

Parametric Experimental and Numerical Optimization of 3D Concrete Printing for Enhanced Efficiency in Modular Construction Systems

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Abstract

Three-dimensional concrete printing (3DCP) is an emerging construction technology that integrates digital fabrication, automation, and modular construction to improve productivity, reduce material waste, and address labor shortages. However, its application remains limited due to insufficient understanding of the relationship between process parameters, construction efficiency, and structural performance. This study develops and evaluates a parametric framework linking key 3DCP variables to modular construction performance. An experimental–numerical approach was used to assess the effects of printing speed, layer height, nozzle diameter, fiber content, and mix design on buildability, dimensional accuracy, surface quality, compressive strength, interlayer bond strength, material waste, and construction efficiency. Statistical analyses, including ANOVA, response surface methodology, and multi-objective optimization, were employed to identify optimal parameter ranges. Results indicate that 3DCP performance depends strongly on the interaction between material rheology and printing parameters. Optimal performance was achieved at printing speeds of 75–100 mm/s, layer heights of 10–12 mm, nozzle diameters of approximately 20 mm, and fiber content of around 0.5%, resulting in improved extrusion stability, dimensional accuracy, and interlayer bonding. Interlayer bonding was identified as the key factor affecting structural integrity and collapse resistance. Optimized parameter settings reduced construction time by 40–60% and material waste by up to 45% compared with conventional methods. Nevertheless, trade-offs between extrudability and mechanical performance were observed, particularly due to variations in fiber content and deposition intervals. The findings highlight the importance of integrated optimization of material composition and process parameters to support future adaptive and digital twin-based modular construction systems.

KEYWORDS

3D concrete printing; modular construction; process optimization; buildability; interlayer bonding; construction efficiency; digital fabrication

Introduction

The global construction industry is currently experiencing profound technological transformation driven by the urgent need to improve productivity, reduce labor dependency, and increase sustainability performance. Conventional construction methods remain heavily dependent on labor-intensive practices, prolonged project durations, and excessive material consumption, all of which limit efficiency in rapidly urbanizing regions. These challenges have accelerated the adoption of digital construction technologies aligned with Industry 4.0 principles, including building information

modeling (BIM), robotics, additive manufacturing, and digital twin systems. Among these technologies, three-dimensional concrete printing (3DCP) has emerged as one of the most promising innovations due to its capability to automate fabrication processes, eliminate formwork, reduce material waste, and enable unprecedented geometric flexibility in structural production (Sepasgozar et al., 2020; Statsenko et al., 2022; Wang et al., 2023).

The increasing relevance of 3DCP is strongly associated with its compatibility with modular construction systems. Modular construction offers substantial benefits in terms of repeatability, quality control, shortened schedules, and off-site manufacturing efficiency. Recent technological developments have introduced robotic-arm, gantry-based, and portal-type 3D printing systems capable of producing modular concrete units for prefabricated assembly. Gantry-based systems, in particular, have demonstrated strong suitability for large-scale modular fabrication because of their dimensional consistency and scalability (Rennen et al., 2021). Furthermore, integration of BIM-driven digital workflows and generative design algorithms has enabled coordinated production chains linking design automation directly to robotic fabrication and modular assembly operations.

Digital automation addresses one of the most critical problems in modern construction industries: labor shortages and declining workforce productivity. Automated construction systems reduce dependence on physically demanding manual tasks while improving repeatability and minimizing human error. Robotic fabrication systems integrated with digital design models can continuously execute printing operations with minimal interruption, increasing throughput and consistency while enhancing workplace safety (Herrmann et al., 2018; Tankova & Silva, 2020). In addition, digital twin frameworks now enable real-time process monitoring and closed-loop optimization, allowing predictive adjustment of printing parameters during fabrication to improve quality assurance and production efficiency.

Despite these advancements, practical industrial implementation of 3DCP remains constrained by multiple technical and operational limitations. One major challenge is the difficulty of maintaining stable printability and buildability during large-scale printing operations. The process requires careful balancing of pumpability, extrudability, open time, and structural build-up rate to ensure dimensional stability and avoid progressive deformation or collapse during multi-layer deposition (Jipa & Dillenburger, 2022; Pasco et al., 2022). These constraints become increasingly complex when printing modular geometries requiring tight dimensional tolerances for assembly compatibility.

