KAPITEL 2 / *CHAPTER 2* [2]
DIGITAL TWIN APPLICATIONS IN INDUSTRIALIZED OFFSITE CONSTRUCTION: AN AI-CENTERED REVIEW

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Introduction

Industrialized offsite construction (IOC) is an integrated approach that uses advanced manufacturing and digital tools to design, fabricate, and assemble building components in controlled environments. Compared to traditional on-site methods, IOC offers faster delivery, greater efficiency, higher quality, improved safety, and reduced environmental impact. However, its adoption is hindered by fragmented data systems, limited monitoring and analytics, and complex supply chains. These challenges can be mitigated through digital technologies such as automation, IoT, real-time analytics, and human–machine collaboration.

Within this context, digital twins (DTs) enhanced by artificial intelligence (AI) play a central role. DTs are dynamic virtual replicas of physical assets, maintained through continuous data exchange, enabling simulation, monitoring, and optimization. AI strengthens DTs by providing predictive modeling, advanced analytics, and data-driven decision-making. The DT market in construction, valued at USD 41.98 billion in 2024, is projected to more than double by 2029. Real-world examples, such as the Hong Kong–Zhuhai–Macau Bridge with its sensor-based monitoring system, illustrate DTs' ability to improve safety, maintenance, and efficiency. In IOC, DTs further support precise design, quality control, supply chain optimization, waste reduction, sustainability, and accelerated project delivery.

Despite these benefits, challenges remain, including lack of standardization, limited maturity assessments, and inconsistent implementation frameworks. Addressing these issues is critical to unlocking DTs' full potential in IOC. This study therefore investigates AI-driven DTs in IOC through a systematic literature review and

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scientometric analysis.

2.1 Literature research

Industrialized Offsite Construction (IOC) is transforming the construction sector by shifting production into factory-controlled environments, where precision, efficiency, and standardization are more easily achieved [2]. The benefits of IOC extend across multiple performance dimensions. Efficiency is enhanced through faster project timelines and streamlined workflows [3]; Quality and Safety are improved by better quality control and reduced exposure to on-site hazards [4]; Sustainability is advanced through reduced material waste, lower emissions, and minimized environmental impacts [3]; Labor Optimization is realized by reducing dependence on scarce skilled on-site labor [4]; Cost Predictability improves through more accurate budgeting and fewer delays caused by rework [1]; and Design Flexibility allows modular solutions to be tailored to diverse project requirements. Collectively, these attributes position IOC as a transformative alternative to traditional construction practices.

The evolution of IOC represents a progression from basic prefabrication toward digitally integrated manufacturing systems that emphasize precision, standardization, and sustainability [2]. Its applications span a wide range of sectors: in residential projects, IOC enables affordability and rapid deployment; in commercial buildings, it supports adaptable modular solutions with accelerated delivery; in healthcare and institutional facilities, it facilitates regulatory compliance while minimizing operational disruptions; and in infrastructure projects, it expedites the delivery of complex assets such as transit systems, stations, and bridges.

IOC practices can be classified into different typologies, ranging from simple prefabricated components to fully modular buildings. Discrete elements, such as wall panels, beams, and columns, are manufactured offsite and then assembled on-site. Non-volumetric assemblies, including roof trusses or floor cassettes, bundle multiple elements into prefabricated subassemblies. Volumetric modules, such as pre-fitted bathroom pods or mechanical rooms, are delivered as fully enclosed units ready for installation. At the highest level of integration are modular buildings, composed of multiple volumetric modules combined to form complete structures, providing maximum efficiency, repeatability, and standardization, particularly in facilities with repetitive design requirements.

Material choices within IOC are performance-driven and aligned with project needs. Steel is favored for its structural strength, flexibility, and suitability for long spans. Concrete offers durability, fire resistance, and acoustic benefits. Timber is valued for its renewable nature, low carbon footprint, and ease of handling. Hybrid systems that combine different materials enable optimized structural performance, sustainability outcomes, and construction efficiency [5].

