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WORK BREAKDOWN STRUCTURE AND CONSTRUCTION PROCESS FRAMEWORK FOR A HYBRID 3D-PRINTED MODULAR BUILDING

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SUMMARY: *Hybrid construction methods that combine 3D concrete printing (3DCP) and modular precast techniques have the potential to improve precision, reduce material waste, and increase automation in building construction. Despite this potential, the lack of defined workflows and activity definitions presents a challenge for practical application. Therefore, this study develops a Work Breakdown Structure (WBS) and a construction process framework to support planning and execution in hybrid 3D-printed modular construction through a systematic review and direct observation in a digital fabrication laboratory. The review identified construction work items for 3DCP and precast modular methods and revealed four distinct sequencing patterns. Among them, one pattern that coordinates robotic-assisted 3DCP and precast concrete fabrication in parallel was identified as the most aligned with current industry practice. A five-level WBS was developed based on this pattern to organize activities across offsite and onsite phases. The WBS then informed the development of a construction process framework that outlines activity sequencing, dependencies, and automation integration points throughout the construction stages. The framework illustrates how automation can support conventional modular workflows, including robotic gantry lifting and real-time extrusion monitoring. The findings provide a foundation for future research and serve as a practical reference for coordinating fabrication and assembly activities.*

KEYWORDS: *3DCP, Modular Construction, Work Breakdown Structure, Construction Process Framework.*

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1. INTRODUCTION

The construction sector remains one of the largest contributors to global economic activity. The industry was responsible for approximately 10% of global GDP and employed over 7% of the world's working population (Gruneberg & Francis, 2018; Kaluthantirige et al., 2023). Despite its impact, the sector's overall performance is still hindered by persistent challenges, where cost overruns, project delays, low productivity, material waste, and safety incidents frequently compromise project outcomes. A recent study indicates that nearly 90% of construction projects exceed budget targets (Abdel-Monem et al., 2022). Additionally, the sector records accident rates more than twice as high as those in other industries, which continues to present a significant threat to worker safety (Heredia Morante et al., 2024).

To improve performance and reduce risk, prefabricated modular construction has gained recognition as an alternative to conventional project delivery methods (Ahmed & Gramescu, 2019). By transferring significant portions of work to controlled offsite facilities, this approach has demonstrated clear advantages, which include shorter project timelines, higher quality control, reduced material waste, and lower on-site labor requirements. Studies report that modular methods can improve project schedule performance by up to 42% (Smith & Rice, 2017) and potentially lower construction waste by up to 80% compared to traditional construction techniques (Y. Zhang & Pan, 2022). Despite these benefits, widespread adoption of the modular construction approach remains constrained by several challenges related to the rigidity of geometric design, high transportation demands, and inflexibility when responding to late-stage design changes or site-specific constraints (Thurairajah et al., 2023).

In parallel, additive manufacturing (AM) has emerged as a transformative technology within the construction domain, with 3D concrete printing (3DCP) at the forefront (Karmakar & Delhi, 2021; Zou et al., 2025). Pilot demonstrations have shown that 3DCP can produce structural components with high geometric precision, reduced workforce, and shortened delivery times (Berawi et al., 2025). For example, Win Sun showcased the potential of 3D printing in constructing ten 200 square-metre houses in a day using high-grade cement and glass fiber (Puzatova et al., 2022).

Moghayedi et al. (2024) reported that 3D printing technology can reduce total construction time by as much as 70%, contributing to lower labor costs, as fewer labor hours are required to complete a project. Nevertheless, 3DCP faces its challenges, including limitations in printing scale, quality control in open environments, material consistency, and lack of expertise and skilled personnel for handling and maintenance (Ambily et al., 2024; Shahzad et al., 2022).

Combining 3DCP and modular construction presents an opportunity to overcome many limitations. When 3DCP is applied within offsite manufacturing environments, its precision and automation benefits remain intact while the typical uncertainties of field conditions can be minimized. This integrated approach may improve construction quality (Munguia-Galeano et al., 2023), expand design flexibility (Su et al., 2023), and reduce on-site disruption, which in turn enhances worker safety and minimizes the impact on surrounding communities (Mohamed & Mohamed, 2024). Despite its promise, the hybrid approach remains underdeveloped in practice and research, with limited structured models describing detailed workflows, task sequencing, and dependencies.

Existing studies on Work Breakdown Structures (WBS) and modular workflows have mostly focused on either traditional precast modular or standalone 3DCP methods without addressing their integration. Few frameworks systematically incorporate 3D printing into modular processes and detail task-level sequencing and automation across offsite and onsite phases. Addressing this gap is particularly important in contexts such as Indonesia, where there is high demand for housing and infrastructure but limited exposure to advanced systems. Without clear models outlining detailed activities, dependencies, and process flows, implementation remains fragmented, and project planning becomes challenging due to the absence of structured WBS references for this hybrid method.

Therefore, this study develops a structured WBS and a construction process framework to support planning and execution in hybrid 3D-printed modular construction, by focusing on the following research questions:

1. What activities should be included in the WBS for building projects involving 3D-printed modular construction?
2. How are the various construction activities and their dependencies structured within a process framework for 3D-printed modular buildings?

These outputs will help project managers, designers, and policymakers evaluate this method's readiness and practical application in real-world projects. The remainder of this paper is organized as follows: Section 2 presents the research methodology, Section 3 discusses the development of the WBS and the construction process framework, and Section 4 concludes with insights and recommendations for future research.

2. RESEARCH METHODS

This study adopts a qualitative, exploratory approach to develop a WBS and a construction process flow model for 3D-printed modular construction. The research was structured in three sequential stages that aligned with the two research objectives (ROs): to (1) develop a WBS for buildings with a 3D-printed modular construction approach, and to (2) construct a process model that captures the execution flow of offsite and onsite construction activities in 3D-printed modular systems. First, a systematic review and observation were conducted to identify the construction work items. Second, these items would then be organized into a hierarchical WBS. Third, translating the WBS into a construction process model illustrates how activities are executed sequentially across offsite and onsite phases.

2.1 Identifying Construction Work Items

2.1.1 PRISMA Protocol

To address the RO1, a Systematic Literature Review (SLR) was conducted to identify construction activities, components, and work items relevant to projects employing 3D printing within a modular construction context. The SLR was selected to provide a structured and replicable approach to capture existing knowledge on task definitions and workflow patterns in previous studies that support the development of a WBS and process framework for hybrid 3D-printed modular construction. The review followed the PRISMA 2020 protocol and was conducted using the Scopus database, which was selected for its broad peer-reviewed coverage in engineering, architecture, and construction domains. Singh et al. (2021) stated Scopus provides wider source inclusion than Web of Science, while, on the other hand, IEEE Xplore was excluded due to its narrower focus on engineering technology rather than construction. The PRISMA consists of four stages: identification, screening, eligibility, and inclusion. The search was conducted in April 2025 and limited to 2020–2025 publications in English, using the query:

("3D printing" OR "additive manufacturing" OR "concrete printing" OR "printable concrete" OR "3D concrete printing") AND ("construction" OR "building" OR "house") AND ("process" OR "activities" OR "automation") AND ("modular" OR "prefabrication")

