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Transforming Modern Construction through Prefabrication and Digital Technologies

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ABSTRACT

The construction sector faces continuing pressure to raise productivity and to reduce waste and emissions. Prefabrication and modular construction shift a large share of building work into controlled factory environments, while digital technologies such as Building Information Modelling (BIM), digital twins, the Internet of Things (IoT), artificial intelligence (AI), robotics and additive manufacturing support the design, coordination and monitoring of that work.

This paper reviews thirty published studies, dated 2006 to 2027, on the combined use of prefabrication and digital technologies. The studies comprise systematic and bibliometric reviews, case studies, an interview study, a questionnaire survey and technical development work, and they are compared by technology, project phase, reported benefits, limitations and research gaps. BIM emerges as the information backbone, digital twins and IoT contribute real-time two-way feedback, and robotics and 3D printing extend automation to manufacturing and assembly. Reported gains include shorter construction time, lower waste and carbon emissions, better quality control and safer sites; one optimisation study records time and carbon reductions of 19.05% and 13.49% respectively. Weak data interoperability, high cost, skill shortages, organisational resistance and limited validation in real projects remain the main barriers, and operation and maintenance is the least studied phase. The paper concludes that the best outcomes arise from integrating prefabrication with BIM, digital twins, AI, IoT and automation, and it proposes lifecycle-wide integration and real-project testing as directions for further work.

Key Words: Prefabrication, Building Information Modelling, Digital Twin, Internet of Things, Industrialised Construction, Sustainable Construction.

INTRODUCTION

The construction sector is a major contributor to economic growth, yet it is also among the heaviest consumers of natural resources and a notable source of waste and greenhouse gas emissions. The literature examined in this paper portrays an industry that is labour-intensive, fragmented and slow to improve its productivity, and one that is still affected by delays, cost overruns and safety risks [1–3]. The reviewed studies quote figures such as roughly 35% of CO_2 emissions and about 600 million tons of construction waste in the United States in 2018 [2, 4], together with material waste of around 40% [5].

Two developments are widely regarded as responses to these problems. The first is industrialisation, in which work moves from the construction site to manufacturing and assembly, as in prefabrication, off-site manufacture and modular construction. The second is digitalisation, in which Building Information Modelling (BIM), digital twins, the Internet of Things (IoT), artificial intelligence (AI) and robotics are used to plan, coordinate and monitor construction activity. Fan et al. [6] conclude that the two developments yield greater benefit when they are integrated than when each is applied separately.

Prefabrication refers to the production of building components, such as panels, precast elements or complete volumetric modules, in a controlled factory environment and their subsequent transport to the site for assembly. Because the work is carried out under controlled conditions, the studies report faster construction, better quality and precision, lower cost, reduced material waste, improved site safety and lesser dependence on manual labour [5, 7, 8]. Waqar et al. [9] associate modern methods of construction (MMC) with better cost efficiency and social performance, but observe that environmental outcomes depend on wider organisational and implementation conditions. Success is not automatic: it depends on suitable technology, careful planning and the experience of professionals [8], and logistical and regulatory issues restrict wider adoption [7]. The limited uptake of factory-based methods in the past is illustrated by the share of only about 2% held by offsite construction in the UK market in 2004 [10].

The literature distinguishes three levels of change. Digitisation is the conversion of information into digital form, for example 3D CAD models in place of paper drawings. Digitalisation is the use of digital platforms to alter how work is done, for example BIM platforms that share models, run clash checks and support costing. Digital transformation extends to the organisation itself, bringing global project access, new roles and new ways of working

(Figure 1). Olanipekun and Sutrisna [1] emphasise that digital transformation is the organisational and business change brought about by technology and not digitisation alone, and Samuelson and Stehn [11] likewise conclude that technology by itself is insufficient.

[Figure 1: From digitisation to digital transformation in construction.]

Placeholder – Three-stage flow: Digitisation (3D CAD models replace paper plans) → Digitalisation (BIM platforms share models, run clash checks, support costing) → Digital transformation (global project access, new roles, new ways of working).

