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Process Parameters and Geometric Accuracy in Robotic Pellet Extrusion of Wood-Based Polylactic Acid (PLA) Composites

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ABSTRACT: Robotic large-scale additive manufacturing (RAM) using wood-based Polylactic Acid PLA pellet extrusion is an emerging route to sustainable manufacturing, but systematic data on dimensional accuracy for this material–system combination remain limited. This paper investigates the influence of robot travel speed, extruder rotation speed, and nozzle temperature on the geometric accuracy of pellet-extruded wood-based PLA composites through a one-factor-at-a-time experimental design. Twenty-four hollow cube specimens were produced using an ABB IRB 1600 robot with a KFM Eco 3D 18 extruder, with the travel speed varied at 15, 30, and 45 mm/s, extruder rotation at 3, 4, and 5 rpm, and nozzle temperature at four levels between 150 and 180 °C. Accuracy was evaluated through mean deviation, mean absolute error, standard deviation, and percentage error. Robot travel speed was the dominant parameter, with severe under-extrusion at 45 mm/s producing cube heights below 25 % of nominal. Within the stable regime (≤ 30 mm/s), the three parameters exhibiting near-separable behaviour within the stable regime on decoupled geometric quantities: speed governed layer height, rotation governed wall thickness, and temperature governed cube height. Material-specific second-order polynomial models were developed, with PLA-10 requiring a temperature–rotation interaction term that captures a 67.4 % cube-height collapse at elevated temperature under low extruder rotation. Overall, the three parameters can be tuned independently within the stable regime, supporting a three-step calibration procedure for geometric control in pellet-based robotic extrusion of wood-based PLA materials.

Keywords: Robotic additive manufacturing; pellet extrusion; wood-based PLA composites; dimensional accuracy; process parameters; OFAT experimental design.

1. Introduction

Additive Manufacturing (AM) enables the layer-by-layer fabrication of complex three-dimensional components directly from digital models and has been widely adopted across aerospace, automotive, construction, and biomedical applications [1,2]. Among the available AM technologies, extrusion-based processes such as Fused Deposition Modelling (FDM) are common due to their relatively simple architecture and compatibility with thermoplastic materials. Conventional FDM systems, however, are limited by Cartesian motion platforms, which restrict both achievable part size and geometric complexity.

To overcome these limitations, industrial robotic manipulators have been increasingly adopted as motion platforms for AM, giving rise to Robotic Additive Manufacturing (RAM). RAM systems offer larger working volumes, higher degrees of freedom, and access to non-planar deposition strategies that are not feasible with Cartesian printers [3–5]. Fry et al. demonstrated this capability using a 12-axis dual-robot system, reporting an increase in tensile load of approximately 57 % for conformal curved layers compared to planar deposition [6]. RAM has consequently attracted increasing research attention in applications ranging from architecture and large-scale component manufacturing to functional structural elements [4,7–9].

In parallel, the move towards sustainable manufacturing has driven interest in wood-based PLA composites, which combine renewable cellulose fibres with a polylactic acid matrix to retain the structural benefits of polymers while reducing environmental impact [10]. These materials are

particularly relevant to pellet-based RAM, where geometric quality depends on the synchronisation between robot motion and material flow. Loss of this synchronisation produces under-extrusion at excessive travel speeds and over-extrusion at excessive material feed, with both failure modes affecting interlayer bonding and dimensional fidelity [11–13]. The heterogeneous microstructure and moisture-sensitive nature of wood-based feedstocks amplify this sensitivity, and Hakimiy and Dröder have shown that fixed parameter settings are insufficient for consistent geometric quality in pellet-based extrusion [14].

Despite this, systematic experimental investigations of geometric accuracy in pellet-based RAM of wood-based PLA composites remain limited. Most existing studies address filament-based FDM with unfilled thermoplastics [6,11,13], and no standardised framework for evaluating geometric accuracy in robotic pellet extrusion has been established. This study addresses these gaps by systematically investigating the influence of robot travel speed, extruder rotation speed, and nozzle temperature on the dimensional accuracy of pellet-extruded wood-based PLA composites, introducing a quantitative evaluation framework and identifying stable processing conditions for this material–system combination.

2. Literature Review

2.1 Robotic additive manufacturing systems

Robotic Additive Manufacturing (RAM) systems use industrial robotic manipulators in place of Cartesian motion stages, providing larger working volumes, higher degrees of freedom, and access to non-planar toolpath strategies. Khosravani and Haghighi confirmed the suitability of RAM for large-scale automated construction [4], Kontovourkis and Tryfonos demonstrated that combining robotic motion with topology-optimised toolpath planning enables architectural geometries that are unattainable on conventional systems [5,7]. These studies highlight the importance of motion flexibility as a key advantage of robotic platforms in additive manufacturing.

Beyond hardware capability, process planning and simulation are critical for stable operation. Pollák et al. used ABB RobotStudio for virtual bead visualisation and pre-selection of speed–flow parameter combinations, reducing process instability during experimental trials [15]. Ziada et al. extended this approach by developing a cyber-physical manufacturing system that integrates hardware-in-the-loop simulation with real-time sensor feedback, illustrating a transition from offline programming towards adaptive and autonomous process control in RAM [16].

2.2 Pellet extrusion of wood-based PLA materials

Fused Granular Fabrication (FGF) systems extrude raw polymer pellets directly, offering higher material throughput and lower feedstock cost than filament-based systems and making them well suited to large-scale RAM applications [14]. The pellet format is particularly advantageous for wood-based feedstocks: filament production typically requires a secondary extrusion step that subjects wood fibres to repeated thermal cycles, increasing the risk of fibre degradation, moisture uptake, and length reduction [17]. Direct pellet extrusion via FGF avoids this additional thermal history and accommodates the higher viscosity and heterogeneous melt behaviour typical of wood-based PLA composites [18]. Jasiński et al. demonstrated that wood particle size is a critical parameter in wood-based PLA extrusion, influencing melt flow behaviour and print quality and requiring careful matching to nozzle geometry [12]. The combined effects of fibre size, distribution, and moisture make extrusion of these materials more sensitive to parameter variations than that of unfilled thermoplastics [11,12].

2.3 Influence of process parameters on geometric quality

The balance between material deposition and robot motion governs geometric quality in robotic extrusion-based AM. The volumetric deposition rate Q is given by (1):

$$Q = V \times H \times W \quad (1)$$

where Q is the volumetric deposition rate, V the robot travel speed, H the deposited layer height, and W the bead width. In the present system only V is an independently commanded input, together with extruder rotation and nozzle temperature; H and W are emergent geometric outcomes of the deposition rather than set parameters. Equation 1 therefore expresses a mass continuity constraint linking commanded motion to the resulting bead geometry: for a given material throughput, any change in travel speed must be accommodated by a corresponding change in the deposited cross-section. Disruption of this balance produces characteristic defects: over-extrusion causes bead swelling and corner bulging, while under-extrusion produces gaps and weak interlayer bonding. Csekei et al. confirmed using an ABB IRB 120 system that loss of synchronisation between robot motion and material flow is the dominant failure mode in RAM [11], and Abadi et al. reported that raster width decreases with increasing print speed while raster deflection increases when speed is reduced at constant feed rate [13]. Nozzle temperature also plays a critical role in interlayer bonding. Reducing extrusion temperature from 190 °C to 180 °C has been shown to decrease tensile strength by approximately 50 %, indicating strong thermal sensitivity of bond formation [13]. For wood-based PLA materials this sensitivity is amplified by moisture effects and by the onset of thermal degradation of natural cellulosic fibres at elevated temperatures, which narrows the stable processing window [19].

2.4 Research gap

Despite the growing body of research on RAM and pellet-based extrusion, four gaps remain relevant to this study. First, most existing investigations vary process parameters in isolation rather than analysing their combined effect on geometric accuracy, and the majority address filament-based FDM with unfilled thermoplastics [6,11,13]. Second, the combination of pellet extrusion, wood-based PLA composites, and a robotic platform remains underrepresented. Third, no standardised methodology for evaluating geometric accuracy in robotic pellet extrusion has been established, with most studies reporting surface roughness or mechanical properties rather than dimensional fidelity. Fourth, the boundaries between stable and unstable deposition regimes, including the transitions between under-extrusion, over-extrusion, and thermally driven failure, have not been systematically characterised for this material–system combination.

