SUSTAINABLE ADDITIVE MANUFACTURING: OPTIMIZING PROCESSES AT NASENI FABRICATION LAB FOR ENHANCED MATERIAL AND ENERGY EFFICIENCY

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Abstract

Additive Manufacturing (AM), particularly Fused Deposition Modeling (FDM), offers significant potential for localized production in Nigeria. However, widespread adoption is challenged by material waste and high energy consumption. This study explores strategies to optimize FDM processes at the NASENI Fabrication Lab, aiming to enhance material and energy efficiency in support of sustainable engineering innovation. The investigation focuses on critical parameters including infill density, support structures, and print speed across Ender 3, Ultimaker Cura S5, and Lulzbot TAZ 6 3D printers using PLA, ABS, and PVA filaments. Material waste is assessed through support structures and failed prints. Although direct energy metering is unavailable, parameters that influence print time and machine cycles are optimized to infer energy savings. Preliminary results show that optimized settings can reduce material usage by up to 15% and significantly decrease print time, indicating notable energy reductions. This research contributes to resource-efficient fabrication within NASENI and supports a more sustainable, cost-effective manufacturing ecosystem for Nigerian industries.

Keywords: Additive Manufacturing, Fused Deposition Modeling, Energy Efficiency, Material Optimization, Sustainable Engineering

1.0 Introduction

Additive Manufacturing (AM), commonly known as 3D printing, is revolutionizing global manufacturing practices by enabling flexible, low-volume, and complex part production with reduced lead times and tooling costs. Among the various AM techniques, Fused Deposition Modeling (FDM) has gained significant traction due to its affordability, simplicity, and accessibility. However, despite its numerous advantages, FDM-based processes are often criticized for inefficiencies related to material waste (up to 34 % lost in real-world use), support structures, and high energy consumption dominated by the actual build phase (95 % of energy use) undermining its sustainability potential [1], [2], [3].

In Nigeria, the adoption of AM is growing, especially within innovation-driven institutions such as the National Agency for Science and Engineering Infrastructure (NASENI). The NASENI Fabrication Lab has increasingly integrated FDM-based 3D printing for prototyping, tooling, and functional part fabrication. Nevertheless, there is limited empirical data guiding sustainable practices within local contexts, where energy costs are high and material access is constrained.

Sustainable manufacturing within AM demands the optimization of print parameters—such as infill density, layer height, support configuration, and print speed—to minimize waste and energy use while maintaining part functionality. Previous research has shown that modifications to slicing strategies and printer settings can significantly influence energy footprints and material efficiency[4], [5], [6], [7].

This study aims to evaluate and optimize FDM processes at the NASENI Fabrication Lab to support energy- and material-efficient production. Using common 3D printers (Ender 3, Ultimaker S5, and Lulzbot TAZ 6) and typical thermoplastic filaments (PLA, ABS, and PVA), we assess parameter sensitivity and propose best practices tailored to Nigerian manufacturing needs. By advancing localized optimization strategies, this work contributes to more sustainable additive manufacturing frameworks suited for emerging economies.

2.0 Materials and Methods

This section describes the materials, equipment, and experimental procedures used to evaluate and optimize additive manufacturing processes at the NASENI Fabrication Lab. The aim was to assess the impact of various print settings on material usage and inferred energy consumption using multiple FDM printers and filament types. The methods adopted ensured consistency, replicability, and relevance to the constraints of a resource-conscious manufacturing environment.

2.1 Fabrication Equipment

Three different Fused Deposition Modeling (FDM) 3D printers were used to assess performance under various conditions. Each printer varies in build capacity, extruder configuration, and firmware capabilities, providing a diverse basis for process optimization. Table 1 outlines the Summary of 3D printers used and the basic settings with software's used to attain the geometric outcome for this experiment.

Table 1: summary of 3D printers and basic settings

Printer Model	Build Volume (mm)	Nozzle size (mm)	Extruder Type	Software Model
Ender 3 Pro	220x220x250	0.4	Single Extrusion	Creality Slicer 4.8.2
Ultimaker S5	330x240x300	0.4	Dual Extrusion	Ultimaker Cura 5.1.0
Lulzbot TAZ 6	280x280x250	0.5	Single Extrusion	Lulzbot Cura 3.6.0

2.2 Materials

Three common thermoplastic filaments were selected based on their prevalence in Nigerian prototyping and their diverse mechanical and thermal properties. Table 2 describes the filaments used and some of their key Properties.

