

Equation to Grain

TPMS in Wood 3D Printing

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Abstract. *This paper presents a fabrication-aware parametric workflow for printing Triply Periodic Minimal Surfaces (TPMS) at architectural scale using wood-paste Liquid Deposition Modeling (LDM). Unlike thermoplastics or concrete, wood paste remains plastic for hours, meaning each deposited layer must support subsequent layers while still yielding. The unsupported spans, tight curvatures, and cumulative self-weight inherent to TPMS toolpaths exceed the paste's fresh-state capacity under conventional slicing, defining a gap between computational TPMS design and physical realization in these materials. The workflow derives material limits from empirical primitive-geometry tests and embeds them in a feed-forward pipeline that evaluates toolpath points against paste-specific failure thresholds. It then addresses the detected conflicts by adjusting per-point velocity, flow, and seam placement while preserving the designed geometry. Across twelve TPMS configurations, it consistently reduced critical failure points and improved printability across varying types, scales, and bounding shapes. Physical validation confirmed that a geometry that collapsed under standard slicing printed successfully. The approach is further demonstrated through a 1.7-meter column of eight printed TPMS segments.*

Keywords. Wood Additive Manufacturing, Triply Periodic Minimal Surfaces, Toolpath Design, Biobased Materials, Computational design.

INTRODUCTION

Fabrication-aware computational approaches increasingly position material behavior, structural logic, and manufacturing constraints as co-productive drivers of architectural form (Brescghello and Naboni, 2022). In parallel, circular construction frameworks call for building systems that maximize resource efficiency through geometry-enabled material reduction (Heisel and Hebel, 2022). Yet applying performance-oriented morphologies at buildable scale remains constrained by construction logics that favor standardized, planar assemblies. The construction sector accounts for approximately 37% of global energy-related CO₂

emissions (UNEP, 2024), driving interest in bio-based material systems. Wood-waste biocomposites processed through Liquid Deposition Modeling (LDM) can incorporate biomass content exceeding 80%, preserving the hygroscopic, acoustic, and thermal properties of the base material (Rosenthal et al., 2018), and recent work confirms their viability as functional building components (Jain et al., 2025; Cohen and Barath, 2025). However, wood-paste LDM introduces a central fabrication challenge: the paste remains in a plastic state for hours, unlike thermoplastic cooling or cement hydration which occur in seconds to minutes, meaning each deposited layer must support the cumulative

load of subsequent layers while still yielding. Printing architecturally complex geometries in such materials therefore demands forms whose curvature and connectivity promote fresh-state stability without relying on support structures or rapid solidification. Triply Periodic Minimal Surfaces (TPMS), a class of doubly-curved surfaces with zero mean curvature, offer a promising geometric framework for this challenge (Feng et al., 2022). Unlike strut-based lattices, which concentrate stress at nodes and are vulnerable in brittle biocomposites, TPMS distribute loads continuously across smooth, doubly-curved membranes, providing simultaneous structural, thermal, and acoustic functionality through their bicontinuous pore networks. At the scale of architectural components, TPMS geometries become spatially operative: their high surface area, continuous porosity, and doubly-curved walls allow them to serve as lightweight partitions, acoustic panels, or thermally active facade modules (Al-Ketan and Abu Al-Rub, 2019). Combining these geometries with wood-based LDM may amplify such performance by leveraging the inherent properties of the wood matrix across the TPMS surface. This performance, however, comes at a fabrication cost. The same doubly-curved walls that distribute loads in the cured component produce demanding toolpath conditions during printing: near-horizontal dome closures at the unit cell apex act as large overhangs, tight curvature transitions induce extruder wobble, and tall thin-walled segments accumulate self-weight before the paste recovers strength. Prior efforts to print TPMS beyond the laboratory have relied largely on concrete (Yu et al., 2025) and ceramic (Jonnalagedda, 2023) systems, whose rapid setting sidesteps the sustained fresh-state instability inherent to wood paste. Realizing TPMS in a slow-curing wood-based paste therefore exposes precisely the overhang, curvature, and buckling failures that fast-solidifying materials avoid. Within parametric design environments, several tools address related fabrication problems. Ovenbird (Zhi et al., 2025) provides per-point