Figure 1: From digitisation to digital transformation in construction.

A broad range of technologies is applied across the lifecycle of prefabricated buildings (Figure 2). BIM serves as a central repository of project information and improves coordination, communication and collaboration among stakeholders [6]. Digital twins maintain a virtual model that is updated with real-time data from the physical project, which is gathered by IoT devices such as RFID tags, LoRa networks and sensors [12, 13]. AI and data analytics assist prediction, scheduling and optimisation [14, 15], whereas robotics, CNC machines and 3D printing automate manufacturing and assembly [16, 17]. Blockchain, GIS and material passports secure information, locate waste facilities and track materials for reuse [2, 4]. BIM is repeatedly identified as the backbone that links these technologies [3, 4, 18].

[Figure 2: Digital technologies layered over the lifecycle of a prefabricated project.]

Placeholder – Layered diagram: lifecycle phases (design, production, construction, operation and maintenance) with BIM as the backbone layer, IoT and digital twins, AI and analytics, robotics and 3D printing, and blockchain, GIS and material passports above them.

Figure 2: Digital technologies layered over the lifecycle of a prefabricated project.

Despite the rapid growth of research, several problems persist. No single system yet combines all the available technologies [2], and research on digital twins in prefabricated construction remains limited [19]. Design tools show technology gaps, for instance in linking BIM with AI, parametric modelling and automation [20], and the operation and maintenance stage receives far less attention than design, production and construction [6]. Barriers such as data interoperability, missing standards, cost, skills and resistance to change recur throughout the literature [4, 11, 18].

The aim of this paper is to review thirty published studies on prefabrication and digital technologies, to compare their methods, findings and limitations, and to identify the barriers and research gaps that call for further attention. The review concentrates on the role of prefabrication in reducing time, cost and waste, on the application of BIM, digital twins, IoT, AI, robotics and 3D printing across project phases, and on directions for future work. The remainder of the paper reviews the literature, compares the studies, sets out research gaps and future scope, and closes with the conclusions.

LITERATURE REVIEW

The review draws on thirty papers published between 2006 and 2027 in journals, conference proceedings and one book chapter. They range from large systematic reviews to a questionnaire survey, an interview study, case studies and technical developments, and eighteen of them date from 2024 onwards (Figure 3). This is consistent with the growth in research output reported by Fan et al. [6], whose analysis of 173 articles shows 6 to 10 papers a year during 2014–2017 rising to a peak of 32 in 2021. Studies that combine several technologies are discussed under more than one theme.

[Figure 3: Distribution of the reviewed papers by publication period.]

Placeholder – Bar chart: number of reviewed papers by publication period, 2006 to 2027 (eighteen of the thirty papers are from 2024 onwards).

Figure 3: Distribution of the reviewed papers by publication period.

Prefabrication and modular construction

Rocha et al. [5] reviewed the environmental, economic and social impacts of prefabrication against conventional methods, taking into account the European Union's 2050 decarbonisation goals, the COVID-19 pandemic and the integration of digital twins. They report lower waste and greenhouse gas emissions, with about 40% of materials and about 28% of the energy footprint quoted, together with faster construction, lower cost and safer sites. Lakhani [7] examined practical cases and found that prefabricated components, modular methods, automation and robotics reduce time, cost and site work while improving quality and precision, although logistics and regulation limit adoption. A literature study by Baghchesaraei et al. [8] reached similar conclusions on time and cost savings, standardisation and quality, on the condition that appropriate technology and experience are available.