3. Experimental Methodology

3.1 Robotic Additive Manufacturing System

The experimental platform integrates a six-degree-of-freedom ABB IRB 1600 robot, controlled via an IRC5 Compact controller, with a KFM Eco 3D 18 screw-based pellet extruder fitted with a 3 mm diameter nozzle and equipped with PID thermal regulation. Toolpaths were generated and pre-validated offline in ABB RobotStudio. The system operates as a cyber-physical manufacturing unit in which robot motion commands and extrusion control signals are synchronised through a shared control architecture, following the approach of Pollák et al. [15]. The integrated experimental setup is presented in **Figure 1**.

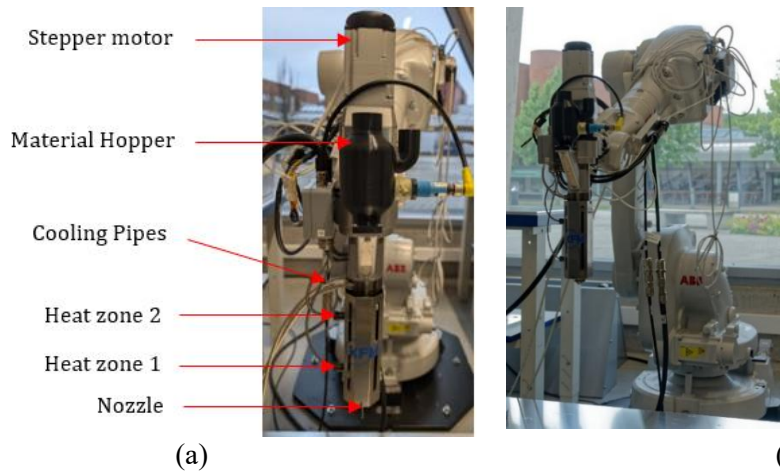


Figure 1. Experimental setup: (a) KFM Eco 3D 18 pellet extruder coupled with (b) ABB IRB 1600 industrial robotic arm.

3.2 Materials

Two wood-based PLA materials were investigated: KCL Formi® 3D Nordic Birch PLA-20 (polylactic acid with 20 wt% cellulose fibre) and KCL Formi® 3D Nordic Birch PLA-10 (polylactic acid with 10 wt% cellulose fibre), both supplied in pellet form by Oy Keskuslaboratorio-Centrallaboratorium Ab (KCL, Lohja, Finland) and used as received [20]. PLA-20 was selected as the primary material because its higher fibre content represents the more demanding extrusion case in terms of melt-flow sensitivity. PLA-10 was included to distinguish material-dependent effects from parameter-driven dimensional variations, and to support the role of fibre fraction in extrusion sensitivity reported by Jasiński et al. [12]. Key supplier-specified properties of the two grades are summarised in **Table 1**.

Table 1. Supplier-specified properties of the wood-PLA materials used in this study

Property	Test method	PLA-20	PLA-10
Density [g/cm ³]	EN ISO 1183	1.20	1.21
Fibre content [wt%]	-	20	10
Tensile strength, 3D printed [MPa]	ISO 527	32	22
Tensile modulus, 3D printed [MPa]	ISO 527	3200	3250
Peak melt temperature [°C]	ISO 11357	135–180	135–180
Glass transition temperature [°C]	ISO 11357	65	60
Melt flow index, 190°C / 10 kg	ISO 1133	16	33
Maximum processing temperature [°C]	-	200	200

3.3 Material Preparation

Moisture in wood-based PLA pellets vaporises at elevated nozzle temperatures during extrusion, producing defects such as bubbling, reduced interlayer bonding, and dimensional instability [21,22]. Both PLA-20 and PLA-10 pellets were therefore dried at 60 °C for 4 h in a convection oven prior to printing. The drying temperature was kept below the glass transition of each grade ($T_g = 65$ °C for PLA-20 and 60 °C for PLA-10) to prevent pellet softening and agglomeration. Preliminary calibration trials confirmed a stable mass plateau, indicating effective moisture removal. Following drying, pellets were transferred to sealed containers and used within the same working day to prevent re-absorption of ambient moisture.

3.4 Experimental design

A one-factor-at-a-time (OFAT) experimental design was adopted to investigate the influence of the three primary process parameters on dimensional accuracy. The OFAT approach was selected as an initial process-window characterisation strategy to identify stable and unstable deposition regimes before committing to a more resource-intensive factorial or response-surface study; it is not intended to optimise across the full parameter space simultaneously. The parameters varied were robot travel speed (V) at 15, 30, and 45 mm/s; extruder rotation speed (N) at 3, 4, and 5 rpm; and nozzle temperature (T) at four discrete levels of 150/155, 160/165, 170/175, and 180/185 °C, where each pair denotes the set-points of heating zones 1 and 2, respectively. A total of 24 specimens were produced across four experimental series using PLA-20 and PLA-10, as summarised in Table 2. OFAT was selected because no processing windows are established for pellet-based extrusion of wood-based PLA materials, and full factorial or response surface designs would allocate a significant proportion of experiments to unstable parameter combinations. The 100 × 100 × 100 mm specimen size also imposes practical limits on experimental throughput. OFAT therefore provides an efficient strategy for initial parameter-space mapping prior to more advanced multi-parameter optimisation. The purpose of the OFAT framework in this study was not global optimisation, but initial process-window mapping and identification of dominant parameter-governing mechanisms under previously unexplored material–system conditions.

Table 2. Experimental test matrix for the OFAT parameter study (robot travel speed in mm/s, extruder rotation in rpm, nozzle temperature in °C).

Sub-series	Process parameter setting (F = fixed, v ₁ /v ₂ /v ₃ = varied levels)			Runs
	Extruder rotation	Nozzle temperature T1/T2	Robot speed	
	rpm	°C	mm/s	
RS1-PLA20	4 ^F	(150/155) ^F	15 ^{v1} , 30 ^{v2} , 45 ^{v3}	3
RS2-PLA20	5 ^F	(150/155) ^F	15 ^{v1} , 30 ^{v2} , 45 ^{v3}	3
NT1-PLA20	3 ^F	(160/165) ^{v1} , (170/175) ^{v2} , (180/185) ^{v3}	30 ^F	3
NT2-PLA20	4 ^F	(160/165) ^{v1} , (170/175) ^{v2} , (180/185) ^{v3}	30 ^F	3
RS1-PLA10	4 ^F	(150/155) ^F	15 ^{v1} , 30 ^{v2} , 45 ^{v3}	3
RS2-PLA10	5 ^F	(150/155) ^F	15 ^{v1} , 30 ^{v2} , 45 ^{v3}	3
NT1-PLA10	3 ^F	(160/165) ^{v1} , (170/175) ^{v2} , (180/185) ^{v3}	30 ^F	3
NT2-PLA10	4 ^F	(160/165) ^{v1} , (170/175) ^{v2} , (180/185) ^{v3}	30 ^F	3
Total specimens				24

3.5 Specimen geometry and toolpath

A hollow cube geometry was selected for its well-defined dimensional features and suitability for evaluating geometric accuracy. Specimens were designed at a nominal size of 100 × 100 × 100 mm and produced via a continuous spiral toolpath of 200 layers at a nominal 0.5 mm layer height and a single-wall thickness of 3 mm. The continuous toolpath eliminates start and stop deposition effects and maintains steady material flow, reducing transient disturbances and enabling clearer identification of parameter-induced deviations, consistent with the approach of Nguyen et al. [9].

The robot executed the full programmed sequence in all tests, with no termination based on measured z-height or operator intervention. Deviations between measured and nominal cube height therefore reflect the cumulative effect of process-induced layer-height variation along the build rather than premature termination. At 45 mm/s, locally measured layer heights represent swollen bead strands produced under intermittent material flow rather than continuous deposition; severe under-extrusion at this speed caused layer skipping and structural detachment between successive deposits, reducing

cumulative vertical build despite the locally elevated bead dimensions. Three geometric quantities were measured per specimen: total cube height, wall thickness, and layer height, evaluated against nominal values of 100 mm, 3 mm, and 0.5 mm respectively.

3.6 Dimensional accuracy metrics

Dimensional accuracy was evaluated using a multi-metric framework based on the deviation between measured dimensions and nominal CAD values, consistent with dimensional-error evaluation in robotic large-scale extrusion studies [13]:

$$\Delta D = D_{printed} - D_{design} \quad (2)$$

where $D_{printed}$ is the measured dimension and D_{design} is the nominal dimension.

