

BIM AND ADDITIVE MANUFACTURING IN 3D CONCRETE PRINTING: A SYSTEMATIC REVIEW OF DIGITAL INTEGRATION FRAMEWORKS

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SUMMARY: This study investigates integrating 3D concrete printing (3DCP) with emerging digital technologies in construction and pursues two connected objectives. First, from a broad perspective, it reviews how 3DCP interacts with various digital technologies—such as Building Information Modeling (BIM), the Internet of Things (IoT), Augmented Reality (AR), and digital twins—to define the digital ecosystem surrounding additive construction. Second, and more specifically, it explores the frameworks that enable collaboration between BIM and Additive Manufacturing (AM), focusing on how BIM can serve as a central platform for integrating digital tools throughout the construction lifecycle. To address these two objectives, we adopt a two-stage methodology: a bibliometric analysis mapping interactions between 3DCP and these technologies, followed by a systematic review guided by the PRISMA and PICO frameworks and focused on BIM–AM integration workflows. Our findings show that BIM not only supports material specification and geometric modeling but also enables performance optimization and fabrication management through parametric design environments and real-time feedback systems. Although several conceptual frameworks propose comprehensive lifecycle integration, practical implementations remain limited to specific phases. The study identifies key challenges in interoperability, environmental sensing, and support for functionally graded materials, and proposes future research directions, including embedded structural analysis, standardized ontologies for AM data, and adaptive control systems. This research contributes to the growing body of knowledge on BIM–AM integration and highlights the potential for scalable, intelligent workflows in large-scale additive construction.

KEYWORDS: construction, additive manufacturing, building information modeling, 3DCP, BIM.

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1. INTRODUCTION

1.1 Context

According to UN-Habitat estimates, by 2030, about 40% of the global population will need access to adequate housing, and one in four people currently lives in conditions that threaten their health, safety, and well-being. The shortage of affordable housing is increasingly recognized as a critical global issue. Meanwhile, transformative technological advances of recent decades—collectively known as the Fourth Industrial Revolution (Industry 4.0)—have inspired researchers in the Architecture, Engineering, and Construction (AEC) sectors to align construction practices with emerging technologies under the umbrella of Construction 4.0. As the construction sector transitions to digital processes, integrating advanced technologies has become essential to improving project efficiency. This paradigm shift marks a transition from human-driven to machine-driven processes in the AEC industry. (Brozovsky et al., 2024). Construction 4.0 offers promising solutions to some of the industry's most pressing challenges, including a shortage of skilled labor (Li, 2025), a high rate of workplace fatalities (Zhang et al., 2025), and comparatively low productivity and efficiency (Rathnayake & Middleton, 2023), and carbon emissions (Monfaredi & Memari, 2026). The industry has evolved from linear workflows to integrated cyber-physical systems that support various applications (Mohsenian et al., 2026), such as energy enhancement (Derazgisou et al., 2018) and adaptive facades (Goharian et al., 2025). Traditional design methods depended on paper-based, 2D drawings shared among stakeholders, often leading to rework. The adoption of digital tools like 3D modeling and Building Information Modeling (BIM) introduced clash detection, enhanced collaboration, and minimized design conflicts. BIM additionally allows for automated compliance checks, cost estimation, scheduling, and energy analysis (Al-Tamimi et al., 2023). Construction 4.0 encompasses a range of technologies that enable varying degrees of machine integration in the AEC sector (Anane et al., 2023). One notable approach is additive manufacturing (AM), commonly referred to as 3D printing (3DP). In construction, this typically refers to 3D concrete printing (3DCP). AM involves adding material layer by layer to create physical objects from 3D model data. In 3DCP, a digital model is created using computer-aided design (CAD) software, sliced into layers, and translated into toolpaths that guide a robotic print head to extrude concrete (Craveiro et al., 2019). The benefits of 3DCP include removing workers from hazardous environments (El-Sayegh et al., 2020), addressing labor shortages (Hossain et al., 2020), optimizing material usage (Ahmed, 2023), eliminating the need for formwork, reducing costs (Raza et al., 2024), CO₂ emissions (Batikha et al., 2022b) and shortening project timelines (Fasihi & Libre, 2024). Despite its maturity and acceptance in other industries, AM has yet to gain significant traction in construction. Although the growing body of academic literature on 3DCP signals increasing interest, challenges such as material behavior, environmental conditions, and subsystem integration continue to hinder widespread adoption (Slepicka & Borrmann, 2024). Over the past two decades, researchers have worked to make 3DCP more reliable by establishing bidirectional information flows between digital design and manufacturing (Batikha et al., 2022). The second phase of Construction 4.0 introduces digital twins and cyber-physical systems that leverage IoT sensors, AI-driven optimization, and predictive analytics. This shift enables a transition from “design-then-build” to “design-while-building,” supported by real-time data exchange (Lawrence et al., 2012), advanced control systems (Slepicka & Borrmann, 2024), and enhanced stakeholder coordination (Aslam et al., 2019). Unlike traditional 2D drawings, BIM models incorporate comprehensive data, including materials, costs, schedules, performance metrics, and maintenance requirements for every building component, enabling a fully digital lifecycle from design through construction, operation, and maintenance.

1.2 Research focus

This review addresses two related questions within Construction 4.0. The first investigates how 3D concrete printing can be integrated with emerging digital technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), Augmented Reality (AR), and digital twins. The second, which is central to this study, examines frameworks that support effective collaboration between BIM and 3D concrete printing (3DCP). BIM is considered the core platform for technology integration in the architecture, engineering, and construction (AEC) sector (Keles et al., 2025). Understanding how these technologies interact is key to creating a unified digital ecosystem. Focusing on BIM helps identify opportunities to develop data exchange protocols and integration frameworks that improve 3DCP workflows. BIM connects design and manufacturing by integrating real-time data from laser scanners, IoT sensors, AR systems, and digital twins into the printing process. Despite this potential, research on collaborative digital ecosystems for 3DCP remains limited (Anane et al., 2023a). Functionally graded

materials (FGMs) highlight both the opportunities and challenges of this integration. Produced via additive manufacturing (Pajonk et al., 2022), FGMs enable material properties to vary within a single component, enhancing structural performance by placing stronger materials in high-stress areas and lighter materials where stresses are lower (Fakhr Ghasemi & Pinto Duarte, 2025). Implementing FGMs in construction requires precise coordination between structural analysis tools and printing systems that can deposit materials precisely, using structural and environmental data to control material distribution (Sacks et al., 2018).

2. METHODOLOGY

This study uses a two-stage methodology. In the first stage, we investigated how 3D Concrete Printing (3DCP) in the Architecture, Engineering, and Construction (AEC) industries interacts with other emerging technologies identified in the literature, including Building Information Modeling (BIM), the Internet of Things (IoT), Augmented Reality (AR), Digital Twin, and Laser Scanning.

To gather relevant literature, we used the Web of Science and Scopus citation databases because of their complete coverage of scholarly publications. Articles were extracted using the keywords listed in Appendix 1. We removed duplicate and retracted entries using Zotero software to guarantee data integrity. We then exported the selected dataset in (.RIS) format and analyzed it using VOSviewer to conduct a bibliometric study. Appendix 2 provides the visualizations generated by VOSviewer.

The analysis of the BIM–3DCP technology pair revealed other technologies in distinct clusters, highlighting BIM’s role as a platform for integrating technologies used to enhance 3DCP. In the AR–3DCP interactive space, BIM appeared in two clusters, showing its capacity to bridge Artificial Intelligence (AI), Virtual Reality (VR), and Extended Reality (XR) with AR–3DCP. Similarly, in the Digital Twin–3DCP domain, BIM facilitated the combination of AI, IoT, and blockchain technologies. BIM also showed a strong presence in the IoT–3DCP space, where it enabled connections with digital twins, deep learning, and machine learning.

A comparative study of keyword frequency across articles, visualized through bibliometric images, supports the hypothesis that BIM acts as a foundational platform for adopting other technologies, thereby shaping the digital ecosystem of 3DCP in the construction sector. Figure 1 illustrates the frequency of published articles linking 3DCP with various digital technologies.

In the second step of our methodology, we examined the integration of Building Information Modeling (BIM) with Additive Manufacturing (AM), broadening the scope of the study through the use of more general search terms. Specifically, we replaced the term “3DCP” with “AM” to capture a wider range of relevant studies. A Boolean systematic review methodology was employed to analyze previous studies, following the principles of the PRISMA framework (Page et al., 2021) and the PICO model (Sharoni et al., 2023). Using the PICO model (Table 1), we identified research keywords based on the thematic literature. This structured approach helped define the review's scope and focus.

Table 1: PICO Framework for Keyword Identification.

No.	Item	Context
1	Population	Concrete construction in the building industry.
2	Interventions	All instances referring to the status of AM and BIM.
3	Comparisons	Concerning researchers, processes, and information technologies
4	Outcomes	The role of BIM in industry's use of AM.
5	Study method	Quantitative and qualitative analysis.

After reviewing the literature, we identified the most commonly used terms related to BIM and additive manufacturing and used them to conduct searches in the selected citation databases. The search terms are presented in Table 2.