overhang analysis, topology-aware continuous toolpath planning, and buildability optimization for extrusion-based 3D printing, with demonstrated application to TPMS geometries. Karamba3D provides finite element structural validation, and has been applied to fresh-state analysis in 3D concrete printing (3DCP). Breseghello and Naboni (2022) demonstrated that per-point speed modulation in robotic 3DCP can control local material deposition for stress-optimized geometries. These tools provide powerful capabilities for diagnosing buildability and optimizing the geometry and toolpath topology of a print. The present work extends this chain by addressing the fabrication parameters: optimizing per-point velocity, flow rate, and seam placement to accommodate the behavior of the wet paste during deposition, while preserving the designed geometry. The gap between computational TPMS design and physical realization at architectural scale in bio-based paste materials defines this research space. To address it, the proposed workflow derives material limits from empirical primitive-geometry tests, embeds them into a feed-forward slicing and toolpath pipeline, and generates G-code that resolves fabrication conflicts before execution while quantifying the resulting printability improvement. The approach is validated on twelve digital TPMS models spanning three types, scales, and bounding shapes, then confirmed by a physical print and a 1.7-meter column demonstrator.

METHODOLOGY

Building on the buildability characterization approach established by Wolfs and Suiker (2019), where simple geometric forms are printed to failure to derive material-specific thresholds, the present work adapts this methodology to the failure modes of viscous paste extrusion. The resulting empirical constraints are embedded directly into a feed-forward slicing and toolpath pipeline, structured as the five-step process described below. The entire pipeline was implemented as a set of custom C# components in the Rhino 8 Script

Editor for Rhinoceros 3D; no third-party slicing or analysis plug-ins were used. The workflow processes each TPMS model through two parallel evaluation paths (Figure 1). In the baseline path (Eval B), the mesh is sliced using standard planar Z-contours and analyzed with constant printing parameters, establishing a reference risk profile. In the optimized path (Eval C), the mesh passes through five sequential steps: (1) a geodesic slicing engine with collision-aware mixing; (2) a custom seam optimizer that places seams on supported interior surfaces; (3) geometric and structural risk analysis; (4) a strategy merger combining physics-aware seam refinement with three-priority speed and flow synthesis; and (5) a G-code generator producing the final machine instructions. Both paths share the same risk analysis components, ensuring that improvements are attributable to the pipeline rather than to differences in evaluation methodology. An improvement evaluator compares the two paths across multiple risk thresholds.

Material system and fabrication setup

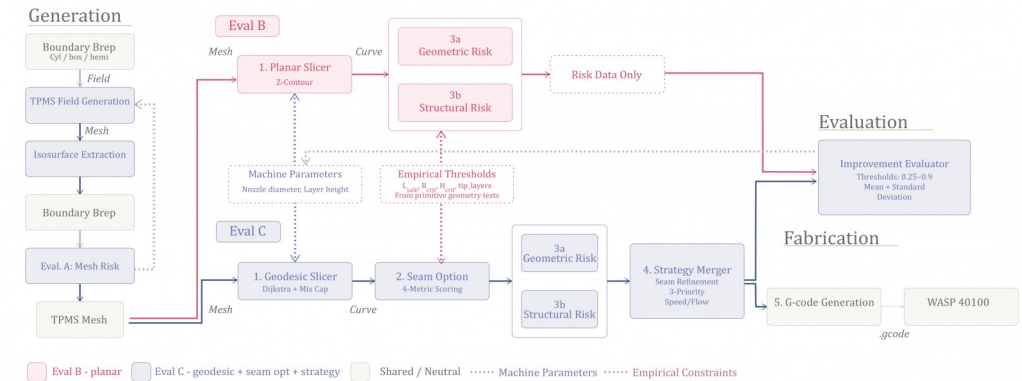
All experiments were conducted on a WASP 40100 delta printer (build volume Ø400 mm by 1000 mm height) equipped with an LDM extruder and an 8 mm nozzle. Layer heights ranged from 2.5 to 4 mm, and print speeds were maintained around 15 mm/s