Four metrics were applied to evaluate geometric performance:

Mean dimensional deviation:

$$\overline{\Delta D} = \frac{1}{n} \sum_{i=1}^n (D_{printed,i} - D_{design}) \quad (3)$$

Mean absolute error (MAE):

$$MAE = \frac{1}{n} \sum_{i=1}^n |AD_i| \quad (4)$$

Standard deviation of dimensional error:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\Delta D_i - \overline{\Delta D})^2} \quad (5)$$

Percentage error relative to the nominal geometry:

$$E_{\%} = \frac{|D_{printed,i} - D_{design}|}{D_{design}} \times 100 \quad (6)$$

These metrics quantify systematic deviation (mean deviation), average error magnitude (MAE), process variability (standard deviation), and relative accuracy with respect to the nominal geometry (percentage error).

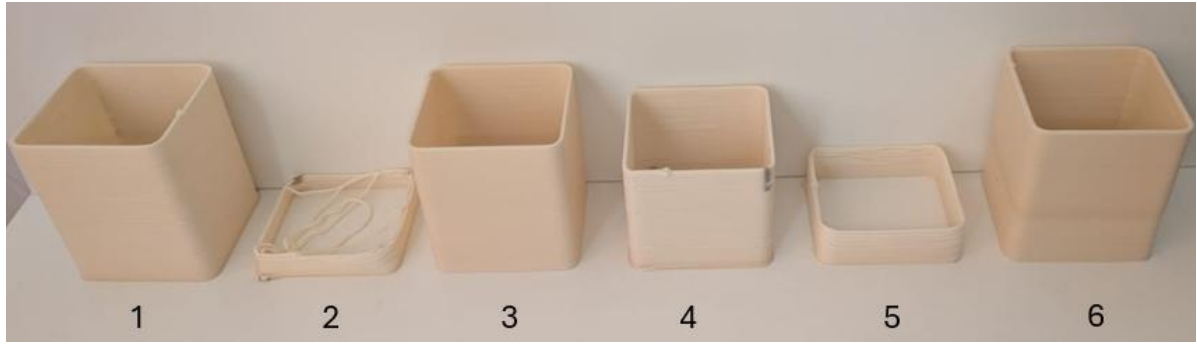
4. Results

4.1 Dimensional Measurements Overview

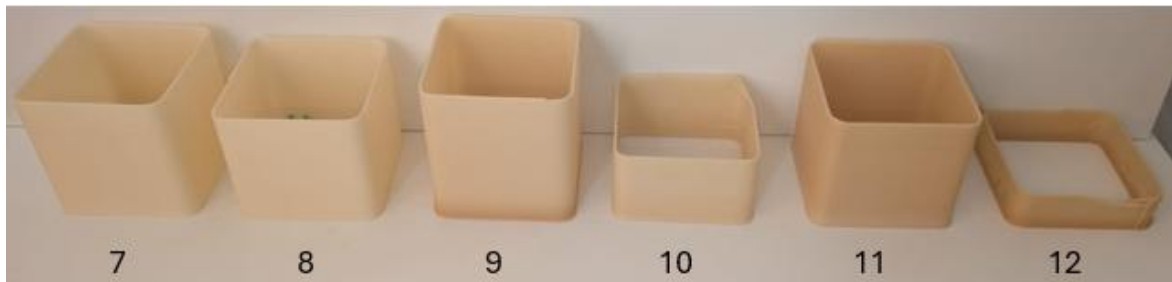
The measured cube height, wall thickness, and layer height for all 24 specimens are summarised in Table 3, evaluated against nominal values of 100 mm, 3 mm, and 0.5 mm respectively. Cube height ranged from 15.47 to 113.35 mm for PLA-20 and from 21.56 to 108.26 mm for PLA-10. Wall thickness varied from 2.78 to 4.00 mm for PLA-20 and from 1.60 to 5.44 mm for PLA-10. Layer height exceeded the nominal value across all specimens, with measured values between 0.55 and 1.86 mm. Representative printed specimens are shown in Figure 2.

Table 3. Measured geometry and deposition regime for all 24 specimens. Nominal values: wall 3 mm, layer 0.5 mm, height 100 mm. Regime is classified by cube height relative to nominal: Stable ≥ 80 %, Sub-nominal 50–80 %, Collapse < 50 % (mechanism indicated). Specimen numbering follows experimental run order and is not sequential within each subset.

Series A — travel speed and rotation varied (nozzle 150/155 °C)							
Spec	Material	N	V	Wall thickness	Layer thickness	Height (mm)	Regime
		[rpm]	[mm/s]	[mm]	[mm]	[mm]	
3	PLA-20	4	15	2.78	0.60	104.37	Stable
3	PLA-10	4	15	2.12	0.70	93.27	Stable
1	PLA-20	4	30	2.98	0.95	113.35	Stable
1	PLA-10	4	30	2.01	0.76	108.26	Stable
2	PLA-20	4	45	3.86	1.10	15.47	Collapse (under-extr.)
2	PLA-10	4	45	4.58	1.86	21.56	Collapse (under-extr.)
6	PLA-20	5	15	3.46	0.70	106.31	Stable
6	PLA-10	5	15	2.42	0.67	102.26	Stable
4	PLA-20	5	30	3.24	1.15	83.56	Stable
4	PLA-10	5	30	2.49	0.80	96.10	Stable
5	PLA-20	5	45	4.00	1.10	28.43	Collapse (under-extr.)
5	PLA-10	5	45	5.44	1.48	74.58	Sub-nominal
Series B — temperature and rotation varied (travel speed 30 mm/s)							
Spec	Material	N	T z1/z2	Wall thickness	Layer thickness	Height (mm)	Regime
		[rpm]	[°C]	[mm]	[mm]	[mm]	
8	PLA-20	3	160/165	2.87	0.65	77.59	Sub-nominal
8	PLA-10	3	160/165	1.71	0.62	87.05	Stable
10	PLA-20	3	170/175	2.86	0.55	82.61	Stable
10	PLA-10	3	170/175	1.72	0.61	57.38	Sub-nominal
12	PLA-20	3	180/185	2.89	0.65	77.54	Sub-nominal
12	PLA-10	3	180/185	1.60	0.86	28.37	Collapse (thermal)
7	PLA-20	4	160/165	3.49	0.75	68.70	Sub-nominal
7	PLA-10	4	160/165	2.02	0.72	95.56	Stable
9	PLA-20	4	170/175	3.29	0.80	62.69	Sub-nominal
9	PLA-10	4	170/175	2.03	0.60	105.40	Stable
11	PLA-20	4	180/185	3.35	0.80	67.51	Sub-nominal
11	PLA-10	4	180/185	2.22	0.74	88.78	Stable



(a)



(b)

Figure 2. Specimen photographs: (a) PLA-20 specimens, (b) PLA-10 specimens.

4.2 Dimensional accuracy metrics

The accuracy metrics calculated from the measured data are summarised in Table 4. Cube height exhibited by far the largest deviations: MAE was 30.00 mm for PLA-20 and 22.77 mm for PLA-10, with negative mean deviations of -26.00 and -20.12 mm respectively, indicating a systematic tendency toward under-sizing accompanied by high dispersion ($\sigma \approx 29$ mm for both materials). Wall thickness deviations were an order of magnitude smaller, with MAE of 0.36 mm for PLA-20 and 1.14 mm for PLA-10, the larger value reflecting greater variability in the lower-fibre material. Layer height showed a consistent positive deviation across all specimens, with MAE of 0.32 mm (PLA-20) and 0.37 mm

(PLA-10), corresponding to percentage errors of 63.3 % and 73.7 %, and a systematic overshoot of the nominal value.

Table 4. Summary of dimensional accuracy metrics (mean deviation, mean absolute error, standard deviation, and percentage error) for cube height and wall thickness, in mm.

Dimension	Material	Mean Dev $\Delta\bar{D}$ [mm]	MAE [mm]	Std Dev σ [mm]	Mean E%
Cube height	PLA-20	-26.00	30.00	28.00	30.0%
Cube height	PLA-10	-20.12	22.77	27.94	22.8%
Wall thickness	PLA-20	+0.26	0.36	0.38	12.0%
Wall thickness	PLA-10	-0.47	1.14	1.15	38.0%
Layer height	PLA-20	+0.32	0.32	0.20	63.3%
Layer height	PLA-10	+0.37	0.37	0.37	73.7%

4.3 Effect of Robot Travel Speed

Travel speed had a strong and direction-dependent effect on all three measured quantities (Figure 3). Cube height (Figure 3a) collapsed at 45 mm/s for both materials, falling to less than 25 % of nominal in the worst case (15.47 mm for PLA-20 at 4 rpm). Closest agreement with the nominal 100 mm was achieved at 30 mm/s and 4 rpm, where both materials remained within approximately ± 10 %. PLA-10 at 5 rpm partially retained height at 45 mm/s (74.58 mm), indicating that elevated extrusion rate compensates in part for under-deposition at high travel speed.