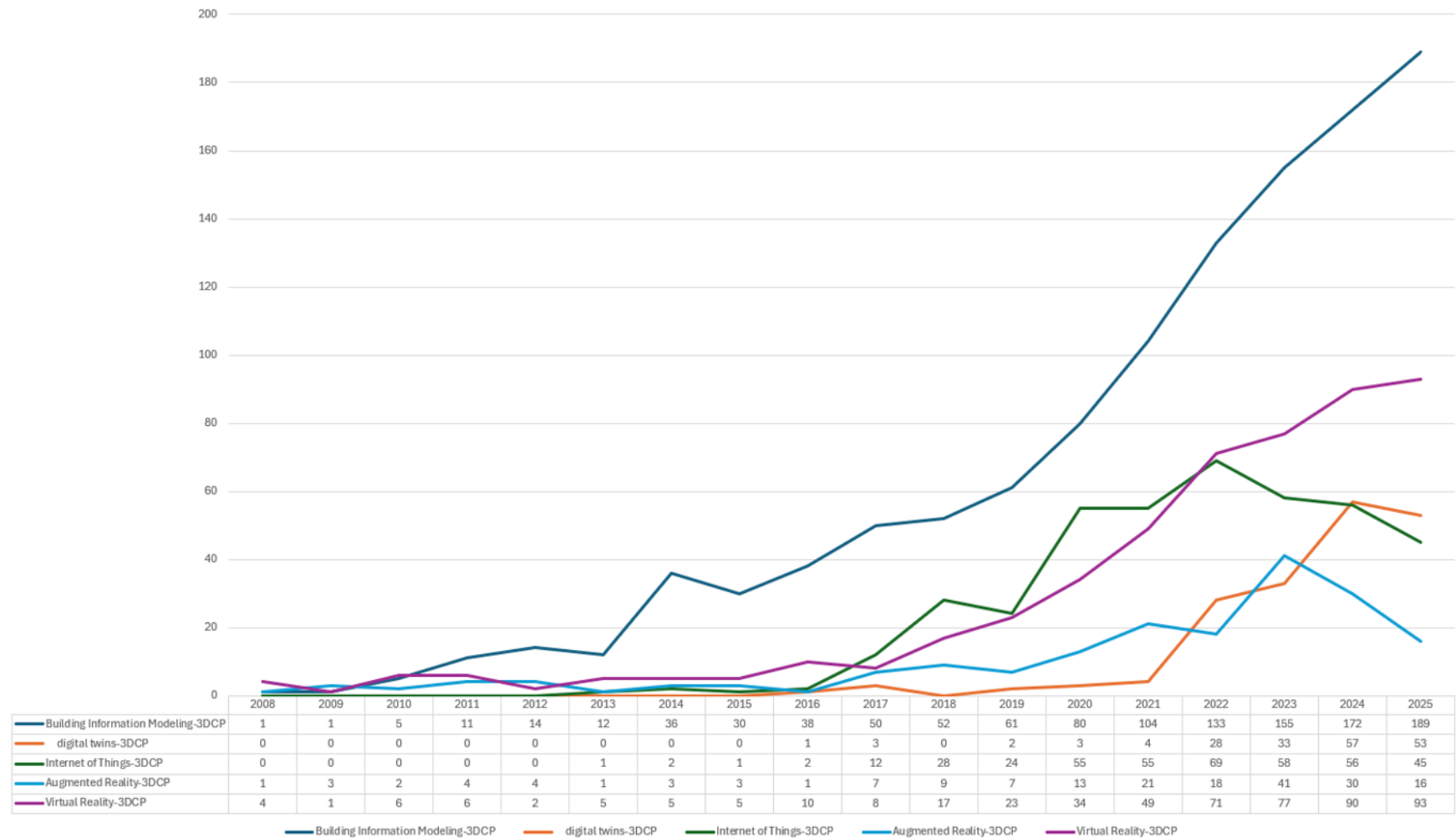


Figure 1: Frequency of published articles linking 3DCP and BIM, Digital twins, Internet of things, Augmented reality, Virtual reality.

We applied the search protocol outlined in Table 2 across the selected databases. In Web of Science, the initial search returned 8,507 records containing the specified terms. To improve relevance, the results were refined by limiting the search to English-language publications and restricting the research areas to Construction & Building Technology and Architecture. This filtering process reduced the dataset to 809 records. Combined with 53 records identified through Scopus, the database search yielded 862 records.

Figure 2 illustrates the study selection process following the PRISMA framework. Before screening, 10 duplicate records and 3 records removed for the reasons indicated in Figure 2 were excluded, leaving 849 records for title and abstract screening. At this stage, 481 records were removed as irrelevant, resulting in 368 records for detailed assessment. Following full-text screening, 321 articles were excluded, leaving 47 studies for eligibility review.

To reduce redundancy and exclude studies with substantial overlap in scope, content, or findings, 19 articles were excluded, leaving 28 studies from the initial search (Stage 1). A second search stage (Stage 2), which included additional studies identified through other sources, contributed 5 more articles. Consequently, 33 studies were included in the final qualitative synthesis and form the basis of the analysis of BIM-additive manufacturing integration workflows.

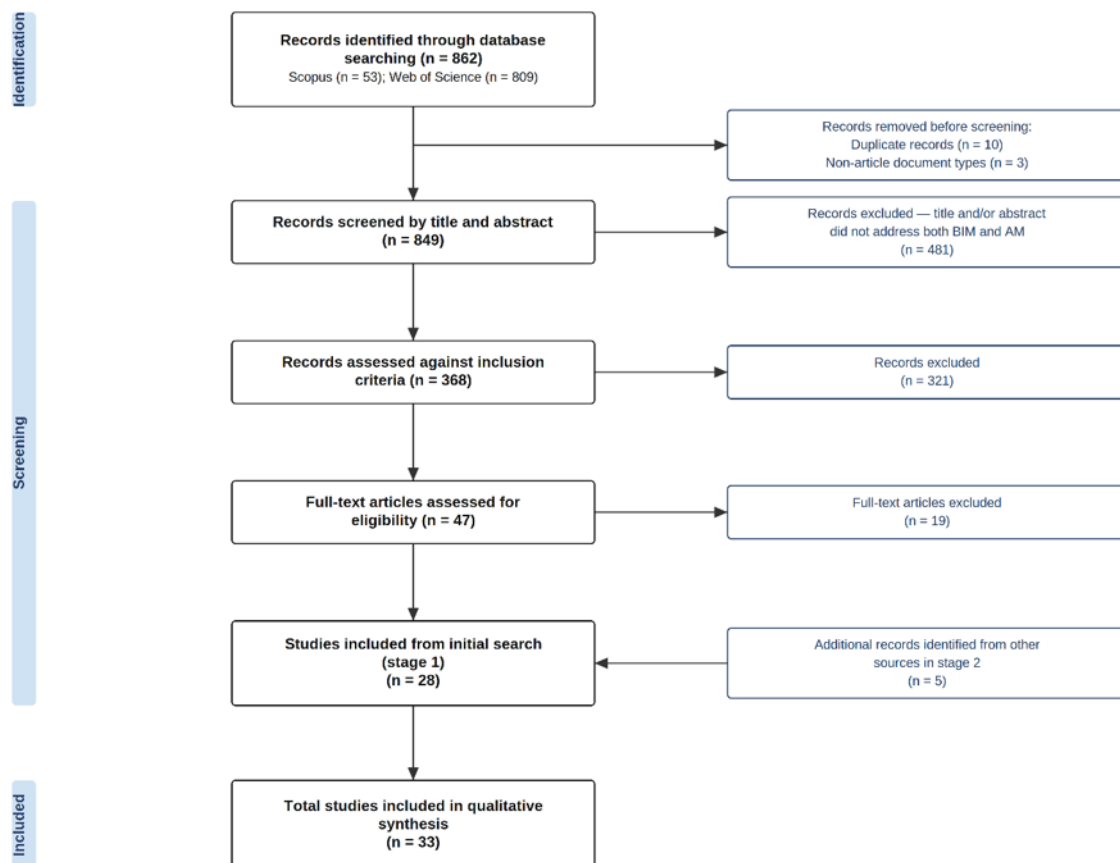


Figure 2: PRISMA Flow Diagram.

To guide the literature identification, selection, and evaluation process, Table 2 outlines our research protocol, including objectives, guiding questions, search parameters, and analytical approach.

Table 2: Research Protocol.

No.	Item	Content
1	Aim	
	Key-objective	To establish contextual knowledge on AM-BIM through the analysis and classification of articles.
2	Research Questions	
	Main question	How can Building Information Modeling (BIM) be integrated with 3D concrete printing (3DCP) to coordinate design, toolpath generation, and fabrication across the construction process?
	Purpose of the synthesis	This review identifies and compares existing BIM–3DCP integration frameworks, characterizes how they handle data exchange, toolpath generation, and process feedback, and determines the gaps that currently limit full lifecycle integration.
3	Search Methods	
	Electronic Databases	Scopus; Web of Science
4	Selection criteria-Filters	
	Scopus string	
	Web of Science string	
	Idiom	English
5	Exclusion criteria	
		Not related to BIM and AM.
		Abstract not available for download.
		Not written in the defined idiom.
6	Method	
	Data extraction	Use R software for integrity data and status based on the protocol.
	Narrative Synthesis	Bibliometric Analysis: Publications over time; Methodology applied. Thematic Analysis: Analysis of selected publications; Description of findings, outcomes and relationships.

To process the bibliometric data, we developed a structured workflow for data extraction, merging, and analysis. We exported records from Web of Science and Scopus in (.bib) format. The combined dataset was then analyzed using bibliometric techniques in R Studio and visualized with VOSviewer. Figure 3 presents this systematic data processing workflow, highlighting the software tools and file formats used at each stage.

To visualize the relationships among key concepts within the scope of this research, a bibliometric analysis was conducted using a procedure similar to the first stage. Co-occurrence was selected as the analysis type, with keywords as the unit of analysis. Out of 8,803 keywords, 185 met the threshold of appearing at least 10 times. Figure 4 presents the co-occurrence of authors' keywords in the reviewed literature. The green cluster indicates a strong research focus on material design, printing processes, and structural capacity. The red cluster highlights BIM's central role in integrating with other digital technologies, underscoring its importance in the broader digital ecosystem.

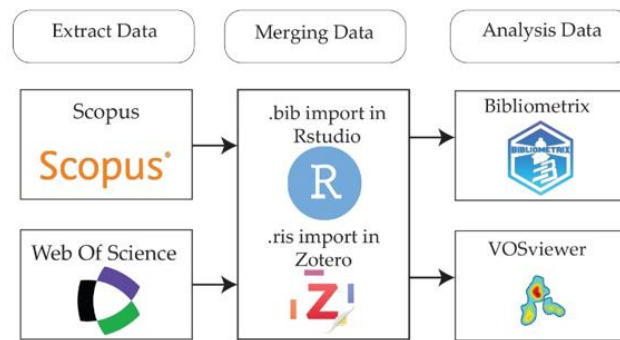


Figure 3: Data Extraction, Merging, and Analysis Workflow (Fakhr Ghasemi & Pinto Duarte, 2025).

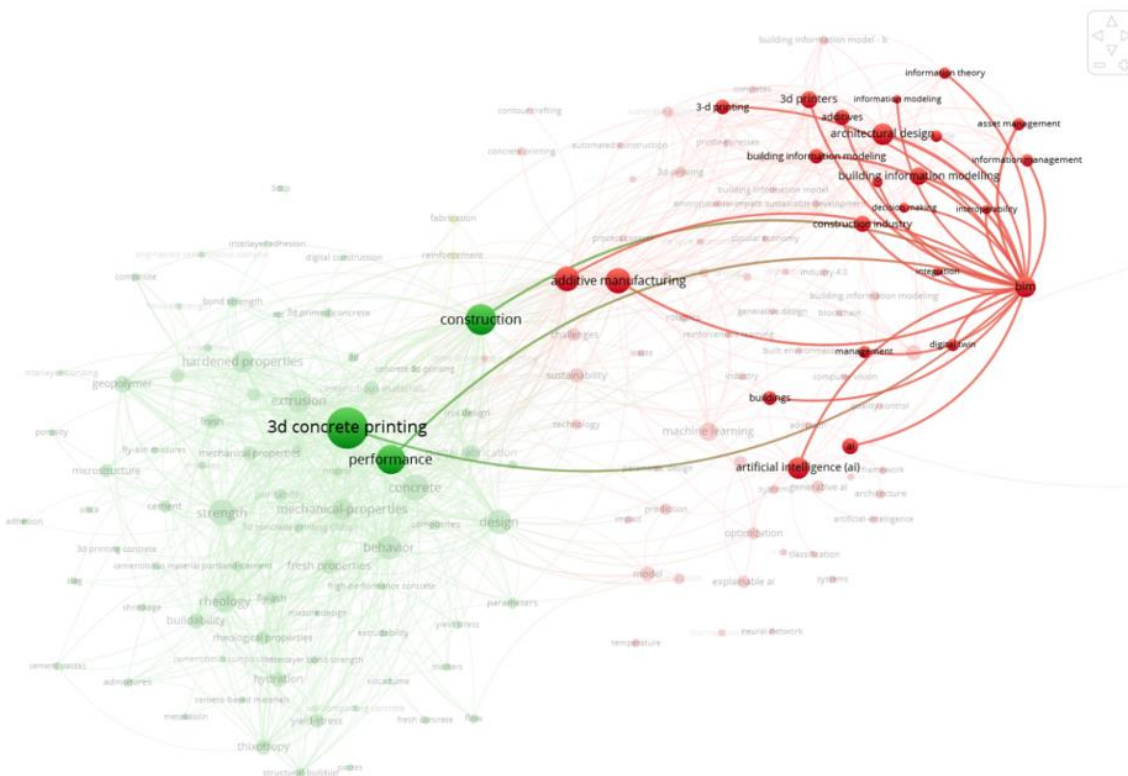


Figure 4: Co-occurrence of Authors' Keywords in the Literature.

