

INTEGRATING METAVERSE-BASED TRAINING FRAMEWORKS FOR CONCRETE 3D PRINTING CONSTRUCTION

Mohamed Ait Gacem¹, & Saleh Abu Dabous²

ABSTRACT

Concrete three-dimensional printing (3DCP) is transforming construction by improving automation, efficiency, and design flexibility. Yet its adoption is hindered by the complexity of integrating cyber–physical systems, which often leads to training inefficiencies, material waste, and unreliable workflows. From a Lean Construction perspective, effective implementation requires zero-waste learning environments, reliable process rehearsal, and continuous skill development. This paper presents a Lean-oriented metaverse-based training method that supports immersive, simulation-driven learning for concrete 3D printing. The method combines digital twins, interactive environments, and virtual production rehearsal to enable safe experimentation without material consumption. Training modules cover hardware familiarization, printer setup, software design workflows, and preventive maintenance, emphasizing flow reliability and the long-term performance impacts of operational decisions. By validating procedures before physical execution, the method reduces rework, improves predictability, and supports continuous improvement. Results show that metaverse-based Lean training enhances experiential learning, strengthens systems understanding, and enables zero-waste process optimization. A validation survey showed that 68.5%–90.7% of participants rated the method as better or much better than conventional training approaches across all evaluated constructs. The proposed approach demonstrates how immersive technologies can align advanced construction methods with Lean principles to improve efficiency, reliability, and sustainable adoption of 3D printing in construction.

KEYWORDS

Concrete 3D Printing (C3DP), metaverse, digital twin, lean construction, training.

INTRODUCTION

The construction industry is undergoing a profound transformation driven by the convergence of digitalization, automation, and advanced manufacturing technologies. Historically, however, construction has been characterized by low productivity growth, fragmented project delivery, and significant levels of waste compared to other industries. These inefficiencies often stem from unreliable workflows, poor coordination, and limited systems thinking. In response, Lean Construction has emerged as a production-oriented philosophy aimed at improving value delivery and minimizing waste across the entire project lifecycle. Lean Construction adapts principles from Lean production to construction by viewing projects as integrated production

¹ Research Assistant, Sustainable Civil Infrastructure Research Group, Research Institute of Sciences and Engineering, University of Sharjah, Sharjah, UAE, mgacem@sharjah.ac.ae, <https://orcid.org/0000-0002-5947-9162>

² Professor, Department of Civil and Environmental Engineering, University of Sharjah, Sharjah, UAE sabudabous@sharjah.ac.ae, <https://orcid.org/0000-0002-8777-2331>

systems that should optimize flow, reduce variability, and support continuous improvement (Aigbavboa et al., 2025). Central Lean principles include defining value from the client perspective, eliminating non-value-adding activities, stabilizing workflows, and fostering collaborative planning environments. As construction transitions toward digital and automated technologies, Lean thinking provides a framework for ensuring that innovation translates into reliable, waste-minimizing production rather than technological complexity without performance gains. Recent research also emphasizes that Lean adoption must extend beyond tools and methods to include educational transformation, interdisciplinary collaboration, and soft-skill development in communication, teamwork, and adaptive problem solving (Patching et al., 2024).

Among these developments, concrete three-dimensional printing (C3DP), also referred to as additive manufacturing for construction, has emerged as a disruptive approach with the potential to redefine traditional construction processes. By enabling automated layer-by-layer fabrication of cementitious elements directly from digital models, C3DP offers significant advantages in terms of geometric freedom, reduced formwork requirements, material efficiency, and labour optimization (Buswell et al., 2018; Lim et al., 2012). These capabilities position concrete 3D printing as a key enabler for the transition toward Industry 4.0 and Construction 4.0 paradigms. From a Lean perspective, such automation has the potential to reduce material waste, stabilize production, and improve workflow predictability. However, Lean research warns that technological advancement alone does not guarantee performance improvement unless it is embedded within collaborative supply chain systems and integrated management practices (Meng, 2019). Despite rapid technological advancements and increasing numbers of pilot projects worldwide, the widespread adoption of C3DP remains limited. One of the primary barriers lies in the complexity of the technology itself, which requires interdisciplinary expertise spanning materials science, robotics, mechanical systems, and digital design workflows (Buswell et al., 2018). Unlike conventional construction methods, concrete 3D printing involves tightly coupled interactions between software-based design parameters, hardware configurations, and time-dependent material behaviour. Errors in any stage of this interconnected process can result in print failures, compromised structural integrity, or irreversible damage to expensive equipment (Lim et al., 2012), generating precisely the types of rework and waste Lean Construction seeks to eliminate.

