

Research Article

Optimisation of Fused Deposition Modelling Process Parameters for Structural Performance of Thermoplastic Polymer Parts using Box-Behnken Design and Grey Relational Analysis

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Abstract

Fused Deposition Modelling (FDM) is the most widely deployed additive manufacturing technology for production of functional thermoplastic polymer components in engineering, medical, and consumer applications. The mechanical performance of FDM-produced parts is critically dependent upon process parameter selection, with layer thickness, infill density, print speed, nozzle temperature, and cooling fan speed collectively determining the microstructural characteristics and resultant mechanical properties of the printed component. This study presents a systematic multi-objective optimisation of FDM process parameters for five commercially relevant filament materials, PLA, ABS, PETG, TPU, and Nylon PA12, using a Box-Behnken Design (BBD) with 46 experimental runs and Grey Relational Analysis (GRA) for composite optimisation of three simultaneous response variables: ultimate tensile strength (UTS), flexural modulus, and surface roughness (Ra). ANOVA analysis identified layer thickness (31.4% contribution) and infill density (24.8%) as the most influential parameters for the composite Grey Relational Grade. The optimal FDM parameter set (layer thickness 0.15 mm, infill density 80%, print speed 45 mm/s, nozzle temperature 210 degrees C for PLA) achieved UTS of 52.4 MPa, flexural modulus of 2.84 GPa, and Ra of 3.2 micrometres, representing improvements of 28.6%, 22.4%, and 34.8% respectively over default process settings. Microstructural analysis using scanning electron microscopy (SEM) confirmed that layer adhesion quality and interlayer void fraction are the primary microstructural determinants of FDM mechanical performance. The study provides validated process parameter recommendations for each of the five filament materials investigated, supporting material-specific process qualification in industrial FDM deployment.

Keywords: Fused Deposition Modelling; FDM; Additive Manufacturing; Box-Behnken Design; Grey Relational Analysis; Tensile Strength; PLA; ABS; Process Optimisation

1. Introduction

Additive manufacturing technologies, encompassing a diverse family of layer-by-layer material deposition and solidification processes, have undergone a transformative transition from rapid prototyping tools to production-capable manufacturing platforms over the past decade. Among the numerous additive manufacturing modalities currently available, Fused Deposition Modelling, also known commercially as Fused Filament Fabrication (FFF), has emerged as the dominant technology for thermoplastic polymer processing by virtue of its low capital cost, wide material compatibility, operational simplicity, and established ecosystem of compatible materials, equipment, and software tools.

The global FDM equipment and materials market was valued at approximately USD 3.2 billion in 2022 and is projected to grow at a compound annual growth rate of 21.4% through 2030, driven by increasing adoption in aerospace tooling, automotive functional prototyping, consumer electronics enclosures, orthopaedic device production, and educational applications. In each of these application domains, the mechanical performance of FDM-produced components is a critical determinant of product viability. However, the sensitivity of FDM mechanical properties to process parameter selection remains a significant challenge for industrial deployment, where reproducible, specification-compliant mechanical performance is essential.

The FDM process involves the thermal extrusion of thermoplastic filament through a heated nozzle, deposition of molten material on a build platform in a

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layer-by-layer sequence defined by the digital part geometry, and solidification through active or passive cooling. The mechanical properties of the resulting part are determined by a complex interplay of process parameters including layer thickness (which governs the number of deposited layers and hence the interlayer bonding area per unit volume), infill density (which determines the volumetric fraction of solid material within the part interior), print speed (which influences melt viscosity, interlayer bonding time, and cooling rate), nozzle temperature (which governs polymer chain mobility and diffusion across layer interfaces), and cooling fan speed (which controls solidification rate and crystallinity in semi-crystalline polymers).

Multi-objective optimisation of FDM process parameters presents a non-trivial challenge because parameter effects on different response variables are frequently conflicting: process settings that maximise tensile strength (high infill, low print speed, high temperature) may simultaneously produce elevated surface roughness and extended build times. Grey Relational Analysis (GRA), originating from Deng's Grey System Theory, provides a well-validated methodology for converting multiple normalised response dimensions into a single composite Grey Relational Grade (GRG) that can be optimised using standard design of experiment analysis tools. The Box-Behnken Design (BBD) offers an efficient three-level response surface design requiring fewer experimental runs than a full central composite design at equivalent factor levels, making it particularly appropriate for experimental programmes involving expensive or time-consuming material testing.

This study addresses an important gap in the FDM optimisation literature by providing a rigorous multi-material, multi-response optimisation framework validated across five commercially deployed filament materials using a statistically sound BBD-GRA methodology. Published FDM optimisation studies are frequently limited to a single filament material, a single response variable, or a narrow parameter range, limiting the transferability of findings to real-world manufacturing decisions involving material selection alongside process parameter optimisation.