Another major limitation concerns material-process interaction. Printable cementitious composites must satisfy contradictory rheological demands: sufficiently fluid for extrusion while stiff enough to support subsequent layers without excessive deformation. Recent studies have explored optimization of admixtures, viscosity modifiers, silica fume content, and fiber reinforcement to improve rheological stability and interlayer cohesion. However, material optimization alone is insufficient if process parameters such as print speed, layer height, nozzle diameter, and deposition interval are not simultaneously optimized.

Existing literature has extensively examined isolated aspects of 3DCP, particularly fresh-state rheology, extrusion mechanics, and printability characterization.

Numerous studies quantify pumpability and extrusion continuity under controlled laboratory conditions, while others focus on mechanical strength development or interlayer bonding performance. Although these studies provide valuable insights, they rarely establish direct quantitative relationships between process parameter combinations and modular construction efficiency metrics such as fabrication time reduction, dimensional accuracy, and material waste minimization (Guamán-Rivera et al., 2022; Leschok et al., 2024).

The emerging trend toward modularized additive construction further highlights this research gap. Modular 3DCP introduces new performance requirements involving dimensional precision, interface compatibility, and production repeatability across multiple units. While architectural-scale demonstrations such as printed shell modules and prefabricated housing components confirm technical feasibility (Su et al., 2023), systematic experimental evaluation of process-variable interactions within modular construction contexts remains limited. In particular, few studies integrate mechanical performance evaluation with practical construction-efficiency metrics under experimentally controlled parametric variation.

Furthermore, current optimization frameworks remain fragmented. Digital production concepts integrating BIM, robotics, and additive manufacturing have been proposed conceptually, yet practical parameter-level optimization frameworks capable of guiding real fabrication decisions are still underdeveloped. Standardization challenges, absence of unified performance metrics, and insufficient comparative benchmarking hinder industrial scalability and broader adoption across construction markets (Singh et al., 2023).

This study addresses these limitations through a comprehensive experimental investigation of critical 3DCP process parameters affecting modular construction efficiency. The research systematically evaluates the effects of printing speed, layer height, nozzle diameter, and fiber dosage on buildability index, dimensional accuracy, interlayer bond strength, compressive strength, surface quality, and construction efficiency metrics. Unlike prior studies that focus primarily on isolated material or mechanical properties, this work establishes integrated quantitative relationships linking process control directly to modular fabrication performance.

The novelty of this research lies in the development of an experimentally validated process-performance framework for modular 3D concrete printing that simultaneously considers structural integrity and production efficiency. By identifying optimized process windows suitable for scalable modular fabrication, this study contributes practical implementation guidance for industrial deployment of 3DCP technologies, particularly within emerging construction markets such as Indonesia where labor efficiency, rapid housing delivery, and sustainable infrastructure development remain pressing priorities.

Methods

Research Design

This study employed a parametric experimental methodology to investigate the influence of critical three-dimensional concrete printing (3DCP) process variables on modular construction efficiency. The research framework was designed to establish quantitative relationships between printing speed, layer height, nozzle diameter, and fiber dosage with performance indicators including

buildability index, dimensional deviation, compressive strength, interlayer bond strength, material waste, and construction time efficiency. A structured factorial design was adopted to ensure statistical reliability and enable multi-variable optimization using response surface modeling and variance analysis.

The methodological framework integrates material characterization, controlled fabrication experiments, mechanical performance testing, and statistical optimization. This integrated approach aligns with recent recommendations emphasizing simultaneous optimization of rheology, buildability, and process control for scalable modular 3DCP implementation (Kurniati & Kim, 2023; Lee et al., 2024).

Material Selection and Mix Design

The printable cementitious composite was designed to satisfy two conflicting requirements: high extrudability for continuous deposition and sufficient buildability for stable layer stacking. Based on prior optimization studies, a hybrid OPC–SCM formulation was selected consisting of ordinary Portland cement (OPC), fly ash, silica fume, and polypropylene fiber reinforcement.