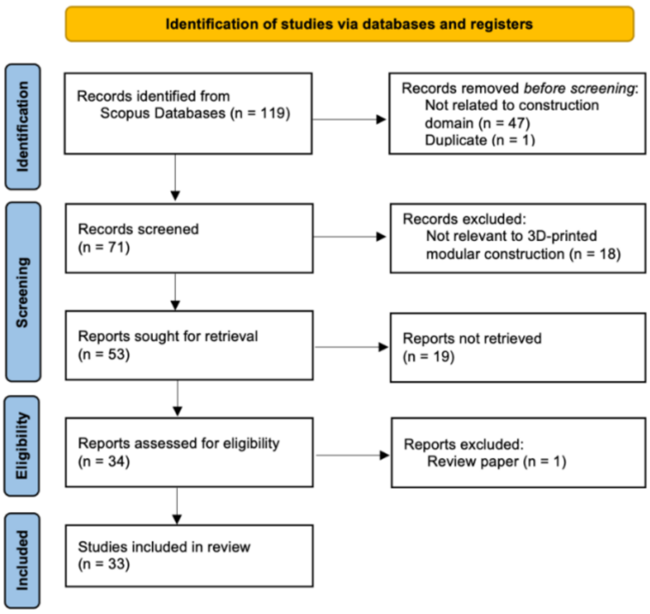

Figure 1: Flow diagram of the PRISMA protocol.

Exclusions were applied to studies that did not relate to construction, failed to reference modular or prefabricated methods, or focused solely on material properties without linking them to construction workflows. Studies presenting only conceptual designs or focusing on robotics without integration into actual building processes, were also excluded. Additionally, works limited to laboratory-scale demonstrations without real-world application were removedThis step resulted in 53 records.

Following this screening, the remaining records advanced to the eligibility stage for full-text analysis. Due to institutional access limitations, 19 records could not be retrieved, so only 34 studies were available for review. However, one was identified as a systematic review paper and was not included in the final dataset. Therefore, 33 records were selected for in-depth analysis. Figure 1 illustrates the PRISMA flow diagram.

These 33 studies were then analyzed to extract detailed construction activities and task groupings used in projects that combine 3D printing with modular construction. The aim was to identify practical work items and understand how they are organized across construction stages. The analysis focused on activities common in 3D-printed modular building projects, examined how these activities are distributed between offsite fabrication and onsite assembly, and identified process elements that are unique to 3D printing. It also explored the logical sequence among activities that could be used to structure a WBS and inform the development of a construction process model. These analytical steps helped produce work items grounded in practice and suitable for process modeling.

2.1.2 Observation at I-CELL Laboratory

To complement the systematic review, a structured direct observation was conducted at Universitas Indonesia's I-CELL Laboratory by the research team, with supervision from lab technicians experienced in digital fabrication workflows, which provided real-time feedback during the observation that informed adjustments in documenting task flows. This method was selected to capture practical insights into task sequencing, transitions, and quality assurance steps often underreported in the literature, so that the framework can reflect operational realities. Although the equipment was designed for metal printing, the observation validated the structure and logic of task sequences relevant to construction-scale 3D concrete printing.

The observation has several stages, starting with the planning stage, which sets the observation scope to examine the operational workflows of a metal 3D printer and validate task sequences relevant to construction-scale 3D concrete printing. The team focused on stages that include model preparation, machine setup, calibration, material loading, printing, post-processing, and quality checks. Subsequently, during the execution stage, the observation took place over one week, during which the team systematically documented workflows without interfering with machine operations. Next, the team collected data through field notes, time logs, photographs, and structured activity tracking sheets in the recording stage. The team analyzed the data by coding the observed activities into task categories and comparing them with findings from the systematic review.

2.1.3 WBS Development Approach: Grouping Logic and Activity Structuring

After identifying relevant construction work items through the systematic review and laboratory observation, this phase organized those items into a WBS for 3D-printed modular construction. The WBS development combined theoretical insights with practical validation to align with the actual project conditions that apply AM.

The WBS development used standard hierarchical decomposition principles from construction project planning, adjusting the unique phases, work clusters, and integration points found in hybrid 3D-printed modular construction. Three key considerations guided this process:

1) Functional decomposition broke high-level phases into detailed components based on findings from the systematic review and observation.
2) Offsite and onsite activities were clearly distinguished to reflect modular construction's spatial and procedural separation.
3) Activity clusters specific to 3D printing, such as digital modelling, slicing, printing, and post-processing, were included.

The resulting WBS followed a hierarchy from general construction stages to operational activities. It includes activities that do not typically appear in conventional construction but are central to AM and modular methods. This study applied a five-level hierarchy to support early-stage planning and analysis for 3D-printed modular construction projects. Level 0 identifies the overall project. Level 1 separates the offsite and onsite phases. Level 2 defines a major work cluster representing essential construction systems or functions. Level 3 outlines work categories that capture grouped activities or key components within each cluster. Level 4 describes the work package, and Level 5 lists the work activity that details the specific operations, procedures, or actions performed within each package.

2.2 Developing the Construction Process Flow

Building on the structured work packages defined in the WBS, this research phase focuses on developing a construction process flow diagram that reflects how offsite 3D-printed modular construction is executed in practice. The model organizes activities logically, capturing their dependencies, transitions between offsite and onsite phases, and integrating printed and non-printed components. It is intended to provide a technical representation of construction execution, and a realistic view of how these activities unfold on actual projects. The sequencing and coordination logic of the model is directly derived from the structure and activity relationships defined in the WBS. Figure 2 below illustrates the research workflow.

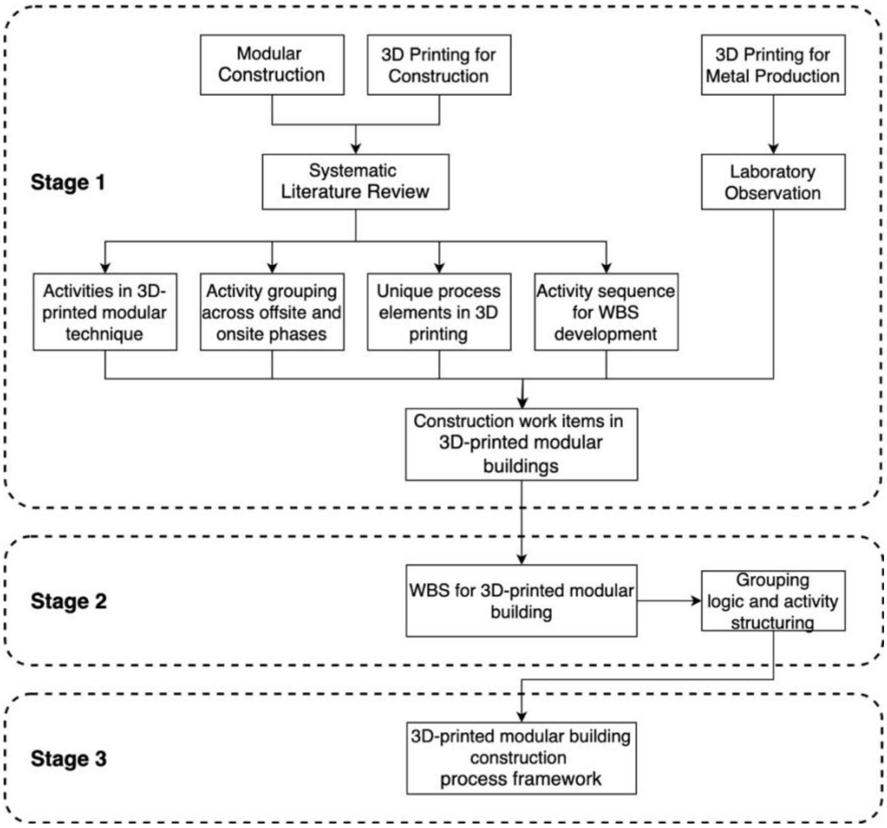

Figure 2: Research methodology flow chart.