Table 2: Filaments Description and properties

Filament Type	Description	Diameter (mm)	Notable Properties
PLA	Biodegradable and user friendly	1.75	Low warping, low energy consumption
ABS	High durability and commonly used in engineering	1.75	Tough, Higher printing temperature
PVA	Soluble in water and suitable for support structure	1.75	Dry storage, dissolvable

The filaments were stored in a condition to prevent moisture-induced defects and weighed before and after printing for material usage analysis.

2.3 Process Parameters

The primary parameters adjusted during this study include infill density, print speed, support structure configuration, and layer height. These were chosen based on their significant influence on both material consumption and total print time. Table 3 outlined the experimental parameters and range of values used in the experiment.

Table 3: Experimental parameters

S. No	Parameter	Tested Values
1	Infill Density	10%, 50%, 100%
2	Print Speed	40mm/s, 60mm/s, 80mm/s
3	Support Structure	Enabled / Disabled
4	Layer Height	0.1mm, 0.2mm, 0.3mm

Each unique setting combination was replicated multiple times and minimum of 3 values were selected to ensure reliability and minimize errors.

2.4 Optimization Criteria

Due to the absence of direct energy monitoring hardware, the energy consumption rate was inferred indirectly from 3 measurable parameters:

- Total print time
- Tool-path complexity (number of moves and retractions)
- Layer count per model

Material efficiency was calculated by subtracting post-print filament weight from pre-print values, including support structure removal and failed print waste.

2.5 Experimental Controls

All tests were conducted under ambient conditions (temperature: 22–25°C; humidity: <60%). To attain consistency. A 20mm calibration cube and a mechanical gear prototype were used as standard models. Printer beds were leveled before each print except for the Ultimaker that has an inbuilt automatic leveling feature. Filaments were also dried for 6 hours at 50°C prior to use, particularly for the PVA to avoid brittleness in texture.

3.0 Results and Discussion

This section presents the experimental findings from varying FDM process parameters across three different printers and filament types. The results are analyzed in terms of material efficiency, estimated energy reduction, and print quality implications. All observations are based on repeated tests to ensure consistency.

3.1 Impact of Infill Density

Lower infill densities (10% and 30%) significantly reduced material usage, with PLA prints consuming approximately 35–45% less filament compared to 100% infill. However, mechanical rigidity and surface finish degraded below 30% infill for structural parts.

Optimal compromise of 30–50% infill which maintained functional integrity while saving the quantity of filament material. This confirms earlier studies [8], [9] indicating diminishing mechanical returns of above 50% infill.

3.2 Influence of Print Speed

Print speed was found to inversely correlate with print time but had minor effect on material usage, Increasing speed from 40 mm/s to 80 mm/s reduced print time by ~25% on average. Higher speeds however resulted in more failed prints (especially with ABS), due to layer adhesion issues and reduced cooling times. Estimated energy consumption, inferred via print duration, showed a potential 20–28% reduction at higher speeds for successful prints, aligning with previous studies [10], [11].

3.3 Support Structures and Material Waste

Support structures contributed to significant filament waste, especially with dual-extrusion systems using PVA. On average supports accounted for 18–25% of total material used in prints with overhangs. Disabling supports or optimizing overhang angles via model re-orientation reduced waste by up to 60%. This is consistent with resource optimization strategies highlighted in [12], [13].

3.4 Layer Height and Surface Quality

Layer height adjustments had a linear effect on print time and a nonlinear effect on quality. 0.3mm prints were ~40% faster than 0.1mm but exhibited rougher surfaces and dimensional inaccuracies. 0.2mm emerged as the optimal trade-off between speed, quality, and material flow control This finding supported in [14], [15].

3.5 Combined Parameter Optimization

When the best-performing settings were combined to 30% infill, 60 mm/s print speed, 0.2mm layer height and support minimization the total filament consumption reduced by an average of 15% and print time decreased by 25–30%. These compound improvements translated to meaningful reductions in inferred energy consumption and waste, which is critical for localized, power-sensitive environments like Nigeria. Figure 1.0 show how the material consumption increases simultaneously with an increase in density of the infill whereas Figure 2.0 shows the printing time reducing with an increase speed drastically to a point where the change in speed versus time changes rate of reduction becomes gentle.