Wall thickness (Figure 3b) showed the opposite trend, rising from 2.78–3.46 mm at 15 mm/s to 3.86–5.44 mm at 45 mm/s across both materials. Material therefore continued to be deposited at high travel speed but accumulated laterally rather than building vertically, consistent with loss of synchronisation between robot motion and material flow.

Layer height (Figure 3c) also increased with travel speed, from approximately 0.60–0.70 mm at 15 mm/s to 1.10–1.86 mm at 45 mm/s. The deviation from the 0.5 mm nominal was therefore largest under high-speed conditions, with PLA-10 at 45 mm/s and 4 rpm producing the worst value (1.86 mm).

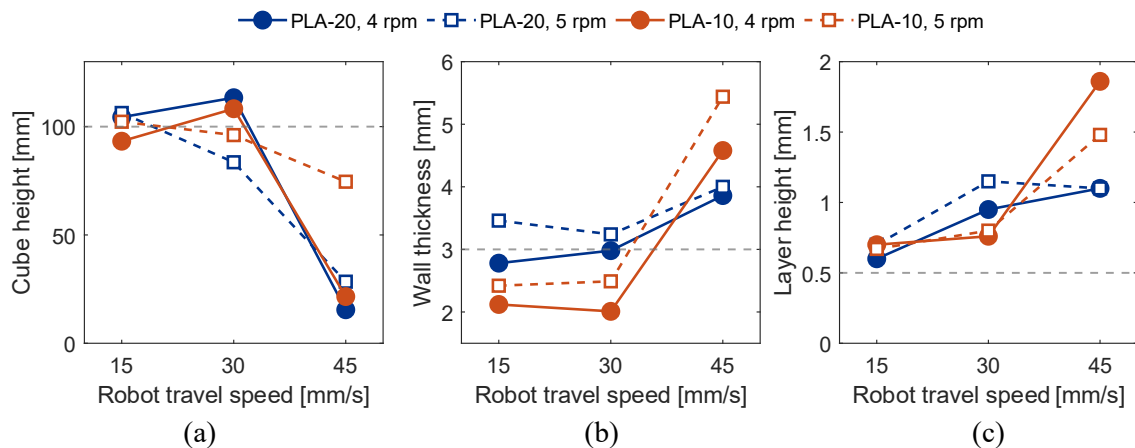


Figure 3. Effect of robot travel speed on geometric outcomes for PLA-20 and PLA-10 at constant nozzle temperature: (a) total cube height, (b) wall thickness, and (c) layer height. Data points are grouped by extruder rotation (4 and 5 rpm). Nominal values are 100 mm, 3 mm, and 0.5 mm respectively.

4.4 Effect of Extruder Rotation Speed

The rotation-speed effect was strongly dependent on travel speed (Figure 4). At 15 and 30 mm/s, cube height (Figure 4a) showed only a weak dependence on rotation: both materials remained within

approximately 83 to 113 mm of the nominal 100 mm. At 45 mm/s, by contrast, increasing rotation from 4 to 5 rpm partially restored cube height, with the largest response observed for PLA-10, which rose from 21.56 to 74.58 mm. Higher extrusion rate therefore compensates in part for under-deposition at elevated travel speed.

Wall thickness (Figure 4b) increased with rotation across all conditions, with the largest values for PLA-10 at 45 mm/s, rising from 4.58 mm (4 rpm) to 5.44 mm (5 rpm). The additional material at higher rpm accumulated laterally rather than restoring vertical build accuracy.

Layer height (Figure 4c) showed only a weak dependence on rotation except for PLA-10 at 45 mm/s, where it decreased from 1.86 to 1.48 mm despite the simultaneous increases in cube height and wall thickness. This indicates a redistribution of material from over-extruded layers into wider deposition tracks.

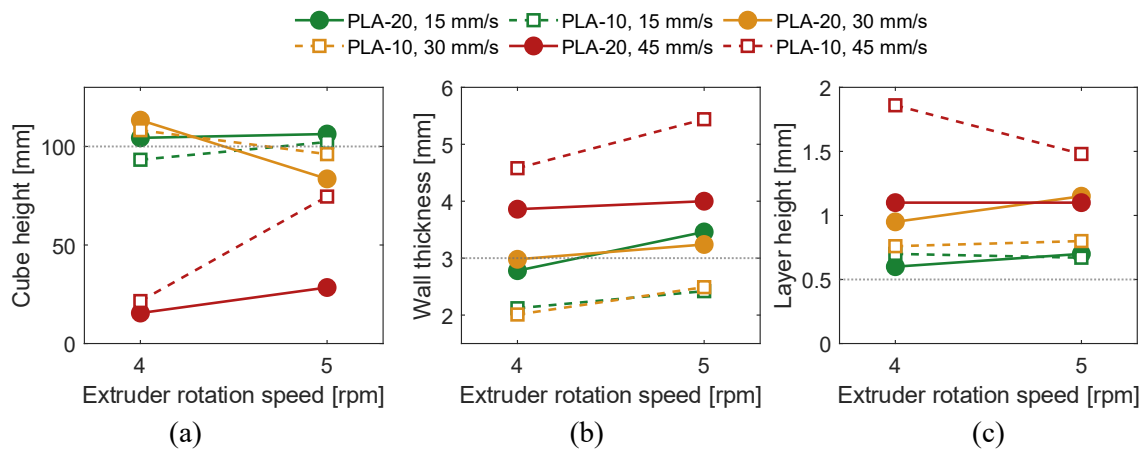


Figure 4. Effect of extruder rotation speed on geometric outcomes for PLA-20 and PLA-10 at constant nozzle temperature (150 °C, zone 1): (a) total cube height, (b) wall thickness, and (c) layer height. Data points are grouped by robot travel speed (15, 30, and 45 mm/s). Nominal values are 100 mm, 3 mm, and 0.5 mm respectively.

4.5 Effect of Nozzle Temperature

Cube height (Figure 5a) showed a strongly rpm-dependent response to temperature. At 3 rpm, PLA-10 collapsed monotonically from 87.05 mm at 160 °C to 28.37 mm at 180 °C, while PLA-20 dropped from 113.35 mm at 150 °C to 77.59 mm at 160 °C and remained within 77 to 83 mm thereafter. At 4 rpm, the response was markedly different: PLA-10 peaked at 105.40 mm at 170 °C and remained near nominal, while PLA-20 stayed within 63 to 69 mm across the tested range. The 4 rpm condition therefore preserved near-nominal cube height for PLA-10, while 3 rpm was more sensitive to temperature and produced the thermal collapse.

Wall thickness (Figure 5b) showed only a weak dependence on temperature, with rotation rate exerting a stronger influence: 4 rpm consistently produced thicker walls than 3 rpm for both materials, consistent with the higher volumetric supply at increased rotation.

Layer height (Figure 5c) exceeded the nominal 0.5 mm in all cases (0.55 to 0.95 mm). PLA-20 at 4 rpm showed the largest single drop, decreasing from 0.95 mm at 150 °C to 0.75 mm at 160 °C and then remaining near 0.80 mm at 170 and 180 °C. At 3 rpm, layer height stayed lower and approximately constant (0.55 to 0.65 mm) across the temperature range, consistent with the lower volumetric supply at reduced rotation.

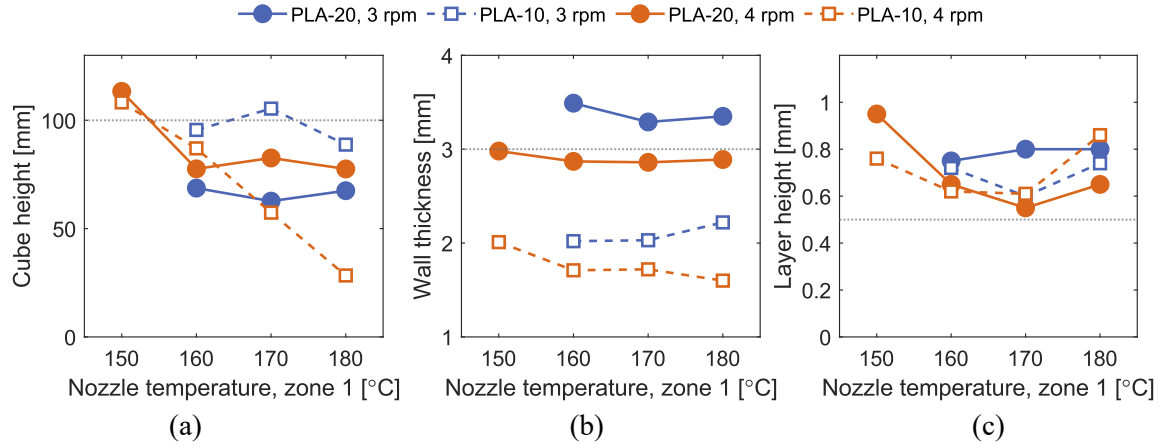


Figure 5. Effect of nozzle temperature on geometric outcomes for PLA-20 and PLA-10 at constant robot travel speed (30 mm/s): (a) total cube height, (b) wall thickness, and (c) layer height. Data points are grouped by extruder rotation (3 and 4 rpm). Nominal values are 100 mm, 3 mm, and 0.5 mm respectively.