3. RESULTS AND DISCUSSION

This section presents the findings from the literature review and observation. It first details the identified activities, categorizes them by phase and feature, and summarizes workflow patterns derived from prior studies. These results are validated through practical observation to align the proposed framework with academic evidence and operational realities.

3.1 WBS for 3D-Printed Modular Construction

3.1.1 Construction Work Items

The PRISMA protocol systematic review identified 33 eligible studies that were analyzed to extract construction activities relevant to 3D-printed modular construction. The review identified work items and examined how these activities appear within offsite fabrication, onsite assembly, and 3D printing-specific processes. This examination provided a foundation for the WBS development and showed how 3D printing modifies modular construction workflows.

Offsite Fabrication Activities

Offsite fabrication includes activities in controlled environments such as fabrication facilities or laboratories, which typically start with digital preparation and continue through material handling, automated production, and quality control. Reported activities include digital modeling and slicing, robotic printer setup and calibration, layer-by-layer extrusion or robotic printing, inline curing, dimensional inspection, and protective packing for transport. These activities reflect a shift from manual procedures to digital and automated fabrication.

The initial step involves material preparation, which requires sourcing and processing key inputs such as fiber-reinforced polymers, cement, aggregates, reinforcement, and additives. These materials form the foundation of printed components (Bodea et al., 2022; M. H. Raza et al., 2024). Once materials are prepared, digital modeling and slicing define geometry and structural logic, including integrated models (Anton et al., 2023), segmenting the design into print-ready parts (Anton et al., 2021), converting geometries into layer-based toolpaths (Li et al., 2023), and preparing sequential 2D layers for printing (Papacharalampopoulos et al., 2020).

Next step is printer setup and calibration, which covers robotic system configuration, extrusion consistency checks, specialized material mix preparation, and print path adjustment (McNeil-Ayuk & Jrade, 2025; Smorzhenkov & Ignatova, 2023). After the calibration, the robotic extrusion begins, sometimes combined with reinforcement methods through automated stud welding during material deposition, which replaces separate reinforcement steps typically found in conventional prefabrication (Classen et al., 2020; Placzek et al., 2021).

After extrusion, components proceed to the curing step, which takes place in chambers, curing bays, or warehousing facilities, to achieve the structural performance before site delivery (Liew & Chua, 2025). Once curing is finished, dimensional inspection is conducted to evaluate geometry, surface quality, and alignment with digital specifications. The inspection is done through scanning, surface refinement, and cross-checking printed parts against digital models (Spyridonos et al., 2025). The final step involves packing and temporary storage to protect during transport.

Onsite Assembly Activities

This activity group includes delivering, placing, and integrating printed components at the construction site. Transporting modules from the fabrication facility is the first step and requires careful planning to protect each component. Studies highlight the need for coordination during this step to avoid damage and maintain the schedule (Elayote & Eleshy, 2023; Ivaniuk et al., 2024; Volpe et al., 2021). The modular design and manageable size of printed components help reduce transport challenges.

After delivery, cranes and other equipment are lifted and positioned on prepared foundations or supports according to the site plan. Temporary supports and site-specific strategies assist with placement under site constraints (Tošić et al., 2022). Once positioned, workers align and anchor the modules along horizontal and vertical axes using interlocking systems or custom anchors to achieve structural stability and meet the design's mechanical requirements (He et al., 2021; J. Liu et al., 2024).

The next step involves connecting the modules using steel bolts, cables, clamps, grouted sleeves, or snap-fit connectors. Sealants or rubber spacers may be added to address joint tolerances and uneven surfaces, which can help maintain load continuity and support efficient on-site assembly (Liew & Chua, 2025).

The final step includes surface treatment and post-assembly inspection to improve finish quality and confirm compliance with the performance criteria. Surface treatment tasks include patching seams, smoothing surfaces, and applying protective coatings to address visible seams or environmental resistance. Alignment, dimensional accuracy, and safety compliance are then checked, with the assembled modules validated against mechanical and buildability requirements before handover for occupancy or finishing work (García-Alvarado et al., 2022). These activities mark the transition from individual 3D-printed modules to an integrated building system and reflect the precision required.

Unique Process Features of 3D Printing

Several activities in the reviewed studies are exclusive to 3D printing and do not appear in conventional modular prefabrication. These activities distinguish AM from traditional offsite construction. Five core features include print file generation and slicing optimization, print path calibration and trajectory tuning, print head positioning and collision avoidance, layer-by-layer geometry monitoring, and real-time feedback control for extrusion.

Print file generation and slicing optimization convert design models into printable instructions that define toolpaths and material deposition logic. Dungrani et al. (2023) applied parametric design to set geometric rules for module variations to support iterative design exploration and component customization. This process includes producing clean stereolithography (STL) files, adjusting slicing parameters, and checking for printability before fabrication. Papacharalampopoulos et al. (2020) emphasized the importance of toolpath optimization during robotic extrusion compared to static molds and repetitive assemblies in prefabrication. Lindner et al. (2022) used Hierholzer's algorithm to compute node sequences for fiber-reinforced paths that produce automated trajectories for robotic arms that handle complex geometries.

Subsequently, print path calibration and trajectory tuning adjust machine movement to match material behavior and print geometry. Adjustments include nozzle distance, spray angle, and speed of material conveyance (He et al., 2021; Placzek et al., 2021).

Print head positioning and collision are critical for producing complex or reinforced components in 3D printing workflows. For example, Classen et al. (2020) demonstrated concrete printing combined with manual stud welding for reinforced panels. Lindner et al. (2022) used structural simulations to predict robotic arm movement and adjust toolpaths to avoid collisions, while TengTeng et al. (2023) developed a method to generate continuous and optimized paths that avoid embedded elements by applying slicing, model meshing, and spatial analysis to direct the robotic system around reinforcement bars without physical interference.

Layer-by-layer geometry monitoring supports dimensional consistency and structural performance. Liew & Chua (2025) described that layer is deposited, cured, and inspected before the next layer, while García-AlvaradoGarcía-Alvarado et al. (2022) detailed slicing walls into segments with tool transitions for complex features, supported by multi-axis robotic arms and digital slicing, which are key to managing curvature and thickness variation.

Finally, the real-time feedback control for extrusion adjusts fabrication based on sensor input and process data. Bodea et al. (2022) described sensor-informed feedback systems for real-time monitoring and corrective action, while Barjuei et al. (2024) take this further by integrating AI-driven decision-making and motion planning into the digital workflow to improve accuracy, reduce waste, and adapt to process changes without manual intervention.

