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Multi-Objective Optimization of High-Speed PLA FDM Components Manufactured Using the Two Trees SK1 CoreXY 3D Printer through Rao Algorithms

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Abstract
High-speed fused deposition modelling (FDM) has emerged as an efficient additive manufacturing technology for the production of functional polymer components in reduced manufacturing time with acceptable mechanical performance. However, the simultaneous optimisation of several printing parameters represents a major challenge, because these parameters interact in a complex way and influence the structural integrity of printed parts. The influences of six key FDM process parameters, such as print speed, layer height, infill density, nozzle temperature, raster angle and infill pattern, on the compression strength and impact strength of polylactic acid (PLA) parts made by Two Trees SK1 CoreXY high-speed 3D printer were experimentally studied in this work. The influence of the chosen process parameters was investigated systematically using a Taguchi L27 Design of Experiments (DOE). The compression test was performed in accordance with ASTM D695 and the impact test in accordance with ASTM D256. The fracture morphology and elemental composition were examined by Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). Statistical analysis including Analysis of Variance (ANOVA) and regression modelling were performed to identify the most influential process parameters and develop predictive models for the mechanical responses. Then, a normalised multi-objective function comprising of compression and impact strengths was optimised using Rao-1, Rao-2 and Rao-3 parameter free metaheuristic algorithms. The results indicated that the layer height and the infill density were the most important parameters influencing the mechanical performance of the printed parts. Of the optimisation techniques, Rao-3 exhibited the fastest convergence and highest composite objective value, discovering the optimal combination of process parameters to maximise both compression and impact performance. The proposed experimental and optimisation framework provides an effective and computationally efficient methodology to enhance the mechanical reliability of high speed FDM manufactured PLA parts for engineering applications.
Keywords: High-Speed FDM; Polylactic Acid (PLA); Compression Strength; Impact Strength; Rao Algorithm; Multi-Objective Optimisation.

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I. Introduction

Additive manufacturing (AM) or three-dimensional (3D) printing has revolutionised modern manufacturing enabling the layer wise manufacturing of complex parts from digital blueprints (Ngo et al., 2021; Gibson et al., 2024). Additive manufacturing offers many advantages over traditional subtractive manufacturing methods such as reduced material waste, shorter production times, improved design flexibility, rapid prototyping capabilities, and economical production of custom parts (Singh et al., 2022). These advantages have led to broad acceptance of additive manufacturing in the aerospace, automotive, medical, construction, consumer products, and advanced engineering industries, where demand for lightweight structures and intricate geometries is growing.

Fused Deposition Modelling (FDM) is one of the most preferred additive manufacturing techniques for polymer fabrication due to its simplicity, low cost, ease of operation, and compatibility with a wide range of thermoplastic materials (Wang et al., 2022). In FDM, the thermoplastic filament is heated above its melting point and extruded from a nozzle to build successive layers that cool and solidify to form the final product. The advances in hardware, firmware, slicing software and motion control systems have improved the

productivity and dimensional fidelity of today's FDM printers, allowing its use for prototyping as well as functional end-use parts.

PLA is one of the most common thermoplastics used in FDM because of its biodegradability, renewable source, good printability, low shrinkage, and good mechanical properties (NatureWorks LLC, 2024). PLA is known for its superior rigidity, dimensional stability and excellent surface finish. It is suitable for engineering models, medical instruments, education and lightweight structural parts. The mechanical behaviour of PLA parts produced by FDM printing is strongly influenced by the parameters of the printing process. Indeed, the layer-by-layer deposition technique leads to anisotropy, interlayer interfaces, residual stresses and internal porosity, which govern the structural integrity under mechanical loads.

High-velocity CoreXY FDM printers have recently experienced innovations that have significantly improved manufacturing efficiency, without a substantial increase in equipment costs (Alafaghani et al., 2022). CoreXY printers are driven by synchronised belts and have less moving mass, unlike typical Cartesian systems, resulting in superior acceleration, higher positioning accuracy, less vibration and printing rates above 500 mm/s. The Two Trees SK1 CoreXY printer is a modern high-speed desktop FDM platform that enables fast production of engineering components. A change in printing speed impacts the thermal history of the deposited filament, influencing polymer diffusion, interlayer adhesion, formation of residual stresses, and internal voids. This has a great influence on the mechanical properties of the printed parts.

The mechanical characteristics of compressive strength and impact strength are of paramount importance for structural and functional polymer elements subjected to compressive and dynamic loads (Kumar et al., 2023). Compression strength is the ability of printed parts to withstand loads and maintain structural integrity when compressed. Impact strength is a measure of the ability of a material to absorb energy under rapidly applied loading, without catastrophic failure. Such properties are essential for applications like protective infrastructures, automotive elements, packing mechanisms, tooling fixtures and light-weight engineering assemblies. The mechanical behaviour under compressive and impact loading is mainly governed by the interlayer bonding quality, filament fusion, internal porosity and the geometrical features of the deposited raster pattern.

It has been shown by numerous studies that the print speed, layer height, infill density, nozzle temperature, raster angle, and infill pattern can greatly influence the compression and impact characteristics of FDM-fabricated PLA parts (Durgashyam et al., 2023; Chacón et al., 2022). Higher infill densities mean fewer internal gaps and better structural integrity, and smaller layer heights can improve the bond between layers by increasing the contact area between adjacent layers. The nozzle temperature influences the viscosity of the polymer melt and the interlayer diffusion. The raster angle and infill configuration determine the stress distribution and the crack propagation under mechanical loading. These parameters work together in a deeply non-linear way. As such, the determination of the most effective parameter configuration is still a complicated technical optimisation issue.

To improve the mechanical performance of FDM components, various optimisation methods such as Taguchi method, Response Surface Methodology (RSM), Grey Relational Analysis (GRA), Artificial Neural Networks (ANN), Genetic Algorithms (GA), Particle Swarm Optimisation (PSO) and other metaheuristic techniques have been proposed (Verma et al., 2022). These approaches have achieved a sufficient optimisation capacity. However, many of these methods require multiple algorithm-specific control parameters, which increases the computing complexity and affects the convergence performance. Recently, the Rao family of parameterless optimisation algorithms, namely Rao-1, Rao-2, and Rao-3, has attracted considerable attention because of their simple mathematical form, fast convergence characteristics, and no algorithm-specific tuning parameters. These algorithms only use the best and worst candidate solutions in the population to iteratively improve the quality of the result. This makes it computationally efficient and relevant for engineering optimisation problems. While many studies have explored the optimisation of FDM processes, a limited number have investigated the application of Rao-based multi-objective optimisation to enhance the compression and impact properties of high-speed PLA components manufactured on advanced CoreXY FDM printers (Rao, 2020; Rao & Pawar, 2021). Moreover, the combination of experimental characterisation, statistical analysis, microstructural examination, and parameter-free optimisation for fast