4.6 Per-test deviation summary

Signed dimensional deviations for cube height and wall thickness across all test conditions are reported in Table 5. The largest negative cube-height deviations occurred at 45 mm/s, reaching -84.53 mm for PLA-20 and -78.44 mm for PLA-10. Wall thickness deviations remained within ± 1 mm for PLA-20 across most conditions, whereas PLA-10 reached up to $+2.44$ mm, reflecting greater variability in thickness control under high travel speed and rotation.

Table 5. Signed dimensional deviations (ΔH and ΔW , in mm) for cube height and wall thickness across all test conditions for PLA-20 and PLA-10.

Test n	Cube Height	ΔH	Cube Height	ΔH	Wall Thickness	ΔW	Wall Thickness	ΔW
	PLA-20		PLA-10		PLA-20		PLA-10	
	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
1	113.35	+13.35	108.26	+8.26	2.98	-0.02	2.01	-0.99
2	15.47	-84.53	21.56	-78.44	3.86	+0.86	4.58	+1.58
3	104.37	+4.37	93.27	-6.73	2.78	-0.22	2.12	-0.88
4	83.56	-16.44	96.10	-3.90	3.24	+0.24	2.49	-0.51
5	28.43	-71.57	74.58	-25.42	4.00	+1.00	5.44	+2.44
6	106.31	+6.31	102.26	+2.26	3.46	+0.46	2.42	-0.58
7	68.70	-31.30	95.56	-4.44	3.49	+0.49	2.02	-0.98
8	77.59	-22.41	87.05	-12.95	2.87	-0.13	1.71	-1.29
9	62.69	-37.31	105.40	+5.40	3.29	+0.29	2.03	-0.97
10	82.61	-17.39	57.38	-42.62	2.86	-0.14	1.72	-1.28
11	67.51	-32.49	88.78	-11.22	3.35	+0.35	2.22	-0.78

12	77.54	-22.46	28.37	-71.63	2.89	-0.11	2.01	-1.40
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4.7 Stable-regime characterisation: parameter interactions and predictive modelling

The analysis in Sections 4.3 to 4.6 establishes the upper boundary of the operational window at 45 mm/s. The following analysis restricts the dataset to the stable deposition regime ($V \leq 30$ mm/s) by excluding Test 2 and Test 5 of both PLA-20 and PLA-10. The reduced dataset of 20 specimens is used to characterise parameter interactions within the usable operating window.

4.7.1 Correlation structure under fixed thermal and fixed kinematic conditions

Pearson correlation matrices were computed under two complementary boundary conditions: a kinematic regime with nozzle temperature held at 150/155 °C (zone 1/zone 2) while travel speed and rotation varied ($n = 4$ per material), and a thermal regime with travel speed held at 30 mm/s while temperature and rotation varied ($n = 8$ per material). The resulting matrices are shown in Figure 6. Because the kinematic subset is small ($n = 4$), the reported correlations are interpreted as descriptive of the data structure rather than as evidence of statistical significance. They are used here only to support qualitative interpretation of parameter effects. Three consistent patterns emerge across both materials and regimes.

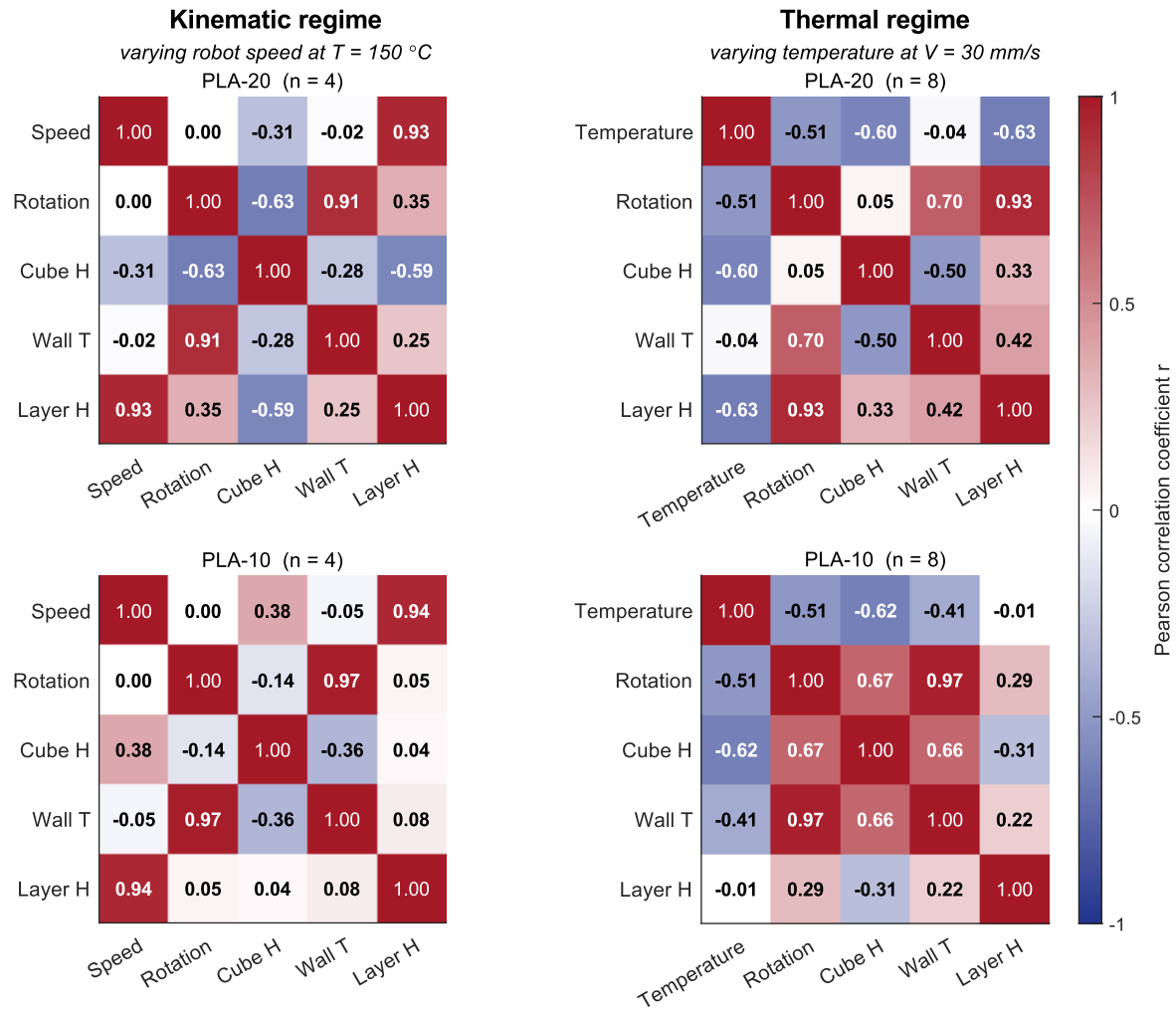


Figure 6. Pearson correlation matrices for the stable deposition regime. Top row: PLA-20. Bottom row: PLA-10. Left column: kinematic regime (varying robot speed at fixed $T = 150\text{ }^{\circ}\text{C}$, $n = 4$). Right column: thermal regime (varying nozzle temperature at fixed $V = 30\text{ mm/s}$, $n = 8$).

Dominant influence of travel speed on layer height: Within the kinematic regime, robot travel speed shows a strong positive association with layer height and negligible association with wall thickness ($n = 4$ per material; coefficients are reported as descriptive indicators rather than precise estimates). Faster robot motion within the stable range therefore produces taller per-layer beads without lateral spreading. This contrasts with the unstable 45 mm/s condition reported in Section 4.3, where simultaneous wall-thickness inflation and cube-height collapse occurred; the present correlation structure applies only to the stable regime.