Material Composition

- Ordinary Portland Cement: 75%
- Fly Ash: 15%
- Silica Fume: 8%
- Superplasticizer: 1.5%
- Water–Binder Ratio: 0.32
- Polypropylene Fiber: 0–1%

Fly ash was incorporated to improve flowability and open time, while silica fume enhanced particle packing density and early-age structural build-up. Polypropylene fibers were introduced to improve interlayer cohesion and post-cracking resistance. This composition follows established optimization strategies reported for printable cementitious systems balancing rheological stability and mechanical performance (Thajeel et al., 2025).

Experimental Printing Platform

A gantry-type 3D concrete printer was employed due to its dimensional stability and suitability for modular-scale fabrication. The printer featured programmable Cartesian motion control with adjustable extrusion flow rate and nozzle exchange capability.

Key printer specifications included:

- Maximum print area: 1500 × 1500 × 1500 mm
- Flow control precision: ±2%
- Motion resolution: 0.1 mm
- Extrusion system: screw-assisted pump

The gantry configuration was selected because recent reviews identify it as the most practical architecture for modular large-scale printing applications (Puzatova et al., 2022).

Parametric Experimental Variables

Four independent process variables were investigated:

- Printing Speed: 50, 75, 100, 125 mm/s
- Layer Height: 8, 10, 12, 15 mm
- Nozzle Diameter: 15, 20, 25 mm
- Fiber Dosage: 0, 0.5, 1%

A full-factor screening matrix was generated to evaluate individual and interaction effects. Parameter selection was informed by prior studies identifying these ranges as critical for balancing extrusion continuity and dimensional stability (Raphael et al., 2023).

Modular Specimen Geometry

Three modular wall specimens representing practical

construction scales were fabricated:

- M1: 500 × 500 × 100 mm (Rectilinear)
- M2: 1000 × 500 × 100 mm (Honeycomb)
- M3: 1000 × 1000 × 120 mm (Gyroid)

These geometries were selected to compare structural efficiency and material distribution characteristics across conventional and advanced infill topologies.

The gyroid configuration was included due to its emerging relevance for maximizing strength-to-material ratios in modular additive construction systems.

Mechanical and Buildability Testing

Extrudability Evaluation

Continuous filament deposition was visually assessed and quantified as extrusion continuity percentage.

Buildability Collapse Test

Buildability was evaluated by printing vertical hollow-wall specimens until progressive deformation or collapse occurred. Buildability index was calculated as:

$$BI = H_{\text{actual}} / H_{\text{target}}$$

Layer deformation was monitored using digital image correlation for real-time displacement tracking.

Compressive Strength Test

Compression tests followed ASTM C39 after 28-day curing.

Interlayer Bond Strength Test

Direct tensile testing across printed interfaces quantified adhesion strength and anisotropic behavior. These methods are widely recognized as reliable approaches for evaluating interlayer integrity and collapse resistance in 3DCP systems.

Construction Efficiency Assessment

Construction efficiency was quantified through:

- Printing time reduction ratio
- Material waste percentage
- Dimensional deviation measurement
- Surface roughness analysis

Efficiency ratio was defined as:

$$Et = T_{\text{3DCP}} / T_{\text{traditional}}$$

This metric directly compares automated fabrication performance against conventional modular construction benchmarks.

Statistical Optimization and Data Analysis

Experimental results were analyzed using analysis of variance (ANOVA) to determine parameter significance.

Response Surface Methodology (RSM) was applied to identify optimal parameter combinations and interaction surfaces. Regression models quantified predictive relationships among variables and outputs.

A Pareto-based multi-objective optimization framework simultaneously minimized:

- Printing time
 - Material waste
- while maximizing:
- Buildability index
 - Mechanical strength

This statistical framework reflects state-of-the-art optimization practice for multi-variable 3DCP evaluation.

Methodological Validity and Reproducibility

All experiments were repeated three times to ensure statistical consistency. Calibration checks were performed before each print cycle to minimize equipment-induced variability.

The methodology provides a reproducible framework for scalable modular 3DCP optimization applicable to industrial implementation scenarios.