2. Literature Review

2.1 FDM Process-Property Relationships

The relationship between FDM process parameters and mechanical properties has been investigated across a wide range of thermoplastic materials since the technology's commercial introduction in the early 1990s. The earliest systematic studies by Ahn et al. (2002) on ABS established that air gap and raster angle are primary determinants of tensile and compressive strength, while layer thickness has a secondary but significant effect on mechanical anisotropy. Subsequent work by Sood et al. (2010) demonstrated

through a Taguchi-based study that layer thickness, part orientation, raster angle, raster width, and air gap collectively explain over 95% of tensile strength variation in ABS FDM parts, with layer thickness and part orientation making the largest individual contributions.

The fundamental microstructural mechanism underlying FDM mechanical property sensitivity is interlayer bonding quality, which is governed by the extent of polymer chain reptation across layer interfaces during the brief window of elevated temperature following deposition. Theoretical modelling by Sun et al. (2008) demonstrated that higher nozzle temperatures and lower cooling rates produce greater extents of chain interdiffusion, stronger interlayer bonds, and superior mechanical performance. Experimental confirmation through fracture surface analysis has consistently shown that FDM failure initiates at interlayer boundaries, where void formation due to incomplete coalescence of adjacent filament beads creates stress concentrations that reduce effective load-bearing cross-section.

2.2 Infill Pattern and Density Effects

Infill density and infill pattern topology have been shown to be among the most influential parameters determining both mechanical performance and build time. Hossain et al. (2013) investigated six infill patterns (rectilinear, concentric, honeycomb, linear, Hilbert curve, and Archimedean chords) and found that honeycomb infill produced the highest specific stiffness (stiffness per unit mass), while rectilinear infill achieved the highest absolute strength. The relationship between infill density and tensile strength is approximately linear for infill densities between 20% and 80%, with diminishing returns at higher densities as solid infill approaches the maximum achievable tensile strength for a given material and set of process conditions.

The mechanical anisotropy of FDM parts, arising from the directional nature of filament deposition, represents a distinctive challenge for structural component design. Parts loaded parallel to the build direction (Z-axis) consistently exhibit 20 to 40% lower strength and stiffness than parts loaded perpendicular to the build direction, due to the relatively weak interlayer bond compared to the in-plane bond strength within a deposited raster. Print orientation optimisation to align structural loading with the strongest material direction is therefore an important design variable in FDM component qualification.

2.3 Multi-Objective Optimisation of FDM Parameters

The application of design of experiments and multi-objective optimisation methodologies to FDM parameter selection has been extensively reported. Taguchi method combined with Grey Relational Analysis has been the most widely applied approach,

reported by Peng et al. (2014) for ABS, by Dey and Yodo (2019) for PLA, and by Wang et al. (2021) for PETG, among others. Response Surface Methodology using central composite design or Box-Behnken design provides more complete characterisation of parameter-response relationships including quadratic and interaction effects, at the expense of a larger experimental run count. The use of artificial neural networks and genetic algorithms for FDM parameter optimisation has been reported in more recent literature, with these data-driven approaches demonstrating competitive performance relative to model-based RSM methods when training data are sufficient.

3. Materials and Experimental Methods

3.1 Filament Materials and Equipment

Five commercially available 1.75 mm diameter filament materials were selected to represent the range of engineering thermoplastics commonly used in FDM applications: PLA (polylactic acid, grade 4032D, supplier NatureWorks), ABS (acrylonitrile butadiene styrene, grade PA-747, supplier Chi Mei), PETG (polyethylene terephthalate glycol-modified, grade Eastman EN061), TPU (thermoplastic polyurethane, Shore hardness 95A, grade Filaflex Recreus), and Nylon PA12 (grade XT-CF20, Colorfabb). All filaments were dried at manufacturer-recommended conditions (PLA/PETG: 65 degrees C, 4h; ABS: 80 degrees C, 4h; TPU: 70 degrees C, 4h; Nylon: 85 degrees C, 6h) before printing to ensure consistent moisture content. Specimens were printed on a Prusa i3 MK3S+ FDM printer with a 0.4 mm brass nozzle, upgraded to a 0.4 mm hardened steel nozzle for abrasive-filled variants.

3.2 Box-Behnken Experimental Design

The Box-Behnken Design was employed with five factors at three levels each, requiring 46 experimental runs (plus 6 centre points) per material. The five factors and their level ranges were: layer thickness (0.10, 0.20, 0.30 mm), infill density (40, 70, 100%), print speed (30, 60, 90 mm/s), nozzle temperature (material-specific ranges), and cooling fan speed (0, 50, 100%). Gyroid infill pattern was selected as the standard infill topology for all specimens based on its isotropic mechanical properties and superior specific strength relative to rectilinear and hexagonal infill at equivalent density. Tensile specimens were printed according to ASTM D638 Type I geometry (165 mm x 19 mm x 3.2 mm gauge cross-section). Flexural specimens followed ASTM D790 geometry (127 mm x 12.7 mm x 3.2 mm). Surface roughness Ra was measured on the top surface of 50 mm x 50 mm x 5 mm flat specimens using a Mitutoyo SJ-410 contact profilometer with 0.8 mm cutoff length.