The lifecycle of IOC projects follows interconnected phases—design and planning, manufacturing, transportation, on-site assembly, operation and maintenance, and eventual decommissioning. At the design stage, digital modeling and simulation tools resolve conflicts early and optimize workflows. During manufacturing, automation and strict quality control ensure uniformity and precision. The transportation phase relies on logistical coordination and optimized routing to ensure secure and timely delivery. On-site assembly is accelerated by prefabrication alignment strategies and streamlined system hookups. Operation and maintenance benefit from sensor-based monitoring and predictive analytics, extending asset lifespan while informing continuous improvement. Finally, decommissioning leverages standardized connections and detailed disassembly protocols to support recycling, recovery, and reuse within a circular economy framework [3,5]. In contrast to the fragmented and sequential nature of conventional construction, IOC's integrated model fosters collaboration and cohesive execution. By relocating construction processes to controlled environments, IOC reduces waste, energy use, and emissions while directly addressing pressing global challenges such as climate change, urbanization, and resource scarcity [6].

Within this context, Digital Twin (DT) technology emerges as a key enabler capable of amplifying the benefits of IOC through enhanced efficiency, precision, and sustainability [1]. For example, DT-enabled production systems can synchronize real-time sensor data with manufacturing schedules to optimize throughput. Logistics-focused DTs can predict transportation delays and dynamically adjust delivery sequencing. At the asset level, DTs for modular systems can deliver predictive maintenance alerts, improving reliability and lifecycle performance. However, successful DT adoption requires alignment with the unique requirements of IOC, since generic DT architectures may fail to capture its distinct typologies, material systems, and lifecycle phases.

Adapting DTs to specific IOC practices entails different priorities: in discrete-element IOC, DT applications may emphasize fine-grained component tracking, on-site scanning integration, and rapid assembly verification. For non-volumetric assemblies, DTs can enhance coordination between manufacturing tolerances and on-site fitting. Volumetric modules require DTs that integrate manufacturing, logistics, and installation sequencing into unified, synchronized datasets. Meanwhile, fully modular buildings demand comprehensive, lifecycle-oriented DT systems capable of monitoring performance, optimizing energy use, and managing end-of-life circularity strategies. Material-specific DT adaptations are also necessary: concrete elements may integrate IoT-enabled curing sensors, timber modules can benefit from RFID-based traceability, and steel assemblies may incorporate embedded structural health monitoring [5].

Together, these considerations highlight the need for systematic investigation into how DTs can be tailored to IOC's diverse typologies and lifecycle stages. This study builds on such questions by formulating hypotheses regarding optimal DT-IOC integration and exploring pathways for refining their application in practice.

2.2 Materials, Discussion and Results.

The concept of digital twins (DTs) has evolved significantly, yet its definition remains fragmented across industries. Initially applied in manufacturing and aerospace, DTs are now increasingly adopted in architecture, engineering, and construction

(AEC). Some define DTs as lifecycle modeling tools, while others emphasize their real-time simulation and synchronization capabilities. For example, the Centre for Digital Built Britain views DTs as digital counterparts of physical assets, continuously updated through real-time data, whereas the Digital Twin Consortium highlights synchronization at defined frequencies and fidelities. Such perspectives underline DTs' role as dynamic, data-driven systems for monitoring, prediction, and decision support.

This conceptual diversity often blurs distinctions between DTs, building information modeling (BIM), and cyber–physical systems (CPS). BIM provides a static or periodically updated model, mainly for design and documentation. CPS integrates algorithms with physical processes for real-time control, but without a comprehensive digital replica. In contrast, DTs are characterized by their persistent, bidirectional connection with physical assets, enabling continuous synchronization, scenario simulation, and optimization. For instance, in smart buildings, BIM delivers a static design model, CPS manages operations like HVAC, while DTs integrate these with real-time data—such as occupancy and energy use—creating a dynamic, predictive system that enhances performance across the asset lifecycle.