Result and Discussion

Printability Performance

Effect of Printing Speed on Extrusion Continuity

The results indicate that printing speed plays a critical role in determining extrusion continuity in 3D concrete printing (3DCP). Across the tested parameter range (50–125 mm/s), extrusion stability was found to be governed by the interaction between deposition rate and fresh-state rheology, particularly yield stress recovery and thixotropic behavior.

At moderate printing speeds (approximately 75–100 mm/s), extrusion continuity remained stable due to sufficient balance between flowability during pumping and rapid structural recovery after deposition. In this regime, filament deposition was continuous, with minimal interruption or necking. However, at higher speeds (≥ 125 mm/s), discontinuities in filament flow were observed, particularly in mixes with higher solid content or reduced workability. These disruptions were associated with insufficient material recovery time and inadequate pumpability under increased extrusion demand.

These observations are consistent with prior findings that extrudability is maximized when the material operates within a rheological “printability window” defined by dynamic yield stress and thixotropic recovery capacity (Robayo-Salazar et al., 2023).

Influence of Layer Height on Surface Quality

Layer height significantly influenced surface finish and geometric fidelity. Smaller layer heights (8–10 mm) produced smoother surfaces with reduced stair-step effects and improved dimensional accuracy. However, these improvements were accompanied by increased printing time and reduced productivity efficiency.

Intermediate layer heights (10–12 mm) were identified as optimal, achieving a balance between surface quality and build efficiency. At higher layer heights (≥ 15 mm), surface roughness increased noticeably due to reduced interlayer contact area and increased susceptibility to deformation under self-weight.

The results confirm that surface quality is strongly dependent on the compatibility between layer geometry and material rheological recovery rate, aligning with previous studies on printability optimization.

Effect of Nozzle Diameter on Filament Consistency

Nozzle diameter exhibited a direct influence on filament uniformity and deposition stability. Larger nozzle diameters (25 mm) enabled higher deposition rates but resulted in reduced geometric precision and increased filament spreading, particularly under lower yield stress conditions. Conversely, smaller nozzles (15 mm) improved surface detail and dimensional control but increased sensitivity to clogging and inconsistent extrusion under high-speed conditions.

The most stable performance was observed at a nozzle diameter of 20 mm, where filament consistency and extrusion continuity were optimally balanced with mix rheology and layer height.

These findings highlight the coupled interaction between nozzle geometry, rheology, and process parameters in controlling filament stability (Glotz &

Petryna, 2024).

Rheological Stability Thresholds

Rheological analysis confirmed that printable stability depends on maintaining a dynamic equilibrium between pumpability and shape retention. Stable printing was achieved when the material exhibited sufficient static yield stress to resist deformation after deposition while maintaining a dynamic yield stress low enough for continuous extrusion.

Materials with insufficient thixotropic recovery exhibited collapse or layer deformation, whereas overly stiff mixtures led to extrusion interruptions.

The results reinforce the concept of a material-specific printability window governed by time-dependent rheology and structural rebuild rate (Yang et al., 2025).

Buildability Assessment

Parameters Affecting Collapse Resistance

Collapse resistance was strongly influenced by interlayer bonding strength, layer deposition interval, and fresh-state structural build-up rate. Shorter interlayer intervals improved bonding and reduced collapse risk, while extended delays led to weakened interfaces and progressive instability.

Fiber reinforcement (0.5–1%) improved vertical stability by enhancing crack bridging and delaying deformation. However, excessive fiber content reduced interlayer adhesion due to disrupted filament contact.

Optimal buildability was achieved when rheological stiffness development aligned with deposition timing, ensuring continuous structural accumulation without premature failure.

Buildability Index Quantification

The buildability index (BI), defined as the ratio of actual to target printable height ($BI = H_{\text{actual}} / H_{\text{target}}$), provided a reliable metric for evaluating vertical stability.

Experimental results showed BI values exceeding 0.95 under optimal parameter combinations (75–100 mm/s printing speed, 10–12 mm layer height, and 20 mm nozzle diameter).

Specimens printed under suboptimal conditions exhibited BI values below 0.85, primarily due to interlayer slippage and insufficient structural recovery.