3. RESULT

3.1 BIM Integration with digital technologies to serve 3DCP

BIM can work with various technologies such as laser scanners, sensors, IoT systems, and robotic fabrication equipment across all building lifecycle stages (Baghalzadeh Shishehgharkhaneh et al., 2022). BIM models evolve throughout the project lifecycle, serving different purposes during design, construction, and operations phases (Sacks et al., 2018). BIM and Augmented Reality (AR) can transform design information into construction processes, support on-site decision-making, and manage stakeholder conflicts (Bhatarai et al., 2025). AR-BIM collaboration can be categorized in 6 functions: Positioning (accurate localization and tracking of BIM models), Interaction (user interface capabilities for digital and physical object manipulation), Visualization (visibility control and graphical fidelity), Collaboration (user communication and information sharing), Automation (minimal-intervention task execution), and Integration (utilization of external technologies and services) (Civera et al., 2025). Automation in the context of AR relies on Artificial intelligence, in particular, computer vision

(Bassyouni & Elhajj, 2021). A systematic review paper by Ahsan et al., 2024 shows how AR visualizes manufacturing systems in real-time, allowing users to interact with virtual models and make informed decisions based on live data streams (Ahsan et al., 2024). One such project is MIT's RoMA (Robotic Modeling Assistant), which lets users design CAD models in AR while a 3D-printing robotic arm concurrently constructs the model's features (Dogan et al., 2022). Aerial additive manufacturing systems developed at the University of Pennsylvania and Imperial College London used AR technology with swarm drones that can collectively 3D-print material while in flight to build and repair structures (K. Zhang et al., 2022). To take advantage of AR systems in BIM, some Commercial tools are available. Microsoft HoloLens enables users to overlay Revit models directly onto construction sites, providing real-time spatial visualization (Park et al., 2021). The polySpectra's "Massless" AR utility allows users to view Stereolithography Standard Tessellation Language (STL) files in real-world environments before 3D printing (Massless Prototyping an Alternative to 3D-Printed Physical Parts, n.d.). Autodesk's AR solutions let users visualize 3D prototypes in real-world environments, detecting design flaws before building physical prototypes, while Unity Technologies provides industrial AR platforms for complex assembly procedures (What Is AR in Manufacturing?, n.d.). Arvizio's mixed reality solutions automatically render point-cloud data from 3D scanners for HoloLens headsets, enabling simultaneous collaboration through virtual display channels while accessing project data and video communications (Jackson, 2018). Figure 5 illustrates various applications of augmented reality in additive manufacturing, including tools that enhance advanced design and fabrication processes.

Augmented Reality (AR) for facilitate additive manufacturing

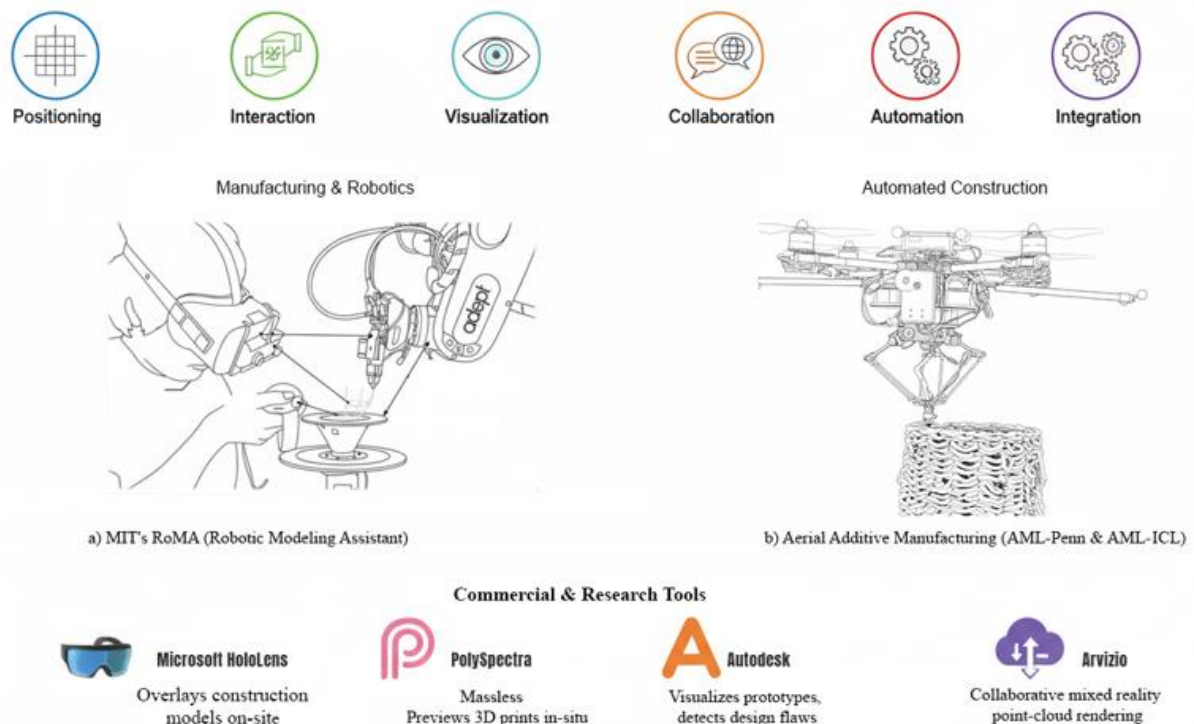


Figure 5: Augmented Reality (AR) Applications in Additive Manufacturing: a) MIT's RoMA (Robotic Modeling Assistant) - an AR-integrated system enabling users to design CAD models while a robotic arm simultaneously fabricates components; b) Aerial Additive Manufacturing Systems (AML-Penn & AML-ICL) - swarm drone technologies utilizing AR for collaborative in-flight 3D printing, aimed at construction and repair tasks. The figure includes both commercial and research-based tools demonstrating advanced AR capabilities in design and fabrication.

One significant benefit of integrating BIM with AM in construction is the ability to generate digital twin models of 3D-printed components (Slepicka et al., 2024). Digital twins offer a real-time virtual representation of physical construction processes and the resulting built assets (Kaur et al., 2020). Unlike static BIM models, digital twins maintain dynamic synchronization between physical reality and their digital counterparts throughout the

construction and operational lifecycle (Rojas & Hasanzadeh, 2024). To achieve accurate digital twin models, a network of sensors must continuously record and transmit real-time data.

The Internet of Things (IoT) serves as the backbone infrastructure, transforming individual sensing devices into a shared monitoring ecosystem (Jedermann et al., 2023). Based on a review of current research on sensor applications in AM for construction, this study categorizes sensor networks into three primary groups, each addressing critical aspects of the 3D printing process:

3.1.1 Environmental monitoring sensors

- Temperature sensors monitor material curing processes, helping prevent cracking in concrete (Q. Zhang, Li, et al., 2025);
- Humidity sensors assess moisture levels in both materials and ambient conditions (Farhan et al., 2023).

3.1.2 Process control sensors

- Pressure sensors detect blockages and monitor material flow within delivery systems (Huang et al., 2019);
- Flow rate sensors ensure even material distribution, maintaining consistent layer thickness as designed (Ahi et al., 2024).

3.1.3 Structural health monitoring sensors

- Stress and strain sensors provide real-time feedback on structural integrity during layer-by-layer printing (Duan et al., 2024);
- Self-sensing concrete enables long-term monitoring of building performance throughout its lifecycle (Civera et al., 2025).

Advanced scanning technologies enhance quality control in digital fabrication. 3D laser scanning and computer vision systems serve dual roles: capturing millions of data points to generate detailed point clouds of site conditions and topography, and enabling robotic construction systems to operate with precision (Bhatarai et al., 2025; Civera et al., 2025). During printing, these systems support real-time quality assurance by detecting dimensional deviations from design specifications and monitoring critical factors such as layer settling, which can affect structural integrity (Sacks et al., 2018).

IoT networks unify these sensor categories, generating large datasets that feed into digital twin models via wireless systems such as cellular IoT, LoRa networks, and edge computing platforms (Biagini et al., 2024; Milani et al., 2024). Commercial solutions like EXACT exemplify this integration by offering continuous data streaming through always-on IoT connections (How Technology Can Help Monitor Concrete Infrastructure, 2022).

Figure 6 illustrates the integrated digital ecosystem for 3D concrete printing, highlighting the interconnection between BIM-AM collaboration tools, IoT sensor networks, real-time monitoring systems, and digital twin implementation.

3.2 BIM platform for 3DCP

The three core elements of (3DCP)—Material, Design, and Fabrication each involve distinct specifications and considerations (Additive Manufacturing — General Principles — Fundamentals and Vocabulary, n.d.). This section examines how digital tools integrated into BIM platforms, or able to work with them, support these elements either separately or as part of a unified system. The focus here is on concrete, the main material discussed in this review. Effective 3D concrete printing relies on four essential material properties:

- Workability: Optimal consistency and setting time to ensure proper layer bonding;
- Buildability: Structural integrity and yield strength to prevent deformation during printing;
- Extrudability: Smooth material flow without segregation or blockages;
- Pumpability: Suitable viscosity for efficient transport without phase separation.