Training and education play a critical role in overcoming these challenges. However, existing training approaches for C3DP are largely inadequate. Conventional methods, such as classroom instruction, static manuals, and limited hands-on demonstrations, fail to capture the dynamic and spatially complex nature of the printing process. Moreover, real-world training using physical concrete 3D printers is constrained by high operational costs, safety risks, limited equipment availability, and material waste (Wolfs et al., 2018). These constraints significantly restrict opportunities for iterative learning, experimentation, and failure-based understanding, which are essential for mastering advanced manufacturing systems and align directly with Lean principles of continuous improvement and learning-based production (Aigbavboa et al., 2025; Howell, 1999). In parallel, immersive digital technologies have demonstrated growing potential in engineering education and professional training. Virtual reality (VR), augmented reality (AR), and mixed reality (MR) systems have been successfully applied in construction safety training, equipment operation, and design visualization, showing improvements in knowledge retention, situational awareness, and skill acquisition compared to traditional methods (Sacks et al., 2013; Wang et al., 2013). More recently, the concept of the Metaverse has emerged as an evolution of immersive technologies, characterized by persistent, shared, and interactive virtual environments that integrate digital twins, real-time simulation, and multi-user collaboration (Mystakidis, 2022).

The Metaverse offers unique opportunities for training in complex cyber–physical systems such as concrete 3D printing. By combining immersive visualization with physics-based simulation and hardware–software integration, Metaverse environments can replicate real-world construction processes with high fidelity while eliminating physical risks and material consumption. From a Lean Construction standpoint, such environments enable zero-waste experimentation, pull-based learning, and reliable rehearsal of workflows before physical execution. Digital twins of construction equipment within the Metaverse allow users to interact with virtual replicas of machines, observe internal processes, and experience the consequences of operational decisions in a controlled setting (Tao et al., 2019). These capabilities directly support Lean objectives of reducing variability, preventing rework, and stabilizing production systems. Such capabilities are particularly relevant for C3DP, where understanding component interdependencies, maintenance procedures, and parameter sensitivities is critical for successful operation.

Recent studies have highlighted the potential of virtual and simulation-based environments for additive manufacturing education, particularly in the context of polymer-based 3D printing and small-scale systems (Ford & Minshall, 2019). However, research focusing on construction-scale additive manufacturing remains scarce. Concrete 3D printing introduces unique challenges that are not addressed by existing training frameworks, including large-scale kinematics, continuous material pumping, nozzle cleaning requirements, and the long-term impact of improper maintenance on system longevity (Table 1). More importantly, current educational models lack integration of Lean principles such as waste reduction, continuous improvement, and system-level learning. The connection between software-driven design decisions and their hardware-level consequences is often weak, limiting trainees' ability to understand process variability and production reliability. This gap highlights the need for a training method that embeds Lean Construction principles within an immersive, end-to-end learning environment.

In response to these gaps, this study addresses the following research question: How can a Metaverse-based training method effectively support the teaching and learning of concrete 3D printing within construction processes? To answer this, the study proposes a Metaverse-based training method that integrates digital design inputs, immersive spatial visualization, simulation engines, hardware–software synchronization, and failure-mode analysis within a unified learning environment. The method emphasizes both hardware-related competencies, such as component identification, printer setup, and cleaning, and software-related competencies, including parametric design, slicing, and translating digital parameters into machine behaviour. Each training stage is aligned with key advantages of Metaverse-based learning, including enhanced experiential understanding, zero-waste experimentation, improved safety, and continuous improvement cycles central to Lean Construction.

The remainder of this paper presents the conceptual design and methodological implementation of the proposed method, demonstrating how Metaverse technologies can support scalable, effective, and industry-relevant Lean Construction training for concrete 3D printing. By addressing current educational limitations and aligning with Lean Construction principles and digital construction trends, this work contributes to the advancement of immersive learning systems for next-generation construction technologies.

Table 1: Comparative analysis of conventional concrete 3D printing training methods.

Training Approach	Merits	Limitations	How the Proposed Metaverse Method Addresses the Limitations
Traditional classroom and manual-based training	Low cost and structured theoretical knowledge delivery	Limited spatial understanding; poor dynamic hardware–software interactions; (Buswell et al., 2018; Lim et al., 2012)	Delivers immersive 3D environments that improve spatial understanding, support Lean learning and system integration, and enable early identification of process inefficiencies before execution.
Physical on-site training with real equipment	High realism and direct hands-on experience	High operational cost, safety risks, material waste, and limited access to equipment (Wolfs et al., 2018)	Enables risk-free, repeatable training scenarios without material consumption or equipment wear, supporting zero-waste experimentation, safe failure-based learning, and Lean continuous improvement practices
Virtual reality (VR)-based training	High immersion and improved engagement; effective for visualization and safety training (Sacks et al., 2013)	Often task-specific; limited integration of real machine logic and software–hardware coupling	Integrates immersive VR with digital twins, real control logic, and end-to-end workflow simulation, enabling holistic Lean production understanding and validation of processes before resource commitment