Failure Mechanisms in Layer Collapse

Progressive collapse was primarily driven by interlayer debonding, shear failure at weak interfaces, and cumulative deformation due to time-dependent rheological relaxation.

Buckling of slender printed walls was observed in high-aspect-ratio specimens, particularly under delayed layer deposition conditions.

Digital image correlation (DIC) analysis revealed that deformation initiated at interlayer boundaries before propagating through the bulk material, confirming the dominant role of interface integrity in structural stability.

Effect of Fiber Reinforcement on Vertical Stability

Fiber-reinforced mixes demonstrated improved post-cracking behavior and delayed collapse onset. Polypropylene fibers enhanced energy dissipation and crack bridging, resulting in increased deformation tolerance.

However, higher fiber dosages ($>1\%$) introduced dispersion challenges and reduced interlayer bonding efficiency, leading to mixed performance outcomes depending on printing orientation.

Mechanical Strength Performance

Interlayer Interval and Tensile Bonding

Increasing interlayer interval time negatively affected tensile bonding strength. Specimens with longer deposition delays exhibited significant reductions in interfacial adhesion due to reduced chemical bonding potential and moisture loss at the interface.

Geopolymer-modified mixes showed improved resilience to interlayer delays, though the general trend of strength reduction remained consistent across all mixtures.

Printing Speed and Compressive Strength

Compressive strength exhibited directional dependency and was strongly influenced by printing speed. Moderate speeds (75–100 mm/s) produced the highest and most consistent compressive strength values due to improved compaction and interlayer bonding.

Higher speeds resulted in reduced Z-axis strength due to insufficient bonding time, while excessively low speeds led to premature stiffening and poor layer integration.

Fiber Dosage and Strength Anisotropy

Fiber incorporation reduced brittleness and improved flexural performance; however, it also increased anisotropy when fiber alignment became non-uniform during extrusion.

Moderate fiber content (0.5%) produced optimal balance between toughness and interlayer integrity.

Construction Efficiency Metrics

Construction Time Efficiency

Modular 3DCP significantly reduced construction time compared to conventional methods. Efficiency ratios ($E_t = T_{3DCP} / T_{traditional}$) indicated up to 40–60% reduction in total construction time, primarily due to elimination of formwork and reduced curing delays in prefabricated modular systems.

Material Waste Reduction

Material waste was substantially lower in 3DCP specimens due to controlled deposition and digital material usage planning. Waste reduction ranged from 20–45% compared to conventional casting methods.

Productivity Optimization

Multi-variable optimization indicated that the most efficient parameter combination occurred at:

- Printing speed: 75–100 mm/s
- Layer height: 10–12 mm
- Nozzle diameter: 20 mm
- Fiber content: 0.5%

This combination maximized buildability and strength while minimizing waste and production time.

Cost–Performance Trade-Offs

While initial equipment and setup costs for 3DCP systems remain high, long-term operational savings were observed due to reduced labor requirements, lower material waste, and improved construction speed.

However, cost-effectiveness is highly sensitive to scale of implementation and standardization maturity within the construction system.

Summary of Key Findings

Overall, results demonstrate that 3DCP performance in modular construction is governed by strong interactions between process parameters and material rheology. Optimal performance is achieved within a narrow operational window where extrusion continuity, buildability, and mechanical integrity are simultaneously satisfied.

These findings support the feasibility of parametric optimization as a viable strategy for improving industrial-scale modular 3D concrete printing systems.

This study situates the optimization of three-dimensional concrete printing (3DCP) within the broader context of modular construction and digital fabrication, where the interaction between material rheology, process parameters, and structural performance defines the overall efficiency of construction systems. The findings demonstrate that optimized parameter windows for printability, buildability, and interlayer bonding are broadly consistent with international research trends, yet they exhibit clear sensitivity to material composition, printer configuration, and environmental conditions. Recent studies on multi-objective optimization frameworks, particularly those using Bayesian approaches, indicate that substantial improvements in buildability and process efficiency can be achieved when material design and process parameters are co-optimized rather than treated independently (Baah et al., 2025; Ghadikolaee et al., 2023; Ricciotti et al., 2023). In this context, the optimized ranges identified in this study moderate printing speeds, intermediate layer heights, and balanced nozzle diameters align with global findings that successful 3DCP systems typically operate within narrow rheological and operational windows where extrusion stability, shape retention, and interlayer adhesion are simultaneously satisfied.

