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IoT-Driven Digital Twin Framework for Precast Concrete Design and Fabrication

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The emergence of cutting-edge technologies such as the Internet of Things (IoT) and Digital Twins (DTs) has transformed industries, including construction, by enabling real-time data monitoring and improving decision-making. Precast concrete components are widely used in construction due to their durability and quality. IoT and DT technologies can drastically reduce labor, material, and energy costs by detecting inefficiencies and streamlining production schedules. Despite the promising potential, the integration of IoT and DT technologies in precast concrete production remains to be explored to overcome the challenges associated with their implementation. This study explores the integration of IoT and DT technologies into the design and fabrication of precast elements. The specific objectives are to 1) conduct a systematic review to characterize the potential applications of Digital Twin and IoT in the design and fabrication of precast elements, and 2) develop a conceptual IoT-enabled Digital Twin framework to enhance the efficiency of the design and fabrication of precast elements. The findings of this study are expected to provide a basis for future studies and insights on how IoT and Digital Twin technologies can be effectively integrated to enhance quality control, optimize production processes, reduce costs, and improve the lifecycle management of precast components.

Keywords: Design, Digital Twin; Fabrication; Framework; IoT; Precast Element.

Introduction

Precast concrete construction offers several benefits, including faster construction time, better quality control, reduced on-site labor, and improved worker safety, potentially resulting in significant cost savings compared with traditional cast-in-place methods. However, despite these notable advantages, the design and fabrication of precast concrete elements still face various challenges that can negatively impact structural integrity, cost efficiency, and project timelines. Some of the major design challenges are related to issues with joint design and structural connections (Choi & Kim, 2012), standardization vis-à-vis the need for customization to meet clients' needs (Kamar et al., 2009), and coordination with other components such as mechanical, electrical, and plumbing (Azhar et al., 2012). Similarly, during the fabrication stage of precast construction, several challenges arise, including maintaining quality control and dimensional accuracy (Bergström & Stehn, 2005), managing formwork efficiency and reusability (Molavi & Barral, 2016), handling and transporting materials effectively (Tam et al., 2007), addressing sustainability and environmental impacts (Zuo et al., 2009), and overcoming limitations related to skilled labor and workforce availability (Nawi et al., 2014).

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In contrast to monolithic cast-in-place concrete, precast components rely on specially designed joints to ensure structural continuity and withstand seismic forces. Inadequate connection design can result in failures under dynamic loads or differential movement (Choi & Kim, 2012; Ghosh, 2010). Although standardization plays a vital role in streamlining fabrication, many construction projects require customized designs to meet specific architectural needs. This conflict between the efficiency of standardized processes and the flexibility of customized solutions often results in higher costs and reduced overall efficiency (Kamar et al., 2009). While the use of digital tools, such as Building Information Modeling (BIM), is becoming increasingly prevalent in precast concrete design, effective integration across disciplines remains a challenge. Tasks such as clash detection, construction sequencing, and logistics planning demand advanced BIM skills and close coordination among project stakeholders (Azhar et al., 2012).

Maintaining precise dimensions and consistent quality in the factory is challenging, particularly for large or complex precast components, as small errors can cause significant problems during on-site assembly (Bergström & Stehn, 2005). Additionally, the fabrication of precast elements requires costly formwork systems, and balancing their reusability with design flexibility presents a common trade-off that can significantly affect both production costs and scheduling efficiency (Molavi & Barral, 2016). Transporting and lifting heavy precast components require meticulous planning and specialized equipment, and logistical challenges can significantly hinder the implementation of precast systems (Tam et al., 2007). Although precast construction reduces on-site waste, it remains environmentally challenging due to cement-related emissions and energy-intensive transportation, with sustainability measures such as modular design and lifecycle assessment still underutilized globally (Zuo et al., 2009). Precast construction offers the advantage of controlled factory production, but it still depends on skilled labor for handling, installation, and post-tensioning (Nawi et al., 2014).

Precast concrete offers significant advantages in speed, precision, and sustainability, but challenges in design coordination, fabrication efficiency, and skilled labor shortages often limit its full potential. Integrating Internet of Things (IoT) and Digital Twin (DT) technologies offers a promising approach to addressing these issues by enhancing quality control, reducing costs, and improving lifecycle management of precast components. However, barriers such as interoperability, high implementation costs, and cybersecurity risks remain significant, especially for small- to medium-sized firms. This study aims to explore the integration of IoT and DT technologies into the design and fabrication of precast concrete elements by developing an IoT-enabled DT framework. Specifically, it seeks to (1) conduct a systematic review to characterize existing applications of IoT and DT across the design, fabrication, and post-installation phases; and (2) develop a phase-oriented framework to support more efficient and intelligent precast workflows. The research addresses key questions regarding how IoT-DT integration can enhance design precision, optimize production processes, and facilitate long-term asset monitoring in precast construction.