Dominant influence of rotation on wall thickness: Extruder rotation shows a strong positive association with wall thickness within the kinematic regime ($n = 4$ per material), while its correlation with speed is structurally zero by experimental design. The rotation–wall thickness coupling persists in the larger thermal-regime subset ($n = 8$), where it is statistically more robust ($r = +0.70$ for PLA-20 and $+0.97$ for PLA-10), confirming that higher rotation deposits more material laterally and thickens the wall regardless of thermal condition.

Dominant influence of temperature on cube height: Within the thermal regime, nozzle temperature correlates negatively with cube height for both materials ($r = -0.60$ for PLA-20 and -0.62 for PLA-10). Correlations with wall thickness and layer height are substantially weaker ($|r| \leq 0.41$ and ≤ 0.63 , respectively, with PLA-10 layer height effectively independent of temperature at $r = -0.01$). Temperature variation within the stable speed range therefore acts primarily on vertical build success,

consistent with reduced melt viscosity at elevated temperatures lowering the load-bearing capacity of freshly deposited beads.

4.7.2 *Decoupled control axes within the stable regime*

Taken together, the correlation matrices in Figure 6 indicate that within the stable regime the three process parameters exhibit approximately separable effects on the geometric quantities: travel speed acts on layer height, rotation acts on wall thickness, and temperature acts on cube height. This is consistent with the physical mechanism of the deposition: speed determines the vertical travel per deposited bead; rotation determines the volumetric flow rate and therefore the bead width; and temperature determines the melt viscosity that controls inter-layer bonding and vertical accumulation.

The practical implication is that parameter selection within the stable regime can be approached as three independent calibration steps rather than a coupled multi-variate optimisation: temperature is set first based on the target cube height and material thermal limits, rotation is then adjusted to achieve the target wall thickness, and finally travel speed is tuned to bring the layer height as close as possible to the slicer-programmed nominal value.

4.7.3 *Thermal stability of the equilibrium cohort*

The 30 mm/s cohort allows a direct comparison of the two materials' response to nozzle temperature at matched rotation. The two materials exhibited fundamentally different thermal behaviour. At 3 rpm, PLA-10 collapsed monotonically across the temperature range, decreasing from 87.05 mm at 160 °C to 57.38 mm at 170 °C and 28.37 mm at 180 °C, a reduction of 67.4 % between 160 and 180 °C, with no stable thermal window observed at this rotation. PLA-20, in contrast, dropped from 113.35 mm at 150 °C to 77.59 mm at 160 °C and then plateaued within 77.54 to 82.61 mm across the 160 to 180 °C range, defining an upper thermal window in which dimensional outcomes are insensitive to temperature. Wall thickness data show the same pattern: PLA-20 remained within 2.86 to 2.98 mm across the four temperatures (coefficient of variation 1.9 %), while PLA-10 stayed within 1.60 to 2.03 mm, with low scatter but consistently below the 3 mm nominal.

The rotation level modulates this thermal response. At 4 rpm, PLA-10 cube height remained close to nominal across the entire range, recording 95.56 mm at 160 °C, peaking at 105.40 mm at 170 °C, and 88.78 mm at 180 °C; the catastrophic collapse seen at 3 rpm did not occur. PLA-20 at 4 rpm was consistently low across the temperature series (62.69 to 68.70 mm). The thermal sensitivity of PLA-10 is therefore a coupled effect of temperature and rotation rather than a pure thermal failure mode: at elevated temperature, reduced rotation starves the wall and triggers structural collapse, while higher rotation supplies sufficient material to preserve dimensional outcomes even at 180 °C. This material- and rate-dependent thermal response motivates the inclusion of a temperature $\times$ rotation interaction term in the predictive modelling presented in the following subsection.

4.7.4 *Empirical polynomial model*

Second-order polynomial models were fitted to the stable-regime cube-height data ($n = 10$ per material) to express the qualitative findings of Sections 4.7.1 to 4.7.3 as quantitative empirical relationships. The two materials were modelled separately, as Section 4.7.3 indicates different thermal–rotation coupling for PLA-20 and PLA-10. The base model expresses cube height H as a second-order polynomial in nozzle temperature T (°C, zone 1) and extruder rotation N (rpm):

$$H = a_0 + a_1T + a_2N + a_3T^2 + a_4N^2 \quad (7)$$

With an interaction term a_5TN added where the data justified it. Because temperature and rotation were not varied simultaneously within a full factorial design, the interaction term should be interpreted as an empirical descriptor of trends in the dataset rather than a rigorously identified interaction effect. Travel speed was excluded as a regressor because it varies only at 150/155 °C in the stable subset and is otherwise held at 30 mm/s, so its main effect is not independently estimable.

Three nested models were fitted by ordinary least squares: linear (M1), quadratic (M2), and quadratic with interaction (M3). Model selection used R^2 , adjusted R^2 (R^2_{adj}), MAPE, and AIC, with R^2_{adj} and AIC used jointly to penalise unjustified complexity. Results are summarised in Table 6.

Table 6. Goodness-of-fit metrics for nested polynomial models of cube height in the stable deposition regime ($n = 10$ per material). Preferred model for each material is shown in bold

Material	Model	R^2	R^2_{adj}	MAPE%	AIC
PLA-20	M1: linear	0.538	0.407	13.03	54.68
PLA-20	M2: quadratic	0.821	0.678	6.99	49.20
PLA-20	M3: quadratic + interaction	0.828	0.613	6.92	50.80
PLA-10	M1: linear	0.549	0.420	22.45	61.19
PLA-10	M2: quadratic	0.843	0.717	11.74	54.67
PLA-10	M3: quadratic + interaction	0.959	0.909	4.35	43.12

Given the limited dataset size ($n = 10$ per material) relative to the number of fitted coefficients, the models may be sensitive to sampling variability, and the fitted parameters should be interpreted with caution.

The two materials require different model structures. For PLA-20, the quadratic model M2 is preferred: adding the interaction term produces negligible improvement in fit (R^2 rising only from 0.821 to 0.828), reduces R^2_{adj} from 0.68 to 0.61, and increases AIC by 1.6 units. The temperature and rotation effects are therefore separable for this material.

For PLA-10, the interaction term is required: it raises R^2 from 0.843 to 0.959, raises R^2_{adj} from 0.72 to 0.91, and lowers AIC by 11.55 units. The fitted interaction coefficient is $a_5 = +2.43 \text{ mm} \cdot ^\circ\text{C}^{-1} \cdot \text{rpm}^{-1}$, indicating that higher extruder rotation counteracts the cube-height loss induced by elevated temperature: increased material supply offsets the thermal starvation that drives collapse at low rotation. This quantifies the rpm-dependent thermal collapse identified in Section 4.7.3.

The fitted equations for the selected models are:

PLA-20 (quadratic, no interaction):

$$H_{\{PLA-20\}} = 3135.27 - 35.412 T - 10.539 N + 0.1035 T^2 - 0.1505 N^2 \quad (8)$$

PLA-10 (quadratic with interaction):

$$H_{\{PLA-10\}} = 1084.85 - 2.6715T - 401.634 N - 0.0222 T^2 + 4.1156 N^2 + 2.4257 T.N \quad (9)$$

Where T is the nozzle zone 1 temperature in °C and N is the extruder rotation in rpm. The corresponding response surfaces are presented in Figure 7. The PLA-20 surface (Figure 7a) is smooth and approximately separable, with the highest cube heights confined to a narrow band at low temperature; the best observed condition was 113.35 mm at 150 °C and 4 rpm, consistent with the thermal plateau observed empirically across 160 to 180 °C. The PLA-10 surface (Figure 7b) shows a strong diagonal gradient driven by the positive interaction term: cube height is preserved along the high-rotation edge and collapses along the low-rotation edge as temperature rises, falling below 30 mm at 180 °C and 3

rpm. The best observed PLA-10 condition was 105.40 mm at 170 °C and 4 rpm, the closest result to nominal in the temperature series. Because the design is one-factor-at-a-time, the fitted surfaces are used here to characterise the direction and coupling of the parameter effects rather than to extract a numerical optimum by extrapolation; the reported optima correspond to the best experimentally observed conditions.