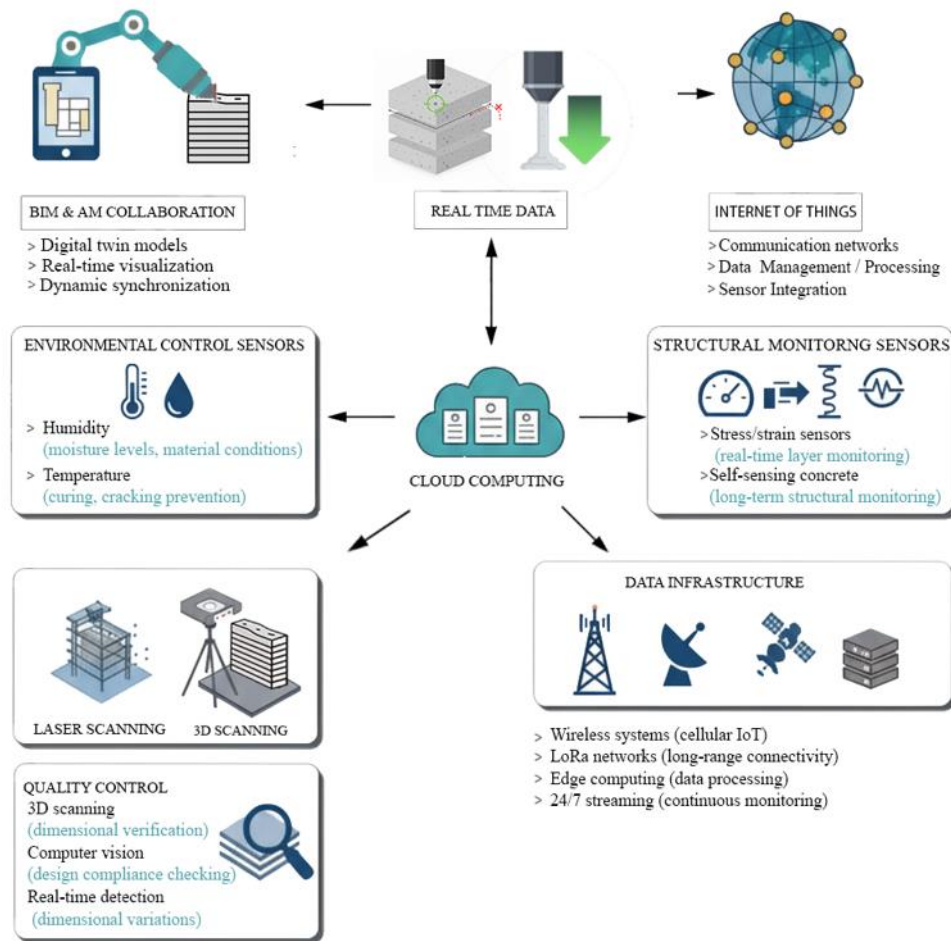


Figure 6: Integrated digital ecosystem for 3D concrete printing. The diagram illustrates the interconnected components of a comprehensive digital ecosystem for additive manufacturing in construction. It highlights the integration of BIM–AM collaboration tools, IoT sensor networks for real-time environmental and structural monitoring, laser scanning systems for quality control, and digital twin implementation. Cloud computing serves as the central hub, enabling seamless data exchange and synchronization across all systems.

BIM platforms can store material specifications, mix designs, and property requirements in structured formats, maintaining these as static parameters (Sacks et al., 2018). Unlike conventional STL file formats, BIM links material data to geometric models via Industry Foundation Classes (IFC). Forcael et al. (2021) demonstrated how BIM can convey material characterization data and spatial relationships using parametric logic, organizing information into categories, families, and elements to allow direct communication between Revit models and robotic arms for concrete printing (Forcael et al., 2021). The Printing Information Modeling (PIM) framework developed by Peralta Abadia et al. (2020) further illustrates BIM’s ability to structure data into three abstract classes: material, geometry, and process. Similarly, Davtalab et al. (2017) introduced POCSAC (Planning and Operations Control Software for Automated Construction), a specialized platform that bridges BIM and robotic construction systems. POCSAC converts IFC-format data from Revit into optimized toolpaths for contour crafting robots, while also managing material procurement and site planning (Davtalab et al., 2018). While BIM supports monitoring through comparisons of “as-built” versus “as-designed” models (Slepicka et al., 2021), controlling concrete rheology, setting time, and structural performance requires integration with external hardware systems. The Digital Twin ecosystem proposed by Rojas and Hasanzadeh (2024) enhances BIM with real-time feedback, incorporating IoT sensors, AI algorithms, and computer vision to dynamically optimize material properties during 3DCP (Rojas & Hasanzadeh, 2024). Figure 7 conceptualizes this development of highly integrated systems as a

hierarchical structure where material properties—workability, buildability, extrudability, and pumpability—flow through the BIM integration platform to support real-time control and feedback mechanisms.

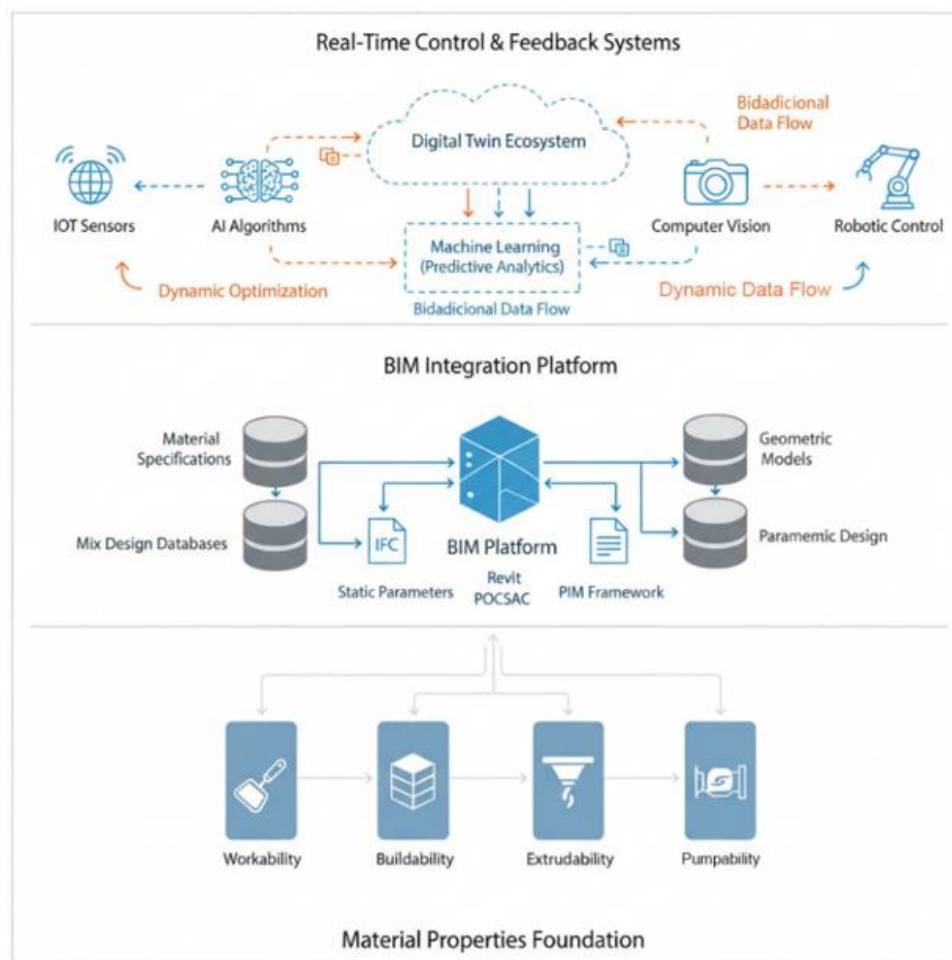


Figure 7: Hierarchical framework for BIM-integrated 3DCP. The diagram presents three operational layers: (top) real-time control and feedback systems; (middle) BIM integration platform managing material specifications, mix design databases, geometric models, and parametric design; and (bottom) material properties foundation, featuring the four critical printability parameters—workability, buildability, extrudability, and pumpability.

Li et al. (2022) introduced a practical decision support framework demonstrating BIM’s ability for knowledge-driven material management through adaptive feedback loops (C. Li et al., 2022).

In the NASA Centennial Challenge, Muthumanickam et al. integrated machine learning into BIM frameworks to enable predictive analytics using real-time data from physical tests with computer vision sensors (Kumar Muthumanickam et al., 2021). Anane et al. (2023) described the transition from loosely coupled to tightly integrated systems, where API-based connections allow BIM platforms like Revit to send print commands to robotic arms while sustaining bidirectional data flow for material adjustments based on performance feedback (Anane et al., 2023a). Ongoing research on concrete properties for 3DCP includes fiber reinforcement (steel, polypropylene, basalt, glass fibers), functionally graded concrete with varying density, porosity, and composition across layers or regions, and reinforced concrete printing with integrated reinforcement. Advanced computational methods are being developed to optimize printing procedures and predict material behavior (Cheng et al., 2024).

However, most studies focus on the feasibility of using these materials for single-element fabrication. A key future application of BIM combined with emerging technologies is the large-scale implementation of these concrete modifications in additive construction, which requires precise control over multiple design and printing parameters.

3.3 Geometric design and performance optimization

Within the scope of this review, the design process in 3DCP encompasses both geometric modeling and toolpath generation (Alhussain et al., 2024). Geometry is shaped by architectural intent as well as structural, thermal, and sustainability performance requirements. Once defined, the geometry must be translated into toolpaths and evaluated against printing criteria such as local and global overhangs, layer adhesion, and buildability constraints (Duarte et al., 2024). Designers can leverage parametric modeling tools and generative design methods, such as the shape grammar approach (Tabassum et al., 2023), to explore innovative geometries, including curved walls, cavity patterns, and topologically optimized structures. These designs are not only visually compelling but also aim to enhance structural efficiency, thermal performance, and material usage. The typical workflow for structural evaluation in 3DCP involves exporting geometry from BIM or other 3D modeling platforms to finite element analysis (FEA) software such as ANSYS or Abaqus (Vantighem et al., 2021). While these tools are robust, they are computationally intensive and often too slow for the rapid, iterative cycles required in parametric design environments.

To address this, some studies have adopted Karamba3D, a structural analysis plugin for Grasshopper 3D, which enables parametric simulation and display FEA results quickly. Duarte et al. developed a 3DCP workflow using Karamba3D, demonstrating how constrained optimization and strategic fabrication sequencing can maintain structural buildability (Duarte et al., 2024). Similarly, Wu et al. created buckling simulation tools within Karamba3D to predict failure modes in fresh concrete structures, allowing real-time structural analysis in parametric environments (ShaunWu, 2020). Despite these advances, Karamba3D has limitations, particularly in handling volumetric models and simulating functionally graded concrete—areas that remain open for further research. Thermal performance analysis follows a similar pattern, typically involving transferring BIM data to Building Energy Modeling (BEM) platforms. The automated BIM-to-BEM workflow has emerged as a key method for streamlining this process (An et al., 2024). Kamel and Kazemian's framework demonstrates how gbXML and The Industry Foundation Classes (IFC) schemas can bridge BIM tools (e.g., Revit) with energy simulation engines like OpenStudio/EnergyPlus, enabling direct geometric-to-thermal data transfer (Kamel & Kazemian, 2023). This approach improves workflow efficiency for complex 3D-printed geometries that are difficult to model using traditional energy simulation tools. Research also shows that thermal conductivity variations in 3D-printable concrete can be integrated into BIM-based thermal models, allowing for performance optimization during the design phase (Kamel & Kazemian, 2023). However, modeling the thermal behavior of functionally graded materials remains challenging in standard BIM environments and requires further development.