Waqar et al. [9] applied the Technology–Organisation–Environment (TOE) framework to a questionnaire survey of 70 observations, analysed through reliability tests, descriptive statistics, correlation and regression. The model returned $R = 0.628$ and $R^2 = 0.386$, so that about 39% of the variation in sustainable construction success is explained, with an ANOVA significance of 0.00656. Procurement change, innovation, organisational readiness and

stakeholder satisfaction influenced adoption, and the authors acknowledge the limits of cross-sectional evidence and sample size. Xu et al. [15] treated the choice between prefabricated and cast-in-place components as a multi-objective problem and applied an ant colony algorithm to minimise cost, time and carbon emissions on a three-storey building model. Cost fell by 0.42%, time by 19.05% and carbon by 13.49% against the baseline, with best-case reductions of 27.89% in time and 18.4% in carbon. The small cost saving beside the large time and carbon savings shows the trade-offs involved, and component selection is named as the main challenge.

Digital transformation in construction

Olanipekun and Sutrisna [1] carried out a grounded-theory review in which 5,797 search hits were narrowed to 36 journal papers (2016–2020); 423 open codes were grouped into 26 categories and then into strategic considerations, enablers and barriers. They identified seven strategic considerations, nine enablers and ten barriers (Figure 4), with collaboration the most influential consideration, supporting six enablers and countering three barriers. Nozari et al. [18] applied PRISMA to 30 Scopus papers (2016–2025) and found that BIM, digital twins, IoT, AI and blockchain are the main tools, that BIM and digital twins improve planning, safety and teamwork, and that IoT enables live monitoring of the site and of materials. Using BIM, AI and IoT together gave better results than any single tool, while skill gaps, high cost and resistance to change remained the main challenges. Samuelson and Stehn [11] found that digital transformation can raise productivity and sustainability but is slowed by industry fragmentation, organisational barriers and limited understanding, and that it requires changes in structures, processes and business models.

[Figure 4: Strategic considerations, enablers and barriers of digital transformation (adapted from [1]).]

Placeholder – Three-column diagram: 7 strategic considerations (process, collaboration, learning, value, lifecycle, choice of digital, data); 9 enablers (champions, training, innovativeness, system support, culture, legitimation, research, etc.); 10 barriers (data processing and ownership, poor integration, low standards, ROI uncertainty, owner buy-in, digital divide, etc.).

Figure 4: Strategic considerations, enablers and barriers of digital transformation (adapted from [1]).

Digital technologies across the project lifecycle

Fan et al. [6] screened 298 Scopus articles (2014–2023) down to 173 and classified them by phase: design (54), production (50), construction (50) and operation and maintenance (19). Design for manufacturing and assembly (DfMA) was the largest design-phase topic with 32 articles, while predictive maintenance (14) and sustainable operation (5) made up the operation phase. In the keyword analysis BIM was the most frequent term with 45 occurrences, whereas digital twin, structural health monitoring (SHM), augmented reality, blockchain and machine learning had the most recent average publication years and are therefore emerging topics. The authors conclude that operation and maintenance receives significantly less attention than the other phases, and they recommend open data standards to overcome the limited support of the IFC standard for prefabrication, robot-assisted mass customisation with 3D printing, automated real-time risk response, and digital twins that cover more building types and occupant experience. They also note that RFID can suffer from limited coverage and unstable transmission on sites, whereas LoRa and NB-IoT can offer better coverage and reliable transmission.

Lu et al. [3] reviewed 72 articles on construction sustainability and technologies including BIM, IoT, big data, AI, AR/VR, digital twins, 3D printing, UAVs, GIS, blockchain, robotics and cloud computing across design, construction, operation and maintenance, and end-of-life stages. BIM was the most widely used technology, and applications centred on integration and collaboration, optimisation and decision-making, monitoring and control, and training. Turner et al. [21] identified AI and data analytics, robotics, BIM, sensors, digital twins and connectivity as the key Industry 4.0 technologies, and attributed the low productivity of construction to skill gaps and labour-intensive methods.