METHODOLOGY

The proposed methodology is founded on the development and deployment of an integrated Metaverse-based training method that functions as a digital twin–driven learning environment for concrete 3D printing within the construction process. From a Lean Construction perspective, the methodology is designed as a learning production system that prioritizes waste minimization, workflow reliability, and continuous improvement through simulation-based validation. The methodology adopts a system-oriented approach in which digital design inputs, immersive visualization, simulation engines, hardware–software synchronization, and failure-mode analysis are cohesively combined to support experiential learning, operational validation, and zero-waste training objectives (Figure 1). This integration reflects Lean principles of treating training as part of the production value stream rather than an isolated activity.

At the initial stage, the methodology begins with the ingestion of digital design inputs generated through parametric modelling and slicing processes. These inputs define the geometric characteristics, layer configurations, and toolpath parameters of the concrete 3D printed structure, including layer height, extrusion width, and spatial coordinates. Rather than treating these parameters as abstract numerical values, the method embeds them directly into a Metaverse environment where they are spatially visualized at full construction scale. This spatial visualization enables trainees to experience the design in an immersive three-dimensional context, fostering a deeper understanding of geometric complexity, constructability constraints, and scale-dependent behaviour that cannot be effectively conveyed through conventional two-dimensional interfaces. In Lean terms, this stage enhances early error detection and reduces downstream rework by improving decision quality before physical execution.

Once the design inputs are established, the methodology transitions into the simulation engine, which serves as the core analytical and instructional layer of the method. Within this engine, component identification is performed using high-fidelity virtual representations of the concrete 3D printer and its subsystems. Each hardware component, including pumps, extrusion

nozzles, material delivery lines, motion axes, and control units, is interactively accessible within the Metaverse. Trainees can inspect components in isolation or as part of the integrated system, enabling them to understand both individual functions and interdependencies. This process establishes a foundational hardware literacy that is essential for subsequent operational tasks and aligns with Lean goals of systems thinking and integrated production awareness.

Following component identification, kinematic mapping is executed to translate digital design coordinates into printer motion logic. The methodology explicitly maps software-defined parameters, such as toolpath coordinates and motion sequences, to the physical movements of the printer's gantry or robotic arm. This mapping is visualized in real time within the immersive environment, allowing trainees to observe how variations in design inputs influence motion trajectories, extrusion timing, and spatial accuracy. By embedding this mapping within the Metaverse, the methodology reduces the cognitive gap between digital commands and physical behaviour, reinforcing systems-level understanding of concrete 3D printing operations. From a Lean perspective, this reduces variability and improves production predictability by strengthening the connection between design intent and execution.

In parallel, the simulation engine incorporates virtual pumping and material flow modelling to replicate the behaviour of cementitious materials during extrusion. This aspect of the methodology accounts for the unique properties of printable concrete, including flow consistency, pressure requirements, and time-dependent behaviour. Through interactive simulation, trainees observe how material properties interact with hardware settings and motion parameters, enabling them to anticipate issues such as over-extrusion, under-extrusion, or material segregation. This approach ensures that material-machine interactions are treated as an integral part of the training process rather than as external variables, supporting Lean objectives of preventing defects and stabilizing process flow.

The methodology then advances to hardware-software synchronization, where digital design data are translated into executable machine instructions using G-code and programmable logic controller commands. This synchronization layer functions as a virtual hardware-software bridge, ensuring that design intent, control logic, and machine behaviour remain consistently aligned. Within the Metaverse, trainees initiate simulated printing operations and monitor system responses, gaining insight into command execution sequences, sensor feedback, and system coordination. This stage reinforces procedural competence while allowing users to experiment with parameter adjustments without the risks associated with physical equipment operation. Such risk-free experimentation embodies Lean principles of safe testing and learning without generating material waste.

A critical component of the methodology is the incorporation of failure mode and stress analysis within the immersive environment. Rather than limiting training to ideal operational conditions, the method deliberately introduces failure scenarios related to inadequate cleaning, component mismatch, and improper preparation procedures. These scenarios simulate the progressive accumulation of material residue, increased mechanical stress, and performance degradation that result from improper maintenance practices. By visualizing the long-term consequences of such failures, including reduced component lifespan and compromised system reliability, the methodology enables trainees to develop causal understanding that is difficult to achieve through real-world observation alone. This failure-aware training directly supports Lean Construction's emphasis on root-cause learning and prevention of recurring defects.