Research Method

To achieve the stated research objectives, several tasks were completed. Each of these tasks discussed in this section explains the research methodology adopted for this study. This study used a combination of sequential and concurrent tasks, as illustrated in Figure 1 below.

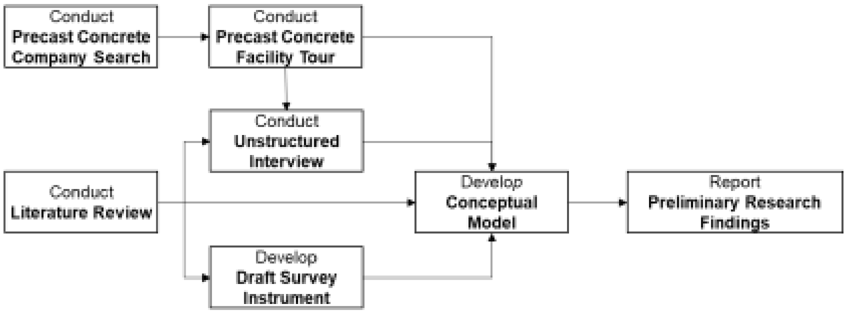

Figure 1. Research Process

Review of the Applications of IoT and DT for Precast Concrete Design and Fabrication

The research team has begun a systematic review of literature by probing databases such as Web of Science, Scopus, Google Scholar, ASCE Library, etc., to identify the different applications of DT and IoT in the design and fabrication of precast elements, as well as existing case studies of IoT- and DT-enabled precast production. The review focused on peer-reviewed studies published between 2020 and 2025. Search terms included combinations of “DT,” “IoT,” “precast concrete,” and “prefabrication.” Inclusion criteria were: (1) relevance to precast concrete applications, (2) use of IoT and/or DT technologies, (3) publication in English, and (4) empirical or framework-based contributions. The initial search across Scopus and Web of Science databases yielded 76 unique records. These records were first screened based on titles and abstracts to assess relevance to the integration of DT and IoT technologies in precast concrete workflows. Full-text screening was then conducted for shortlisted studies using the inclusion criteria. To improve reliability and minimize selection bias, two reviewers independently assessed the final pool of studies. Any disagreements were resolved through discussion and consensus. The final selection included 18 peer-reviewed articles, which were then categorized by lifecycle phase (design, fabrication, post-fabrication) and analyzed for technology focus and reported outcomes. Table 1 presents the included articles, their context, involved phase, main technologies, and key outcomes.

Table 1. Summary of Reviewed Studies on IoT-DT Applications in Precast Concrete

Source	Context	Phase	Main Technologies	Key Outcomes
Baghalzadeh et al. (2022)	Literature review and analysis	All	IoT, BIM, DT	Bibliometric and network analysis of integration trends
Ismail (2022)	Thermal comfort in precast	Design	IoT, BIM	Framework for BIM-IoT integration for precast design climate control
Lu et al. (2020)	Smart manufacturing overview	Fabrication	DT	Model for DT-driven manufacturing with reference architecture
Sacks et al. (2018)	BIM foundations	Design	BIM	General BIM principles and adoption guidance
Zhang et al. (2022)	Construction DTs	All	DT	Definitions, use cases, and levels of detail for construction DTs
Zhao et al. (2019)	IoT in prefab	Fabrication	IoT	Improving prefab performance using IoT sensors
Zhou et al. (2021)	DT modeling	Fabrication	DT	Modeling DT workflows for prefabricated buildings
El Mokhtari et al. (2022)	Cognitive DT	Design	DT, BAS, ML	DT integrating BAS, cloud data, and cognition for design/ops
Cole et al. (2024)	DT architecture	Fabrication	DT, IoT	Control architecture for curing and quality assurance