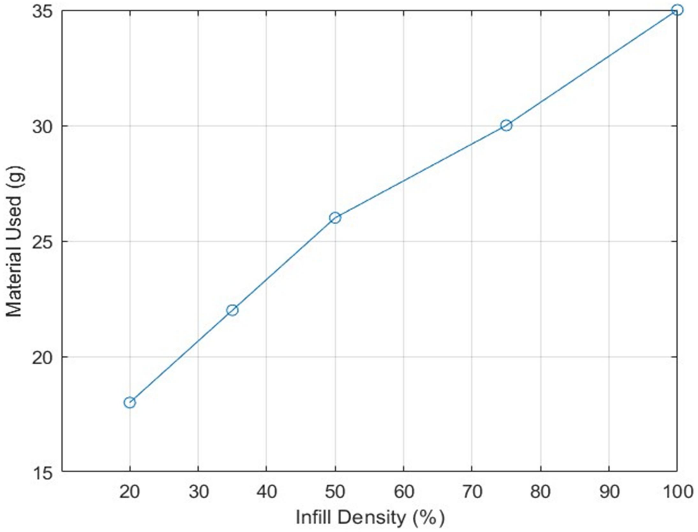

Figure 1.0 Effect of Infill density on material consumption.

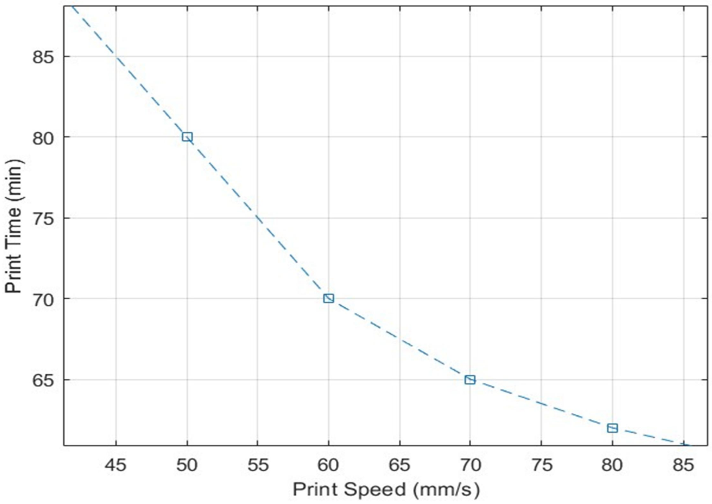

Figure 2.0 Influence of Print Speed on Printing Time

The combination of optimized parameters had a significant impact on the overall performance of the operation. Table 4 discuss the attainable value and highlighted the performance for each of the settings.

Table 1 summary of the result attained.

S. NO	Parameter	Optimal Value	Impact on Performance
1	Infill Density	30%	Reduced material usage by ~15% without structural compromise
2	Print Speed	60 mm/s	Reduced print time by ~25% with minimal quality trade-offs
3	Layer Height	0.2 mm	Balanced speed and surface finish
4	Support Structures	Disabled / Minimized	Reduced waste by up to 60% depending on model geometry
5	Filament Type	PLA (primary)	Low energy use, minimal warping, biodegradable
6	Estimated Efficiency	–	~15% material savings; ~25–30% energy/time reduction

These findings support the thesis that sustainable additive manufacturing is achievable through smart parameter tuning, even without advanced metering tools or proprietary systems. They validate strategies promoted by several energy-focused AM studies [14], [17], [18], [19] .

The Key findings in this work are:

- Reducing infill density to 30–50% provides up to 15% material savings while maintaining part integrity.
- Increasing print speed to 60 mm/s reduces print time by approximately 25% without major quality losses.
- Disabling or minimizing support structures reduces filament waste, especially in dual-extrusion systems using PVA.
- A 0.2 mm layer height provided an optimal trade-off between print speed, detail resolution, and dimensional accuracy.

4.0 Conclusion

This study investigated sustainable additive manufacturing strategies using Fused Deposition Modeling (FDM) at the NASENI Fabrication Lab. Through systematic parameter optimization across multiple 3D printers and filament types, it was demonstrated that significant material and energy savings can be achieved without compromising part functionality.

Although direct energy consumption data was not available, print time was used as a valid proxy because the energy used by most additive manufacturing systems is strongly correlated with their operating duration. In such machines, the primary energy demand comes from continuously running components such as motors, heaters, and cooling systems. These components draw relatively constant power during the printing process, meaning that a longer print time generally results in higher total energy consumption, and vice versa. Therefore, by comparing print durations under different parameter settings, it is possible to estimate relative changes in energy usage and, by extension, resource efficiency. This approach is supported in literature, where print time has been used as an indirect but reliable indicator for process energy demand in the absence of direct power measurements. These findings support the feasibility of deploying sustainable 3D printing practices in local Nigerian contexts, particularly where power and material costs can become limiting factors.

Future work will involve integrating power metering devices for real-time energy tracking, expanding to other additive manufacturing methods (such as SLA or SLS), and exploring the use of recycled filament materials. Ultimately, this research lays the groundwork for a more resource-conscious digital manufacturing framework that aligns with Nigeria’s drive for localized innovation and industrial self-reliance.

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