An iterative correction loop supports adaptive learning by guiding trainees to revisit earlier workflow stages when failures or inefficiencies arise. They can adjust parameters, refine cleaning procedures, or reconfigure components, mirroring real-world troubleshooting in a zero-risk environment. This repeatable process eliminates material waste and equipment damage, reflecting Lean continuous improvement (*kaizen*) within training. The final stage focuses on output validation. Simulation results are assessed against criteria such as safety

compliance, hardware durability, and structural integrity, ensuring all testing occurs virtually before physical deployment. Successful completion confirms operational readiness, while the method can issue certifications based on demonstrated competence. Overall, the methodology establishes a closed-loop, immersive training ecosystem integrating design, simulation, and validation, embedding failure-aware learning, and enabling safer, more efficient, and scalable training for concrete 3D printing, aligned with Lean Construction principles of reliability, waste reduction, and continuous improvement.

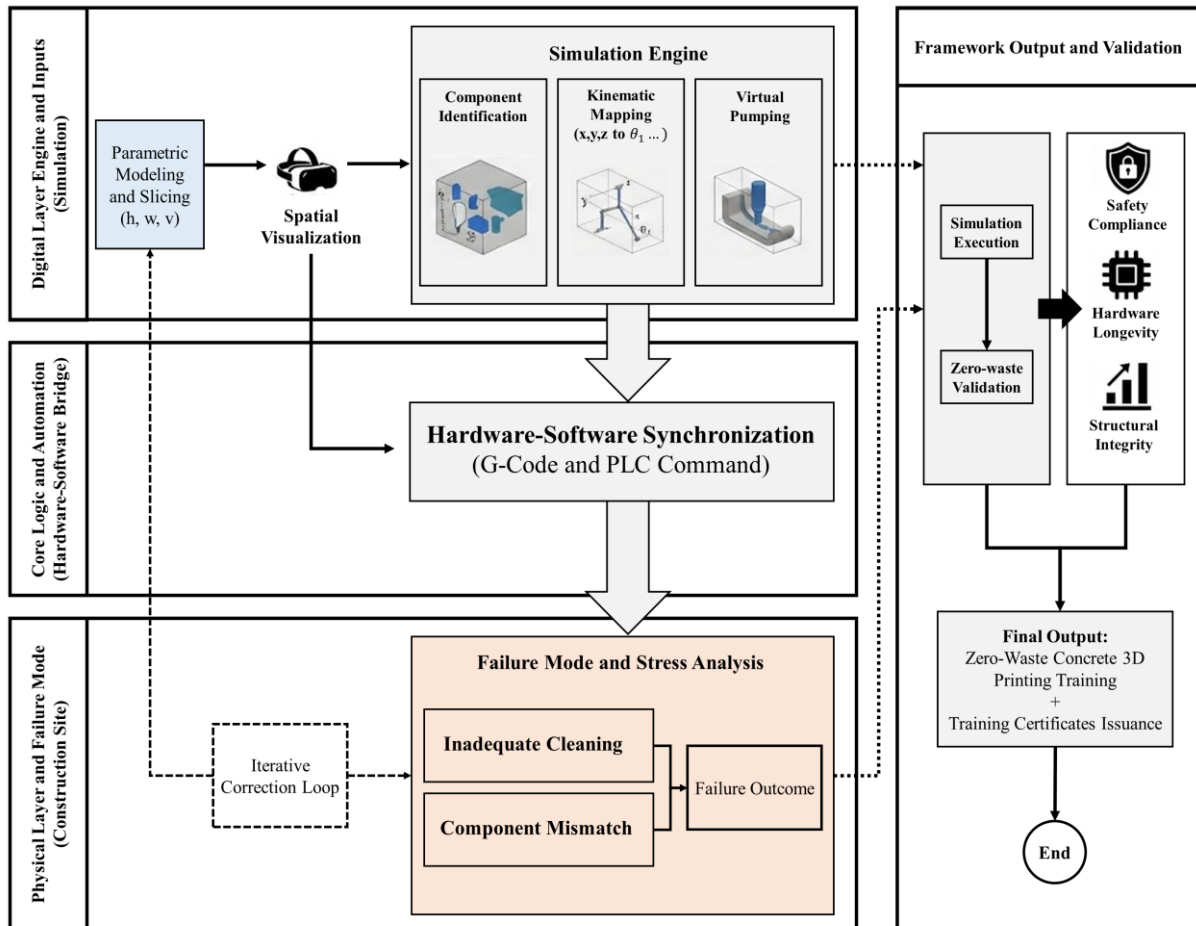


Figure 1: Summarized methodology flowchart.