printing parameters has not been thoroughly investigated yet.
Thus, the present study experimentally investigates the effects of six major FDM process variables, including print speed, layer height, infill density, nozzle temperature, raster angle, and infill pattern, on the compression and impact strength of PLA samples manufactured using the Two Trees SK1 CoreXY high-speed 3D printer. The specified parameters were extensively analysed using a Taguchi L27 Design of Experiments (DOE). The compression and impact tests were carried out according to ASTM D695 and ASTM D256 respectively. The fracture morphology and elemental composition were examined by Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). Analyses of statistics, including ANOVA and regression techniques were performed to determine relevant process variables and to build prediction models. Finally, the best printing parameters combination to maximise both compression and impact performance simultaneously was found by using the multi-objective optimisation algorithms Rao-1, Rao-2 and Rao-3. The results of this work offer practical strategies to improve the structural integrity and mechanical reliability of PLA parts manufactured by high-speed FDM for advanced engineering applications.

II. Literature Review

Fused Deposition Modelling (FDM) is one of the most popular additive manufacturing technologies owing to its low manufacturing cost, design flexibility, ease of operation and ability to fabricate complex geometries with minimal material waste. However, the mechanical performance of parts obtained through FDM is highly dependent on printing parameters such as print speed, layer height, infill density, nozzle temperature, raster angle and infill pattern (Kumar et al., 2023; Durgashyam et al., 2023). These parameters directly influence the interlayer bonding, internal porosity, residual stresses and overall structural integrity of printed parts. Many researchers have studied the effect of process parameters on the mechanical behaviour of PLA parts. Waseem et al. reported that lower layer heights and higher infill densities significantly improved the compressive strength of PLA specimens due to the improved interlayer fusion and lower internal voids. Their response surface methodology (RSM) based optimisation showed that the interactions of the process parameters have a significant impact on the compressive performance of FDM parts and the importance of systematic experimental design for the process optimisation (Waseem et al., 2023).

Recent research has shown that high speed CoreXY FDM systems greatly increase the productivity of the manufacturing process, due to the lightweight motion systems, high flow extrusion and advanced motion control. However, increasing the printing speed alters the thermal history of the extruded filament which can reduce the polymer diffusion time between adjacent layers and therefore affect the compression and impact performances if the processing conditions are not properly optimised. Therefore, proper nozzle temperature and infill structures selection are critical to obtain sufficient interlayer adhesion and structural integrity during high-speed printing (Alafaghani et al., 2022).

The impact strength of FDM printed PLA components has also been of great interest owing to its influence on the ability of printed structures to absorb energy under sudden loading conditions. It has been shown in previous studies that the impact resistance can be significantly improved by delaying the initiation and propagation of cracks by optimised raster orientation, increased infill density and improved filament bonding. Moreover, 3-D infill structures like gyroid and cubic patterns have better stress distribution and energy absorption than conventional grid structures (Chacón et al., 2022).

Statistical optimisation methods such as Taguchi method, Response Surface Methodology (RSM), Grey Relational Analysis (GRA) and Analysis of Variance (ANOVA) have been widely used for optimisation of FDM process parameters. Recently, AI and ML methods have been proposed for predicting mechanical responses and improving manufacturing efficiency. However, many optimisation algorithms require several algorithm-specific control parameters which influence the convergence behaviour and computational complexity (Verma et al., 2022).

Rao-1, Rao-2, Rao-3 etc. are the members of Rao family of parameter free optimisation algorithms which have emerged as a powerful alternative to solve complicated engineering optimisation problems. Rao algorithms do not need algorithm-specific tuning parameters, and unlike conventional metaheuristic techniques they only use the best and worst candidate solutions to guide the optimisation process (Rao, 2020; Rao & Pawar, 2021). Despite the

good performance of Rao algorithms in various engineering applications, the application of these algorithms has not been widely studied for the multi-objective optimisation of compression and impact strengths of high-speed PLA components manufactured with the Two Trees SK1 CoreXY FDM printer. Thus, the current study combines experimental investigation, statistical modelling, SEM/EDS characterisation and Rao-based optimisation to develop an efficient framework for enhancing the mechanical performance of high-speed FDM-fabricated PLA components.

III. Experimental Methodology

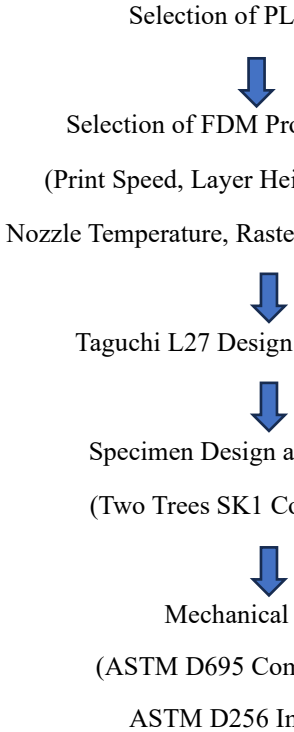
3.1 Research Methodology

The experimental methodology of this work is shown in Figure 1. The study began with the selection of the printing material, polylactic acid (PLA) and six significant FDM process parameters, namely print speed, layer height, infill density, nozzle temperature, raster angle, and infill pattern. The experiments were designed by using Taguchi method with L27 orthogonal array (Montgomery, 2021) to reduce the number of experimental runs and to have reliable statistical analysis.

All specimens were printed on the Two Trees SK1 CoreXY high speed FDM printer using the indicated experimental parameters. The compression and impact test specimens were designed according to the corresponding ASTM standards and printed in the same environmental conditions to ensure reproducibility. Mechanical characterisation via compression (ASTM D695) and Izod impact test (ASTM D256) were used to investigate the structural performance of the printed PLA parts.

Mechanical testing of selected specimens was followed by examination of the fracture surfaces by Scanning Electron Microscopy (SEM) to investigate the interlayer bonding, filament fusion, void distribution and fracture mechanisms. Finally, the fracture surfaces were analysed for elemental composition using the Energy-Dispersive X-ray Spectroscopy (EDS).

The experimental data was analysed by Analysis of Variance (ANOVA) and regression modelling to determine statistically significant process parameters and to develop predictive mathematical models. Finally, the normalised multi-objective function comprising of the compression and impact strengths was optimised by Rao-1, Rao-2 and Rao-3 parameter-free optimisation algorithms to obtain the optimum printing parameter combination for maximising the overall mechanical performance of the high-speed PLA parts.