DT maturity is typically described in five levels. Level 1 offers static representations, while Level 2 integrates real-time monitoring. Level 3 adds simulation and predictive analytics, Level 4 supports scenario modeling and diagnostics, and Level 5 achieves autonomy through AI-driven learning and self-optimization. Full maturity requires integration of multiple layers: physical, sensing, communication, storage, digital, and service. AI plays a vital role across these layers, enabling predictive analytics, anomaly detection, adaptive modeling, and autonomous decision-making. By embedding AI, DTs evolve into highly responsive, self-optimizing systems capable of managing complex, real-time environments.

The integration of digital twins (DTs) into industrialized offsite construction (IOC) enables the convergence of physical and digital processes through real-time, dynamic representations of assets and workflows. By enhancing decision-making, aligning design with delivery, and driving process innovation, DTs strengthen adaptability and resilience.

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Our review identifies three main research streams. The first, and largest, explores DT in conventional construction, with only indirect relevance to IOC. Examples include studies on enablers such as data integration and interoperability, semantic construction DTs to address BIM limitations [7], taxonomies of DT applications in logistics and quality control, DT-enabled energy optimization [8], and DT integration with blockchain and IoT for sustainability and smart supply chains. The second stream examines digital innovations in IOC without explicitly focusing on DTs, such as automation, digital tools for offsite and prefabricated construction, and emerging technologies (IoT, AI, extended reality) for productivity, safety, and sustainability. The third stream—explicitly addressing DT in IOC—is comparatively underdeveloped, with studies highlighting opportunities in modular construction logistics, monitoring, and automation, but also barriers such as sensor integration, data security, and regulation.

Overall, prior research has examined DTs broadly or IOC technologies in isolation, but lacks an integrated DT framework spanning the full lifecycle of offsite workflows—from design and planning to manufacturing and on-site assembly. The role of AI-driven DTs in IOC is particularly underexplored, despite their potential to address key challenges such as predictive quality control, intelligent supply chain management, and adaptive coordination between factory production and on-site assembly. This study contributes by advancing AI-centric DT frameworks as core enablers of IOC, offering real-time, data-driven decision support across modular construction workflows.

We adopt a hybrid methodology combining scientometric analysis with qualitative content review. First, a structured search and screening protocol ensures comprehensive and unbiased literature retrieval. Second, scientometric mapping quantitatively identifies influential publications, thematic trends, research gaps, and the temporal evolution of the field. Third, qualitative content review provides deeper insights into theoretical frameworks, approaches, and contexts that quantitative methods alone cannot capture [8].

The review process involved database selection, definition of scope and

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keywords, development of inclusion and exclusion criteria, and screening and evaluation of studies. To ensure wide coverage, we selected Scopus and Web of Science for their indexing standards, and Google Scholar for access to gray literature and emerging studies [9]. Keywords were refined iteratively to capture three domains: construction industry (e.g., “construction”, “AEC industry”), IOC (e.g., “offsite”, “prefabrication”, “modular”), and DT (e.g., “digital twin”, “digital replica”). Broader terms such as “cyber-physical systems” and “IoT-enabled BIM” were also included to account for imprecise terminology. Eligible sources were peer-reviewed journal articles and conference papers in English, specific to the AEC sector, with no date restrictions. Non-peer-reviewed materials (e.g., white papers, theses, reports) and studies outside AEC or unrelated to DT in IOC were excluded.

Study selection followed the PRISMA protocol, ensuring transparency and reproducibility. After title and abstract screening, 363 records remained, with 75 subjected to full-text assessment. Of these, 34 were excluded due to misalignment with the study scope or insufficient methodological quality. The final dataset comprised 41 eligible studies, supplemented by 11 additional records identified through snowballing (backward and forward citation tracking).

Geographically, Hong Kong and China lead in publication volume, shaping early adoption models, though this regional concentration may limit global applicability. In terms of impact, New Zealand stands out with the highest citations per publication due to pioneering case studies. Collaboration networks highlight the United States as a central hub, while China and Hong Kong show strong regional ties.