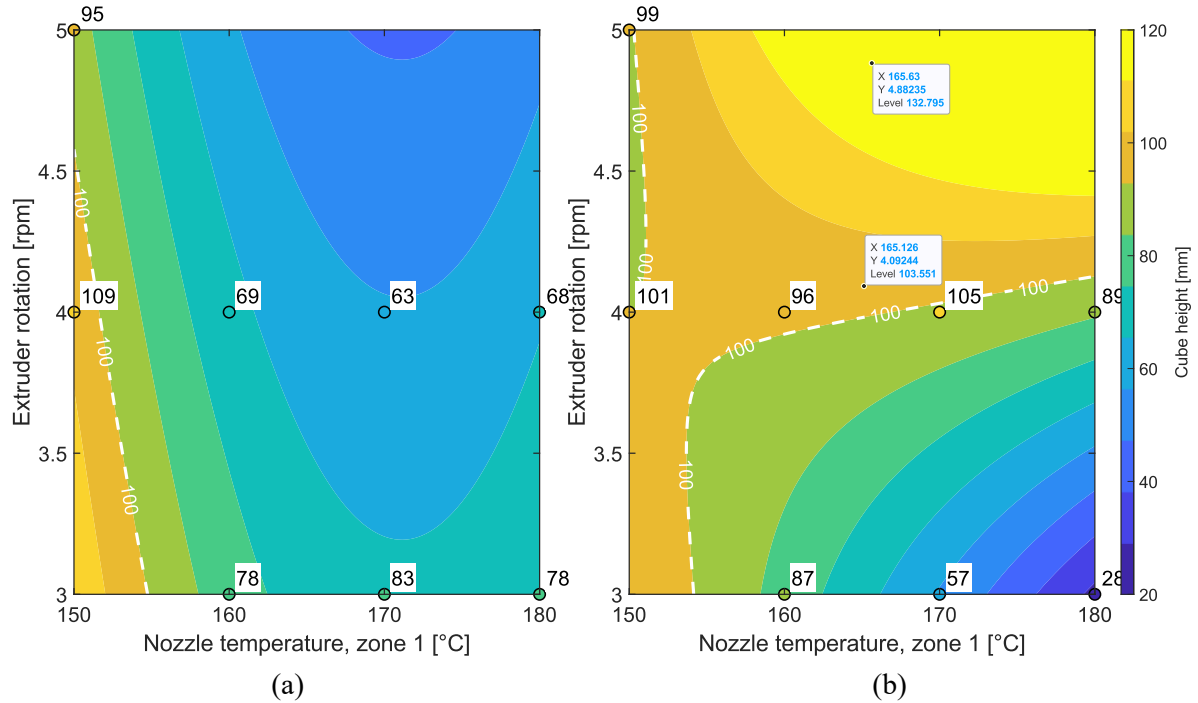


Figure 7. Polynomial response surfaces for cube height as a function of nozzle temperature (T , °C) and extruder rotation (N , rpm) in the stable deposition regime: (a) PLA-20, quadratic model without interaction (Equation 8); (b) PLA-10, quadratic model with temperature–rotation interaction (Equation 9). The white dashed contour marks the 100 mm nominal target.

The fitted models reproduce the dominant structural behaviour of the process window within the investigated parameter range: the PLA-10 model captures both the near-nominal high-rotation response and the low-rotation thermal collapse, with residuals below 9 mm at every observed condition. Although external validation outside the training dataset remains necessary, the agreement between the fitted surfaces and the observed material behaviour indicates that the models provide a useful empirical description of the parameter–accuracy relationships within the tested range, rather than a validated predictive tool.

The process regimes identified across both experimental series are summarised in Figure 8, which maps each observed condition against the cube-height accuracy thresholds defined in Table 3.

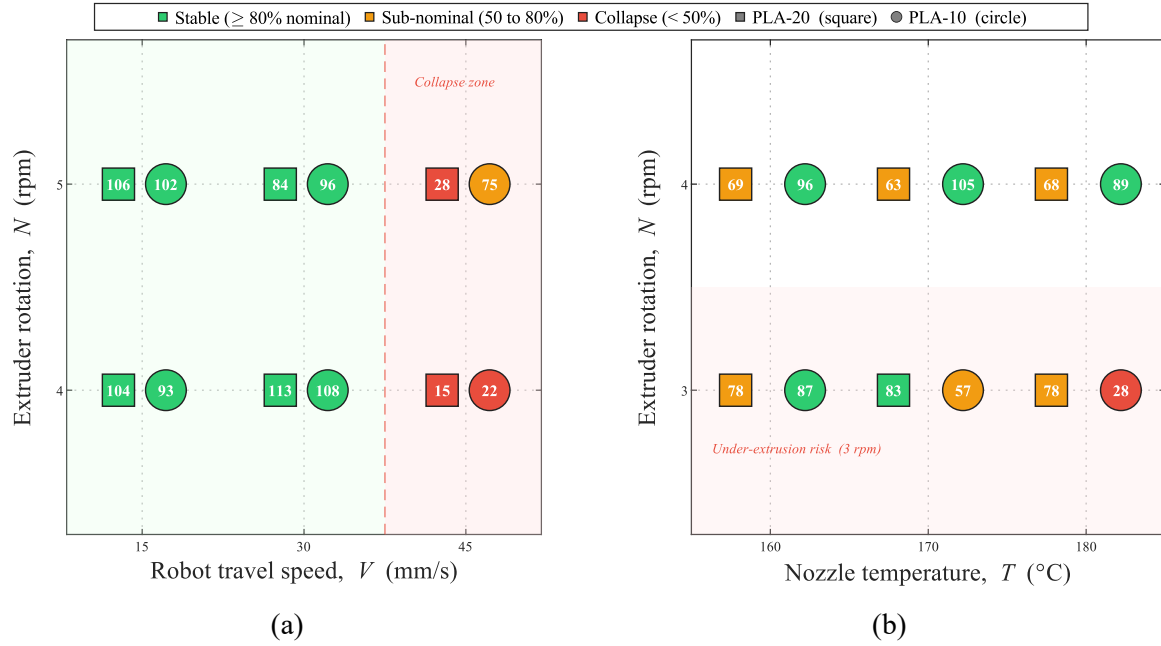


Figure 8. Process regime map for cube-height accuracy. (a) Kinematic regime at fixed nozzle temperature (150 °C), showing the under-extrusion collapse at 45 mm/s for both materials at all tested rotation speeds. (b) Thermal regime at fixed travel speed (30 mm/s).

Two limitations apply. First, the model coefficients were fitted on $n = 10$ specimens per material without external validation; the reported R^2_{adj} values therefore reflect training fit rather than out-of-sample predictive accuracy, and the one-factor-at-a-time design does not support extraction of a numerical optimum by surface extrapolation. Second, the calibration is specific to the system used here (ABB IRB 1600 with KFM Eco 3D 18 extruder) and to the cube geometry; Equations (8) and (9) are not expected to transfer to other systems without recalibration. Independent verification at the identified operating conditions and extension of the dataset using a multi-parameter design (e.g. Taguchi or response surface methodology) are identified as priorities for future work.

5. Discussion

5.1 Dominant Role of Robot Travel Speed

The 45 mm/s cube-height collapse identifies an upper boundary of the operating envelope for this material–system combination. The simultaneous wall-thickness inflation observed at the same condition (Figure 3b) confirms that the failure mode is loss of synchronisation between robot motion and material flow, in which material continues to be deposited but accumulates laterally rather than building vertically (Figure 8a). The relatively narrow window between stable behaviour at 30 mm/s and collapse at 45 mm/s reflects the heterogeneous melt behaviour of cellulose-fibre-filled PLA, which reduces the tolerance of the process to kinematic–extrusion synchronisation errors compared with filament-based systems using unfilled thermoplastics.

This observation is consistent with findings in the broader FGF and RAM literature: Csekei et al. reported that robot movement speed was the primary determinant of print quality in thin-walled robotic extrusion, with excessive speed producing wall thinning and structural discontinuity [11], and Abadi et al. similarly identified travel speed as the dominant process parameter governing dimensional outcomes in large-scale robotic polymer printing, with speed-dependent raster deformation observed above system-specific thresholds [13].

5.2 Parameter Coupling and the Limits of the Decoupled Control Structure

The decoupled correlation structure observed in Figure 6 (speed → layer height, rotation → wall thickness, temperature → cube height) is consistent with the physical degrees of freedom of the deposition process. Speed determines the vertical advance per deposited bead, rotation determines the volumetric flow rate and therefore the bead width, and temperature determines the melt viscosity that controls inter-layer bonding. Each parameter therefore acts on a distinct geometric quantity and can be tuned independently, supporting the three-step calibration procedure proposed in Section 4.7.2.