3.1.2 Patterns of Activity Sequences in 3D-Printed Modular Construction

Identifying construction work items in Section 3.1.1 highlights various activities involved in 3D-printed modular construction. However, how these activities are arranged and coordinated varies depending on project requirements, technological setup, and integration strategies. Four distinct logic patterns were identified from the analysis of the reviewed studies, which reflect different printing, reinforcement, assembly, and automation sequencing across offsite and onsite phases.

Pattern A: Fully Robotic Offsite Printing + Manual Onsite Assembly

This pattern clearly separates automated offsite fabrication and conventional onsite assembly. All 3D printing work takes place in a controlled factory or laboratory, which allows precise operations using robotic extrusion systems, gantry setups, or multi-axis robotic arms. Typical activities in this phase include digital slicing, material deposition, automated toolpath execution, and post-print modifications such as drilling or trimming. Studies have shown that these fully digital workflows can produce geometrically complex components with limited human intervention during fabrication(Anton et al., 2023; Ivaniuk et al., 2024; Xiao et al., 2022).

After fabrication, the printed components are transported to the construction site for manual assembly. Site activities include unloading, positioning, bolting, and dry-joint fitting with cranes and lifting equipment operated by construction workers. This transition from automated production to manual assembly illustrates a delivery model that separates fabrication and onsite work, with minimal overlap once components leave the factory. Research indicates that this approach works best in projects that use controlled printing environments and conventional assembly methods on site (He et al., 2021; Papacharalampopoulos et al., 2020).

Pattern B: Prefab Reinforcement Integrated Printing

This pattern integrates structural reinforcement with 3D printing through coordinated prefabrication and sequencing. Projects using this pattern print structural shells, molds, or partial elements, then add reinforcement during pauses in the printing process or after printing finishes. Unlike Pattern A, offsite and onsite phases in Pattern B show more interdependence, as reinforcement tasks align closely with printing activities. This coordination between automated and manual steps helps projects improve load-bearing performance and design flexibility within modular systems.

Studies show how reinforcement can be done during or after printing. Bodea et al. (2022) applied robotic filament winding to embed reinforcement within the fabrication step. Anton et al. (2021) used an automated concrete printing platform to produce columns with reinforcement designed in the digital modeling phase. Volpe et al. (2021) demonstrated how modular blocks printed with embedded features can simplify steel reinforcement insertion. Other studies by García-Alvarado et al. (2022) and Hua et al. (2023) described workflows where printed exterior shells combine with reinforced concrete cores.

Various studies also reported diverse approaches for incorporating reinforcement, such as edge mesh placement, microstructured print paths, post-print embedding, robotic extrusion, and the use of recycled prefabricated systems (Meibodi et al., 2021; Zhang et al., 2024). These methods follow a clear sequence that aligns printing and reinforcement under a unified workflow and result in components that combine geometric precision with structural inserts to achieve the required performance in modular construction.

Pattern C: Hybrid Precast and Printed Components with Robotic Assist

This pattern uses a coordinated and robot-assisted process to use precast concrete elements and 3D-printed components. The fabrication streams for printing and precasting proceed in parallel. Printed parts act as connectors, joint interfaces, or detailed surface features, and precast elements serve as the main structural units. Integration in Pattern C depends on digital precision, robotic placement, and consistent tolerances across both systems. This method suits projects that seek the casting speed of precast elements and the geometric detail possible through additive manufacturing.

Several studies describe workflows that reflect this hybrid approach. For instance, Engel et al. (2025) combined a precast concrete plate with 3D-printed ribs to add structural depth and reduce labor by removing the need for extra formwork. Li et al. (2023) used a 3D-printed plastic shell as an outer geometry that was later filled with reinforced concrete to create a structural core. Lindner et al. (2022) applied yarn fixation and guiding systems to produce textile reinforcement modules with high dimensional accuracy, which were then embedded in precast elements to improve performance. Placzek et al. (2021) described printing a core that underwent robotic edge milling and surface refinement to improve dimensional quality before integration with other parts. Elayote & Eleshy (2023) reported using robotic systems during façade assembly to handle printed and precast components precisely. These cases show how printing and casting can proceed as two coordinated systems within one workflow.

Pattern D: Onsite Printing with In-situ Integration

This pattern places the 3D printing process directly at the construction site. Instead of factory production, structural or non-structural elements are fabricated in place using mobile or gantry-based systems. The printed modules take shape at their final location, which reduces transportation and handling needs. This pattern suits large-scale or monolithic structures and projects where site conditions limit offsite logistics. Integration with conventional construction activities such as cast-in-place concrete, embedded reinforcement, or manual component placement often complements the printed work.

Teng et al. (2023) presented a case where onsite printing occurred as robotic systems simultaneously placed reinforcement into the structure. This example shows a continuous workflow integrating onsite material deposition and structural assembly. Ali et al. (2021) described robotic manipulators designed for transporting materials and conducting concrete printing on-site. Their system used a digital toolchain to support precise print path execution and material delivery. These studies illustrate how Pattern D applies a coordinated onsite workflow that merges printing and construction tasks within the same environment. Table 1 categorizes the 33 reviewed studies across the four patterns.

Table 1: 33 Reviewed Studies into the 3D-Printed Modular Patterns.

No.	Reviewed Studies	Pattern A	Pattern B	Pattern C	Pattern D
1	(Elayote & Eleshy, 2023)			√	
2	(Bodea et al., 2022)		√		
3	(Engel et al., 2025)			√	
4	(Dolz et al., 2023)		√		
5	(Ivaniuk et al., 2024)	√			
6	(M. H. Raza et al., 2024)	√			
7	(Anton et al., 2023)	√			
8	(Anton et al., 2021)		√		
9	(Barjuei et al., 2024)		√		
10	(J. Liu et al., 2024)	√			
11	(Lindner et al., 2022)			√	
12	(Dungrani et al., 2023)			√	
13	(Liew & Chua, 2025)		√		
14	(Volpe et al., 2021)		√		
15	(García-Alvarado et al., 2022)		√		
16	(Tošić et al., 2022)		√		
17	(S. Raza et al., 2024)		√		
18	(Y. Liu & Hua, 2024)		√		
19	(Li et al., 2023)			√	
20	(Xiao et al., 2022)	√			
21	(Hua et al., 2023)		√		
22	(Spyridonos et al., 2025)	√			
23	(Smorzhenkov & Ignatova, 2023)	√			
24	(Teng et al., 2023)				√
25	(McNeil-Ayuk & Jrade, 2025)				√
26	(Al Masri et al., 2024)	√			
27	(N. Zhang et al., 2024)		√		
28	(Papacharalampopoulos et al., 2020)	√			
29	(Ali et al., 2021)				
30	(Classen et al., 2020)		√		
31	(Placzek et al., 2021)			√	
32	(Meibodi et al., 2021)		√		
33	(He et al., 2021)	√			

Among the four patterns, Pattern C reflects current practices in combining 3D concrete printing with modular construction. Besides prefabricated components, this pattern brings 3D printing into the fabrication process, where printed elements act as connectors or geometric interfaces and conventional modules serve as primary structural parts. Pattern C applies a coordinated model in which digital fabrication and precast methods progress together. This model supports the delivery of full-scale buildings by joining design flexibility with the structural reliability of established modular systems. Given its balance of precision, scalability, and practical deployment, the WBS developed in this study adopts the logic of Pattern C as a representative model for modular construction projects that use 3D printing. Table 2 compares the four patterns to show how each organizes offsite and onsite activities and highlights their key characteristics and differences.