Source	Context	Phase	Main Technologies	Key Outcomes
Yitmen et al. (2023)	Cognitive DTs	Design	DT	CDTs for quality assurance in wall design
Omrany et al. (2023)	Industry-wide DT review	All	DT	Comprehensive review of DT applications and technologies
Kosse et al. (2024)	Semantic DT	Fabrication	DT, AAS, RDF	Dynamic scheduling and production tracking framework
Rausch et al. (2023)	Quality control	Fabrication	3D scanning, ML	Point-cloud validation of precast geometries
Awouda et al. (2024)	IoT framework	Fabrication	IoT, DT	IoT-DT reference model based on IoT-ARM for Industry 5.0
Jiang et al. (2022)	On-site synchronization	Fabrication	DT, IoT	DT-SYNC system for PSE during onsite assembly
Tuhaise et al. (2023)	Synchronized construction	Fabrication	DT, Robotics	Linking DTs to in-plant robots and logistics
Shehu et al. (2025)	Tracking tools	Post-fabrication	QR/RFID	Circular economy and lifecycle traceability benefits
Torzoni et al. (2024)	Infrastructure DT	Post-fabrication	DT	Structural monitoring framework with predictive capability
Sahin et al. (2024)	Hybrid DTs	Post-fabrication	DT, PINNs	Physics-informed neural networks for fatigue modeling

Stakeholders' Perception of Impact of IoT-Enabled DT on Precast Concrete Design and Fabrication

To obtain practical information, the team developed and implemented a selection procedure to identify precast concrete companies. Seven (7) precast concrete manufacturing companies were identified and contacted. The team secured the agreement of a precast concrete company and toured their facility. During the tour, the research team conducted an unstructured interview, engaging in a natural, conversational dialogue without predetermined questions or a set sequence. To gather preliminary practitioner perspectives, an exploratory consultation was conducted during a scheduled plant visit at a regional precast manufacturer. The engagement involved an unstructured group interview with three participants: a production manager, an operations manager, and a quality assurance specialist. The discussion lasted approximately one hour and focused on challenges and expectations related to digitalization in precast workflows. Notes were taken manually and synthesized after the session to extract common themes and practical considerations. While insights provided valuable grounding for the framework, this input is limited in scope and should not be interpreted as representative of the broader industry. The approach was chosen for its flexibility, enabling deeper exploration and open communication.

Development of an IoT-Enabled DT Framework

Based on the findings, a framework was developed to model the critical components of an IoT-enabled DT system for the design and fabrication of precast elements, including the design phase, IoT sensor integration, fabrication, transportation, installation, and post-installation monitoring.

Results

IoT and DT Integration for Precast Concrete Design and Fabrication

This section provides a systematic review of recent peer-reviewed literature to identify how IoT and DT technologies are being applied in the design, fabrication, and post-installation management of precast concrete elements. By evaluating these applications, the review highlights key benefits, limitations, and future research directions necessary for developing a holistic IoT-DT framework.

Applications in the Design Phase

DT technology enhances precast design by providing real-time, simulation-enabled models that evolve in response to input data. Unlike traditional 3D modeling tools, DTs integrate geometric, structural, and environmental data, allowing for highly responsive design iterations. For example, Cole and Sianaki (2024) proposed a DT architecture that incorporates feedback from structural sensors to refine future precast designs. Yitmen et al. (2023) demonstrated the use of DTs for quality assurance in precast wall design, thereby improving design fidelity and reducing rework. Furthermore, Omrany et al. (2023) highlighted that BIM-integrated DTs can be used for early clash detection, energy simulations, and thermal modeling, thereby enabling more resilient and efficient designs. These systems enable scenario-based simulations, such as load testing or thermal stress analysis, before fabrication, thereby significantly reducing risk and uncertainty.

Kosse et al. (2024) explored a dynamic scheduling framework for optimizing precast element production by integrating DTs with real-time data acquisition throughout the manufacturing lifecycle. Central to this framework is the use of Asset Administration Shells as a semantic interface, enabling the aggregation of high-fidelity production data through Resource Description Framework serialization and ontological representations. This structure supports a simulation-based scheduler that interacts with the DT through a Service-oriented Architecture, facilitating rapid adjustments to supply chain variability and environmental influences. In practice, these DT-driven simulations are enhanced through cognitive capabilities supported by integrated software ecosystems. For example, advanced DT implementations aggregate real-time and historical data from building automation systems into cloud-based platforms, enabling memory, perception, and reasoning functions. Secure streaming architectures transmit sensor data, such as from BACnet devices, to scalable time-series databases. These databases are then linked to BIM and stored in relational systems for synchronized access. Visualization and interaction with this data are facilitated through high-performance tools such as Autodesk Revit, integrated with Forge or Tandem, and Dassault Systèmes 3D experience, which support semantic exploration and cognitive analytics in design environments (El Mokhtari et al., 2022).