This decoupled structure is specific to the stable regime. If the full envelope is analysed including the 45 mm/s specimens, speed appears to correlate strongly with both layer height and wall thickness, but that apparent coupling is driven by the simultaneous failure modes at the boundary of the operating window and does not reflect the underlying control structure of the process within its usable regime. The distinction is methodologically important: parameter sensitivity analyses that aggregate stable and unstable regimes risk attributing control authority to parameters that, within the usable window, are actually independent.

5.3 Material-Dependent Behaviour: PLA-20 vs PLA-10

PLA-10 collapsed monotonically at low rotation (3 rpm), falling from 87.05 mm at 160 °C to 28.37 mm at 180 °C, while PLA-20 plateaued across the same range. At 180 °C, reduced rotation starved the wall and produced the most severe cube-height loss observed in the temperature series, whereas higher rotation (4 rpm) preserved near-nominal height; the collapse is therefore a coupled temperature–rotation effect rather than a pure thermal failure mode. The KCL technical data sheets give PLA-10 a melt flow index of 33 g/10 min at 190 °C / 10 kg (ISO 1133), approximately double that of PLA-20 (16 g/10 min). Combined with the lower fibre fraction (10 wt% versus 20 wt%) and the correspondingly reduced mechanical reinforcement of the melt during deposition, PLA-10 has a less viscous, less fibre-stabilised melt that is more sensitive to the volumetric feed rate. At 180 °C this sensitivity becomes critical: when the extruder rotation is low (3 rpm), the runnier melt cannot sustain a continuous, self-supporting wall, leading to progressive wall thinning, loss of inter-layer continuity, and the 67.4 % cube-height collapse between 160 and 180 °C. At 4 rpm the higher volumetric supply compensates for the low melt strength and maintains a stable wall even at 180 °C.

The collapse is rpm-dependent: at 4 rpm, PLA-10 remained at 88–105 mm across the temperature range, with no catastrophic failure. The thermal sensitivity of PLA-10 is therefore a coupled temperature–rotation effect rather than a pure thermal mode, and parameter selection for this material cannot be made on thermal grounds alone. PLA-20 retained comparable thermal stability at both rotation levels, consistent with its higher fibre fraction providing sufficient melt-strength reinforcement across the tested range.

5.4 Empirical Modelling and Per-Material Optima

The material-specific divergence in thermal–rotation coupling is captured quantitatively by the polynomial models in Section 4.7.4: PLA-20 is well described by a separable quadratic model, while PLA-10 requires a temperature–rotation interaction term whose fitted coefficient ($a_5 = +2.43 \text{ mm} \cdot ^\circ\text{C}^{-1} \cdot \text{rpm}^{-1}$) is the quantitative expression of the rotation-dependent thermal stabilisation observed empirically, higher rotation offsets the thermal starvation that collapses cube height at low rotation. The best observed conditions differ in both temperature and rotation (PLA-20: 150 °C / 4 rpm; PLA-10: 170 °C / 4 rpm), with the PLA-10 optimum sitting in a thermally elevated region of the parameter space that nonetheless requires adequate rotation to remain stable, and that would not be reached by a single processing recipe applied to both materials. Within the limits of the present dataset, the models therefore

support parameter selection as a material-specific exercise, with the expectation that further wood-based PLA grades will require their own fitted surfaces rather than transferred coefficients.

5.5 Systematic layer height deviation

Every specimen across both materials and all 24 conditions produced a layer height above the 0.5 mm nominal, with values ranging from 0.55 to 1.86 mm. Two contributions explain the systematic overshoot. The first is die swell at the nozzle exit, a known property of wood-based PLA melts that produce a deposited bead height larger than the geometric layer height programmed in the slicer. The second is the calibration offset between the commanded nozzle position and the effective deposition height of the bead in contact with the previous layer, which depends on compaction during deposition and the z-zero reference of the robotic system. The strong association of layer height with travel speed within the stable regime indicates that the overshoot is governed by kinematic control rather than by material flow rate, and that layer height calibration in pellet-based robotic systems must be addressed at the system level rather than through slicer settings alone.

6. Conclusion

This study investigated the influence of robot travel speed, extruder rotation, and nozzle temperature on the dimensional accuracy of pellet-extruded wood-based PLA composites, combining a full-envelope characterisation of 24 specimens with a stable-regime analysis of parameter interactions and predictive modelling.

Robot travel speed was the dominant parameter at the envelope level, with the 45 mm/s condition producing cube heights below 25 % of nominal and identifying the upper boundary of the operating window; the regime map provides a consolidated view of the full parameter–accuracy envelope. Within the stable regime ($V \leq 30$ mm/s), Pearson correlation analysis revealed a decoupled control structure in which speed governs layer height, rotation governs wall thickness, and temperature governs cube height ($r \approx -0.60$ to -0.62 , $n = 8$). The three parameters can therefore be tuned sequentially within the stable window through a three-step calibration procedure — set temperature to target cube height, rotation to target wall thickness, and speed to target layer height — proposed here as a transferable initialisation framework for pellet-based robotic extrusion systems, subject to recalibration for different material–machine combinations.

The two materials exhibited fundamentally different thermal sensitivities. PLA-10 at 3 rpm collapsed monotonically from 87.05 mm at 160 °C to 28.37 mm at 180 °C (a 67.4 % reduction), while at 4 rpm it remained near nominal across the same range and PLA-20 plateaued in the 160 to 180 °C range. The asymmetry is consistent with the supplier-specified melt rheology (PLA-10: MFI = 33 g/10 min, 10 wt% fibre; PLA-20: MFI = 16 g/10 min, 20 wt% fibre) and is rpm-dependent for PLA-10, with the collapse driven by wall starvation at low rotation rather than by temperature alone. Second-order polynomial models captured this behaviour, with PLA-20 well described by a separable model ($R^2_{\text{adj}} = 0.68$) and PLA-10 requiring a temperature–rotation interaction term ($R^2_{\text{adj}} = 0.91$, $a_5 = +2.43$ mm·°C⁻¹·rpm⁻¹). The best observed conditions were 150 °C / 4 rpm for PLA-20 (113.35 mm) and 170 °C / 4 rpm for PLA-10 (105.40 mm), demonstrating that parameter selection for this material class is material-specific rather than universal.

A consistent positive layer-height deviation was observed across all specimens (0.55 to 1.86 mm against the 0.5 mm nominal), correlating strongly with travel speed within the stable regime and indicating that layer-height calibration in pellet-based robotic systems is governed by kinematic control and must be addressed at the system level.

The contributions of this work are the establishment of a quantitative dimensional accuracy framework for pellet-based robotic extrusion of wood-based PLA composites; the identification of a decoupled control structure within the stable operating window, supporting independent calibration of speed, rotation, and temperature; and the demonstration that material-specific predictive models are required for parameter selection across different wood-based PLA grades.

Three limitations apply. The polynomial models were fitted on $n = 10$ specimens per material without external validation, so the reported R^2_{adj} values reflect training fit rather than out-of-sample predictive accuracy. Each parameter combination was produced as a single specimen; without replication at individual conditions, run-to-run process variability cannot be separated from measurement uncertainty, so the reported deviations characterise the overall response across the parameter space rather than the repeatability of any single condition. The calibration is specific to the system used here (ABB IRB 1600 with KFM Eco 3D 18 extruder) and to the cube geometry, and the fitted coefficients are not expected to transfer to other systems without recalibration.

Future work should prioritise two directions. First, external validation of the polynomial models under the identified operating conditions, using a small number of additional specimens, would establish whether the fitted surfaces generalise beyond the training data. Second, extending the experimental programme to a multi-parameter design, such as a Taguchi array or a central composite design within the stable regime, would enable estimation of interaction effects that the OFAT framework cannot resolve and would support optimisation across the full stable parameter space. Extension to more complex deposition geometries, including parts with sharp corners and variable toolpath curvature, would also test the transferability of the decoupled control framework beyond the cube geometry used here.

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CRedit authorship contributions statement

Osama A. Q. Ziada: Conceptualisation, Data curation, Investigation, Methodology, Software, Visualisation, Writing – original draft, Writing – review & editing; **Ares A Gomez-Gallegos:** Investigation, Methodology, Visualisation, Writing – review & editing, and Supervision.

Generative Artificial Intelligence (AI) Disclosure Statement

The AI tools Grammarly, ChatGPT (OpenAI), and Claude (Anthropic) were used to improve the manuscript's language and structure. The authors independently conducted all literature review, scientific analysis, data interpretation, and conclusions, and verified all content before inclusion.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data supporting the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.20784513>, under a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.

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Consent to participate: Not applicable.

Consent for publication: Not applicable.

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