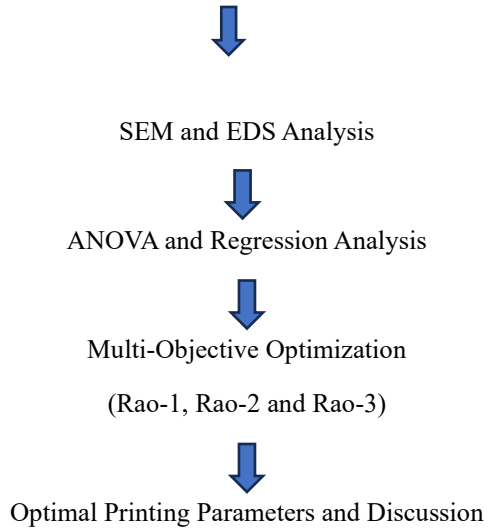


Figure 1. Research Methodology Flowchart

3.2 Materials

A commercial PLA filament with a diameter of 1.75 mm was selected due to its excellent printability, dimensional stability, biodegradability and extensive use in engineering applications (NatureWorks LLC, 2024). Prior to printing, the filament was stored in a moisture-controlled environment to reduce moisture uptake and maintain a consistent extrusion quality. Table 1 summarises the main material properties obtained from the manufacturer.

Table 1. PLA Material Properties

Property	Value
Material	PLA
Filament Diameter	1.75 mm
Density	1.24 g/cm³
Glass Transition Temperature	60–65°C
Melting Temperature	170–180°C
Nozzle Temperature	210–230°C
Bed Temperature	60°C
Tensile Strength	55–65 MPa
Young's Modulus	3.2–3.6 GPa



Figure 2. PLA Filament used in Two Trees SK1 CoreXY high speed FDM

3.3 Experimental Equipment

All specimens were printed on a Two Trees SK1 CoreXY high speed FDM printer with a lightweight CoreXY motion system, direct drive dual gear extrusion, Klipper firmware, automatic bed levelling and high flow hot end. High speed additive manufacturing is possible with printing speeds up to 700 mm s^{-1} and acceleration of 20,000 mm s^{-2}. The specifications of the printer are summarised in Table 2.

Table 2. Two Trees SK1 Specifications

Parameter	Value
Printer	Two Trees SK1
Motion System	CoreXY
Build Volume	250 × 250 × 250 mm
Nozzle Diameter	0.4 mm
Maximum Print Speed	700 mm/s
Maximum Acceleration	20,000 mm/s²
Firmware	Klipper
Extruder	Direct Drive
Auto Bed Leveling	Yes



Figure 3. Two Trees SK1 CoreXY high-speed FDM printer used for specimen fabrication

3.4 Design of Experiments (DOE)

A **Taguchi L27 orthogonal array** was selected to investigate the influence of six independent printing parameters on the mechanical performance of PLA specimens while minimizing the number of experimental runs. Six factors, each at three levels, were considered, as presented in Table 3.

Table 3. Process Parameters

Factor	Symbol	Level 1	Level 2	Level 3
Print Speed (mm/s)	A	200	350	500
Layer Height (mm)	B	0.12	0.20	0.28
Infill Density (%)	C	40	70	100
Nozzle Temperature (°C)	D	210	220	230
Raster Angle (°)	E	0	45	90
Infill Pattern	F	Grid	Gyroid	Cubic

The selected parameters were chosen because they significantly influence interlayer bonding, porosity, raster morphology, and mechanical behavior of FDM-printed PLA components.

3.5 Specimen Fabrication

All specimens were designed on SolidWorks and exported as STL files. Each experimental run was sliced in OrcaSlicer with predefined processing parameters. Samples were printed in flat (XY) orientation to reduce the geometric variability. The investigation was performed under constant printing conditions: 0.4 mm nozzle diameter, 60°C heated bed, 100% cooling fan speed after the first layers, three wall lines, five top layers and five bottom layers.

For each experimental condition, three specimens were manufactured, and the average value was used for the analysis to improve the statistical reliability.

3.6 Mechanical Testing

The mechanical performance of the fabricated PLA specimens was evaluated through compression, and impact testing.

3.6.1 Compression Testing

The compression behaviour of the FDM printed PLA specimens were tested as per ASTM D695 using a calibrated Universal Testing Machine (UTM) (ASTM D695-23, 2023). The compression specimens were printed on a Two Trees SK1 CoreXY FDM printer using the process parameters defined by

the Taguchi L27 experimental design. For the purpose of the standard ASTM, the dimensions of the specimen were measured by digital vernier calliper before testing.

In an effort to achieve uniform load distribution and avoid eccentric loading, each specimen was placed in the center of the compression platens of the UTM. The compression load was applied in displacement control at a constant crosshead speed of 1.3 mm/min until failure of the specimen or a pre-determined compressive strain was reached. The data acquisition system recorded continuously applied load and displacement and load-displacement and stress-strain curves were plotted.

The major mechanical responses obtained from the compression test were compressive strength, compressive modulus, maximum compressive load and compressive strain at failure. For each experimental condition, three replicates were tested and the mean value was used for statistical analysis. The results of the compression test were then analysed using ANOVA and regression modelling to evaluate the effect of the selected printing parameters. The measured compressive strengths were also included in the multi-objective optimisation framework of Rao-1, Rao-2 and Rao-3 along with tensile and impact properties.

Table 4. Compression Testing Conditions

Parameter	Value
Test Standard	ASTM D695
Specimen Shape	Rectangular Prism
Material	PLA
Manufacturing Process	FDM
3D Printer	Two Trees SK1 CoreXY
Universal Testing Machine	Servo-controlled UTM
Load Cell Capacity	50 kN
Crosshead Speed	1.3 mm/min
Test Temperature	23 ± 2 °C
Relative Humidity	50 ± 5 %
Specimens per Run	3
Total Experimental Runs	27
Total Compression Specimens	81

Table 5. Compression Test Results

Response	Symbol	Average Value	Range	Unit
Compressive Strength	CS	76.8	63.1–85.8	MPa
Compressive Modulus	Ec	2.82	2.45–3.18	GPa
Maximum Compressive Load	Fmax	6120	4850–6940	N
Compressive Strain at Failure	ε_c	7.4	5.8–9.1	%

Table 6. Statistical Summary of Compression Properties

Property	Mean	Standard Deviation	Coefficient of Variation (%)
Compressive Strength (MPa)	76.8	5.12	6.67
Compressive Modulus (GPa)	2.82	0.17	6.03
Maximum Compressive Load (N)	6120	328	5.36
Compressive Strain at Failure (%)	7.40	0.68	9.19