This study examines Pattern C alongside digital fabrication and robotic construction models to clarify its role as an extension of these approaches for hybrid 3D-printed modular projects (see Table 3). Research in digital fabrication by Bischof et al. (2023), García Alvarado (2012), and Skoury et al. (2024) has achieved high precision and rapid prototyping within design and prefabrication phases but has focused on component-scale outputs. Skoury et al. developed robotic fabrication workflows with digital thread integration for pavilion-scale structures, and García Alvarado emphasized parametric scripting to guide CNC fabrication in controlled environments. These studies demonstrate effective fabrication and monitoring but do not address modular system delivery.

In robotic construction, studies by Kulz et al. (2025), Pan et al. (2018), and Zied (2007) have advanced task automation and BIM-supported processes for site operations and component handling but often lack a clear connection to modular workflows. Pattern C builds on these contributions by aligning offsite 3D concrete printing and modular precast production with onsite assembly in a coordinated process. This approach supports structured planning for hybrid project delivery and contributes to discussions on integrating digital fabrication and robotics within modular construction.

Table 2: Comparison Across Four Logic Patterns in 3D-Printed Modular Construction.

Aspect	Pattern A	Pattern B	Pattern C	Pattern D
Offsite Activities	- Digital modeling and slicing - Printer setup and calibration - Layer-by-layer extrusion (inline or chamber curing) - Quality inspection - Packing and storage	- Rebar-integrated parametric design - Hybrid printing with reinforcement - Material batching and monitoring - Rebar insertion/ tensioning - Dimensional testing - Preparation for transport	- Print-precast coordination - Precast large elements - Robotic printing of joints - Print-precast integration - Edge treatment and fitting - Logistics coordination	- None
Onsite Activities	- Transport to site - Crane-assisted placement - Manual alignment and anchoring - Joint sealing - Final QA and surface finishing	- Site delivery and layout - Module connection - Cast-in-place integration - Anchoring and sealing - Inspection and compliance checks	- Placement of hybrid components - Robotic alignment - Joint connection - MEP system integration - Final inspection and joint checks	- Site preparation - Printer setup and calibration - Printing onsite - Curing and monitoring - Reinforcement insertion - MEP integration - Finishing and post-print treatment
Characteristics	High precision, clear offsite-onsite split, conventional onsite assembly	Print–pause reinforcement workflows, improved structural capacity	Dual fabrication streams, robotic fit-up, BIM coordination	Prints structures on-site, reduces transport, adaptable layouts
Differences	Maximizes factory control, limits onsite complexity	Merges printing and reinforcement, structural enhancement	Combining precast robustness with printed complexity	Suitable for large sites, eliminates module transport

Table 3: Comparison with Digital Fabrication and Robotic Construction.

Aspects	Digital Fabrication	Robotic Construction	Hybrid 3DCP-Modular (Pattern C)
Scope	Model prototyping, prefabrication, design phase focus	Task automation, sustainability, on-site focus	Integration of offsite 3DCP with modular precast and on-site assembly
Strengths	High design precision, rapid prototyping	On-site automation, BIM integration	Combines digital fabrication flexibility with modular assembly for hybrid delivery
Limitations	Limited to design and prefabrication stages	Fragmented workflows, lack of linkage with modular delivery	Requires adaptation to project scale and local site conditions
Automation Applied	Laser cutting, CNC, digital threads	Robotic drilling, modular robotics, BIM	Robotic gantry lifting, path calibration, extrusion monitoring
Comparative Advantage	Delivers precision but lacks project-wide workflows	Advances in task automation do not align with modular sequencing	Merges digital and robotic methods with modular delivery in a hybrid process

3.1.3 Validation through observation at the i-CELL Laboratory

This section presents observations at the I-CELL Laboratory to ground the findings in practical application by comparing AM workflows with the construction activities found in the review obtained in section 3.1.2. The observation used a metal 3D printer applying a dual-material system with wax-bound metal filament and temporary ceramic supports (see Figure 3).

The process began with digital model preparation in computer-aided design (CAD) software. It was then exported in STL format and uploaded to an online platform (eiger.io) connected to the printer. This initial stage confirmed the presence of early-stage digital activities such as model setup, file conversion, and print path definition, which were frequently mentioned in the literature as essential in initiating the fabrication process.

The setup stage included machine calibration, filament loading, and parameter adjustments before the automated layer-by-layer deposition. The printing process followed extrusion workflows noted in the review and required manual activation that aligned with findings on printer calibration and path control.

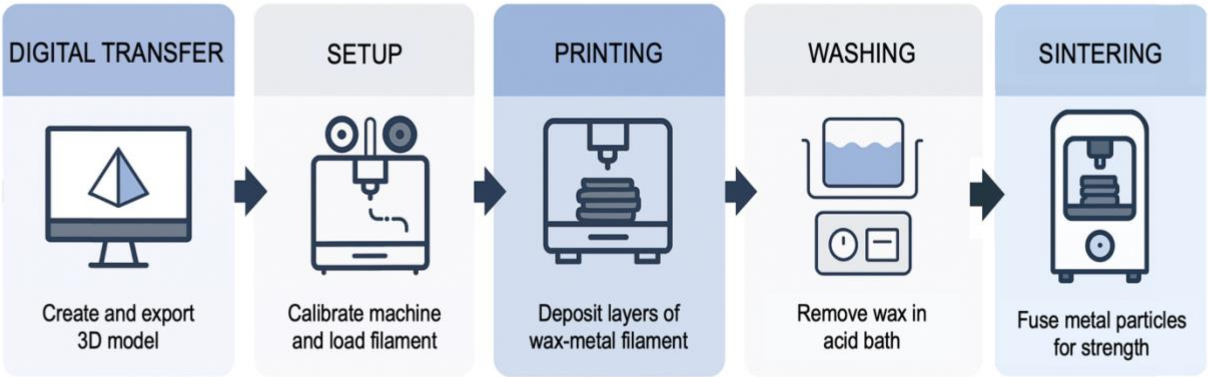

Figure 3:Workflow Stages during Metal 3D Printing at the I-CELL Laboratory.

After printing, the part moved to a washing stage where immersion in a sulfuric acid bath (H_2SO_4) removed wax and weakened ceramic supports. Such intermediary activities confirmed the importance of handovers and material transformation, which are often underrepresented in high-level workflow models.

The final stage involved sintering in a high-temperature chamber with liquid argon to fuse metal particles for structural cohesion. It separated environmental control from thermal regulation and reflected curing and strengthening stages in construction-scale AM. During observation, additional activities such as safety checks, material repositioning, machine resetting, and quality inspections were noted. These activities are usually absent in conceptual models, yet they play a critical role in process continuity and safety, which supports their inclusion in the WBS.

The observed sequence aligned with the activity categories from the literature, with clear divisions between modeling, fabrication, and post-processing outlined in Section 3.1.1. Supporting activities from observation added depth to the WBS and confirmed the need for detailed segmentation in practical workflows. Although the printer was not designed for large-scale modules, digital preparation, material handling, fabrication, and post-processing showed parallels with modular construction. This phase revealed that specialized tasks in 3D printing, such as slicing, layer control, and thermal treatment, should be integrated into modular construction frameworks.