3.4 Slicing and path generation strategies

In additive manufacturing, a toolpath specifies the machine instructions for motion, deposition rate, and related parameters that transform a digital model into a physical object (*ISO 6983-1*, n.d.). In 3D concrete printing, the workflow typically begins with a solid or surface CAD model, built using Constructive Solid Geometry (CSG) or Boundary Representation (B-rep), which is exported as an STL file and sliced into cross-sections that carry surface-geometry information (Craveiro et al., 2019). Although structural and thermal analyses guide the initial design, toolpath generation imposes its own constraints: layer orientation, infill pattern, and deposition sequence influence structural anisotropy and thermal bridging, so toolpath design and performance simulation must inform one another iteratively (Vantighem et al., 2020). A range of digital tools now supports slicing and toolpath generation within parametric design environments. Dynamo for Revit enables slicing and toolpath control directly within the BIM environment (Weng et al., 2021), while Grasshopper for Rhino provides scripting for slicing, simulation, and robot-code export through a set of purpose-built plugins. Several of these tools target concrete or large-format printing. Concre3DLab (Vantighem et al., 2021), Ovenbird (Zhi et al., 2025), Termite (Termite, 2023), and the general-purpose Droid (Droid, 2018) offer capabilities such as voxelization and simulation-file generation, deformation analysis, robot-code conversion, gradient multi-material printing, and travel-path optimization. As the present authors have not independently tested all of these tools, this discussion relies on the developers' documented descriptions. Conventional horizontal slicing has known limitations, prompting alternative strategies (Carneau et al., 2020). Non-parallel slicing connects the bottom and top surfaces via a rotating center point and a curved guide, producing membrane-like formwork suited to freeform geometries and optimized stress distribution

(Tabassum & Pinto Duarte, 2024). Creased slicing treats each surface of a complex shape separately, enabling formwork-free printing of curved surfaces (Lowke et al., 2024). Toolpaths can also be aligned with principal stress lines identified through graphic statics, linking fabrication directly to structural behavior (Zhi et al., 2024).

Whatever the slicing strategy, an effective toolpath must manage overhangs, ensure inter-layer adhesion, and maintain buildability, defined as the capacity of deposited filaments to hold their shape under the load of subsequent layers (Lowke et al., 2024). Real-time feedback is increasingly central to meeting these requirements, particularly buildability, defined as the capacity of deposited filaments to retain their shape and structural stability under the load of subsequent layers (Lowke et al., 2024). Toolpath datasets derived from G-code enable the monitoring of deposition quality across varying layer orientations and thicknesses, while material-aware strategies embed concrete properties such as workability, open time, extrudability, pumpability, and flowability within BIM objects. This integration allows printing parameters to be adjusted dynamically as slicing orientation and layer geometry evolve (Slepicka et al., 2024; Wolfs et al., 2024).

3.5 BIM-based strategies for managing the fabrication process

Building on the preceding discussion of material control and Design for Additive Manufacturing (DfAM) workflows, this section turns to BIM-based strategies for managing fabrication. Across the reviewed frameworks, sophistication increases along three dimensions: data exchange has moved from static file transfers to dynamic, API-based communication that preserves parametric relationships; the information managed has expanded from geometry alone to include material properties, process parameters, environmental conditions, and structural performance; and Feedback has evolved from post-print comparison of the finished object against the intended model to real-time sensor integration that enables adaptive control during printing.

Early efforts established the basic link between BIM and robotic fabrication. POCSAC used the IFC format to connect Revit models to Contour Crafting robots and to manage robot families and material structure within BIM (Davtalab et al., 2018). The Printing Information Modeling (PIM) framework organized manufacturing data into material, geometry, and process classes to capture interactions between concrete rheology and printing parameters (Abadia et al., 2023). Subsequent frameworks closed the digital–physical loop more tightly. Fabrication Information Modeling (FIM), developed by Derou et al. and extended by Slepicka and colleagues, combined real-time data exchange, IoT sensor networks, and automated quality control (Slepicka et al., 2024). Forcael et al. eliminated lossy format conversion through direct, bidirectional Revit–KUKA communication with laser-scanning verification (Forcael et al., 2021). The most recent proposals extend integration toward autonomy and scale. The digital-twin architecture of Rojas and Hasanzadeh transforms static models into dynamic systems through a seven-layer cyber-physical structure (Rojas & Hasanzadeh, 2024), and the NASA Centennial Challenge system of Muthumanickam et al. incorporates machine-learning prediction, computer-vision feedback, and functionally graded materials at large scale (Kumar Muthumanickam et al., 2021).

Anane et al. frame these differences as a spectrum of coupling. Loosely coupled systems rely on file exchange and format conversion, offering simplicity at the cost of bidirectional communication; moderately coupled systems use visual programming and parametric design within a unified environment to support rapid iteration. Tightly coupled systems, built on API-based or direct BIM–robot links, achieve the highest synchronization but demand the most technical infrastructure (Anane et al., 2023a). Table 3 summarizes the reviewed frameworks along these lines, comparing their data-exchange methods, integration depth, and feedback mechanisms.

Table 3: Comparison of BIM-Driven Fabrication Frameworks.

Framework	Year	Key Innovation	Data Exchange	Toolpath Generation	Feedback Mechanism	Primary Scope
POCSAC (Davtalab et al.)	2017	First BIM-CC integration	IFC format	POCSAC optimization	Material testing phase	Robot definition, site planning, material procurement
PIM (Peralta Abadia et al.)	2020	Semantic three-class system	IFC enhanced	CNC command generation	Metamodeling approach	Material-geometry-process interaction
FIM (Slepicka et al.)	2015-2024	Digital-physical loop closure	Multi-format, RTDE	Integrated multi-platform	Real-time IoT, laser feedback, automated QC	Digital fabrication lifecycle
Direct Communication (Forcael et al.)	2021	Eliminates format conversion	Revit-Dynamo native	Dynamo visual programming	Laser scanning point cloud	BIM-to-robot direct protocols
Tightly Coupled (Anane et al.)	2023	Integration classification	API/Speckle/native	Multiple methods	Cloud-based collaboration	Framework analysis
DT Ecosystem (Rojas & Hasanzadeh)	2024	Real-time BIM enhancement	IoT + Cloud APIs	AI-optimized	IoT sensors, CV, AI/ML	Seven-layer cyber-physical architecture
NASA Framework (Muthumanickam et al.)	2021	ML predictive analytics	Dynamo-based	ML-optimized with CV	Computer vision sensors	Large-scale, FGM, extraterrestrial construction



4. DISCUSSION

BIM is shifting from a simple modeling tool to a comprehensive coordinating platform, integrating material specifications and parametric geometry through slicing and toolpath creation within a unified system. Mature frameworks show that this coordination extends to physical fabrication: Fabrication Information Modeling and the Direct Communication approach have proven viable on actual construction projects (Slepicka et al., 2024; Forcael et al., 2021). Systems with tight API-based integration enable bidirectional data flow, real-time feedback, and laser-scanning verification. This demonstrates the potential for transitioning from detailed BIM models to monitored, robotic fabrication, at least in controlled environments.

However, this apparent progress is inconsistent and fragile. Validation mainly covers individual phases rather than entire project lifecycles. Some comprehensive proposals, like POCSAC and digital-twin ecosystems, remain conceptual, not fully demonstrated (Rojas & Hasanzadeh, 2024). The gap between theory and practice persists, exacerbated by reliance on file format conversions that risk losing or corrupting data. Quality assurance is fragmented: semantic validation, real-time sensor corrections, and laser scans address different stages but lack integration, often reflecting application-specific priorities instead of standardized practices. Environmental effects on materials are poorly captured, and the high computational costs of real-time simulation and machine learning limit their use during active fabrication. Avoiding these challenges typically requires tightly coupled systems that demand infrastructure and expertise beyond what most firms can provide, making it harder to implement solutions for integration issues.

These limitations highlight the remaining work. Reducing reliance on data conversions requires lightweight standards and ontologies for additive manufacturing that retain key parameters while reducing computational load, building on PIM's semantic base. Incorporating structural analysis directly into parametric BIM models would enable toolpath adjustments based on performance feedback, integrating design and analysis. Embedding environmental sensing more closely into concrete rheology models could improve print reliability. Finally, hierarchical sensor systems focusing on critical print quality parameters, rather than exhaustive data collection, may make in-process monitoring feasible at an industrial scale.

5. CONCLUSION

Despite significant academic interest in 3D concrete printing, a major challenge lies in bridging research validation with real-world application. As this review has shown, that gap is rooted in the sensitivity of print quality to many interacting parameters, a source of risk that industry remains reluctant to absorb. BIM, coupled with IoT sensing, digital twins, and augmented reality, offers a credible path forward, but the evidence so far validates individual phases rather than complete project lifecycles.

Answering this gap will depend less on pursuing full end-to-end system integration than on a few targeted advances. Three directions are most promising: lightweight data-exchange standards that preserve critical fabrication information at lower computational cost; hierarchical sensor arrangements that isolate the parameters most decisive for print quality, enabling targeted rather than exhaustive monitoring; and validation protocols for BIM-AM workflows that can be exercised in controlled industrial settings to generate empirical evidence of improved reliability. Advancing these specific fronts offers a practical route to establishing 3DCP as a dependable industrial practice.

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Conflicts of Interest: Dr. Duarte and The Pennsylvania State University own equity in X-HAB 3D, whose activity is related to concrete printing. Their ownership in this company has been reviewed by the University's Individual and Institutional Conflict of Interest Committees and is currently being managed by the University. Jose Pinto Duarte has equity in a company, X-Hab 3D, whose activity is related to concrete printing.