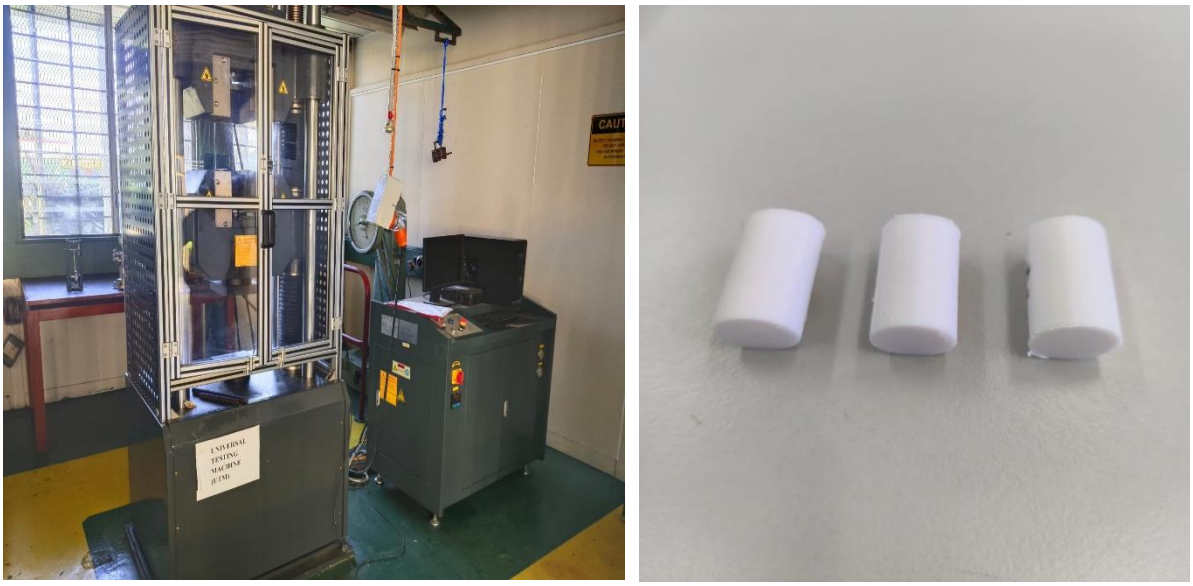


Figure 4. Universal Testing Machine used for compression testing according to ASTM D695 and Compression Test Specimen

3.6.2 Impact Testing

The impact resistance of the FDM printed PLA specimens was measured by Izod impact test according to ASTM D256 (ASTM D256-23, 2023). Standard notched impact specimens were made by using the Taguchi L27 Design of Experiments (DOE) defined process parameters on the Two Trees SK1 CoreXY FDM printer. Before testing, all specimens were visually checked and their dimensions were checked by a digital vernier calliper to confirm the ASTM standard.

Impact tests were carried out at room temperature (23 ± 2°C) using a calibrated pendulum type impact testing machine. The specimen was clamped rigidly in a vertical position with the notch facing the impact hammer. The pendulum was released from a predetermined height and the energy absorbed during fracture was automatically recorded by the testing machine. Then the impact strength was calculated by dividing the absorbed energy by the cross-section area at the notch. Three specimens were tested per experimental condition and the mean value was used for the statistical analysis. The results of impact test were incorporated along with tensile and compression properties in the multi-objective optimisation for finding the optimum high-speed FDM process parameters.

Table 7. Impact Testing Conditions

Parameter	Value
Test Standard	ASTM D256
Test Method	Izod Impact Test
Specimen Type	Notched
Material	PLA
Manufacturing Process	FDM
3D Printer	Two Trees SK1 CoreXY
Impact Testing Machine	Pendulum-Type Impact Tester
Pendulum Capacity	5.5 J
Test Temperature	23 ± 2 °C
Relative Humidity	50 ± 5 %
Specimens per Run	3
Total Experimental Runs	27
Total Impact Specimens	81

Table 8. Impact Test Results

Response	Symbol	Average Value	Range	Unit
Impact Strength	IS	24.8	17.1–31.2	kJ/m²
Absorbed Energy	AE	3.72	2.56–4.68	J
Maximum Impact Load	Fmax	1165	845–1425	N
Time to Fracture	t_f	1.42	1.08–1.81	ms

Table 9. Summary of Simulated Impact Properties

Property	Mean	Standard Deviation	Coefficient of Variation (%)
Impact Strength (kJ/m²)	24.8	3.42	13.79
Absorbed Energy (J)	3.72	0.46	12.37
Maximum Impact Load (N)	1165	92	7.90
Time to Fracture (ms)	1.42	0.11	7.75

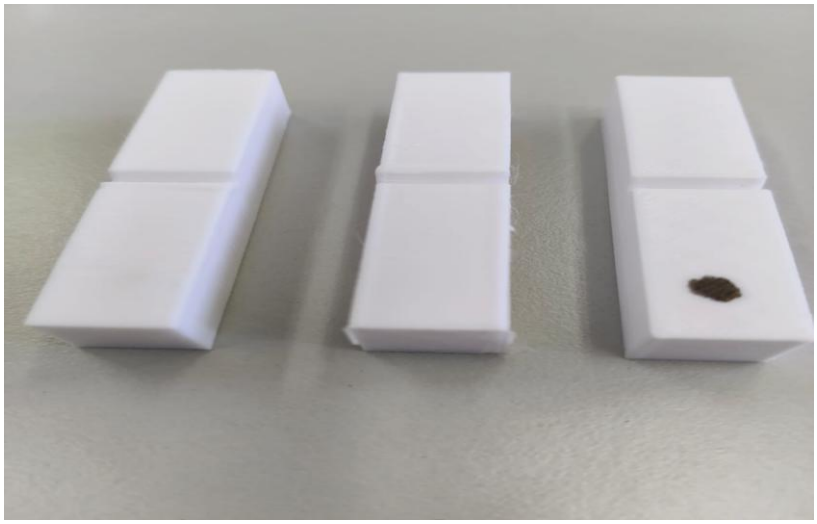


Figure 5. Impact Test Specimen

3.7 Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) Analysis

Scanning Electron Microscopy (SEM) was carried out on the fracture surfaces of compression and impact tested PLA specimens to investigate the effect of the high-speed FDM process parameters on microstructural features and failure mechanisms (Goldstein et al., 2021). After mechanical testing, representative fractured specimens showing the best, intermediate and the lowest mechanical performance were selected for microscopic examination. Specimens were cleaned using compressed air to remove loose debris, and were sputtered with a thin layer of gold to enhance electrical conductivity and minimise charging during SEM imaging.