Applications in the Fabrication Phase

The controlled nature of precast manufacturing provides fertile ground for implementing IoT and DT. In this phase, IoT sensors collect real-time data on curing conditions, mold alignment, and material properties. This data feeds into the DT to dynamically monitor and control the production environment. For instance, a DT architecture developed for a leading construction company in Melbourne demonstrated how advanced IoT sensors, machine learning algorithms, and simulation tools can optimize temperature and moisture control during the curing process, improving operational efficiency and ensuring compliance with industry standards (Cole et al., 2024). Rausch et al. (2023) used 3D point cloud data and machine learning to detect dimensional deviations in precast panels, enhancing quality assurance. Kosse et al. (2024) also proposed a DT framework with asset administration shells to create digital records for each component, tracking its production history and compliance. IoT may also enable predictive maintenance of equipment. Awouda et al. (2024) introduced a standardized IoT-based framework for the development and implementation of DTs, emphasizing sustainability, resilience, and human-centricity. Their framework, built upon the IoT Architectural Reference Model (IoT-ARM), provides structured architectural tools to support system modeling and integration of real-time monitoring capabilities. A proof-of-concept application in a vertical farming context demonstrated how streaming data from physical assets to secure cloud environments can enable dynamic asset tracking, decision-making, and operational adaptability, principles equally valuable in manufacturing sectors like precast production, where minimizing downtime and enhancing equipment resilience are crucial. Jiang et al. (2022) proposed a DT-enabled real-time synchronization system (DT-SYNC) to enhance planning, scheduling, and execution (PSE) during on-site assembly in prefabricated construction. By leveraging real-time information on resource status and construction progress, the system facilitates dynamic task allocation and performance optimization, particularly in urban settings with limited buffer space. Drawing on functional ticketing systems, DT-SYNC integrates cyber-physical visibility and traceability to ensure the right resources are allocated to the right tasks at the right time, thereby improving operational resilience and on-site collaborative decision-making. Similarly, research by Tuhaise et al. (2023) outlined a synchronized construction framework that links DTs to in-plant robots and lifting systems, aligning production with on-site sequencing requirements. Furthermore, technologies used include Trimble Tekla, Siemens MindSphere, and customized SCADA platforms that connect directly with structural sensors, RFID tags, and quality-control equipment embedded throughout the casting and curing processes (Zou et al., 2021).

Applications in the Post-Fabrication Phase

Following installation, precast components are continuously monitored using embedded sensor networks. DTs enable comprehensive lifecycle management by assimilating real-time data on structural health, environmental conditions, and material degradation, thereby supporting informed maintenance and operational decisions. Continuous data collection and analysis enable more effective maintenance strategies and can predict potential failures, thereby extending the lifespan of precast elements (Lu et al., 2018). Shehu et al. (2025) evaluated digital tracking tools, such as RFID and QR codes, in Swedish precast systems, demonstrating improvements in traceability and integration with the circular economy. Torzoni et al. (2023) outlined a data-driven DT model for infrastructure monitoring, which could be adapted for precast systems to predict wear and schedule maintenance. These post-installation applications support proactive asset management, thereby extending the service life of critical infrastructure, such as bridges and tunnels.

In a complementary study, Sahin et al. (2024) demonstrated how hybrid dynamic tests using physics-informed neural networks can monitor the behavior of concrete beams under dynamic loads, predicting microcrack propagation and fatigue failure. Moreover, platforms such as Bentley iTwin provide a robust foundation for integrating installed precast components into asset management systems, enabling real-time visualization of sensor data, streamlined inspection workflows, and comprehensive full-lifecycle tracking. Dassault 3D experience’s Virtual Twin extends this capability by simulating asset behavior and evolution throughout its lifecycle, integrating real-time performance data to support decision-making and enable predictive interventions. Projects involving precast tunnels, bridge decks, and modular construction increasingly leverage these platforms for performance benchmarking and extended asset intelligence (Bentley Systems, 2024).

Gaps and Challenges

Despite the rapid advancements, several challenges hinder the widespread adoption of IoT and DT technologies in the precast construction industry. One major challenge is the lack of standardization across platforms and data formats, which restricts interoperability between design, manufacturing, and operational systems. This fragmentation complicates data sharing and reduces the efficiency of end-to-end integration. The need for specialized hardware, software, and trained personnel represents a significant barrier to investment. Furthermore, data security and privacy concerns, especially when transmitting real-time data from construction sites or public infrastructure, remain under-addressed in most implementations. Moreover, while many studies demonstrate successful applications in isolated phases, such as design or manufacturing, comprehensive frameworks that span the entire lifecycle, from concept to decommissioning, are scarce. There is also limited practical evidence on the long-term return on investment and performance improvements of DT systems in actual precast construction environments.