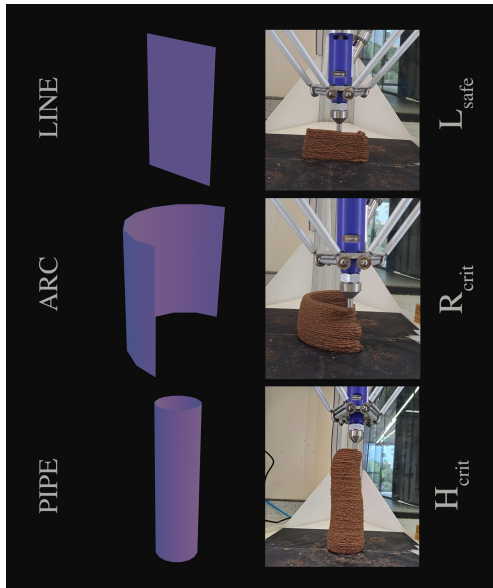
with a working range of 10 to 20 mm/s adjusted according to local bridging and curvature conditions. The paste formulation consists of 66.5% water, 12% carboxymethyl cellulose (CMC), and 21.5% sawdust by weight, based on Cohen and Barath (2025). The sawdust is a multi-species blend of 37% pine wood, 45% oak wood, and 18% pine bark, sourced from local industrial wood-processing waste. A single formulation was used consistently across all stages, from primitive calibration tests through digital evaluation to the final architectural demonstrator, ensuring that empirically derived rules remain valid throughout the workflow. The material exhibits approximately 15% volumetric shrinkage upon drying; however, print failures in this study occurred during wet deposition rather than drying, confirming that fresh-state stability is the governing constraint for TPMS printability in wood-paste LDM.

Empirical heuristic derivation

Three primitive geometry tests were conducted in which isolated forms were printed to the point of failure, identifying threshold values specific to the wood-paste formulation (Figure 2). Each test was performed at three sizes with three repetitions per size. The line test (straight bridging) printed incrementally longer unsupported spans at three lengths (50, 100, 150 mm) to determine the Safe

Figure 1

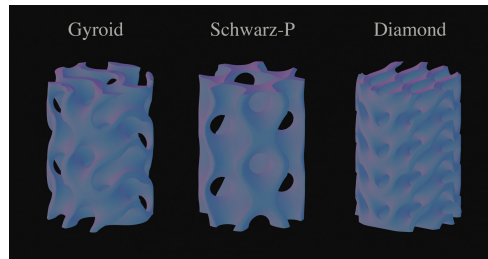




Length (L_{safe}): the maximum distance the wet paste can sustain before gravity causes collapse. This threshold dictates when the machine must accelerate to pull the bead taut across a gap. The arc test (constant curvature) printed arcs at three radii (40, 80, 120 mm) to establish the Critical Radius (R_{crit}): the threshold below which the extruder's mass induces mechanical resonance and wobble in the deposited bead, validated under dynamic curvature conditions using variable-curvature paths. Below R_{crit} , the machine sprints through the curve rather than decelerating. The pipe test (vertical stacking) printed cylindrical pipes at three diameters (15, 25, 40 mm) to measure the Critical Height (H_{crit}) for buckling onset under self-weight and the Maximum Step-Over (Δx_{max}) as a fraction of nozzle width, replacing the conventional 45-degree overhang rule with a paste-specific horizontal limit. The specific threshold values are reported in the Results section and serve as inputs to the risk analyzers in Step 3.

Experiment design

TPMS geometries were generated by a custom C# component that evaluates the implicit level-set functions of the three types (Gyroid, Schwarz-P, Diamond) within user-defined bounding volumes in Rhinoceros 3D, producing meshes representing the sheet-based TPMS topology at the specified unit cell size, isovalue, and shell thickness. This study generated twelve TPMS configurations organized in two sets. The core set comprises nine cylindrical models: three TPMS types (Gyroid, Schwarz-P, Diamond; Figure 3) at three scales ($\varnothing 150$, $\varnothing 250$, and $\varnothing 370$ mm), providing a controlled comparison



isolating the effect of scale on printability for each type. A generalization set of three additional models tests the Schwarz-P type at the largest scale ($\varnothing 370$ mm) in three different global shapes: box, chamfered truncated pyramid, and sine-wave box (a rectangular volume whose vertical edges follow a sinusoidal profile with two amplitudes, producing continuously varying cross-sections at each layer height), demonstrating that the workflow is not geometry-specific. Across all twelve models, unit cell size (2 mm), isovalue ($c = 0$), and shell thickness (1.5 mm) were held constant, so that global scale remains the sole independent variable in the core set. As described above, the three scale variants were generated through uniform geometric scaling from a single master mesh per TPMS type, deliberately preserving topological identity across scales so that observed differences in printability can