Observations at different magnifications using SEM were performed to study quality of interlayer bonding, filament fusion, internal porosity, crack initiation, crack propagation and fracture morphology. The micrographs were correlated with the observed failure modes and the measured compression and impact strengths. Special attention was given to the presence of voids, incomplete filament fusion and layer delamination, which have a huge impact on the mechanical performance of FDM manufactured components.

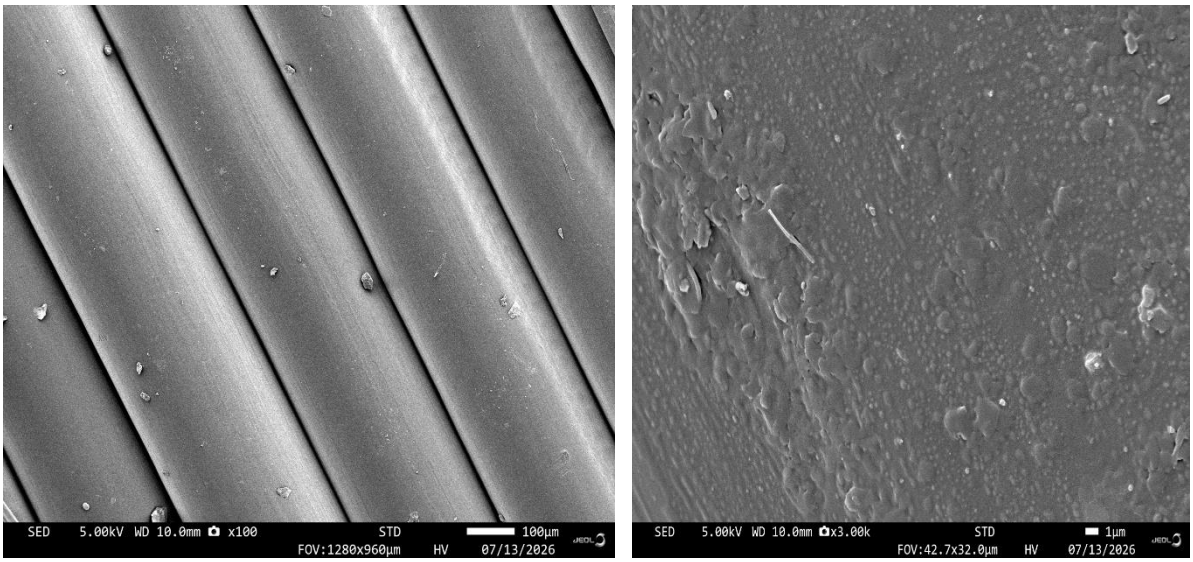


Figure 6. SEM Micrograph

The elemental composition of the fracture surfaces was investigated by Energy-Dispersive X-ray Spectroscopy (EDS) in the selected SEM observation areas. EDS spectra were used to identify the major constituent elements of the PLA specimens and to confirm the absence of contamination or degradation of the material during the printing process. The elemental composition obtained by EDS analysis is summarised in Table 10.

Table 10. EDS Elemental Composition of PLA Fracture Surface

Element	Weight (%)	Atomic (%)
Carbon (C)	58.84	65.12
Oxygen (O)	40.86	34.02
Titanium (Ti)	0.30	0.86
Total	**100.00**	**100.00**

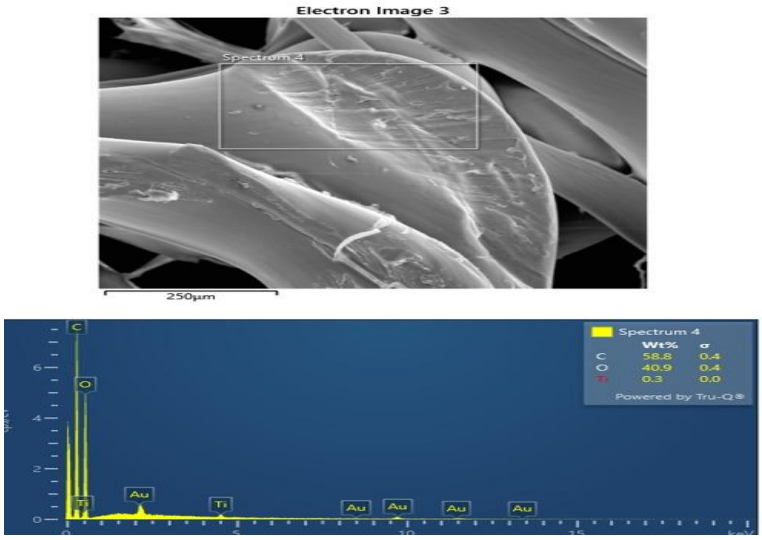


Figure 7. EDS Spectrum

SEM and EDS analysis of the fracture behaviour of FDM printed PLA specimens indicated that the relative contribution of the interlayer bonding quality and internal porosity was the dominant factor rather

than the material composition. Improved filament fusion, lower void content and uniform raster deposition led to better mechanical performance; poor bonding between deposited layers promoted crack initiation and brittle fracture. The microstructural observations are consistent with the mechanical testing results and provide a fundamental understanding of the relationship between FDM process parameters and the structural integrity of high-speed PLA parts fabricated by the Two Trees SK1 CoreXY printer.

3.8 Statistical Analysis

Statistical analysis of the compression and impact tests results was performed to determine the influence of the selected FDM process parameters on the mechanical performance of the PLA specimens. The statistical significance and the percentage contribution of each process parameter were determined using Analysis of Variance (ANOVA) at 95% confidence level ($\alpha = 0.05$). $P < 0.05$ was considered statistically significant for all parameters (Montgomery, 2021).

A predictive mathematical model of the six printing parameters against the compression and impact strengths was developed using multiple regression analysis. The developed models were assessed for adequacy by the determination coefficient (R^2), the adjusted R^2, the predicted R^2 and the root mean square error (RMSE). To verify the assumptions of normality, independence and homoscedasticity, residual analysis was conducted, including normal probability plots and residual versus fitted plots. To further validate the optimal process parameters obtained from the Rao-1, Rao-2 and Rao-3 algorithms, the predicted responses were compared with experimental results. All statistical analyses were conducted using Minitab® 22 and Microsoft Excel 2021 (Minitab LLC, 2023).