REFERENCES

- Abadia, P. P., Ahmad, M. E., & Smarsly, K. (2023). Printing Information Modeling (PIM) for Additive Manufacturing of Concrete Structures. *Applied Sciences*, 13(23). <https://doi.org/10.3390/app132312664>
- Additive manufacturing—General principles—Fundamentals and vocabulary. (n.d.). Retrieved November 16, 2025, from <https://store.astm.org/f3177-21.html>
- Ahi, O., Ertunc, O., Bundur, Z., & Bebek, Ö. (2024). Automated flow rate control of extrusion for 3D concrete printing incorporating rheological parameters. *AUTOMATION IN CONSTRUCTION*, 160. (WOS:001182009800001). <https://doi.org/10.1016/j.autcon.2024.105319>
- Ahmed, G. H. (2023). A review of “3D concrete printing”: Materials and process characterization, economic considerations and environmental sustainability. *Journal of Building Engineering*, 66, 105863. <https://doi.org/10.1016/j.jobe.2023.105863>
- Ahsan, M. M., Liu, Y., Raman, S., & Siddique, Z. (2024). Digital Twins in Additive Manufacturing: A Systematic Review (arXiv:2409.00877). *arXiv*. <https://doi.org/10.48550/arXiv.2409.00877>
- Alhussain, A., Duarte, J., & Brown, N. (2024). Developing a data-driven filament shape prediction model for 3D concrete printing. *FRONTIERS IN BUILT ENVIRONMENT*, 10. (WOS:001182618300001). <https://doi.org/10.3389/fbuil.2024.1363370>
- Al-Tamimi, A., Alqamish, H., Khaldoune, A., Alhaidary, H., & Shirvanimoghaddam, K. (2023). Framework of 3D Concrete Printing Potential and Challenges. *BUILDINGS*, 13(3). (WOS:000954161000001). <https://doi.org/10.3390/buildings13030827>
- An, N., Li, X., Yang, H., Pang, X., Gao, G., & Ding, D. (2024). From Building Information Modeling to Building Energy Modeling: Optimization Study for Efficient Transformation. *Buildings*, 14(8), 2444. <https://doi.org/10.3390/buildings14082444>
- Anane, W., Iordanova, I., & Ouellet-Plamondon, C. (2023a). The Use of BIM for Robotic 3D Concrete Printing. In S. Walbridge, M. Nik-Bakht, K. T. W. Ng, M. Shome, M. S. Alam, A. el Damatty, & G. Lovegrove (Eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021* (pp. 325–336). Springer Nature. https://doi.org/10.1007/978-981-19-1029-6_25
- Anane, W., Iordanova, I., & Ouellet-Plamondon, C. (2023b). The Use of BIM for Robotic 3D Concrete Printing. In S. Walbridge, M. Nik-Bakht, K. T. W. Ng, M. Shome, M. S. Alam, A. el Damatty, & G. Lovegrove (Eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021* (pp. 325–336). Springer Nature. https://doi.org/10.1007/978-981-19-1029-6_25
- Aslam, M., Baffoe-Twum, E., & Saleem, F. (2019). Design Changes in Construction Projects – Causes and Impact on the Cost. *Civil Engineering Journal*, 5(7), 1647–1655. <https://doi.org/10.28991/cej-2019-03091360>
- Baghalzadeh Shishehgharkhaneh, M., Keivani, A., Moehler, R. C., Jelodari, N., & Roshdi Laleh, S. (2022). Internet of Things (IoT), Building Information Modeling (BIM), and Digital Twin (DT) in Construction Industry: A Review, Bibliometric, and Network Analysis. *Buildings*, 12(10), 1503. <https://doi.org/10.3390/buildings12101503>
- Bassyouni, Z., & Elhajj, I. H. (2021). Augmented Reality Meets Artificial Intelligence in Robotics: A Systematic Review. *Frontiers in Robotics and AI*, 8. <https://doi.org/10.3389/frobt.2021.724798>
- Batikha, M., Jotangia, R., Baaj, M., & Mousleh, I. (2022a). 3D concrete printing for sustainable and economical construction: A comparative study. *AUTOMATION IN CONSTRUCTION*, 134. (WOS:000740339100001). <https://doi.org/10.1016/j.autcon.2021.104087>
- Batikha, M., Jotangia, R., Baaj, M. Y., & Mousleh, I. (2022b). 3D concrete printing for sustainable and economical construction: A comparative study. *Automation in Construction*, 134, 104087. <https://doi.org/10.1016/j.autcon.2021.104087>
- Bhatarai, R., Banihashemi, S., Shakouri, M., & Antwi-Afari, M. (2025). Integration of Augmented Reality with Building Information Modeling: Design Optimization and Construction Rework Reduction Perspective.

- Archives of Computational Methods in Engineering, 32(4), 2233–2254. <https://doi.org/10.1007/s11831-024-10211-6>
- Biagini, C., Bongini, A., & Marzi, L. (2024). From BIM to digital twin. IOT data integration in asset management platform. *Journal of Information Technology in Construction (ITcon)*, 29(49), 1103–1127. <https://doi.org/10.36680/j.itcon.2024.049>
- Brozovsky, J., Labonnote, N., & Vigren, O. (2024). Digital technologies in architecture, engineering, and construction. *Automation in Construction*, 158, 105212. <https://doi.org/10.1016/j.autcon.2023.105212>
- Carneau, P., Mesnil, R., Roussel, N., & Baverel, O. (2020). Additive manufacturing of cantilever—From masonry to concrete 3D printing. *Automation in Construction*, 116, 103184. <https://doi.org/10.1016/j.autcon.2020.103184>
- Cheng, H., Radlinska, A., Hillman, M., Liu, F., & Wang, J. (2024). Modeling concrete deposition via 3D printing using reproducing kernel particle method. *CEMENT AND CONCRETE RESEARCH*, 181. (WOS:001237923400001). <https://doi.org/10.1016/j.cemconres.2024.107526>
- Civera, M., Naseem, A., & Chiaia, B. (2025). Recent advances in embedded technologies and self-sensing concrete for structural health monitoring. *Structural Concrete*, 26(5), 5300–5334. <https://doi.org/10.1002/suco.202400714>
- Craveiro, F., Duarte, J. P., Bartolo, H., & Bartolo, P. J. (2019). Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0. *Automation in Construction*, 103, 251–267. <https://doi.org/10.1016/j.autcon.2019.03.011>
- Davtalab, O., Kazemian, A., & Khoshnevis, B. (2018). Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. *Automation in Construction*, 89, 13–23. <https://doi.org/10.1016/j.autcon.2018.01.006>
- Derazgisou, S., Bausys, R., & Fayaz, R. (2018). Computational optimization of housing complexes forms to enhance energy efficiency. *Journal of Civil Engineering and Management*, 24(3), 193–205.
- Dogan, M. D., Baudisch, P., Benko, H., Nebeling, M., Peng, H., Savage, V., & Mueller, S. (2022). Fabricate It or Render It? Digital Fabrication vs. Virtual Reality for Creating Objects Instantly. Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems, CHI EA '22, 1–4. <https://doi.org/10.1145/3491101.3516510>
- Duan, Z., Deng, Q., Xiao, J., Lv, Z., & Hu, B. (2024). Experimental realization on stress distribution monitoring during 3D concrete printing. *Materials Letters*, 358, 135878. <https://doi.org/10.1016/j.matlet.2024.135878>
- Duarte, G., Duarte, J., Brown, N., Memari, A., & Gevaudan, J. (2024). Design for early-age structural performance of 3D printed concrete structures: A parametric numerical modeling approach. *JOURNAL OF BUILDING ENGINEERING*, 94. (WOS:001259731800001). <https://doi.org/10.1016/j.jobbe.2024.109986>
- El-Sayegh, S., Romdhane, L., & Manjikian, S. (2020). A critical review of 3D printing in construction: Benefits, challenges, and risks. *Archives of Civil and Mechanical Engineering*, 20(2), 34. <https://doi.org/10.1007/s43452-020-00038-w>
- Fakhr Ghasemi, A., & Pinto Duarte, J. (2025). A Systematic Review of Innovative Advances in Multi-Material Additive Manufacturing: Implications for Architecture and Construction. *Materials*, 18(8), 1820. <https://doi.org/10.3390/ma18081820>
- Farhan, K. Z., Shihata, A. S., Anwar, M. I., & Demirboğa, R. (2023). Temperature and humidity sensor technology for concrete health assessment: A review. *Innovative Infrastructure Solutions*, 8(10), 276. <https://doi.org/10.1007/s41062-023-01255-x>
- Fasihi, A., & Libre, N. A. (2024). From pumping to deposition: A Comprehensive review of test methods for characterizing concrete printability. *Construction and Building Materials*, 414, 134968. <https://doi.org/10.1016/j.conbuildmat.2024.134968>

- Forcael, E., Pérez, J., Vásquez, Á., García-Alvarado, R., Orozco, F., & Sepúlveda, J. (2021). Development of Communication Protocols between BIM Elements and 3D Concrete Printing. *Applied Sciences*, 11(16), 7226. <https://doi.org/10.3390/app11167226>
- Goharian, A., Mahdavinnejad, M., Ghazazani, S., Hosseini, M., Zamani, Z., Yavari, H., Ghafarpour, F., & Shoghi, F. (2025). Designing Adaptability Strategy to a Novel Kinetic Adaptive Façade (NKAF): Toward a Pioneering Method in Dynamic-objects Daylight Simulation (Post-Processing). *Journal of Daylighting*, 12(1), 69–90. <https://doi.org/10.15627/jd.2025.5>
- Hossain, M. A., Zhumabekova, A., Paul, S. C., & Kim, J. R. (2020). A Review of 3D Printing in Construction and its Impact on the Labor Market. *Sustainability*, 12(20). <https://doi.org/10.3390/su12208492>
- How Technology Can Help Monitor Concrete Infrastructure. (2022, February 14). For Construction Pros. <https://www.forconstructionpros.com/concrete/equipment-products/technology-services/article/22043292/how-technology-can-help-monitor-concrete-infrastructure>
- Huang, Y., Fan, X., Chen, S.-C., & Zhao, N. (2019). Emerging Technologies of Flexible Pressure Sensors: Materials, Modeling, Devices, and Manufacturing. *Advanced Functional Materials*, 29(12), 1808509. <https://doi.org/10.1002/adfm.201808509>
- ISO 6983-1:2009. (n.d.). ISO. Retrieved November 17, 2025, from <https://www.iso.org/standard/34608.html>
- Jedermann, R., Singh, K., Lang, W., & Mahajan, P. (2023). Digital twin concepts for linking live sensor data with real-time models. *Journal of Sensors and Sensor Systems*, 12(1), 111–121. <https://doi.org/10.5194/jsss-12-111-2023>
- Kamel, E., & Kazemian, A. (2023). BIM-integrated thermal analysis and building energy modeling in 3D-printed residential buildings. *Energy and Buildings*, 279, 112670. <https://doi.org/10.1016/j.enbuild.2022.112670>
- Kaur, M. J., Mishra, V. P., & Maheshwari, P. (2020). The Convergence of Digital Twin, IoT, and Machine Learning: Transforming Data into Action. In M. Farsi, A. Daneshkhah, A. Hosseinian-Far, & H. Jahankhani (Eds.), *Digital Twin Technologies and Smart Cities* (pp. 3–17). Springer International Publishing. https://doi.org/10.1007/978-3-030-18732-3_1
- Keles, C., Rios, F. C., & Hoque, S. (2025). Digital Technologies and Circular Economy in the Construction Sector: A Review of Lifecycle Applications, Integrations, Potential, and Limitations. *Buildings*, 15(4). <https://doi.org/10.3390/buildings15040553>
- Kumar Muthumanickam, N., Pinto Duarte, J., Nazarian, S., Bilén, S. G., & Memari, A. (2021). BIM for Design Generation, Analysis, Optimization, and Construction Simulation of a Martian Habitat. 1208–1219. <https://doi.org/10.1061/9780784483374.112>
- Lawrence, T. M., Watson, R. T., Boudreau, M.-C., Johnsen, K., Perry, J., & Ding, L. (2012). A new paradigm for the design and management of building systems. *Energy and Buildings*, 51, 56–63. <https://doi.org/10.1016/j.enbuild.2012.04.016>
- Li, C., Zahedi, A., & Petzold, F. (2022). Pragmatic Design Decision Support for Additive Construction Using Formal Knowledge and Its Prospects for Synergy with a Feedback Mechanism. *Buildings*, 12(12), 2072. <https://doi.org/10.3390/buildings12122072>
- Li, S. (2025, January 10). Construction Key Themes 2025: Rebound in sight. Oxford Economics. <https://www.oxfordeconomics.com/resource/construction-key-themes-2025-rebound-in-sight/>
- Lowke, D., Anton, A., Buswell, R., Jenny, S., Flatt, R., Fritsch, E., Hack, N., Mai, I., Popescu, M., & Kloft, H. (2024). Digital fabrication with concrete beyond horizontal planar layers. *CEMENT AND CONCRETE RESEARCH*, 186. (WOS:001308434400001). <https://doi.org/10.1016/j.cemconres.2024.107663>
- Massless Prototyping an Alternative to 3D-Printed Physical Parts. (n.d.). Retrieved September 23, 2026, from <https://www.plasticstoday.com/3d-printing/-massless-prototyping-an-energy-saving-alternative-to-3d-printed-physical-parts>