BIM-based design, information management and risk

Zhou et al. [20] used an autoethnographic approach, with focus groups, reflective journals and thematic and narrative analysis, and found that BIM improves coordination and efficiency in the design of prefabricated buildings but that technology gaps remain in its integration with AI, parametric modelling and automation. Henao-Rios et al. [22] developed Dynamo scripts for Revit to automate prefabricated additive construction and tested them on a 3D-printed house; BIM linked prefabricated and additive construction, and the automation accelerated component design and manufacturing. Li et al. [14] proposed the Hybrid Construction Intelligence Framework (HCIF-Net), which combines BIM data with predictive analytics. Using 1,300 project records balanced with SMOTE, TabNet, a Bayesian network, a temporal attention LSTM and Monte Carlo simulation were combined for prediction, and NSGA-II-based mixed-integer optimisation was used to reduce cost, completion time and risk. The framework reached an accuracy of 98.88% and is contrasted by the authors with expert-based methods that are often reactive.

Fawad et al. [23] automated the SHM system of a four-span, 600 m bridge in Poland by means of finite element analysis (FEA), field load tests, visual programming that generated the finite element model from BIM, and an Arduino-based IoT platform. The system could be managed remotely, bridge health data were visualised online, and the load tests provided reliable data for sensor calibration. The case concerns a bridge rather than a prefabricated building, but it demonstrates how BIM, IoT and finite element modelling can be linked to automate monitoring.

Digital twins in prefabricated construction

Cheng et al. [24] screened 457 records down to 171 journal papers (2013–2022) and mapped them onto a digital twin loop (Figure 5) in which DfMA and BIM form the virtual world and supply chain management the physical world, joined through data acquisition, integration, analysis and decision-making. DfMA was the most studied topic (26.5%), followed by data integration (19.4%), data analysis (13.8%), data acquisition (10.4%) and decision-making (8.1%). The authors explain that BIM provides one-way guidance to the site, whereas a digital twin adds two-way, real-time feedback. Moghimi et al. [25] followed the PRISMA method to a final dataset of 50 papers and observed growing applications in scheduling, monitoring, predictive analysis and automation, with black-box AI, data sovereignty and fragmented standards as barriers; their roadmap points to cognitive and autonomous ecosystems based on neuro-symbolic AI, Digital Product Passports and Operator 5.0. Rangasamy and Yang [19] found rapid growth in the use of digital twins after 2017 but limited research in prefabricated construction, with lack of standards, data issues and scalability as the main problems.

[Figure 5: Digital twin loop for offsite and prefabricated construction and the share of papers on each part (adapted from [24]).]

Placeholder – Loop diagram: virtual world (DfMA, BIM) and physical world (supply chain management) linked by data acquisition (10.4%), data integration (19.4%), data analysis (13.8%) and decision-making (8.1%); DfMA 26.5%.

Figure 5: Digital twin loop for offsite and prefabricated construction and the share of papers on each part (adapted from [24]).

Application studies support these findings. Zhou et al. [26] built a BIM-integrated digital twin that monitors production, transportation and assembly, predicts component damage and deformation in real time, and helps to identify safety risks earlier. Lu et al. [13] developed a digital twin platform based on the SERIC model (Scene, Entity, Relationship, Incident, Control) and IoT, with a 1+5+N architecture, and implemented it on Jinan Metro Line 8, where progress, safety monitoring, quality control and efficiency improved. They note that BIM alone has synchronisation gaps and IoT lacks standardisation, and that prefabricated stations show higher dimensional accuracy, less material waste and lower environmental impact than cast-in-place construction. Wang et al. [27] reviewed Web of Science and CNKI literature on prefabricated buildings and digital-twin-based intelligent construction; policy changes, cost issues, shortage of managers, worker training and coordination were named as the main risks, and standardisation, better information sharing and smart operation and maintenance as future needs.

Internet of Things and intelligent prefabs

Zhao et al. [12] developed intelligent prefabs that combine RFID, LoRa, sensor networks, BIM and cloud computing. RFID tags and strain sensors collect site data, LoRa transmits it over a low-cost, long-range network, and a cloud-based BIM model stores and displays project information. Tested on a real precast project, the system provided reliable data, accurate component location and effective structural monitoring during installation, in place of manual tracking that is time-consuming and error-prone. Wang et al. [28] proposed an IoT-based intelligent construction system that links the design, manufacturing, transportation and construction stages to improve information sharing, traceability and decision-making. Together with the platform of Lu et al. [13], these studies show that IoT supplies the real-time data on which digital twins and BIM dashboards depend.