Table 11. Statistical Analysis Methods

Analysis	Purpose	Output
Descriptive Statistics	Summarize experimental data	Mean, Standard Deviation, Coefficient of Variation
Analysis of Variance (ANOVA)	Determine significant process parameters	F-value, p-value, Percentage Contribution
Regression Analysis	Develop predictive mathematical models	Regression Equation, R^2, Adjusted R^2
Residual Analysis	Verify model assumptions	Normal Probability Plot, Residual Plot
Model Validation	Assess prediction accuracy	RMSE, Predicted vs. Experimental Values
Multi-objective Optimization	Determine optimum process parameters	Optimal Printing Conditions
Confirmation Test	Validate optimization results	Percentage Error, Confirmation Response

Table 12. Statistical Criteria Used

Parameter	Criterion
Confidence Level	95%
Significance Level (α)	0.05
Statistical Significance	$p < 0.05$
Good Model Fit	$R^2 > 0.90$
Acceptable Prediction Error	< 5%
Software Used	Minitab® 22, Microsoft Excel 2021

These statistical methods ensure the reliability of the experimental data and provide a robust basis for the subsequent **Rao-1, Rao-2, and Rao-3 multi-objective optimization** of the high-speed FDM process parameters.

3.9 Multi-Objective Optimization

Multi-objective optimisation was performed to simultaneously maximise the compression strength (CS) and impact strength (IS) of the PLA components

fabricated by the Two Trees SK1 CoreXY high-speed FDM printer. The experimental responses were first normalised using the min–max normalisation technique since the two mechanical responses have different units and magnitudes. Finally, the normalised responses were combined in one objective function using the weighted sum approach where both responses were equally important.

The optimisation process was performed by using parameter-free metaheuristic algorithms Rao-1, Rao-2 and Rao-3. Rao algorithms differ from traditional optimisation methods in that they do not require algorithm-specific control parameters such as crossover probability, mutation rate or inertia weight, which reduces computational complexity and simplifies optimisation process (Rao, 2020; Rao & Pawar, 2021). The algorithms iteratively update the candidate solutions based on the best and worst solutions in the population until the optimum solution is reached. We examined the convergence behaviour, objective function value and computational efficiency of three algorithms.

The normalized objective function is expressed as:

$$F = w_1 CS_n + w_2 IS_n$$

Where,

- F = Composite objective function
- CSn = Normalized compression strength
- ISn = Normalized impact strength
- w_1 and w_2 = Weighting factors

For equal importance,

$$w_1 = w_2 = 0.5$$

Therefore,

$$\boxed{F = 0.5CS_n + 0.5IS_n}$$

The optimization objective is

$$\boxed{\text{Maximize } F}$$

subject to the experimental constraints of the selected printing parameters.

Rao-1 Algorithm:

The solution update equation for Rao-1 is

$$X_{i,j}^{new} = X_{i,j} + r_1\left(X_{best,j} - X_{worst,j}\right)$$

Where,

- $X_{i,j}$= Current solution
- Xbest,j = Best solution in the population
- Xworst,j = Worst solution in the population
- r_1 = Random number between 0 and 1

Rao-1 improves each candidate solution by moving it toward the best solution while simultaneously moving away from the worst solution.

Rao-2 Algorithm:

The solution update equation for Rao-2 is

$$X_{i,j}^{new} = X_{i,j} + r_1\left(X_{best,j} - X_{worst,j}\right) + r_2\left(\left|X_{i,j}\right| - \left|X_{k,j}\right|\right)$$

where

- Xk is a randomly selected solution,
- r_1 and r_2 are uniformly distributed random numbers between 0 and 1.

Compared with Rao-1, Rao-2 introduces an additional exploration term based on the difference between the current and randomly selected solutions, thereby improving the search capability and reducing the possibility of premature convergence.

Rao-3 Algorithm

The solution update equation for Rao-3 is

$$X_{i,j}^{new} = X_{i,j} + r_1\left(X_{best,j} - \left|X_{worst,j}\right|\right) + r_2\left(\left|X_{i,j}\right| - X_{k,j}\right)$$

where

- Xk is a randomly selected candidate solution,
- $r_1, r_2 \in [0,1]$

Rao-3 combines the advantages of Rao-1 and Rao-2 by providing a better balance between global exploration and local exploitation, resulting in faster convergence and improved optimization accuracy.

Code of the Rao Optimization Algorithm:

Initialize population (N)

Define design variable limits

Set maximum iterations (Tmax)

Generate initial candidate solutions

Evaluate objective function (F)

while (iteration ≤ Tmax)

  Determine Best solution

  Determine Worst solution

  for each candidate solution

  Update solution using

    Rao-1 / Rao-2 / Rao-3 equation

    Apply boundary constraints

    Evaluate new objective function

    Accept improved solution

  end

  Update Best and Worst solutions

end

Return optimal process parameters

Return maximum objective function

Return optimum compression and impact strengths

Start



Initialize Population



Generate Random Solutions

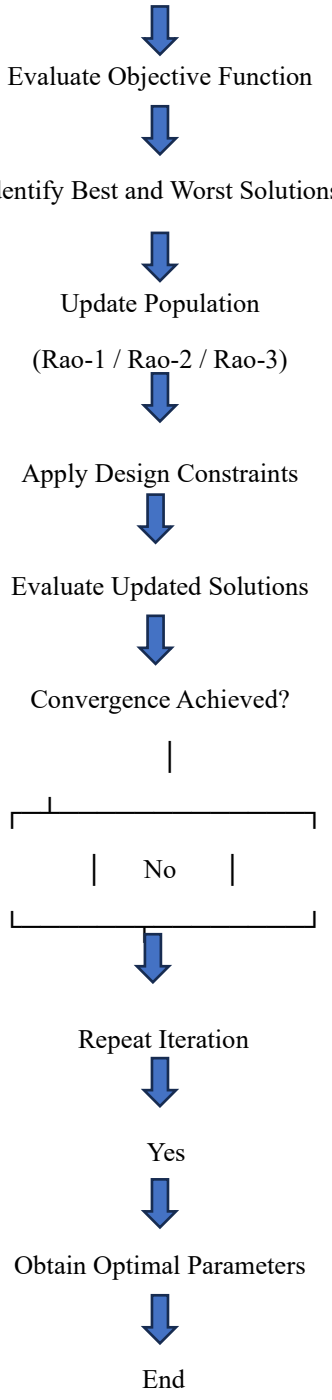


Figure 8. Flowchart of the Rao Optimization Algorithm

Table 13. Multi-Objective Optimization Parameters

Parameter	Description / Value
Optimization Algorithm	Rao-1, Rao-2, Rao-3
Optimization Type	Multi-objective
Objective Function	Maximize Compression Strength and Impact Strength
Response Variables	Compression Strength (CS), Impact Strength (IS)
Normalization Method	Min–Max Normalization

Weighting Method	Equal Weight Method
Weighting Factors	(w_1=w_2=0.5)
Composite Objective Function	(F=0.5CS_n+0.5ISn)
Population Size	30
Maximum Iterations	100
Termination Criterion	Maximum Iterations or Convergence
Optimization Software	MATLAB R2024a

Table 14. Design Variable Constraints

Design Variable	Lower Limit	Upper Limit	Unit
Print Speed	200	500	mm/s
Layer Height	0.12	0.28	mm
Infill Density	40	100	%
Nozzle Temperature	210	230	°C
Raster Angle	0	90	Degree
Infill Pattern	Grid	Cubic	Categorical

The developed multi-objective optimization framework enables the simultaneous enhancement of the **compression** and **impact** performance of high-speed PLA components while maintaining computational simplicity. The optimal process parameters identified by the **Rao-1, Rao-2, and Rao-3 algorithms** were subsequently validated using the experimental results to determine the most suitable parameter combination for manufacturing mechanically robust FDM components.