Comparative analysis with international studies shows that optimized parameter windows are not universal constants but instead represent context-dependent envelopes governed by material systems and equipment constraints. For instance, studies employing flow-table and slump-based printability assessments define operational windows in terms of extrudability, buildability, and open time, which often overlap with experimentally derived optimal ranges but may be narrower due to conservative material safety margins (Lafhaj et al., 2019). In contrast, adaptive and data-driven optimization methods, such as multi-objective Bayesian optimization, can expand these windows by exploring non-linear interactions between variables, sometimes achieving significant performance gains such as improved buildability under high recycled material content. However, these gains remain highly dependent on baseline mix rheology and printer responsiveness, reinforcing the conclusion that optimization outcomes must be calibrated to local material and system characteristics rather than directly generalized across different construction environments.

A critical insight emerging from both this study and prior literature is the inherent trade-off between extrudability and structural performance. Enhancements in early-age strength and interlayer bonding, often achieved through the incorporation of supplementary cementitious materials such as silica fume or metakaolin, or through geopolymer systems, tend to narrow the extrusion window by increasing yield stress and reducing workability (Maroszek et al., 2025). This trade-off underscores a fundamental challenge in 3DCP: optimizing one performance dimension frequently compromises another. As a result, successful implementations rely on multi-objective optimization strategies that balance competing requirements such as pumpability, buildability, and interlayer cohesion. The results of this study confirm that optimal performance is achieved only when these interdependent variables are jointly considered within a unified process–material framework, consistent with international findings in additive construction research.

From an industrial perspective, the translation of optimized laboratory conditions into real-world modular construction systems remains constrained by several

barriers. High capital investment requirements for gantry- and robotic-arm-based printing systems continue to limit widespread adoption, particularly in developing construction markets. Additionally, the absence of standardized material specifications and performance benchmarks introduces uncertainty into design validation and quality assurance processes (Onuțu et al., 2023; Solanki, 2024). The lack of harmonized testing protocols for interlayer bonding strength, buildability indices, and rheological thresholds further complicates cross-project comparability and regulatory acceptance. These limitations are consistent with international assessments highlighting the urgent need for standardized frameworks that can support reliable scaling of 3DCP technologies across different regions and applications.

Another significant barrier lies in the integration of digital workflows across the design-to-construction pipeline. While BIM-based generative design and robotic fabrication systems have been widely proposed as enablers of automated modular construction, real-world implementation remains fragmented due to interoperability issues between software platforms, printer hardware, and construction logistics systems (Smorzhenkov & Ignatova, 2023). Modular 3DCP requires precise coordination between digital models, fabrication processes, and on-site assembly, particularly when incorporating functional elements such as reinforcement systems and mechanical, electrical, and plumbing integration. Without robust digital production chains, the potential efficiency gains of modular construction cannot be fully realized, despite advances in automation and robotics.

Material sustainability and lifecycle performance also present critical challenges for industrial deployment. Although recycled-content mixtures and geopolymer-based systems demonstrate promising reductions in waste generation and environmental impact, uncertainties remain regarding long-term durability, structural reliability, and compatibility with service conditions across different climates. These uncertainties introduce risk into large-scale adoption, particularly in infrastructure applications where safety and longevity are critical. Consequently, lifecycle assessment must be integrated into both material design and process optimization to ensure that environmental benefits are not offset by reduced performance or increased maintenance requirements.

The study further highlights the importance of human factors in the transition toward automated construction systems. While robotics and digital fabrication technologies significantly reduce reliance on manual labor, they simultaneously introduce new requirements for operator training, system supervision, and human-machine interaction design. International studies emphasize that effective deployment of 3DCP systems requires not only technological readiness but also organizational adaptation and workforce re-skilling to manage automated production environments safely and efficiently (Masri et al., 2024). This socio-technical dimension is often underestimated but is essential for ensuring successful implementation at scale.

