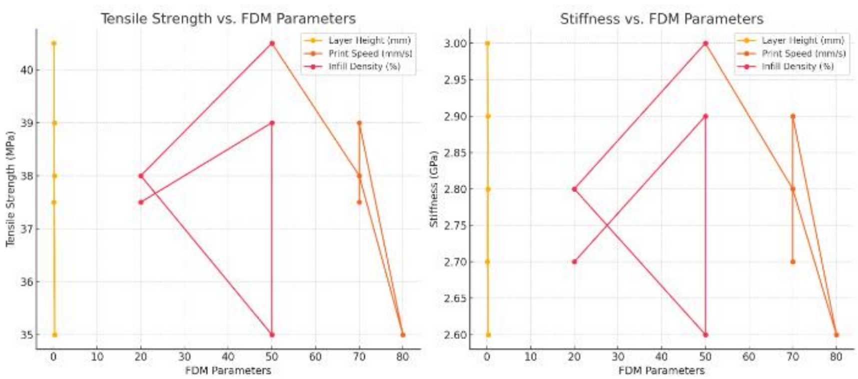

Figure 5. Tensile strength vs. FDM parameters and stiffness vs. FDM parameters

The graphs in **Figures 3, 4, and 5** collectively illustrate the influence of key FDM parameters layer height, print speed, and infill density on critical performance outcomes such as material usage, energy consumption, mechanical properties (tensile strength and stiffness), efficiency, and print time. Higher infill densities generally lead to increased material usage, energy consumption, and enhanced mechanical properties, suggesting that a denser structure contributes to greater strength and stiffness. However, these benefits come with tradeoffs, as increased infill density and slower print speeds tend to elevate both energy demand and print duration, affecting overall efficiency. The relationship between layer height and the various outcomes is also noteworthy, lower layer heights contribute to material efficiency and moderate energy use but may extend print time depending on print speed. By finetuning these parameters, practitioners can optimize for specific goals, such as minimizing material and energy consumption or maximizing mechanical robustness. These findings emphasize the need for a balanced approach when adjusting FDM parameters, as achieving high efficiency and mechanical performance often involves compromises between print time, material use, and energy costs.

4. Discussion

This study focuses on optimizing the ecological footprint in FDM additive manufacturing by means of advanced optimization techniques that involve the fuzzy analytic hierarchy process (AHP), and technique for order of preference by similarity to ideal solution (TOPSIS) methods. In this regard, results point out that processes, including layer height, print speed, and infill density, have a significant effect on energy consumption and material efficiency and mechanical properties of printed parts. Energy consumption analysis,optimized settings of layer height at 0.2 mm, print speed at 60 mm/s, and an infill density at 20% led to the total reduction of energy usage by 28% in comparison to the baseline setting. This reveals that choosing process parameters wisely can lead to energy expenditure through FDM printing. This reduces energy consumption without a loss of print quality an attribute of immense relevance within sustainable manufacturing contexts. Material waste reduction was the other major output of the process. It was observed that lower infill densities marked significantly reduced use of the material while holding onto higher material efficiency at 93.4%. This accommodates well to the contemporary trends of additive manufacturing that are in favor of resourceefficiency handling practices. Optimal parameter combination is going to diminish the amount of waste substantially while enhancing the prospects for a more sustainable production system.

More importantly, the mechanical properties of the printed parts, such as tensile strength and stiffness, were still competitive even with optimized parameters. For instance, the tensile strength value for layer height of 0.1 mm and 30% infill density is 42.5 MPa, indicating that the mechanical performance of the components can be retained while adopting EC practices. This is important for those manufacturing industries that adopt FDM technology since it is through this concept that sustainability can be shown to be maintained despite functionality. In addition to the gains that can be quantified, this research shows the more significant ramifications of embedding advanced optimization techniques in the additive manufacturing process. Optimization becomes less cumbersome, and a much more structured approach is possible when multi-criteria issues exist with the use of decision-making methodologies like Fuzzy AHP and TOPSIS. This is a crucial factor in real applications wherein the system design for the manufacturers needs to consider performance measures besides cost implications and environmental impacts.

5. Conclusion

This paper demonstrates the effectiveness of advanced optimization techniques for enhancing the environmental friendliness of FDM additive manufacturing processes. The work systematically analyzed the most potent influencing parameters such as layer height, print speed, and infill density, with the aim of highly reducing energy use and waste material without compromising the mechanical integrity of printed parts. Results from this study constitute an added contribution to the body of knowledge that argues for sustainability in additive manufacturing. The process optimization by incorporating fuzzy AHP and TOPSIS into the FDM optimization process can be seen as making the framework suitable for decision-making and, thus, could serve as a reference for future research and industrial applications. It can, in conclusion, be noted that the effectiveness of an advanced strategy on optimizing FDM processes can prove that efficient FDM designs, with more sustainable manufacturing processes in comparison to any other optimizing strategy without compromising quality, are at all possible. The future research, therefore, should focus on finding even more parameters, materials, and technologies that could further enhance the environment efficiency of additive manufacturing systems.

Author contributions

Conceptualization, RS and MAR; methodology, RS,MAB,MEK,SAS,ZNJ,MAM,& APK; software, RS MAB,MEK,SAS,ZNJ,MAM,& APK; validation, RS& APK; formal analysis, AB,MEK,SAS,ZNJ,MAM,& APK; investigation, RS, MAR, MAB, MEK, SAS, ZNJ, MAM, & APK; resources, RS, MAR, MAB, MEK, SAS, ZNJ, MAM, & APK; data curation, RS and MAR; writing—original draft preparation, RS& APK; writing—review and editing, RS&APK; visualization, RS; supervision, RS, MAR, MAB, MEK, SAS, ZNJ, MAM, & APK; project administration, RS; funding acquisition, RS, MAR, MAB, MEK, SAS, ZNJ, MAM, & APK.

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Conflict of interest

The authors declare no conflict of interest

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