Stakeholders' Perception

Several key insights emerged from the unstructured interview conducted with practitioners at the precast facility. First, the practitioners emphasized frequent issues with late design changes and misalignment between architectural and structural plans, underscoring the need for better coordination between Precast manufacturers and the National Precast Concrete Association to create a more user-friendly system for design engineers to access sizing, burial depth, and related information. They noted that early involvement of precast manufacturers in the design phase could significantly improve coordination and reduce rework. Design engineers should reach out to Precasters for information that could expedite their final design and lead to cost savings during installation, shorter timelines, and fewer change orders. They also highlighted a shortage of skilled labor, especially for specialized tasks such as rebar tying and formwork preparation, which require technology integration, automation, and robotics. While there was growing interest in automation and digital tools such as BIM, full implementation remained limited by costs, training needs, and resistance to change among older workers.

Outdated cast-in-place details should be eliminated from plans. If cast-in-place is shown, accept the precast options with drawings and sealed calculations furnished in the submittal process. The wheel load information should be updated and consolidated where applicable to eliminate confusion and interpretation issues. Develop a clear understanding that some specific items are more expensive than others because the precaster uses different forms. In-house handset items are commonplace with most manufacturers, but checking with the precaster could save time and money. Some municipalities require special items for structures and castings, which can be expensive and time-consuming, and in most instances, delays will occur. Municipalities should reach out to the manufacturers for information. Although the plant maintains strict quality assurance protocols, the practitioners acknowledged the current heavy reliance on traditional methods and reinforced the need for real-time monitoring tools to further reduce human error. Practitioners expressed awareness of the environmental impact of concrete production and showed interest in alternative materials and carbon-reduction techniques, though adoption remained in its early stages. Overall, the interview provided valuable practitioner perspectives, reinforcing themes found in literature while offering practical insights into real-world challenges and emerging trends in precast construction.

IoT-Driven DT Framework

The process of precast concrete element fabrication is constrained by inefficiencies stemming from uncoordinated flow between the design and fabrication phases, a lack of real-time quality feedback, and the absence of smart monitoring and tracking systems. Deviations or errors in element geometry, curing defects, and reinforcement displacements usually go unnoticed until final product review, thereby leading to increased rework, waste, and safety risks. Based on the findings from the literature, a 5-layer framework that models the flow of design through fabrication processes and technology integration, including post-production monitoring to ensure good quality maintenance throughout the production process, has been developed. This framework presents an ontology-supported semantic for integrating intelligent/smart data mapping. It uses a closed-loop feedback system for real-time design monitoring and adjustments. This framework is illustrated in Figure 2 and described as follows.