- Milani, S., Garlisi, D., Carugno, C., Tedesco, C., & Chatzigiannakis, I. (2024). Edge2LoRa: Enabling edge computing on long-range wide-area Internet of Things. *Internet of Things*, 27, 101266. <https://doi.org/10.1016/j.iot.2024.101266>
- Mohsenian, S., Keivan, Z., Jafari, A. M., Haghighatjoo, M., & Mirzamohammadi, M. (2026). Privacy aware synthetic building energy data for cross building generalization. *Discover Artificial Intelligence*. <https://doi.org/10.1007/s44163-026-01525-4>
- Monfaredi, P., & Memari, A. (2026). Mechanical and Structural Evaluation of Carbon Geocrete as an Alternative to Portland Cement Concrete. <https://scholarsphere.psu.edu/resources/5b45e969-c524-4bc7-8076-5185ec0c419a>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71. <https://doi.org/10.1136/bmj.n71>
- Pajonk, A., Prieto, A., Blum, U., & Knaack, U. (2022). Multi-material additive manufacturing in architecture and construction: A review. *Journal of Building Engineering*, 45, 103603. <https://doi.org/10.1016/j.jobbe.2021.103603>
- Park, S., Bokijonov, S., & Choi, Y. (2021). Review of Microsoft HoloLens Applications over the Past Five Years. *Applied Sciences*, 11(16). <https://doi.org/10.3390/app11167259>
- Rathnayake, A., & Middleton, C. (2023). Systematic Review of the Literature on Construction Productivity. *Journal of Construction Engineering and Management*, 149(6), 03123005. <https://doi.org/10.1061/JCEMD4.COENG-13045>
- Raza, M. H., Besklubova, S., & Zhong, R. Y. (2024). Economic analysis of offsite and onsite 3D construction printing techniques for low-rise buildings: A comparative value stream assessment. *Additive Manufacturing*, 89, 104292. <https://doi.org/10.1016/j.addma.2024.104292>
- Rojas, J., & Hasanzadeh, S. (2024). Novel Digital Twin Architecture for 3D Concrete Printing in the AEC Industry. 1337–1346. <https://doi.org/10.1061/9780784485262.136>
- Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers. John Wiley & Sons. <https://books.google.com/books?hl=en&lr=&id=IU9mDwAAQBAJ&oi=fnd&pg=PR17&dq=BIM+Handbook:+A+Guide+to+Building+Information+Modeling+for+Owners,+Designers,+Engineers,+Contractors,+and+Facility+Managers&ots=NgovHw4rtN&sig=-09dazU0GQBAPHsLNl0lMmpYQA>
- Sharoni, L.-O., Sacks, R., Yeung, T., Alhava, O., Laine, E., & Ribon, J. M. (2023). The PICO framework for analysis and design of production systems for construction. Annual Conference of the International Group for Lean Construction. <https://bim2twin.eu/wp-content/uploads/2024/07/The-PICO-Framework-for-Analysis-and-Design-of-Production-Systems-for-Construction.pdf>
- ShaunWu. (2020, March 9). Buckling Simulation for 3D Printing in Fresh Concrete. ShaunWu. <https://shaunwu25.github.io//2020/03/09/Buckling-Simulation.html>
- Slepicka, M., & Borrmann, A. (2024). Fabrication Information Modeling for Closed-Loop Design and Quality Improvement in Additive Manufacturing for construction. *Automation in Construction*, 168, 105792. <https://doi.org/10.1016/j.autcon.2024.105792>
- Slepicka, M., Mawas, K., Borrmann, A., Maboudi, M., & Gerke, M. (2024). Digital Twinning in Additive Manufacturing—Closing the Digital-Physical-Digital Loop by Automated Integration of Captured Geometric Data into Fabrication Information Models. In S. Skatulla & H. Beushausen (Eds.), *Advances in Information Technology in Civil and Building Engineering* (pp. 459–478). Springer International Publishing. https://doi.org/10.1007/978-3-031-35399-4_34
- Slepicka, M., Vilgertshofer, S., & Borrmann, A. (2021). Fabrication Information Modeling: Closing the gap between Building Information Modeling and Digital Fabrication. *International Symposium on Automation*

- and Robotics in Construction (ISARC) Proceedings, 2021 Proceedings of the 38th ISARC, Dubai, UAE, 9–16. <https://doi.org/10.22260/ISARC2021/0004>
- Tabassum, N., Duarte, J., & Nazarian, S. (2023). Advancing 3D concrete printing for affordable housing: A shape grammar-based approach to print spanning roof structures. <https://scholar.google.com/scholar?cluster=13077571424806459339&hl=en&oi=scholar>
- Tabassum, N., & Pinto Duarte, J. (2024). Exploring Multi-Directional 3D Printing for Enclosures on Earth and Beyond: Sensitivity Analysis of Buildability. 821–832. <https://doi.org/10.1061/9780784485736.073>
- Termite. (2023, February 28). [Text]. Food4Rhino. <https://www.food4rhino.com/en/app/termite>
- Vantghem, G., Ooms, T., & De Corte, W. (2021). VoxelPrint: A Grasshopper plug-in for voxel-based numerical simulation of concrete printing. *AUTOMATION IN CONSTRUCTION*, 122. (WOS:000608116800004). <https://doi.org/10.1016/j.autcon.2020.103469>
- Vantghem, G., Steeman, M., De Corte, W., & Boel, V. (2020). Design Optimization for 3D Concrete Printing: Improving Structural and Thermal Performances. In F. P. Bos, S. S. Lucas, R. J. M. Wolfs, & T. A. M. Salet (Eds.), *Second RILEM International Conference on Concrete and Digital Fabrication* (pp. 720–727). Springer International Publishing. https://doi.org/10.1007/978-3-030-49916-7_72
- Weng, Y., Mohamed, N. A. N., Lee, B. J. S., Gan, N. J. H., Li, M., Jen Tan, M., Li, H., & Qian, S. (2021). Extracting BIM Information for Lattice Toolpath Planning in Digital Concrete Printing with Developed Dynamo Script: A Case Study. *Journal of Computing in Civil Engineering*, 35(3), 05021001. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000964](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000964)
- What is AR in Manufacturing? | Autodesk. (n.d.). Retrieved November 15, 2025, from <https://www.autodesk.com/solutions/augmented-reality>
- Wolfs, R., Bos, D., Caron, J., Gerke, M., Mesnil, R., Buswell, R., Ducoulombier, N., Hack, N., Keita, E., Kinnell, P., Mawas, K., Mechtcherine, V., Miranda, L., Sokolov, D., Versteeg, J., & Roussel, N. (2024). On-line and in-line quality assessment across all scale levels of 3D concrete printing. *CEMENT AND CONCRETE RESEARCH*, 185. (WOS:001306979400001). <https://doi.org/10.1016/j.cemconres.2024.107646>
- Zhang, K., Chermprayong, P., Xiao, F., Tzoumanikas, D., Dams, B., Kay, S., Kocer, B. B., Burns, A., Orr, L., Alhinai, T., Choi, C., Darekar, D. D., Li, W., Hirschmann, S., Soana, V., Ngah, S. A., Grillo, C., Sareh, S., Choubey, A., ... Kovac, M. (2022). Aerial additive manufacturing with multiple autonomous robots. *Nature*, 609(7928), 709–717. <https://doi.org/10.1038/s41586-022-04988-4>
- Zhang, Q., Li, Y., Huang, Y., Li, Y., Yang, Y., & Hu, Y. (2025). Utilizing 3D Printing and Distributed Optic Fiber to Achieve Temperature-Sensitive Concrete. *Materials*, 18(9), 1897. <https://doi.org/10.3390/ma18091897>
- Zhang, Q., Liu, Z., & Yang, S. (2025). Enhancing construction workers' health and safety: Mechanisms for implementing Construction 4.0 technologies in construction organizations. *Engineering, Construction and Architectural Management*, 32(13), 68–103. <https://doi.org/10.1108/ECAM-11-2024-1517>
- Zhi, Y., Chai, H., Teng, T., & Akbarzadeh, M. (2025). Automated toolpath design of 3D concrete printing structural components. *Additive Manufacturing*, 100, 104662. <https://doi.org/10.1016/j.addma.2025.104662>
- Zhi, Y., Teng, T., & Akbarzadeh, M. (2024). Designing 3D-printed concrete structures with scaled fabrication models. *Architectural Intelligence*, 3(1), 28. <https://doi.org/10.1007/s44223-024-00070-3>

APPENDIX 1-1: SCOPUS STRING

Table 4. Scopus string (article title, abstract, keywords).

N.O	Technologies space	Scopus string (article title, abstract, keywords)
1	AR – 3DCP	("3DCP" OR "3D concrete printing" OR "additive manufacturing") AND ("built environment" OR "building" OR "construction") AND ("Augmented Reality" OR "AR")
2	BIM – 3DCP	("3DCP" OR "3D concrete printing" OR "additive manufacturing") AND ("built environment" OR "building" OR "construction") AND ("Building Information Modeling" OR "BIM")
3	IOT – 3DCP	("3DCP" OR "3D concrete printing" OR "additive manufacturing") AND ("built environment" OR "building" OR "construction") AND ("IoT" OR "Internet of Things")
4	digital twin – 3DCP	("3DCP" OR "3D concrete printing" OR "additive manufacturing") AND ("built environment" OR "building" OR "construction") AND ("Digital twin")
5	3D Laser– 3DCP	("3DCP" OR "3D concrete printing" OR "additive manufacturing") AND ("built environment" OR "building" OR "construction") AND ("3D laser scanning" OR "structural health monitoring")

APPENDIX 1-2: WEB OF SCIENCE STRING

Filters: (Article or Review Article (Document Types) and English (Languages) and Construction Building Technology or Architecture (Research Areas)).

Table 5. Web of Science string.