This study adopted a structured quantitative validation to assess the effectiveness of the proposed training approach (Figure 2). The validation was organized into three sequential phases, namely user recruitment and exposure, data collection, and data processing and modelling. A total of 54 participants were recruited for the study. All participants were based in the United Arab Emirates and consisted of individuals who had prior exposure to training programs. Data were collected using a comparative perception survey developed on a five-point Likert scale, where 1 represented strong disagreement and 5 represented strong agreement. The survey instrument was designed to capture three core constructs central to training effectiveness: learning effectiveness, learning performance, and practical applicability. Learning effectiveness focused on the extent to which the training enhanced knowledge acquisition and understanding, while learning performance assessed perceived improvements in skills and task execution. Practical applicability examined the relevance of the training content to real-world contexts. Each construct was measured using four items, resulting in a total of twelve survey questions.

The collected data were processed by calculating the average score for each construct. Specifically, the responses to the four items within each construct were aggregated and divided

by the number of items to obtain individual construct scores for learning effectiveness, learning performance, and practical applicability. These scores provided a normalized measure of each dimension on the same Likert scale. To obtain an overall measure of effectiveness, a Composite Effectiveness Index was computed by averaging the three construct scores. The index was evaluated on a scale from 1 to 5, where a value of 3 indicated neutrality and equivalence to traditional training methods such as lectures, video-based instruction, or on-site sessions. Values above 3 reflected improved effectiveness compared to traditional approaches, whereas values below 3 indicated lower effectiveness.

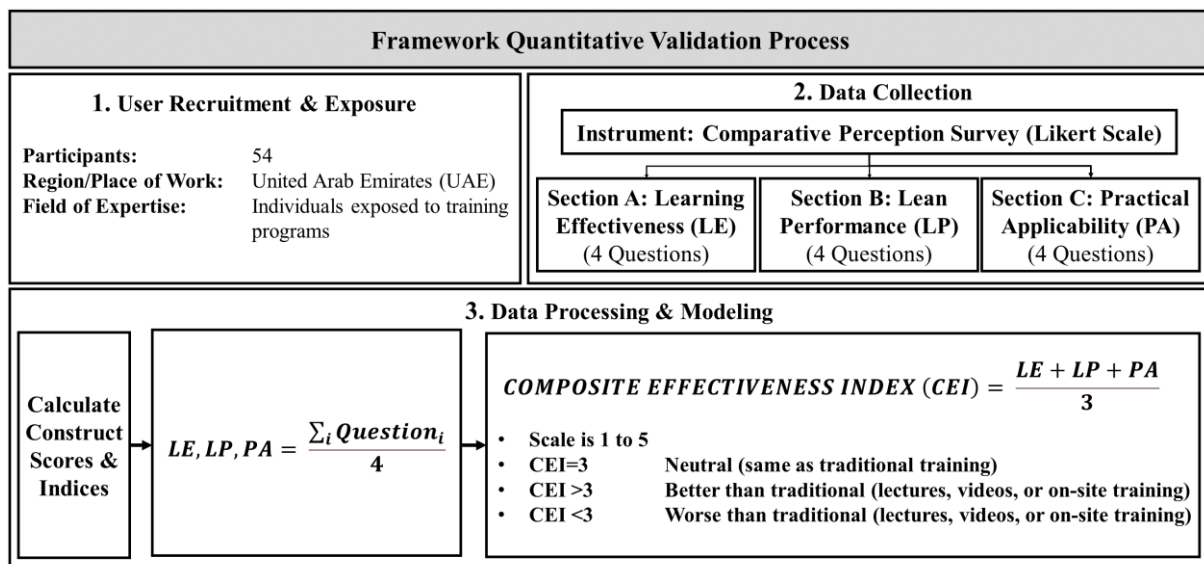


Figure 2: Validation methodology flowchart.

RESULTS AND DISCUSSION

The metaverse-based simulation environment successfully operationalized the proposed training method by enabling a continuous, end-to-end learning workflow that connects printer hardware familiarization, software-based design preparation, virtual printing rehearsal, and maintenance-oriented failure demonstrations within a single persistent immersive space. From a Lean Construction perspective, this unified workflow reflects an integrated production value stream in which training, validation, and operation are treated as interconnected processes rather than isolated activities. The performed simulations demonstrate that the method is capable of presenting concrete 3D printing as an integrated cyber–physical process rather than a set of disconnected activities, thereby making the relationships between design inputs, machine behaviour, and maintenance quality directly observable to the trainee. This visibility supports Lean objectives of reducing variability and preventing defects by strengthening causal understanding across the system.