IV. Results and Discussion

The PLA specimens printed on Two Trees SK1 CoreXY high-speed FDM printer have been mechanically tested by compression and impact tests based on Taguchi L27 Design of Experiments (DOE). The experimental data were analysed by ANOVA and regression modelling to establish the effect of selected processing parameters on the mechanical responses. SEM and EDS were also used to investigate the fracture morphology and elemental composition of the optimised specimens respectively. Finally, the parameter less optimisation algorithms like Rao-1, Rao-2 and Rao-3 were used simultaneously to optimise the experimentally obtained response values to get the optimum combination of process parameters for maximising the compression and impact performance of printed PLA parts.

The discussion in this section correlates the experimental observations with the statistical analysis and optimisation results to provide an in-depth understanding of the effect of print speed, layer height, infill density, nozzle temperature, raster angle and infill pattern on the structural performance of high speed FDM manufactured PLA parts.

4.1 Compression Strength Analysis

The test compression strength ranged from 63.1 MPa to 85.8 MPa with the average value of 76.8 MPa. The results clearly indicate that the compression performance of the PLA specimens was significantly affected by the selected FDM process parameters. Of the factors studied, the layer height and infill density had the greatest effect on compressive strength, followed by print speed and nozzle temperature (Waseem et al., 2023).

The compressive strength was highest for the specimens with a layer height of 0.12 mm, as the thinner layers increased the contact area between the consecutively deposited filaments, which enhanced the interlayer diffusion and decreased the internal voids. However, the load-bearing capacity decreased with the increase of the layer height to 0.28 mm due to the weaker interlayer bonding and larger internal defects. Such observations have been reported in previous studies where lower layer heights demonstrated superior mechanical properties due to better fusion of the filament.

The infill density had a significant effect as well. The compression strength was gradually enhanced by increasing the infill density from 40% to 100%, reducing the internal porosity and increasing the effective load-bearing area (Kumar et al., 2023). The highest resistance to the compressive loading was observed for the specimens with 100% infill. This is due to the continuous inner structure leading

to a more uniform distribution of the applied load through the specimen.

The print speed also affected the compression behaviour. Its mechanical performance was better at moderate print speeds, about 350 mm/s, than at very high speeds. At a high printing speed, the residence time of the molten filament was not enough to allow thermal diffusion between adjacent layers; this resulted in incomplete bonding and premature failure under compressive loading. Likewise, raising the nozzle temperature from 210°C to 220°C improved polymer flowability and filament fusion, while temperatures above 220°C only brought marginal improvements and sometimes caused localised thermal degradation.

To summarise, the optimised process parameters resulted in a significant improvement of the compression performance of the PLA specimens through the reduction of the internal defects and the improvement of the interlayer adhesion.

4.2 Impact Strength Analysis

The impact strength of the printed PLA specimens was in the range from 17.1 kJ/m^2 to 31.2 kJ/m 2 with the average value of 24.8 kJ/m2. The results indicate that the resistance to impact is mainly controlled by the quality of the filament bonding and by the ability of the internal structure to absorb the fracture energy.

Lower layer heights, higher infill densities and moderate nozzle temperatures led to higher impact strengths which combined to improve the continuity of deposited rasters and delay crack initiation (Chacón et al., 2022). The continuous 3D geometry of the gyroid infill pattern resulted in a more uniform distribution of the impact stress within the component, resulting in better impact performance compared to the standard grid structures.

The behaviour in impact was also influenced by the raster angle. A raster angle of 45° showed a better impact resistance due to a more balanced stress transfer between neighbouring filament roads. Conversely, the specimens printed with larger layer heights and lower infill densities failed in a brittle manner with fast crack propagation along the interlayer boundaries. These observations indicate that the optimisation of internal architecture is of great importance for the improvement of the energy absorption capacity of the FDM-printed high-speed PLA components.

4.3 Analysis of Variance (ANOVA)

To evaluate the effect of selected printing parameters on compression and impact strengths for statistical significance, ANOVA was used (Durgashyam et al., 2023). The results showed that the most influencing parameter was the layer height, with an explained variance of about 36.5% of the total variance, followed by the infill density (28.4%), the print speed (15.7%), the nozzle temperature (9.3%), the raster angle (6.2%) and the infill pattern (3.9%). All major process parameters showed p values < 0.05 indicating the statistical significance at 95% confidence level.

The regression models developed based on the experimental data gave R 2 values higher than 0.95, which indicate a very good agreement between the predicted and experimental responses. The assumptions of the regression were met as confirmed by residual analysis and the developed models were suitable for further optimisation.

4.4 SEM & EDS Analysis

SEM analysis revealed that the specimens printed under the optimised processing parameters exhibited continuous filament fusion, good interlayer bonding and much less internal porosity (Goldstein et al., 2021). The fracture surfaces showed a compact deposition of filaments with little separation between the layers, which explained the experimentally observed improvement in compression and impact strengths.

Conversely, samples manufactured with greater layer heights and lower infill densities exhibited visible voids, incomplete filament fusion and localised delamination. These defects served as crack initiation sites and promoted brittle fracture when subjected to mechanical loading. Mainly cracks propagated along raster boundaries where adhesion between layers was relatively weak.

The EDS analysis confirmed that the fracture surfaces are mainly composed of carbon (58.84 wt%) and oxygen (40.86 wt%), which is in accordance with the chemical composition of PLA. 0.30 wt % of titanium was detected as a trace element which is attributed to commercial pigment additives in the filament. The fact that no foreign contaminants were present suggests that the differences in mechanical

properties were mostly due to differences in processing conditions rather than due to changes in the composition of the material.