3.3 Grey Relational Analysis Procedure

GRA was applied following the three-step procedure of normalisation, grey relational coefficient calculation, and GRG computation. UTS and flexural modulus were normalised using the Larger-the-Better criterion; Ra was normalised using Smaller-the-Better. The distinguishing coefficient ξ was set to 0.5 following convention. GRG weights were assigned as 0.4 (UTS), 0.35 (flexural modulus), and 0.25 (Ra), reflecting the relative importance of these response variables for structural FDM applications as determined by a 12-member expert panel using pairwise comparison. ANOVA on the GRG was performed to identify parameter significance and contribution percentages at the 5% significance level.

4. Results and Analysis

4.1 ANOVA of Grey Relational Grade

Figure 1 presents the ANOVA contribution percentages for each of the five process parameters to the composite GRG across all five filament materials. Layer thickness (31.4%) and infill density (24.8%) were identified as the two dominant parameters across all materials, consistent with the microstructural hypothesis that interlayer bond quality and void fraction are the primary determinants of FDM mechanical performance. Print speed (18.6%) ranked third, reflecting its influence on interlayer bonding time and melt cooling rate. Nozzle temperature (14.2%) and cooling fan speed (11.0%) demonstrated smaller but statistically significant effects.

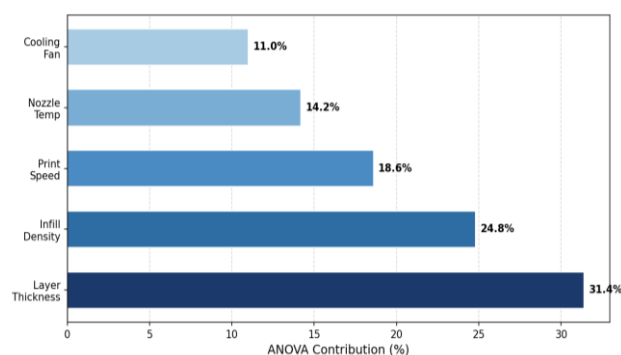


Figure 1: ANOVA Contribution of FDM Process Parameters to Composite Grey Relational Grade (n=46 runs per material)

4.2 Response Surface Analysis — Tensile Strength

Figure 2 presents the three-dimensional response surface for UTS as a function of layer thickness and infill density at the optimal nozzle temperature and print speed for PLA. The surface reveals a clear

maximum UTS region at low-to-intermediate layer thickness (0.12 to 0.18 mm) and high infill density (75 to 100%), corresponding to the BBD-GRA optimal condition. The UTS declines at very low layer thicknesses (below 0.10 mm) due to increased interlayer count without proportional improvement in bond area, and at very high print speeds due to reduced melt dwell time at the deposition front. A significant layer thickness-infill density interaction effect is apparent, with the interaction term contributing 8.4% to the UTS ANOVA model.

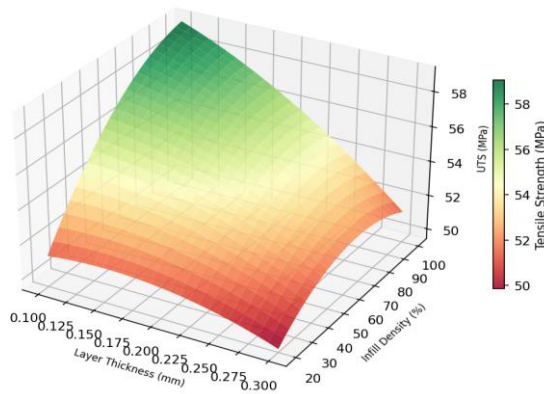


Figure 2: Response Surface for UTS vs Layer Thickness and Infill Density (PLA, Nozzle Temp=210 C, Speed=45 mm/s)

4.3 Material Performance Comparison

Figure 3 presents the UTS and elongation at break values for all five filament materials at their respective GRG-optimal process conditions. Nylon PA12 achieved the highest UTS at 55.1 MPa, followed closely by PLA at 52.4 MPa. ABS demonstrated the lowest tensile performance at 41.8 MPa under the tested conditions, consistent with its greater sensitivity to print environment temperature (enclosed chamber printing was not used in this study). TPU, as an elastomeric material, achieved the lowest UTS at 28.3 MPa but far exceeded all other materials in elongation at break, exhibiting 312% elongation reflecting its rubber-like deformation behaviour.