3.1.4 WBS of the Hybrid Precast and 3D-Printed Components

This subsection presents the WBS for hybrid construction using 3D-printed and precast components. The WBS structure reflects Pattern C, which combines digital fabrication and robotic-assisted onsite assembly, by organizing activities into a five-level hierarchy. Activities were grouped based on two considerations: the phase in which they occur (offsite or onsite) and the nature of the activity (printed, non-printed prefabrication, or integration).

The WBS structure has two phases at the highest level: offsite and onsite. Each phase is further broken down into work clusters, categories, and packages that follow the construction sequence. Figure 4 illustrates the overall structure from the work phase to Level 4 work packages.

The offsite phase contains two clusters: 3DCP and precast concrete production. Each cluster captures its procedures, including preparation, material processing, fabrication, quality checks, and post-processing. The 3D printing cluster includes digital activities such as BIM modeling and slicing, followed by robotic operations such as extrusion and toolpath calibration. In contrast, the precast concrete cluster follows standard procedures with formwork, reinforcement placement, and manual casting. Both clusters end with wrapping and packing activities to prepare the components for transport.

The onsite phase begins with site preparation and continues with structural, mechanical, electrical, plumbing (MEP), and architectural works. Robotic systems assist in module installation to place and align components accurately. Activities such as "Module hoisting using robotic gantry" and "Robotic assist for alignment verification” indicate how robotic systems manage precision activities that are difficult to complete manually.

Additional onsite activities include temporary support installation, sealing, dimensional inspection, and finishing, which follow the sequence of physical assembly.

The work packages are divided into Level 5 work activities that outline the procedures and checks required for each activity (see Table 4). Manual methods are used for inspection to reflect site conditions, using total stations and laser levels. Scanning, measuring, and deviation checks maintain accuracy after installation across printed and precast components.

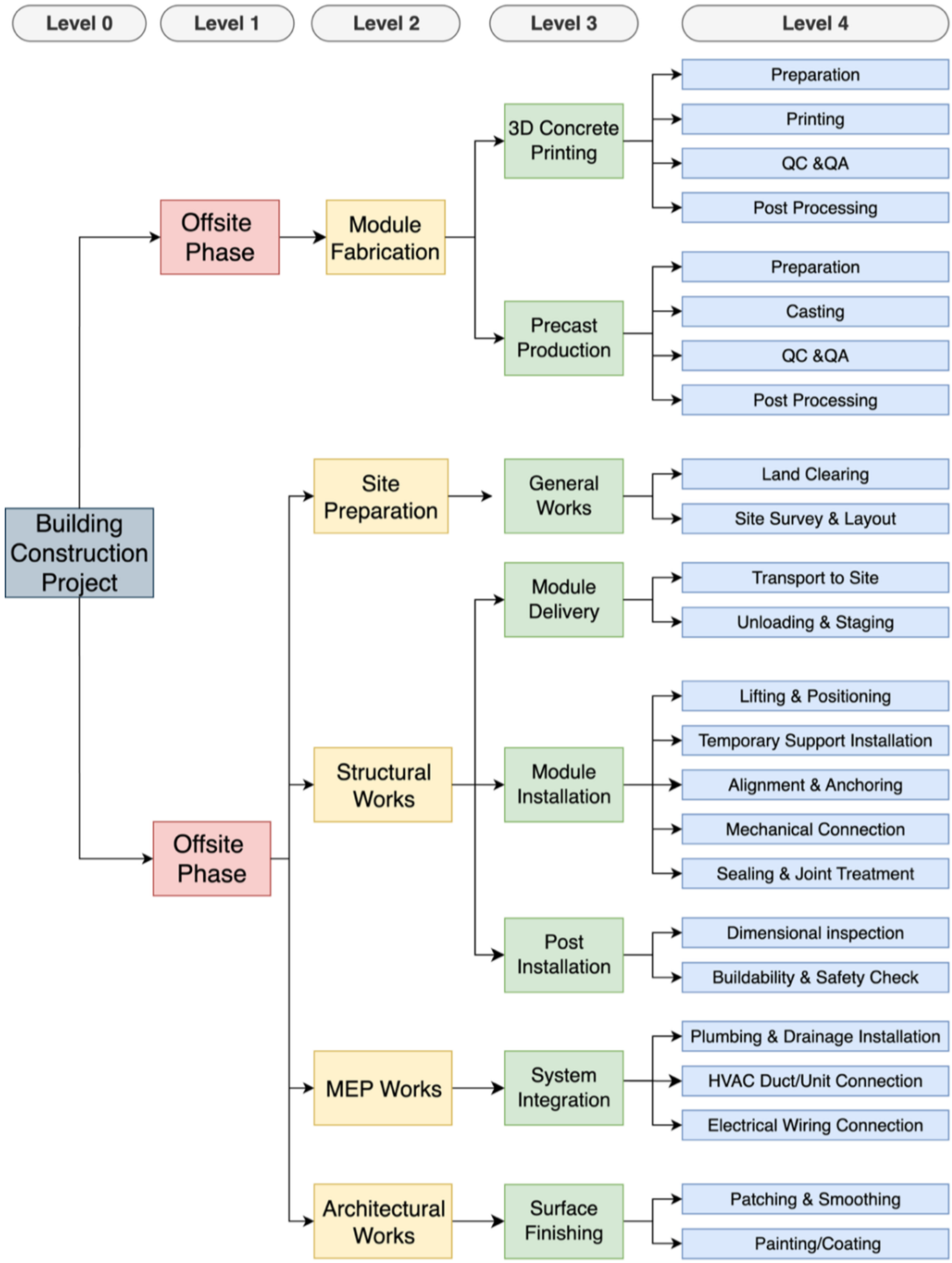

Figure 4: Four-Level WBS.

Table 4: Five-level WBS.

Level 1 Phase	Level 2 Work Cluster	Level 3 Work Category	Level 4 Work Package	Level 5 Work Activity
Offsite	Building Module Fabrication	3D Concrete Printing	Preparation	BIM 3D model development
				Slicing and toolpath generation
				3D printer setup and calibration
				Concrete mix design
			Printing Process	Slump flow test
				Concrete printing
				Print path calibration
				Geometry monitoring
				Print head positioning
				Real-time feedback extrusion control
			QC & QA	Dimensional inspection
				Concrete testing
				Concrete curing
			Post-processing	Packing for transport
				Wrapping and temporary storage
		Precast Concrete Production	Preparation	Formwork (molding)
				Reinforcement installation
				Concrete mix design
			Casting process	Slump test
				Concrete casting
			QC & QA	Concrete testing
				Dimensional inspection
				Concrete curing
			Post-processing	Packing for transport
				Wrapping and temporary storage
Onsite	Site preparation	General works	Land clearing	Removal of vegetation and debris
				Excavation and grading
				Soil compaction
				Access route preparation
			Site surveying and layout	Baseline and grid establishment
				Elevation benchmarking
				Module layout marking
				Tolerance check and recalibration
	Structural works	Module delivery	Transport to site	Route planning
				Loading & prefabricated
				Securing modules for transport
				Transporting modules
			Unloading and staging	Positioning cranes and lifting equipment
				Crane setup and safety check
				Module unloading
				Visual inspection upon arrival
				Temporary staging and alignment preparation
		Module Installation	Lifting and positioning	Rigging and hooking
				Module hoisting using robotic gantry