The first set of simulation outputs confirms that the metaverse environment supported stable persistent multi-user presence and task-oriented interaction through an embodied avatar, a persistent scene, and a real-time interaction interface (Figure 3). The simulation displayed a current metaverse user profile indicator, a trainee avatar within the environment, a chat or interaction panel, and a simulated concrete 3D printing cell consisting of a robotic arm, a nozzle/extrusion end-effector, and a print platform. The presence of these elements demonstrated that the method can simultaneously support a human-centred training perspective. Importantly, the simulation allowed the trainee to physically navigate the workspace and approach the printer from multiple viewpoints, which enabled inspection behaviours that mirror real-world site practice, including close-range observation of the extruder head and proximity-

based inspection of mechanical subsystems. From a Lean standpoint, this spatial freedom supports experiential learning, early problem detection, and safer rehearsal of operational tasks without generating material waste or equipment downtime. By enabling repeatable, risk-free inspection and interaction, the method reinforces Lean principles of continuous improvement and learning-based production stabilization. The simulation showed that trainees could perform component-oriented inspection within a virtual printing cell by approaching the simulated concrete 3D printer and examining key subsystems at multiple scales.

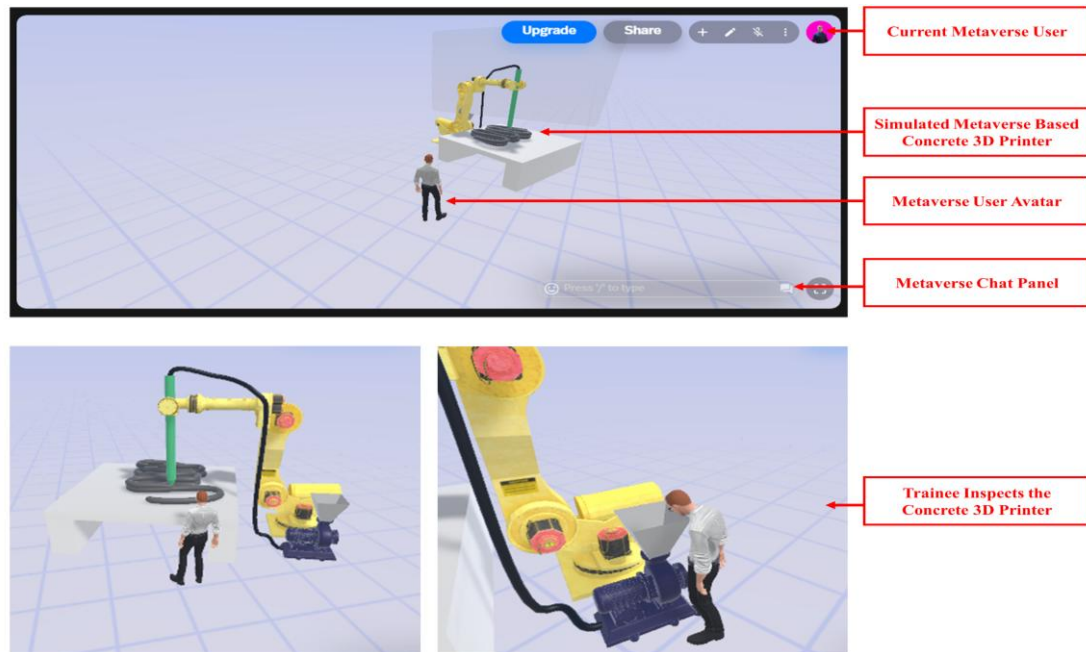


Figure 3: Illustration of the Metaverse-based concrete 3D printing training environment.

The results confirm that the metaverse environment can act as a safe proxy for early hands-on exposure, allowing repeated inspection and recognition of printer components before interacting with physical equipment. From a Lean Construction perspective, this risk-free repetition supports early error detection, standardized learning, and waste reduction by minimizing misuse and procedural mistakes. Additionally, the simulation demonstrates that the method can integrate design and pre-processing tasks directly into the immersive environment through external software interfaces displayed as in-world panels (Figure 4).