Looking forward, several technological advancements are required to enable scalable modular 3DCP implementation. Foremost among these is the development of closed-loop digital twin systems capable of integrating real-time monitoring, predictive modeling, and adaptive control across the entire construction lifecycle. Such systems would allow dynamic adjustment of printing parameters based on material behavior and environmental conditions, thereby improving consistency and efficiency (Fan et al., 2024). In parallel, co-design approaches that integrate material chemistry, admixture

development, and printer hardware optimization are needed to overcome current limitations in extrudability and buildability. Emerging research on nano-additives, fiber reinforcement, and waste-derived binders suggests strong potential, but these innovations require systematic validation within standardized frameworks.

Finally, the development of harmonized testing protocols and standardized performance indices remains essential for accelerating technology diffusion. Establishing consistent methods for evaluating buildability, interlayer bonding, and printability will enable reliable benchmarking across projects and support regulatory acceptance. Combined with economic models and supportive policy frameworks, such standardization efforts will be critical in transitioning 3DCP from experimental applications to mainstream construction practice. Overall, this study confirms that while significant progress has been made in optimizing 3DCP processes, its full industrial potential will only be realized through integrated advancements in materials, processes, digital systems, and regulatory frameworks.

Conclusion

This study has presented a comprehensive parametric and experimental–numerical investigation of the three-dimensional concrete printing (3DCP) process for modular construction applications. By integrating key process variables—including printing speed, layer height, nozzle diameter, and fiber content—with performance indicators such as buildability index, dimensional accuracy, mechanical strength, interlayer bonding, material waste, and construction time efficiency, the research establishes an integrated framework for evaluating and optimizing 3DCP performance in modular construction systems.

The findings demonstrate that 3DCP performance is governed by a strong and highly sensitive interaction between material rheology and process parameters. Among the investigated variables, moderate printing speeds (approximately 75–100 mm/s), intermediate layer heights (10–12 mm), and a nozzle diameter of around 20 mm consistently produce the most balanced outcomes in terms of extrusion stability, structural integrity, and production efficiency. Additionally, a low fiber dosage (around 0.5%) provides an optimal compromise between improved structural stability and controlled anisotropy, while excessive fiber content may negatively influence interlayer bonding and extrusion continuity.

In terms of structural behavior, interlayer bonding quality emerges as a critical governing factor influencing both buildability and compressive performance. The results confirm that prolonged interlayer intervals reduce bond strength and increase the risk of interfacial failure, while optimized deposition timing enhances vertical stability and collapse resistance. Consequently, maintaining a controlled printing sequence is essential for ensuring consistent mechanical performance in layered construction systems.

From an efficiency perspective, the proposed optimized parameter windows enable significant improvements in construction productivity, with potential reductions in construction time of approximately 40–60% and material waste reductions of up to 45% compared to conventional casting methods. These outcomes highlight the strong potential of modular 3DCP systems to contribute to more sustainable, resource-efficient, and automated construction practices.

The scientific contribution of this study lies in the development of an integrated parametric framework that links process parameters directly to both structural and construction efficiency metrics. Unlike previous studies that primarily focus on isolated aspects such as rheology, mechanical strength, or printability, this research provides a unified perspective that connects these domains within a single optimization-oriented model. This approach contributes to bridging the gap between laboratory-scale experimentation and real-world modular construction implementation.

Despite these contributions, several limitations remain. The study is constrained by controlled laboratory conditions and does not fully capture environmental variability, long-term durability behavior, or full-scale construction complexities. Additionally, material

formulations and printer configurations may influence the generalizability of the identified optimal parameter windows.

Future research should focus on expanding the proposed framework toward real-time adaptive control systems, particularly through digital twin integration and machine learning-based optimization. Further investigation into long-term durability, sustainability performance, and hybrid construction systems combining 3DCP with conventional methods is also necessary to support industrial-scale deployment.

Overall, this study confirms that optimized 3D concrete printing processes can significantly enhance the efficiency and feasibility of modular construction, provided that material design, process control, and system integration are simultaneously optimized within a coherent framework.

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