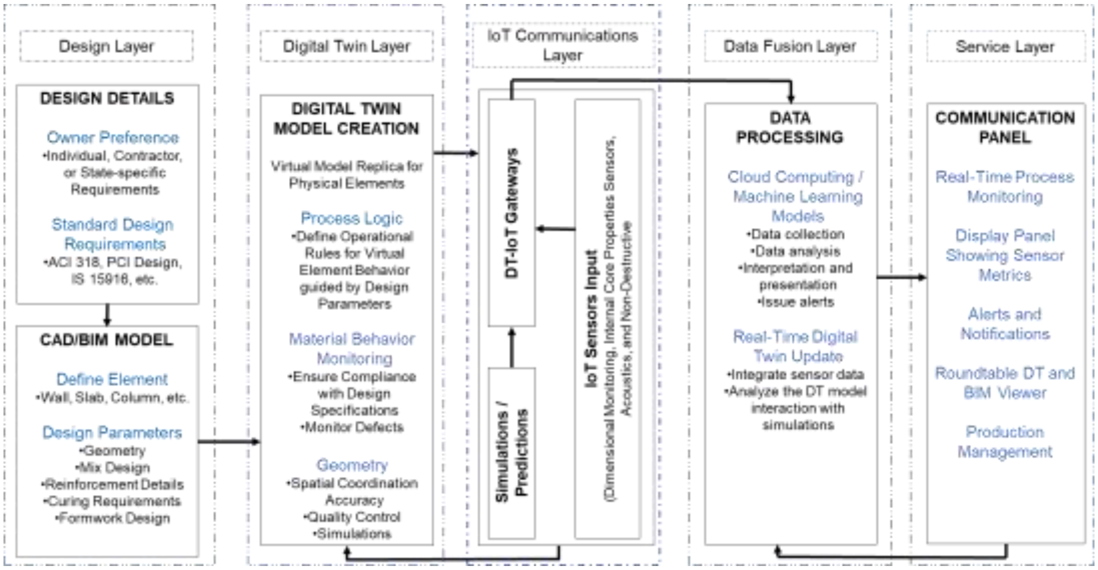

Figure 2. Conceptual IoT-Driven DT Framework for Precast Concrete Design and Fabrication

Furthermore, Table 2 illustrates how each layer of the proposed framework is grounded in specific themes from the reviewed literature and supported or challenged by feedback from the plant-level consultation.

Table 2. **Mapping Framework Layers to Literature and Practitioner Input**

Layer	**Supported By Literature**	**Informed by Practitioner Input**
Perception Layer	El Mokhtari et al. (2022); Rausch et al. (2023); Lu et al. (2020)	Need for real-time sensor feedback on curing and quality
Network Layer	Awouda et al. (2024); Jiang et al. (2022)	Concern about secure, low-latency wireless data transfer
Data Processing Layer	Kosse et al. (2024); Zhou et al. (2021)	Request for simplified dashboards and unified data views
Service Layer	Tuhaise et al. (2023); Torzoni et al. (2024)	Interest in simulation and predictive alerts for scheduling
Application Layer	Omrany et al. (2023); Shehu et al. (2025)	Need for lifecycle tracking and digital documentation

IoT-DT Framework Layers for Precast Concrete Production

The proposed IoT-DT framework for precast concrete elements is structured around five interconnected layers that collectively enable real-time monitoring, decision-making, and lifecycle optimization tailored to the unique demands of precast fabrication. The Design Layer defines element-specific details, including standardized precast mold geometry, reinforcement cage scheduling, lifting inserts, and loading requirements. These are modeled using Autodesk Revit or other BIM platforms, and each precast component is embedded with RFID or QR codes to support traceability from off-site fabrication through to site installation. The DT Layer creates a dynamic virtual representation of each precast element by integrating sensor data from curing beds and storage yards into BIM models. This simulation captures behavioral phenomena, including temperature gradients during curing, early-age shrinkage, and crack initiation, enabling predictive analysis of structural integrity prior to lifting or transport. The IoT Communications Layer acts as a bridge between physical precast units and their digital counterparts, enabling seamless real-time transmission of data from embedded sensors (e.g., strain gauges, humidity probes, ultrasonic sensors) via wireless protocols (e.g., Wi-Fi, LPWAN). It also includes yard condition monitoring and logistics tracking for precast panel movement. The Data Fusion Layer utilizes cloud-based AI and machine learning algorithms to synthesize sensor streams, flag production anomalies, recommend design or process adjustments, and predict equipment maintenance or curing inconsistencies. Finally, the Service Layer provides plant managers and engineers with intuitive dashboards that display real-time production metrics, schedule formwork reuse, and verify QA/QC records, supporting agile decision-making across the entire precast production workflow.

Conclusion

This study has explored the integration of IoT and DT technologies into the design and fabrication processes of precast concrete elements. Through a structured review of recent peer-reviewed literature and an exploratory consultation with industry practitioners, we developed a conceptual five-layer IoT-DT framework to enhance real-time monitoring, feedback, optimization, and lifecycle management in precast production. While the proposed framework offers a theoretically grounded contribution to the field, it remains conceptual and untested in a real-world production environment. The insights from stakeholders were derived from a single plant visit and should be interpreted as preliminary, given the limited sample size and informal methodology. Furthermore, although challenges such as cybersecurity vulnerabilities and high implementation costs were identified, this paper does not offer mitigation strategies; instead, it positions these as critical areas for future research.

To enhance the practical value of this work, future efforts should focus on implementing and validating the framework within operational precast facilities. This will not only test the feasibility of the layered architecture but also generate empirical data on cost-effectiveness, system resilience, and return on investment. Expanding stakeholder engagement through broader interviews or focus groups will further enrich the understanding of industry needs and readiness. Ultimately, the integration of IoT and DT into precast workflows promises to reduce defects, improve traceability, and optimize resource use across the full lifecycle, but realizing these benefits will require robust validation, cross-disciplinary collaboration, and strategic investment.

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