In the performed simulation, the trainee operated in a shared space where the concrete 3D printing cell remained visible while design software interfaces were simultaneously accessible. This created an explicit co-presence of “digital design” and “physical printing,” which is a central objective of the method. The observed outcome is that the trainee can learn design generation and adjustment while continuously referencing the simulated printer, thereby reinforcing the mapping between software parameters and hardware execution constraints. Rather than teaching CAD and slicing as abstract screen-based tasks, the simulation situates these tools alongside the printer, enabling the trainee to interpret geometry, scale, and printability relative to the printing system. This integration aligns with Lean principles of connecting design and production within a unified value stream, reducing disconnects that typically generate inefficiencies, rework, and workflow instability in construction processes. A core result illustrated by the performed simulation is the feasibility of running virtual printing rehearsals prior to operating a physical concrete 3D printer (Figure 4). The simulation displays training on running virtual printing simulations, emphasizing pre-validation of designs inside the metaverse environment. This establishes that the method can support a “zero- waste

validation” concept, wherein trainees can test toolpaths, visualize motion and deposition, and identify potential failure points without material consumption or physical risk. From a Lean Construction standpoint, this capability reinforces principles of defect prevention and reliable workflow preparation by shifting experimentation upstream, where corrections can be made before committing physical resources.

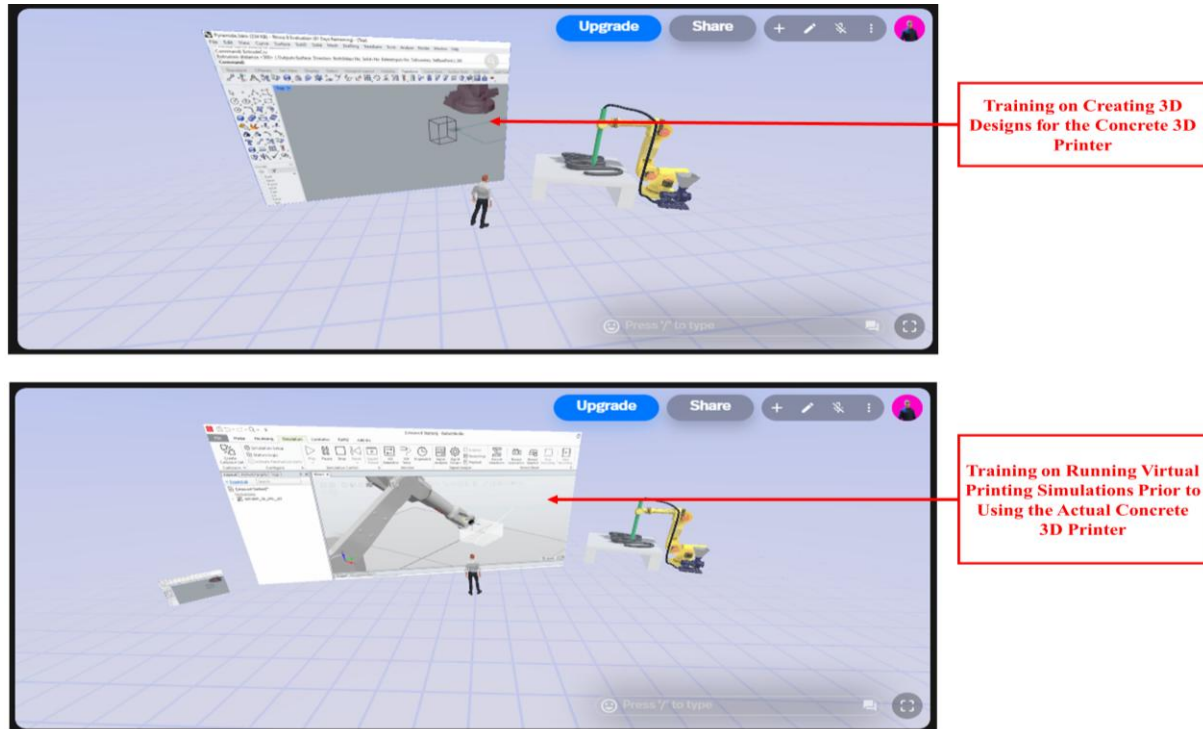


Figure 4: Illustration of embedding design and pre-processing activities directly into the immersive Metaverse-based concrete 3D printing training environment.

The most distinctive simulation result concerns the maintenance and cleaning training scenario, where the method demonstrates the effect of improper cleaning through a visible progression of concrete accumulation within the nozzle (Figure 5). The performed simulation explicitly visualized the gradual build-up process and connected it to training on the impact of improper cleaning on equipment condition. This outcome confirms that the metaverse environment can represent time-dependent degradation mechanisms that are difficult to observe in real training settings, where the effects of inadequate cleaning may only become apparent after extended operation, sudden clogging events, or component failure. By making long-term consequences immediately visible, the method supports Lean Construction goals of preventive maintenance, root-cause awareness, and production reliability, encouraging trainees to adopt disciplined operational practices that minimize downtime and equipment-related waste.