Automation, robotics and next-generation manufacturing

Chea et al. [16] reviewed automation and robotics in five steps: design, management, robotic manufacturing, autonomous transport and robotic assembly. BIM is described as the information hub linking design, schedule, transport tracking and robots, and laser-scanner inspection is found to be more accurate than image-based methods and unaffected by lighting. Examples of proven use at scale include the Pilbara automated freight rail (2019, US$940 million) and a seven-storey steel frame built with Obayashi robots (2012); the limits listed are that most robots are not networked through BIM, that on-site welding robots need long set-up and that the payload of UAVs is small. Lund et al. [17] studied multi-robot welding and angular distortion in T-joints, corner joints and single-V butt joints using FEA and welding experiments, with a digital twin calculating the robot position and pre-setting the welding angle. Pre-setting reduced angular misalignment within the tolerance limits of EN ISO 5817 and EN ISO 13920, with benefits for small and medium enterprises through lower set-up time and fixturing cost. Pasquire et al. [10] looked beyond prefabrication to digital fabrication, rapid prototyping and UK research on Freeform Construction, and concluded that 3D printing can bring major change and automation to construction, that digital fabrication enables complex shapes and optimised components, and that lean thinking supports efficient production.

Waste management and the circular economy

Wu et al. [2] reviewed 214 papers (2000–2023) on intelligent technologies in construction and demolition waste management and studied 73 key papers in detail; AI and BIM were the most widely used technologies, with GIS helping to site waste facilities, big data predicting waste quantities and BIM reducing waste at the design stage. No single system combines all technologies, and lifecycle waste management and blockchain are pointed out as future directions. Keles et al. [4] reached 179 papers on digital technologies and the circular economy after snowballing from 120, found BIM at the core of most integrations, and noted that blockchain with material passports can support the full lifecycle although its use is limited; lack of standards, policies and data integration, and privacy and security risks, were the barriers. Alsaoudi and Acquaye [29] interviewed 18 construction professionals in the UAE and found that BIM, digital twins and data-driven tools improve material visibility, reuse and waste recovery, that leadership commitment and

early stakeholder engagement are foundational, and that fragmented systems, weak data governance and cost-driven procurement constrain circular outcomes. Salles et al. [30] analysed circular building projects in Europe with the 10R framework and found that most projects focus on reducing, reusing and recycling, while refusing and rethinking are less developed; reversible joints, prefabrication and modular design, material passports, and QR codes, RFID and IoT tracking support reuse, and digital technology is judged essential for practical circular construction.

In summary, the thirty studies agree that prefabrication shortens construction, reduces waste and improves quality, provided that planning, knowledge and supporting technology are in place [5, 7, 8]. BIM is the information backbone present in almost every integration [3, 4, 6], digital twins and IoT add real-time and two-way information [12, 13, 24], robotics and 3D printing extend automation to manufacturing and assembly [10, 16, 17], and AI supports prediction and optimisation [14, 15]. The studies also agree on the main barriers: weak interoperability and standards, cost, skills, organisational resistance and lack of validation in real projects [11, 18, 19, 27].

COMPARATIVE ANALYSIS AND DISCUSSION

The reviewed papers apply several kinds of method. Eight are large review studies, whose scale is compared in Table 1, and two further reviews (Rangasamy and Yang; Wang et al.) have a narrower scope. The remainder comprise an interview study [29], a questionnaire survey [9], an autoethnographic study [20], case-based and experimental developments [12–15, 17, 22, 23, 26] and other review and conceptual papers [5, 7, 8, 10, 11, 16, 21, 28, 30]. The review studies differ in database, period and screening, which explains why their counts differ and why their findings cannot simply be added together. Scopus is the most common database where one is stated, and Rangasamy and Yang name the exclusive use of Scopus as a limitation of their own study [19].