Level 1 Phase	Level 2 Work Cluster	Level 3 Work Category	Level 4 Work Package	Level 5 Work Activity
				Robotic assist for alignment verification
				Position adjustment based on layout
			Temporary support installation	Install adjustable shoring frames
				Check stability and plumb
				Secure temporary anchors or props
			Alignment and anchoring	Horizontal and vertical alignment
				Mechanical anchor installation
				Anchor torque testing
				Temporary brace removal
			Mechanical connection	Install connection brackets or bolts
				Tighten and torque connections
				Inspect joint alignment and strength
			Sealing and joint treatment	Apply sealant to joints
				Install weatherproof membranes if needed
				Clean excess materials and finish surfaces
		Post-installation	Dimensional inspection	Laser scanning of installed components
				Alignment and level measurement
				Record deviations and prepare report
			Buildability and safety check	Verify installation sequence and tolerances
				Structural stability assessment
				Hazard and safety risk audit
	MEP Works	Systems Integration	Plumbing and drainage installation	Piping layout installation (cold, hot, waste)
				Valves and fixture connectors installation
				Securing pipe brackets and hangers
				Leakage and flow testing
			HVAC duct or unit connection	Ductwork and fittings installation
				Connection to the HVAC unit
				Seal joints and insulation
				Functional airflow and system test
			Electrical wiring connection	Conduit installation
				Cable routing and pulling
				Termination at junction boxes
				Continuity and insulation testing
	Architectural works	Surface finishing	Patching and smoothing	Surface cleaning
				Mortar patching of joints
				Edge and corner smoothing
				Curing compound application
			Painting or coating	Surface cleaning and sanding
				Primer application
				Topcoat application
				Drying and touch-up

3.2 Construction Process Framework

This section presents a construction process framework that shows the sequence and interdependencies of offsite and onsite activities in hybrid 3D-printed modular building projects. The framework builds on the WBS developed in the previous section and arranges the work activities into a logical sequence. This sequencing uses findings from reviewed studies that detail coordination requirements, inspection steps, and cross-phase dependencies (Friese et al., 2023; J. Liu et al., 2024; McNeil-Ayuk & Jrade, 2025). The framework reflects the parallel workflows of 3D printing and precast fabrication and identifies where automation is applied.

The process starts with the offsite phase, which includes parallel workflows for 3D-printed components and precast modules. It begins with planning and design, covering technical requirements, scheduling, cost planning, and BIM model development. These models provide the geometric and structural data needed for print instructions and documentation for both workflows.

The 3D printing sequence starts with slicing and toolpath generation, followed by printer setup and calibration. The concrete mix is formulated and evaluated for printability with a slump flow test. After verification, the print path calibration finalizes the robot movement instructions. Printing includes steps such as print head positioning, geometry checks, and real-time extrusion control, which support accuracy in layer geometry and material consistency. After printing, a dimensional inspection checks alignment with the design model. Modules passing the checks move to strength testing and controlled curing. After curing, the modules are packed and stored for transport. This workflow demonstrates a high level of automation, monitoring, and quality control.

In the precast concrete production workflow, fabrication includes formwork and reinforcement placement. The concrete mix is tested through a slump test for workability before casting. Unlike 3D printing, this process depends on manual reinforcement placement and formwork alignment. After casting, modules undergo dimensional inspection and strength testing. Approved modules are cured under controlled conditions before packing and storage. This workflow has more manual steps and less embedded automation, especially during early steps.

The onsite phase begins once the modules are delivered. Site preparation includes land clearing, excavation, soil compaction, and creating access routes. These steps build a stable work platform and support logistics. Site surveying follows, including baseline checks, elevation marks, placement layout, and tolerance checks to confirm the site is ready for modular installation.

After preparation, structural work proceeds with module delivery and installation. Transport is coordinated based on lifting plans and staging requirements. Once modules arrive, they are unloaded, checked for damage, and aligned in staging areas. Cranes and robotic gantries assist in lifting and positioning to improve accuracy and reduce manual adjustments. Once in place, modules are anchored to foundations using mechanical connections. Torque testing and joint sealing complete this stage to achieve structural continuity and weather resistance.

Post-installation checks confirm build quality. Dimensional inspection was performed using laser scanning to verify module alignment with the design model, followed by alignment checks and deviation reports. Any issues are addressed before system integration to avoid compounding errors in MEP installations. In parallel, buildability and safety checks assess sequence compliance, stability, and site safety. Automation in this phase uses robotic lifting and laser inspection to improve placement accuracy and reduce human error.

After the structural works and post-installation checks are completed, the project advances to MEP system integration, which includes three major work packages that proceed in a coordinated order: plumbing and drainage installation, HVAC duct and unit connection, and electrical wiring connection. Plumbing is typically executed first to define drainage systems' required slopes and vertical drops, followed by HVAC installation, and electrical conduit and wiring, which can adjust around other systems. Each system undergoes quality checks, with plumbing tests for flow and leaks, HVAC checks for sealing and airflow, and electrical checks for continuity and insulation. This coordination reduces conflicts and rework and supports alignment with openings and embedded connection points planned during offsite fabrication. Although it relies on manual labor, the BIM environment supports routing precision and clash detection, and verification of connection points embedded during offsite fabrication.

The final stage is architectural work, which begins once all MEP systems are confirmed. Surface finishing includes patching seams, smoothing surfaces, corner detailing, and applying mortar. A curing compound is then used to stabilize patched areas. Painting is then followed by primer, topcoat, and drying steps. Touch-ups correct any defects from system integration. This stage supports visual quality and surface protection. It is scheduled last to prevent damage from technical installations. While this stage uses minimal automation, its success depends on precise work in earlier stages. Figure 5 shows the process and interdependencies of offsite and onsite activities in hybrid 3D-printed modular building projects.