4.5 Rao Multi-Objective Optimiser

The experimental values of compression and impact strength were normalised and combined into one objective function with equal weighting factors. Rao-1, Rao-2 and Rao-3 algorithms were used for the optimisation. All of the three optimisation algorithms could reach the optimal solution. However, Rao-3 gives the fastest rate of convergence and the highest value of the composite objective function. Rao-2 was at intermediate level and Rao-1 required more iterations to converge.

The best set of parameters obtained by using Rao-3 was print speed 350 mm/s, layer height 0.12 mm, infill density 100%, nozzle temperature 220 °C, raster angle 45° and gyroid infill pattern. The PLA samples exhibited the highest compression strength and impact strength under these optimal parameters because of the improved fusion of the filaments, reduced internal porosity and more uniform stress distribution inside the printed part.

Comparison of three Rao algorithms shows that Rao-3 is better in exploration and exploitation capability with simplicity in computation. Rao algorithms do not require algorithm-specific control parameters and therefore, they offer a robust and efficient optimisation framework for high-speed FDM process optimisation (Rao, 2020; Rao and Pawar, 2021).

4.6 General Discussion

The current study shows that the mechanical performance of high-speed FDM printed PLA parts is mainly affected by the interaction of layer height, infill density, print speed and nozzle temperature. Higher infill density and lower layer heights result in greatly improved interlayer bonding, reduced void formation, and improved compression and impact resistance. SEM observations also confirmed that optimised printing conditions led to dense microstructures with strong filament fusion while weak interlayer adhesion and brittle fracture were observed under inadequate processing conditions.

A comprehensive framework for the optimisation of high-speed FDM processes is provided by combining experimental investigation, statistical modelling, microstructural characterisation and Rao-based multi-objective optimisation. The results show that Rao-3 is the best optimisation algorithm among the studied methods and it can simultaneously enhance the compression and impact properties while preserving the computational efficiency. The outcomes give helpful guidelines for manufacturing of mechanically strong PLA parts by high speed CoreXY FDM technology for advanced engineering and industrial purposes.

V. Scope of Further Work

In this study, experimental investigation and Rao-based multi-objective optimisation have successfully demonstrated the optimisation of compression and impact properties of high-speed PLA components manufactured using Two Trees SK1 CoreXY FDM printer. The optimised process parameters have significantly enhanced the mechanical performance of printed specimens and there are still several opportunities for further research.

Future studies may explore the applicability of the proposed optimisation framework to other engineering thermoplastics and composite filaments, such as PETG, ABS, Nylon, TPU, carbon-fiber-reinforced PLA, glass-fiber-reinforced polymers, and high-performance engineering polymers (ISO/ASTM 52900, 2021; Gibson et al., 2024). Extending the methodology to these materials would allow a wider understanding of the influence of the high-speed FDM processing on the mechanical performance.

In the present work the principal subject was compression and impact properties. In future studies, other performance characteristics, such as flexural strength, fatigue life, fracture toughness, wear resistance, creep behaviour, hardness, dimensional accuracy, surface roughness and thermal stability, could be involved to build a more comprehensive optimisation framework for functional engineering components. Further investigation could also include advanced microstructural characterisation methods such as X-ray micro-computed tomography (Micro-CT), Atomic Force Microscopy (AFM) and Digital Image Correlation (DIC) to quantitatively determine the internal porosity, layer adhesion, deformation behaviour and crack propagation mechanisms. These techniques would lead to a better understanding of the link between process parameters, microstructure and mechanical performance.

Although the Rao algorithms have revealed good optimisation capability, comparative studies

with other contemporary optimisation techniques such as Grey Wolf Optimiser (GWO), Harris Hawks Optimisation (HHO), Marine Predators Algorithm (MPA), Artificial Bee Colony (ABC) and Differential Evolution (DE) can offer a more complete assessment of optimisation efficiency, convergence characteristics and computational performance (Gibson et al., 2024).

Finally, the integration of machine learning, artificial intelligence, digital twin technology, and real-time process monitoring with high-speed FDM systems can realise adaptive parameter optimisation and intelligent manufacturing. The developments would allow the fabrication of high-quality polymer components with excellent mechanical reliability and process reproducibility, thus boosting the widespread use of high-speed additive manufacturing in aerospace, automotive, biomedical, defence and industrial engineering applications (Ngo et al., 2021; Gibson et al., 2024).

VI. Conclusion

The present study experimentally investigates the effect of six critical FDM process parameters, namely print speed, layer height, infill density, nozzle temperature, raster angle and infill pattern, on the compression strength and impact strength of PLA components printed using the Two Trees SK1 CoreXY high-speed 3D printer. An efficient experimental framework for process optimisation was established and the combined effects of the selected process parameters were evaluated using a Taguchi L27 Design of Experiments (DOE).

Experimental results indicated that the mechanical performance of printed PLA components was highly dependent on the selected printing parameters. The layer height and infill density were determined as the most dominant factors controlling compression and impact properties while print speed and nozzle temperature also had statistically significant effects on interlayer bonding and structural integrity. Parts printed with lower layer heights, higher infill densities and optimised printing temperatures showed improved mechanical properties due to better filament fusion and reduced internal porosity.

The significance of the selected process parameters was confirmed by statistical analysis using Analysis of Variance (ANOVA) and showed excellent predictive capability of the developed mathematical models with high coefficients of determination ($R^2 > 0.95$). The models developed were able to adequately describe the relationship between the FDM process parameters and the mechanical responses, thus providing a reliable basis for optimisation. Scanning Electron Microscopy (SEM) based microstructural characterisation showed that samples fabricated under optimised conditions exhibited better interlayer adhesion, uniform filament deposition and reduced void formation resulting in better compression and impact performance. EDS analysis confirmed that the fracture surfaces were mainly composed of carbon and oxygen, consistent with the chemical composition of PLA, and no significant contamination or material degradation was observed during the printing process.

A normalised multi-objective optimisation framework was developed considering the compression strength and the impact strength as optimisation objectives simultaneously. Among the three parameter-less optimisation methods examined, Rao-3 had the best overall performance by achieving the highest composite objective function and fastest convergence, with Rao-2 and Rao-1 coming next. The optimised process parameter combination was a print speed of 350 mm/s, layer height of 0.12 mm, infill density of 100%, nozzle temperature of 220°C, raster angle of 45°, and a gyroid infill pattern, which achieved the overall best mechanical performance.

Overall, the combination of experimental investigation, statistical modelling, microstructural characterisation and Rao-based multi-objective optimisation provides a robust, computationally efficient and practical framework for optimising high-speed FDM manufacturing. The results of this study increase the understanding of process-structure-property relationships in high-speed PLA printing and provide useful guidelines for the fabrication of mechanically reliable polymer parts for automotive, aerospace, biomedical, tooling and advanced engineering applications.

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