Figure 2
Primitive geometry tests for empirical threshold derivation. Line test (L_{safe}), arc test (R_{crit}), and pipe test (H_{crit})

Figure 3
Three TPMS types investigated: Gyroid, Schwarz-P, and Diamond, shown as sheet-based topologies.

be attributed to the increasing severity of toolpath conditions rather than to parameter variation.

Step 1- Slicing engine

The slicing engine processes the TPMS mesh through a hybrid planar-geodesic slicing approach informed by recent work on curvature-aware path planning for non-planar 3D printing of doubly-curved surfaces (Mitropoulou et al., 2025). The component constructs a geodesic distance field on the mesh by propagating distances from the bottom vertices using Dijkstra's algorithm (Chen et al., 2022), then blends this field with the standard Z-height field according to a user-defined mixing ratio. A mixing ratio of zero produces purely planar Z-contours; increasing the ratio shifts contours toward geodesic paths that follow the surface curvature of the TPMS walls. Critically, the component analyzes the maximum geodesic slope on the mesh relative to the physical nozzle geometry (nozzle height, tip diameter, and top diameter) and computes a safe mixing cap. The limiting slope is the ratio of the nozzle height to its horizontal clearance per side, taken as half the difference between the top and tip diameters, so that a steeper geodesic contour would drive the widening nozzle body into the previously deposited material; the cap is this limit divided by the steepest slope present on the mesh, with a safety margin applied. If the user-specified ratio exceeds what the geometry can physically support without nozzle collision, the engine clamps it to the safe limit. Contour curves are then extracted from the blended field at the target layer height interval, joined, and optionally smoothed. The output is a data tree of curves organized by layer index, preserving the field ordering required for downstream G-code generation.

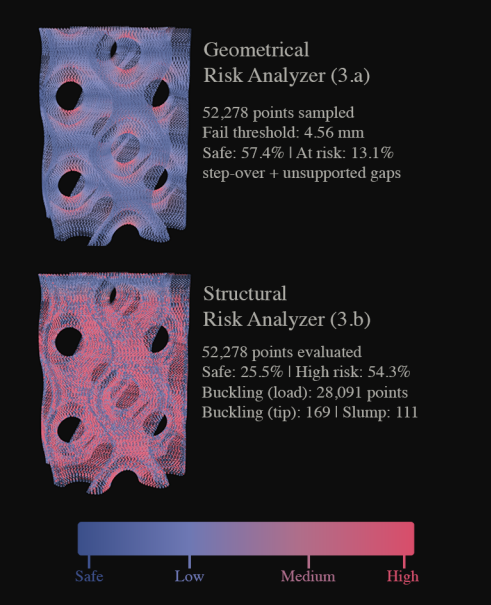
Step 2: Curve sequencing and seam management

The sliced curves are then processed through a custom seam optimizer developed for this workflow. For each closed loop, the component samples

candidate start points around the curve and evaluates them against the supporting curve in the layer below. It first retains only the candidates whose step-over to that support stays within the safe limit, then, among these, selects the point closest to the model interior, placing the seam on an inner surface where it is least visible. When no candidate is sufficiently supported, the safest available point is chosen instead. Open curves pass through unchanged. This geometric placement is later refined by the strategy merger in Step 4, once risk data becomes available.