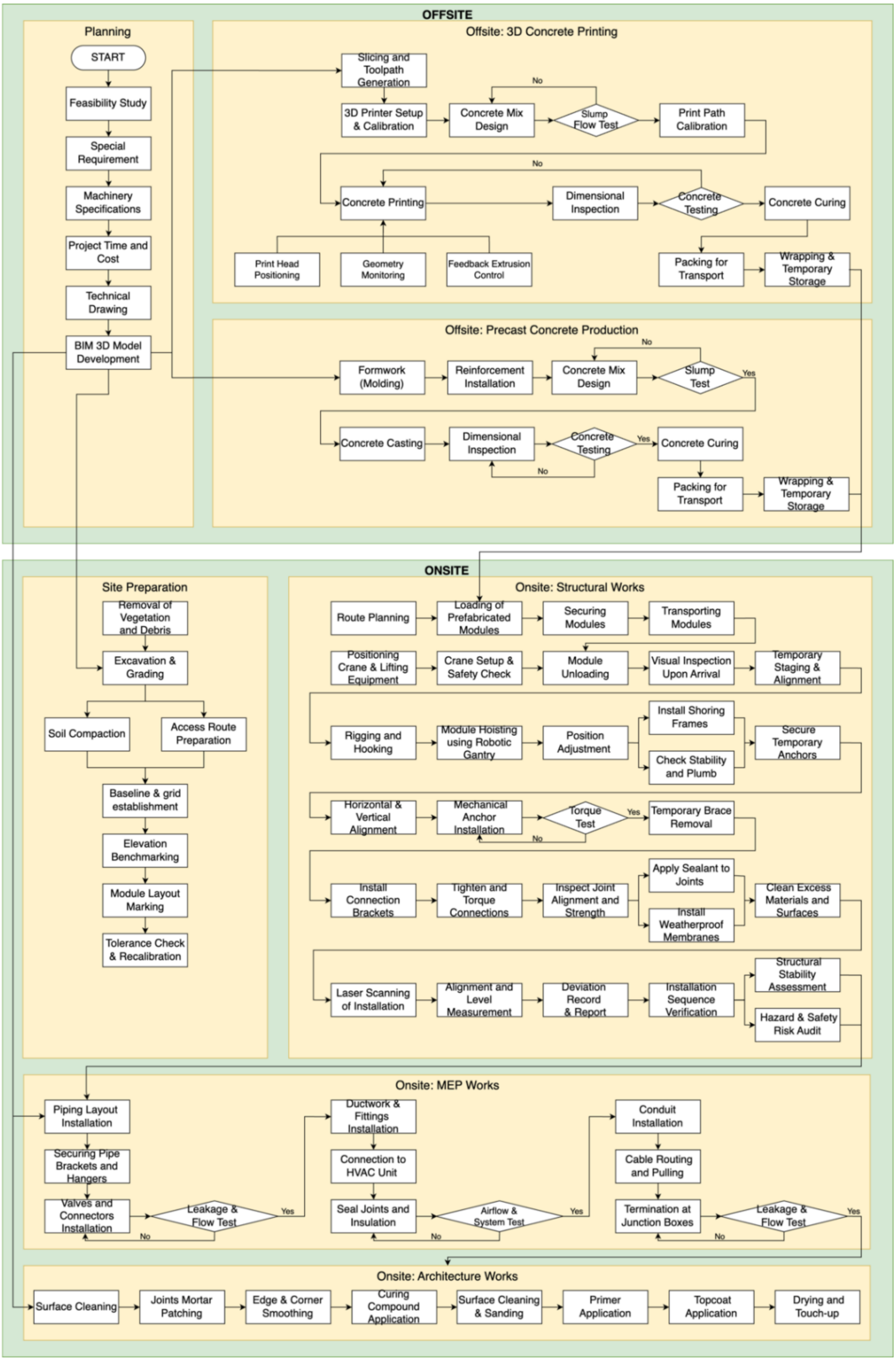

Figure 5: Construction Process Framework.

The proposed construction framework presents a basic model for hybrid 3D-printed modular construction, but its application depends on the specific conditions of each project. Larger projects may require more detailed task breakdowns to coordinate work across multiple fronts. On the other hand, smaller projects with limited resources may need to combine steps to match local capabilities. Manual work may replace automated tasks in locations where advanced printing equipment is unavailable. Local factors such as labor availability, road conditions, and supply chain reliability influence which tasks are practical and how the construction process should be organized.

A mid-rise housing project in Jakarta, the capital city of Indonesia, classified as medium-scale and located in an urban area, might rely on local precast suppliers and a construction workforce trained in conventional methods. Labor for assembly and reinforcement is generally available within the city and surrounding districts. However, specialists in 3D printing and robotic systems may be concentrated in certain technology centers. Transporting large precast components across the city may face delays due to traffic congestion or limited access routes. Materials used for 3D printing, such as specialty binders and robotic parts, may depend on imports, which introduces risks of delivery delays. In these conditions, the framework can be adapted by reducing reliance on heavy transport, adjusting task sequences to suit local constraints, and carrying out equipment setup activities near the project site.

This example shows that the framework is not a one-size-fits-all solution. Its main use is to provide a reference that helps teams plan and adapt hybrid construction methods based on the project's size, location, workforce, and access to technology.

3.3 Discussion

This study developed a WBS and a construction process framework that contribute to the theoretical advancement of modular construction and digital fabrication integration. By systematically identifying work activities across offsite and onsite phases, the framework provides a reference for researchers exploring workflow optimization, cost estimation, and automation in hybrid 3D-printed modular projects. While prior studies on modular workflows (Smith & Rice, 2017; Y. Zhang & Pan, 2022) and 3D printing in construction (Moghayedi et al., 2024; Puzatova et al., 2022) have highlighted efficiency and precision benefits, they often focus on these systems in isolation. This study builds on and extends these findings by demonstrating how 3D concrete printing and modular precast methods can be coordinated within a unified process framework supported by a detailed WBS.

Compared to previous frameworks in additive construction (Papacharalampopoulos et al., 2020) and lean modular workflows (Thurairajah et al., 2023), the framework developed in this study explicitly maps points of automation, such as robotic calibration and real-time extrusion monitoring, within conventional modular delivery. This expands previous work by showing how these digital fabrication tasks can align with manual and precast operations under a hybrid delivery system (Munguia-Galeano et al., 2023).

From a practical perspective, the framework offers potential to support modular project planning by outlining clear activity sequences, inspection steps, and coordination points for managing hybrid workflows. It can assist practitioners in structuring procurement timelines, aligning fabrication and onsite assembly, and incorporating automation steps without disrupting conventional construction practices.

The framework is intended as a flexible guide rather than a rigid model. Project teams may adapt it according to project scale, site conditions, and supply chain availability. Larger projects may require further breakdown of logistics and staging tasks, while remote or constrained sites may necessitate adjusted transport and installation workflows. These considerations position the framework to support a range of contexts while advancing the planning and execution of hybrid 3D-printed modular construction.

4. CONCLUSION

This study investigated the integration of 3D concrete printing (3DCP) with modular construction by developing a structured Work Breakdown Structure (WBS) and a construction process framework for building projects. Key findings include identifying four workflow patterns from existing literature, classifying construction work items into offsite and onsite phases, and developing a five-level WBS that provides for both printed and precast components. Based on this WBS, a construction process framework was prepared to present activity sequences, task dependencies, and potential points for automation across the project. Among the patterns, Pattern C was identified as the most consistent with current practice and demonstrates that 3D printing and precast fabrication can proceed in parallel with robotic support.

The study shows the novelty of integrating automation, such as robotic gantries, print-path calibration, and real-time extrusion monitoring, into workflows that are typically manual. This integration advances the potential of hybrid 3D-printed modular construction to improve precision, reduce rework, and enhance workflow predictability. Regarding practical implications, the WBS and construction process framework provide project teams with structured references for planning, scheduling, and coordinating hybrid construction activities. They can guide practitioners in aligning procurement schedules, managing the handover between offsite and onsite tasks, and clarifying inspection and quality control responsibilities in automated workflows.

This study has several limitations. The observation used to refine the framework took place in a laboratory with a metal 3D printer, which differs from concrete applications. The framework remains conceptual and has not been tested in real-world projects, though it outlines how digital fabrication can connect with conventional precast workflows and identifies stages where automation may improve construction processes. Future research can test the framework through simulations and pilot projects, measure productivity and cost outcomes, and apply digital twins for workflow tracking to support practical use.

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