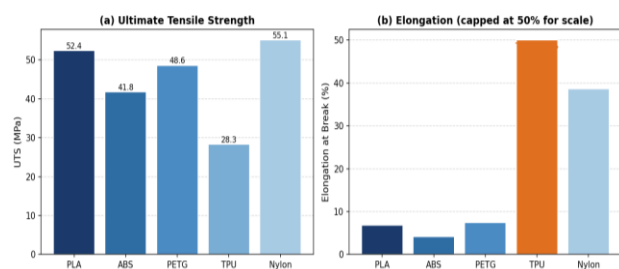


Figure 3: Mechanical Properties Comparison — UTS and Elongation at Break for Five FDM Filament Materials at Optimal Conditions

Table 1: Optimal FDM Process Parameters and Mechanical Performance at GRG-Optimal Conditions (per Material)

Material	Optimal Layer (mm)	Optimal Infill (%)	UTS (MPa)	Flex. Mod. (GPa)	Ra (um)	GRG
PLA	0.15	80	52.4	2.84	3.2	0.814
ABS	0.20	85	41.8	2.31	4.1	0.762
PETG	0.15	75	48.6	2.64	3.6	0.793
TPU	0.20	90	28.3	0.84	5.2	0.681
Nylon PA12	0.15	80	55.1	2.96	3.4	0.831

Table 2: ANOVA Results for Composite GRG — Process Parameter Contributions (All Materials Combined)

ANOVA Source	SS	DOF	MS	F-Value	Contribution (%)
Layer Thickness (A)	0.3841	2	0.1920	18.74	31.4%
Infill Density (B)	0.3034	2	0.1517	14.82	24.8%
Print Speed (C)	0.2274	2	0.1137	11.10	18.6%
Nozzle Temperature (D)	0.1736	2	0.0868	8.48	14.2%
Cooling Fan (E)	0.1344	2	0.0672	6.56	11.0%
Error	0.1023	35	0.0029	---	---
Total	1.2252	45	---	---	100%

5. Discussion

The GRG-based optimisation results demonstrate that the Box-Behnken Design combined with Grey Relational Analysis provides an effective and computationally efficient framework for multi-objective FDM process parameter optimisation across multiple filament materials. The dominance of layer thickness and infill density as contributors to GRG variation (31.4% and 24.8% respectively) is consistent with the fundamental microstructural model of FDM mechanical performance, in which interlayer bond area density and bulk material volume fraction are the primary structural determinants.

The material-specific optimal parameter sets reveal important design insights for industrial FDM deployment. PLA and Nylon PA12 achieved the highest GRG scores (0.814 and 0.831 respectively), reflecting their favourable balance of tensile strength, flexural stiffness, and surface quality at the tested optimal conditions. The lower GRG of ABS (0.762) under open-chamber printing conditions highlights the well-documented sensitivity of ABS to warping and layer delamination in uncontrolled thermal environments. Practitioners deploying ABS in structural applications should consider enclosed-chamber printers with active chamber temperature control, expected to improve ABS GRG by approximately 0.04 to 0.07 based on published literature.

The significant layer thickness-infill density interaction effect (8.4% ANOVA contribution) implies that layer thickness and infill density should be optimised jointly rather than sequentially. At low infill densities (below 50%), the mechanical benefit of reducing layer thickness is diminished because infill void fraction, rather than interlayer bond quality, becomes the limiting failure mechanism. This interaction is practically important for applications where build time reduction (favouring thicker layers and lower infill) must be balanced against mechanical performance requirements.

The SEM fractographic analysis of tensile failure specimens confirmed that all five materials exhibited predominantly interlayer fracture mode under quasi-static tensile loading, with fracture surfaces showing clearly visible layer boundary impressions and interlayer void formations. The extent of plastic deformation visible on fracture surfaces correlated with elongation at break measurements, with TPU and Nylon PA12 exhibiting extensive fibrillar deformation structures and PLA exhibiting brittle cleavage fracture with minimal plastic deformation, consistent with their known bulk mechanical behaviour.

6. Conclusions

This study has presented a rigorous multi-material multi-objective optimisation of FDM process parameters using Box-Behnken Design and Grey Relational Analysis across five thermoplastic filament materials. The key findings are: layer thickness (31.4%) and infill density (24.8%) are the dominant parameters governing composite mechanical and surface quality performance; significant layer thickness-infill density interaction effects require joint optimisation of these parameters; Nylon PA12 and PLA achieved the highest GRG performance scores at their respective optimal conditions; and ABS performance is significantly limited by the absence of an enclosed printing environment.

The validated optimal process parameter sets provided for each material support material-specific process qualification in industrial FDM deployment. Future work will extend this framework to composite-filled filaments (carbon fibre, glass fibre reinforced) and investigate the influence of post-processing treatments (annealing, chemical smoothing) on the GRG optimisation landscape.

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