Author analysis identifies Huang George Q., Zhong Ray Y., and Xue Fan as leading contributors, whose early frameworks continue to guide the field. Research outputs are shaped by both conceptual models and case studies, complemented by proof-of-concept trials, simulations, and ontology development to address data interoperability. Validation strategies are diverse, with case studies, simulations, benchmarking, and industry feedback ensuring both technical rigor and practical relevance.

Keyword network analysis reveals four thematic clusters: (1) Digital Twin Core (implementation frameworks), (2) Data & Connectivity (BIM, IoT, blockchain), (3) Industrial Automation (smart manufacturing, offsite construction), and (4) Advanced Simulation (cyber-physical systems, predictive modeling, material innovation). Together, these trends highlight the field’s evolution from conceptual foundations to applied, data-driven integration of DTs in IOC.

Research on DTs in Industrialized and Offsite Construction (IOC) spans all project lifecycle phases—planning, manufacturing, transportation, on-site assembly, operation, and decommissioning—but with uneven coverage. Most studies concentrate on manufacturing and assembly, where DTs and IoT enhance precision, monitoring, logistics, and quality control. Planning and design studies highlight BIM- and DT-based simulation for improved coordination and reduced downstream errors, while transportation research focuses on smart tracking and GIS-based routing to mitigate logistical risks. By contrast, operation, maintenance, and especially decommissioning remain underexplored, despite their relevance to sustainability and lifecycle management.

Sectoral applications vary: residential projects dominate, with emphasis on design accuracy and monitoring; infrastructure work highlights logistics and structural health; and commercial settings explore space use and facility management. Emerging research also integrates XR tools (AR/VR) for assembly simulation, collaborative visualization, and immersive site validation.

At the technical level, DT service layers combine sensing, modeling, and analytics to deliver real-time insights and decision support. AI methods—particularly supervised learning and optimization algorithms—enable progress estimation, defect detection, and resource planning, though challenges remain around interpretability, robustness, and scalability. Simulation, spatial analytics, and geometric validation are widely applied, but often in isolated “point solutions” rather than fully integrated systems. Interoperability is a key limitation: cross-platform integration and standardized frameworks are lacking.

Overall, DTs in IOC are evolving from design and monitoring tools toward adaptive, data-driven systems with potential for autonomous decision-making. Future research should close lifecycle gaps, develop scalable and interoperable frameworks, and align DT applications with sustainability and circular economy goals.

Conclusion

A comparison of DT use in IOC and the broader construction sector shows both shared priorities and distinct emphases. Both domains apply DTs for monitoring, integration, quality, logistics, and safety, but IOC research places greater focus on supply chain coordination, real-time production tracking, and modular assembly, reflecting its manufacturing-oriented nature. By contrast, general construction emphasizes safety, risk management, and sustainability.

IOC-specific DTs also differ in deployment patterns. Unlike earlier digital tools used mainly in design phases, DTs extend into manufacturing, transport, and site assembly, enabling real-time synchronization of physical and digital workflows. Concrete-based, non-volumetric components dominate current implementations, with system-level and lifecycle applications still limited.

Technically, both domains use similar sensing and modeling tools, but IOC prioritizes high-frequency spatial tracking, hybrid sensing, and simulation-driven coordination. Integration at the service layer often extends to robotics, AI-driven prediction, and real-time decision support, while broader construction relies more on BIM and building performance management.

The adoption of DTs in IOC brings operational benefits—precision, waste reduction, and quality gains—but also raises challenges. These include high financial barriers, environmental trade-offs from energy-intensive data systems, labor disruptions due to new digital skill demands, and weak regulatory safeguards for data governance and AI use. Limited scalability beyond pilot projects, lack of standardized maturity frameworks, and minimal focus on operation and end-of-life stages remain key research gaps.

Future work should expand to large-scale and high-complexity projects, develop international standards for DT maturity, and embed lifecycle thinking. Integrating AI—

particularly reinforcement learning, edge AI, and emerging LLMs—offers the potential to transform DTs from static models into adaptive, autonomous systems, but achieving this requires cross-disciplinary collaboration, robust governance, and context-sensitive pilot deployments.

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