Step 3: Geometric and structural risk analysis

The curves from Step 2 are passed into two parallel analysis branches that evaluate fundamentally different categories of risk (Figure 4). The analysis resolution is controlled by a density parameter relative to nozzle width: at 100% resolution, sampling points are spaced one nozzle-width apart; at 200%, spacing halves for finer evaluation. The geometric risk branch (Step 3a) evaluates every sampled point by searching backwards through previous layers to find the nearest support point within a valid Z-range. The horizontal distance between the current point and its closest support is measured and normalized against a failure threshold set at 95% of nozzle width. Points with no support within the search window receive a maximum risk score of 1.0. The output is a per-point risk value between 0 and 1, visualized as a color gradient from safe (blue) through medium (pink) to high risk (red). The structural risk branch (Step 3b) evaluates the same point set using a U-shaped buckling model that captures two distinct failure zones. Load risk models the accumulated weight of material above a given point, which compresses lower wall segments; it is computed as the height of material above the point relative to a critical height derived from the pipe tests. Tip risk models the instability of the topmost fresh layers, which have not yet recovered thixotropic strength; it decays



exponentially from the print surface downward over a configurable number of fresh layers. Both risks are modulated by a curvature-based stiffness factor: tighter local curvature provides greater lateral rigidity, mitigating both failure modes, while flat, straight wall segments are most vulnerable. The combined buckling risk is the maximum of load and tip risks, multiplied by one minus the stiffness score. Slump risk is evaluated separately, assessing whether the total curve length falls below the Safe Length threshold (L_{safe}). The final structural risk at each point is the maximum of slump and buckling scores.

Step 4: Strategy synthesis

Step 4 performs two sequential operations. First, a physics-aware seam refinement re-evaluates the start points assigned in Step 2 using the now-available risk data. For closed loops, it computes a composite score at every point, weighting gap risk five times higher than structural risk,

and rotates the seam to the point with the lowest score. For open curves, it compares the composite risk at both endpoints and reverses the path direction if the far end is safer, ensuring that extrusion always begins at the most stable location. Second, the merger translates the risk scores into per-point machine instructions through a three-priority override system, as summarized in Table 1. Each point is flagged as normal, wobble-corrected, or bridge-corrected, providing diagnostic transparency. The output is a set of seam-optimized point trees with per-point speed and flow multiplier trees passed to Step 5.

Struct. risk	Geo. risk	Speed	Flow	Flag
Low	Low	Base	Base	Normal
Low	High	Sprint	Max increase	Bridge
High	Low	Decrease	Base	Normal
High	High	Sprint (override)	Max increase	Bridge

*Anti-wobble override applies at any risk level if local radius < R_{crit} .

Step 5: G-code generation

The final step receives the optimized point trees, dynamic speed trees, and flow multiplier trees and generates machine-readable G-code through a custom post-processor. The engine operates in relative extrusion mode, computing the extrusion value for each segment as the product of segment length, a base extrusion rate derived from nozzle diameter and layer height, and the per-point flow multiplier from Step 4. A dual-threshold check distinguishes open C-shaped curves from closed loops: a curve is treated as a closed loop only when the gap between its start and end points is smaller than both three times the nozzle diameter (absolute limit) and 25% of the total curve length (relative limit). This prevents long open curves with coincidentally close endpoints from being misidentified as loops. Closed loops receive a forced closure move across the gap followed by a configurable seam overlap that extrudes past the start point, eliminating visible seam

Figure 4
Dual risk analysis on a Schwarz-P cylinder: geometric step-over risk (3a) and structural buckling risk (3b).

Table 1
Strategy synthesis decision matrix

artifacts. Open curves receive standard start and stop sequences with retraction. The post-processor handles travel moves with Z-hop clearance, generates the complete G-code header and footer, and exports the final file ready for fabrication.

Enhancement evaluation

The improvement evaluator receives the risk data from both Eval B (baseline) and Eval C (optimized) paths and performs a multi-threshold comparison. Rather than evaluating at a single risk cutoff, the component automatically analyzes at five thresholds (0.25, 0.4, 0.6, 0.8, 0.9), computing the percentage of risk points eliminated at each level. It reports the mean improvement and standard deviation across all thresholds, providing a measure of both magnitude and consistency. A sensitivity classification (low, moderate, or high) indicates whether the improvement is threshold-dependent. At the primary threshold (0.8), the evaluator breaks down results into three categories: resolved points (high risk in baseline, low in optimized), validated points (already safe in both), and remaining points (still at risk after optimization). The evaluator further decomposes the total improvement into contributions from slicing strategy (geodesic versus planar) versus machine parameter adaptation (speed and flow overrides), enabling direct reporting of which stage of the pipeline delivers the greater benefit. These results are reported in the following section.