N.O	Technologies space	Web of Science string (article title, abstract, keywords)
1	AR – 3DCP	((AK=("3DCP")) OR AK=("3d concrete printing ")) AND (AK=("Augmented Reality ")) OR AK=("AR")) link: https://www.webofscience.com/wos/woscc/summary/5c5d94ea-c1ea-4de8-8127-8d4f063fe45f-017fc06220/relevance/1
2	BIM – 3DCP	((AK=("3DCP")) OR AK=("3d concrete printing ")) AND (AK=("BIM")) OR AK=("Building Information Modeling")) link: https://www.webofscience.com/wos/woscc/summary/2f17dc15-3082-43b8-b3f2-646bd57c25f9-017fbcd30f/relevance/1
3	IOT – 3DCP	((AK=("3DCP")) OR AK=("3d concrete printing ")) AND (AK=("IOT")) OR AK=("Internet of Things")) link: https://www.webofscience.com/wos/woscc/summary/ed04910f-a408-42e5-9db9-f6261d751547-017fbc6540/relevance/1
4	digital twin – 3DCP	((AK=("3DCP")) OR AK=("3d concrete printing ")) AND (AK=("digital twin")) OR AK=("digital twins")) link: https://www.webofscience.com/wos/woscc/summary/f9655947-ce1e-441a-8d0c-74b977243f74-017fc139f0/relevance/1
5	3D Laser– 3DCP	((AK=("3DCP")) OR AK=("3d concrete printing ")) AND (AK=("3D laser scanning ")) OR AK=("structural health monitoring")) link: https://www.webofscience.com/wos/woscc/summary/accd6a3c-b7d5-4c57-9404-27f010b9ee88-017fc1e4ab/relevance/1

APPENDIX 2: BIBLIOMETRIC ANALYSIS

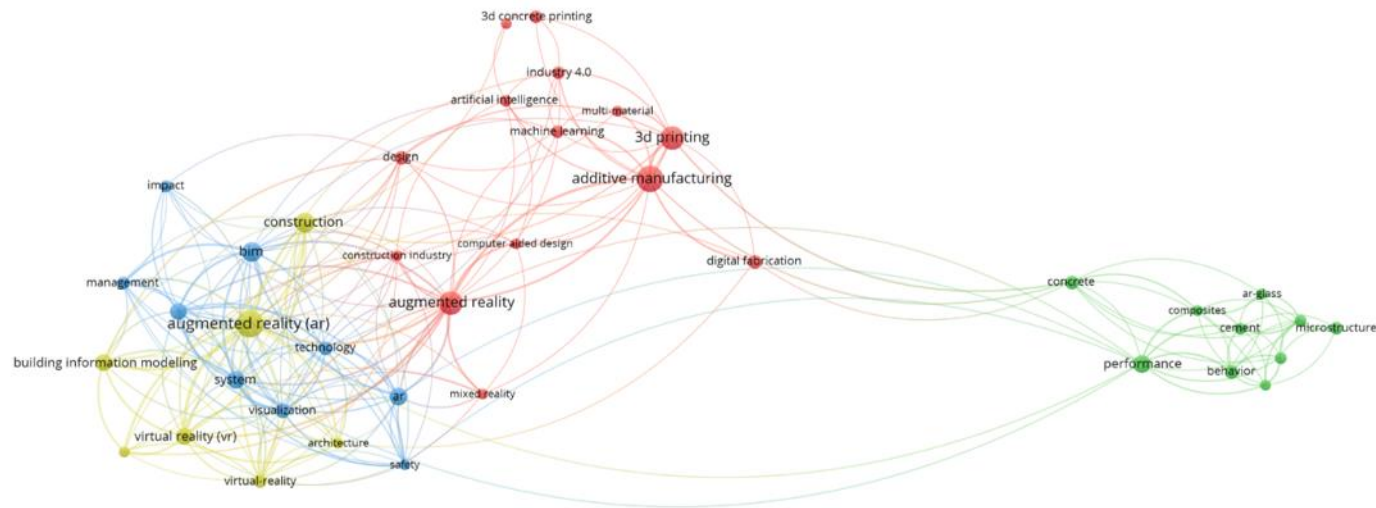


Figure 8: Reviewing Co-occurrence of authors' keywords in the literature of AR and 3DCP.

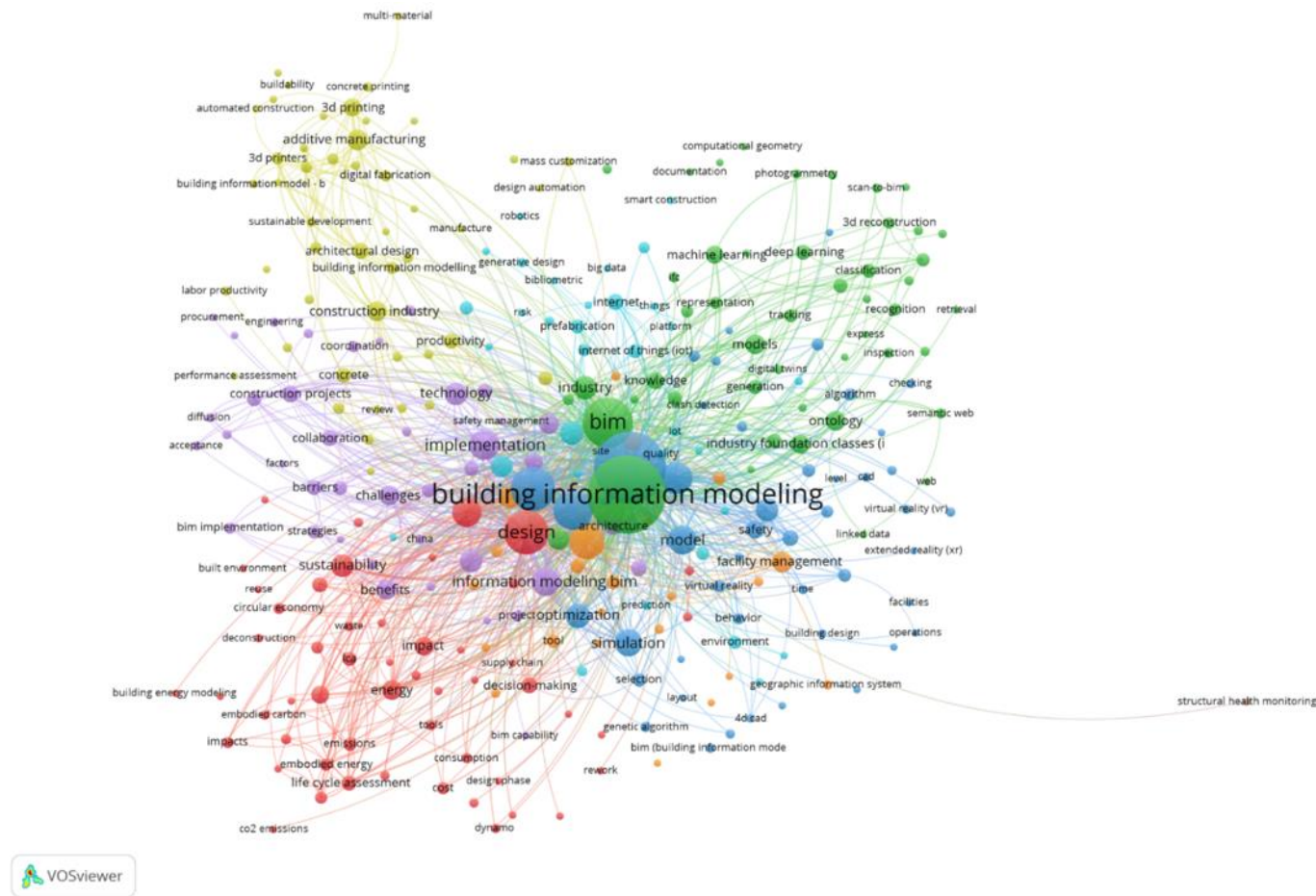


Figure 9: Reviewing Co-occurrence of authors' keywords in the literature of BIM and 3DCP.

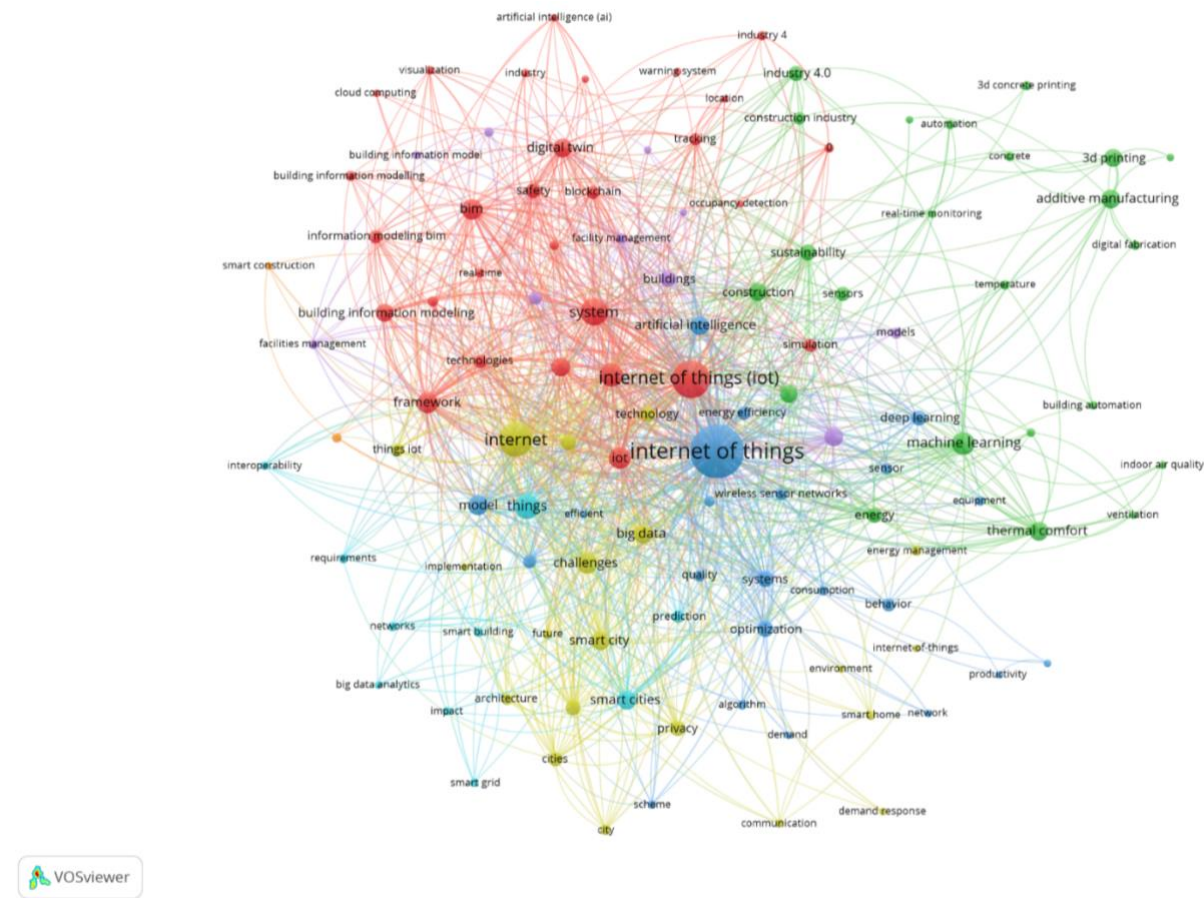


Figure 11: Reviewing Co-occurrence of authors' keywords in the literature of IOT and 3DCP.