The quantitative analysis yielded a Composite Effectiveness Index (CEI) of 4.08 out of 5, indicating that the proposed metaverse method was perceived as better than traditional training overall. At the construct level, the mean scores were 4.13 for Learning Effectiveness (LE), 4.04 for Lean Performance (LP), and 4.08 for Practical Applicability (PA), with all values exceeding the neutral benchmark of 3.00. These findings confirm that participants rated the method positively across all three evaluation dimensions. Participants who found that the proposed metaverse method was better (score 4) or much better (score 5) accounted for 81.4% for improving understanding of concrete 3D printing systems, 79.6% for improving understanding of design–machine–material interactions, 81.5% for enhancing learning of cause–effect relationships, and 81.5% for improving confidence in performing tasks. Likewise, 77.8% reported that the method was better or much better for improving identification of waste in

processes, 75.9% for improving defect prevention before execution, 81.5% for improving workflow reliability understanding, and 68.5% for improving awareness of maintenance impacts.

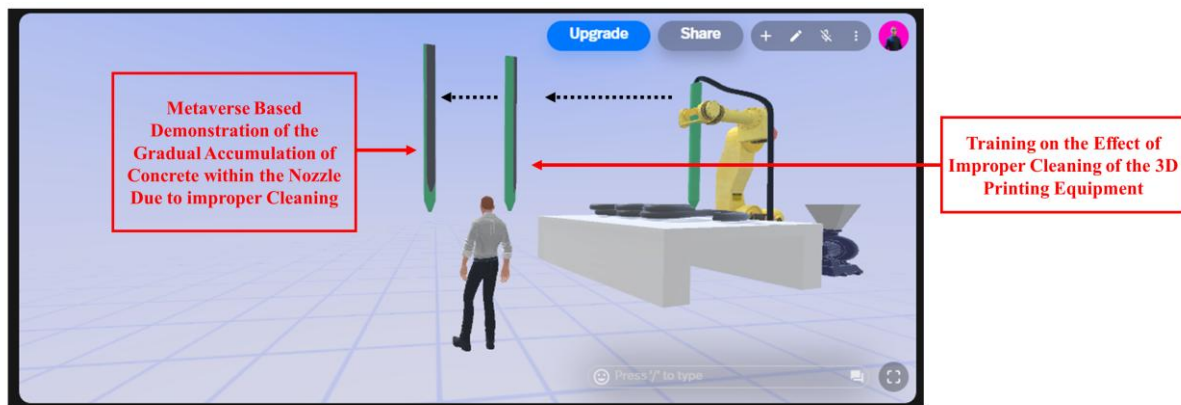


Figure 5: Illustrating effect of improper cleaning through a visible progression of concrete accumulation through the Metaverse-based concrete 3D printing training environment.

For the practical outcome items, participants who rated the method as better or much better accounted for 74.1% for preparing trainees for real-world tasks, 90.7% for reducing material waste during training, 75.9% for improving readiness before on-site work, and 79.6% for being more effective overall than traditional training. Overall, the reported results indicate that the proposed metaverse method was widely regarded as a more effective alternative to conventional training approaches.

CONCLUSION

This study presented a metaverse-based training method for concrete 3D printing and demonstrated its feasibility as an integrated, immersive learning environment that unifies design, machine operation, and maintenance within a tightly coupled cyber-physical system. From a Lean Construction perspective, the method supports systems-level learning, reduces variability, prevents rework, and enhances production reliability by enabling trainees to experience the full lifecycle of concrete 3D printing in a coherent, interactive, and risk-free environment. Simulation results demonstrate that the metaverse environment can effectively support hardware-oriented training by allowing users to inspect printer components at realistic scale and understand their functional roles without safety risks or equipment wear. By minimizing material waste and equipment downtime, the method supports Lean principles of efficient resource use and zero-waste learning. Integrating software-based design within an immersive environment strengthens the connection between parametric design, slicing parameters, and physical execution, reducing gaps between design and production while promoting continuous flow and value stream integration. The system enables virtual printing rehearsal and zero-waste validation, allowing trainees to anticipate issues, evaluate toolpaths, and verify designs before physical implementation, supporting early defect prevention and reliable workflows. Maintenance and cleaning simulations further enhance training by illustrating the consequences of poor practices, encouraging preventive maintenance and extending equipment lifespan. The effectiveness of the proposed method was further validated through quantitative analysis. The results yielded a Composite Effectiveness Index (CEI) of 4.08 out of 5, indicating that the method is perceived as better than traditional training methods. In addition, a substantial proportion of participants rated the method positively, with 68.5% to 90.7% of respondents indicating that it was better or much better than traditional training across the evaluated constructs. Future work will explore the integration of advanced Lean-oriented

analytics and performance indicators, such as real-time performance feedback and value stream monitoring, to further enhance continuous improvement and process optimization within the training environment.

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