RESULTS

Empirical heuristic constants

The primitive geometry tests yielded four empirical constants for the 8 mm nozzle and the wood-paste formulation. The Safe Length (L_{safe}) was approximately 150 mm, the Critical Radius (R_{crit}) approximately 60 mm, the Critical Height (H_{crit}) approximately 58 mm, and the Maximum Step-Over less than 0.5 times the nozzle diameter. These values confirmed that for viscous paste materials, horizontal

offset rather than overhang angle governs failure. These empirically derived constants served as the quantitative inputs to the geometric and structural risk analyzers described in the methodology.

Digital printability evaluation

The twelve digital models were evaluated using the two-path architecture described in the Methodology. Each model was processed through Eval B (planar slicing, constant parameters) and Eval C (geodesic slicing, seam optimization, strategy synthesis), and the improvement evaluator compared the results across five risk thresholds (0.25 to 0.9). Table 2 summarizes the results for the nine-model core set and the three-model generalization set.

Table 2
Digital printability
evaluation results

Type	Boundary	Ø (mm)	Baseline risk %	Risk after workflow %	Total improvement
Core set (9 cylindrical models)					
Gyroid	Cylinder	150	22.6	11.3	+9.2
Gyroid	Cylinder	250	35.8	4.8	+21.6
Gyroid	Cylinder	370	47.0	3.0	+29.1
Schwarz-P	Cylinder	150	25.2	12.0	+10.6
Schwarz-P	Cylinder	250	40.6	4.6	+24.4
Schwarz-P	Cylinder	370	52.2	3.0	+32.3
Diamond	Cylinder	150	22.5	11.0	+8.3
Diamond	Cylinder	250	30.7	4.3	+18.9
Diamond	Cylinder	370	40.7	2.8	+25.6
Generalization set (Schwarz-P Ø370 mm)					
Schwarz-P	Box	370	70.5	2.4	+43.1
Schwarz-P	Ch. Pyramid	370	64.2	3.7	+39.7
Schwarz-P	Sine-wave box	370	34.0	3.3	+21.9

Baseline failure rates increased consistently with scale across all TPMS types, confirming that larger models produce more severe toolpath conditions under standard slicing. Schwarz-P exhibited the highest baseline risk at every scale due to its near-horizontal dome closures, while Diamond produced the lowest, benefiting from nodal geometry that distributes overhangs more evenly. The full pipeline delivered greater improvement where baseline risk was more

severe, ranging from +8.3% (Diamond Ø150) to +32.3% (Schwarz-P Ø370), and up to +43.1% for the box-bounded generalization model. After optimization, final printability scores converged to a narrow range (53.8 to 60.8) despite baselines as disparate as 17.6 and 50.8, indicating that the integrated pipeline acts as an equalizer across types, scales, and bounding shapes.

Physical validation and architectural demonstrator

A Schwarz-P cylinder (Ø370 mm, height 273.6 mm) was selected for physical validation for its high baseline failure rate (30.1% at threshold 0.8), with structural failures accounting for 88% of all risk points. The model was first printed using standard planar slicing at constant speed (14.2 mm/s) and flow (Eval B condition). It failed at roughly 30% completion through buckling on tall wall segments, bridging collapse at dome closures, bead tearing at tight curvature zones, and repeated nozzle-tip collisions during travel moves without Z-hop clearance. These modes are characteristic of the wood paste: the dominance of structural over geometric risk indicates that self-weight buckling during the material's prolonged plastic phase, rather than instantaneous collapse, governed failure. The same model was reprinted using the full Eval C pipeline (geodesic slicing at mix 0.10, seam

optimization, and strategy synthesis). The merger modified 82.7% of toolpath points for speed and 96.8% for flow, applied 626 bridging overrides and 440 anti-wobble corrections, and relocated 318 seams to lower-risk zones. Speed ranged from 7.1 to 14.2 mm/s, with flow compensation up to 1.5× at bridging zones to counter sagging of the wet bead under the paste's slow structural recovery. This print completed successfully, achieving a final printability score of 61.4 (up from 44.5 baseline) with remaining critical points reduced to 2.9% (Figure 5).The workflow was then applied to a 1.7-meter Schwarz-P column demonstrator (Ø370 mm) of eight segments, each processed through the full pipeline (Figure 6). The column features a gradient unit cell frequency, with denser pores at the base opening toward the top, exercising the

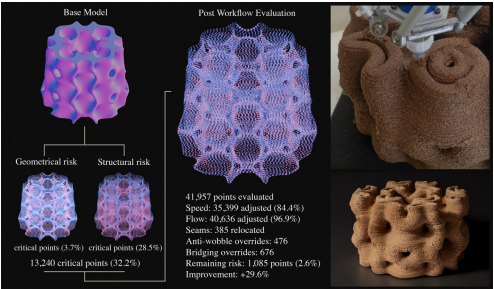


Figure 5
Schwarz-P
(Ø370mm) physical
validation: baseline
risk analysis,
post-pipeline
evaluation, and
fabrication result.



Figure 6
Columndemonstrator:
1.7-meter
Schwarz-P column
(Ø370 mm)
composed of eight
segments with
gradient unit cell
frequency. Left:
digital model
segment. Center:
LDM printing.
Right: assembled
column over pine
log base.

pipeline across varying conditions within a single element. The segments are suspended on four steel wire ropes, with cable clamps and washer discs as spacers. The assembly is mounted above a natural pine log base, linking the raw biomass source to the computationally processed biocomposite.

DISCUSSION AND CONCLUSION

This work demonstrates that TPMS geometries at architectural scale produce toolpath conditions that systematically exceed the fresh-state capacity of wood-paste LDM, and that per-point machine parameter adaptation can address the majority of these conflicts while preserving the designed geometry. The integrated pipeline acted as an equalizer across the twelve evaluated models, converging printability scores to a consistent range regardless of TPMS type, scale, or bounding shape. The physical validation provided direct confirmation: the same Schwarz-P geometry that collapsed under standard slicing printed successfully with the full pipeline, and the 1.7-meter column demonstrator extended this result to architectural scale across varying geometric conditions. These outcomes are specific to the slow-recovering wood paste: because the material stays plastic for hours, the governing failure mode was cumulative self-weight buckling rather than the rapid collapse seen in fast-setting systems, which is why per-point speed and flow adaptation, rather than slicing geometry alone, accounted for the improvement. The workflow contributes a fabrication parameter optimization layer that can be chained alongside existing design-to-fabrication tools. The pipeline itself was built entirely from custom C# components and does not depend on third-party plug-ins. Related tools nonetheless address complementary stages: within the Grasshopper environment, Ovenbird (Zhi et al., 2025) optimizes geometry and toolpath topology, while Karamba3D provides structural validation through finite element simulation. The present pipeline completes this chain by translating an optimized geometry into per-point velocity,

flow, and seam instructions that accommodate the rheological behavior of the wet paste. Although demonstrated on TPMS, the workflow is formulated around general geometry-process relationships rather than TPMS-specific rules. The step-over metric, bridging-span limit, cumulative-load model, and seam logic apply equally to any complex geometry intended for paste-based LDM at architectural scale. The empirical heuristic derivation is likewise transferable to other materials: by repeating the primitive geometry tests with a different paste formulation or nozzle size, the workflow can be recalibrated for a new material system without modifying the pipeline architecture. Further research could develop TPMS-specific fabrication rules that relate unit cell parameters directly to printability thresholds, potentially enabling predictive assessment before slicing. Additional directions include extending the pipeline to other bio-based material systems and larger-scale robotic platforms, as well as characterizing the structural, acoustic, and thermal performance of printed TPMS components. By enabling the reliable fabrication of complex, high-surface-area geometries in waste-derived biocomposites, this work contributes toward realizing computationally designed and environmentally responsive architecture through additive manufacturing with bio-based materials.

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