Table 1: Scale and sources of the review studies.

Study	Database(s)	Period	Papers retrieved and selected
Fan et al. [6]	Scopus	2014–2023	298 retrieved, 173 selected
Olanipekun and Sutrisna [1]	Not stated	2016–2020	5,797 hits, 36 journal papers; 423 codes, 26 categories, 3 groups
Moghimi et al. [25]	Scopus, Compendex	Not stated	165, then 80, then 36; 14 added, 50 final (40 journal, 10 conference)
Cheng et al. [24]	Scopus, ScienceDirect	2013–2022	457 screened, 171 journal papers
Wu et al. [2]	Not stated	2000–2023	214 analysed, 73 studied in detail
Nozari et al. [18]	Scopus (PRISMA)	2016–2025	30 papers
Keles et al. [4]	Scopus	2015–2023	120 found, 179 after snowballing
Lu et al. [3]	Not stated	Trends 2020–2023	72 articles
Rangasamy and Yang [19]	Scopus	Not stated	Bibliometric and systematic review
Wang et al. [27]	Web of Science, CNKI	Not stated	Literature review

Table 2 groups the findings by technology. BIM appears in nearly every study and acts as the common platform, but the studies also show that it does not work alone: it needs IoT for real-time data, digital twins for two-way feedback and AI for prediction. Digital twins are among the newest topics, together with SHM, augmented reality, blockchain and machine learning, as the recent average publication years in the keyword analysis of Fan et al. [6] indicate. Robotics and 3D printing, in turn, are held back by cost, accuracy and standardisation issues.

Table 2: Roles and limitations of the main digital technologies.

Technology	Main roles reported	Studies	Limitations reported
BIM	Information backbone; coordination and clash detection; LCA, scheduling and FE model generation; risk dashboards	[3, 4, 6, 14, 20, 22, 23]	Gaps in integration with AI, parametric modelling and automation; limited IFC support for prefabrication; synchronisation gaps without IoT

Technology	Main roles reported	Studies	Limitations reported
Digital twin	Real-time monitoring; two-way feedback; prediction of component damage; risk warning; scheduling	[13, 19, 24–27]	Lack of standards, data issues and scalability; black-box AI; data sovereignty
IoT, RFID and LoRa	Component tracking and traceability; site and structural monitoring; real-time data for BIM and digital twins	[12, 13, 23, 28]	Lack of standardisation; RFID coverage and transmission problems on sites
AI and machine learning	Risk prediction; optimisation of cost, time and carbon; waste prediction	[2, 14, 15, 18]	Data quality; black-box behaviour; selection of components
Robotics and automation	Robotic manufacturing, welding and assembly; autonomous transport	[6, 16, 17]	Robots not networked through BIM; long set-up of on-site welding robots; small UAV payload
3D printing and digital fabrication	Customised and freeform components; layered manufacturing; additive construction	[6, 10, 22]	Geometric accuracy; comparative slowness and higher cost than mass production
Blockchain and material passports	Secure information exchange; lifecycle tracking of materials; reuse	[2, 4, 30]	Limited use in practice; privacy, security and standards
GIS and big data	Siting of waste facilities; measurement and prediction of waste quantities	[2]	No single system combines all technologies

Only some of the studies report numerical results, and Table 3 collects them. They are not directly comparable because they stem from different methods, but they indicate the size of the effects. The optimisation study of Xu et al. shows large savings in time and carbon with a very small saving in cost (Figure 6). The survey of Waqar et al. explains about 39% of the variation in sustainable construction success, which means that technology and method choices are important but are not the only influence [9].

Table 3: Quantitative results reported in the reviewed studies.

Study	Measure	Reported value
Xu et al. [15]	Reduction in cost, time and carbon	0.42%, 19.05% and 13.49%; best case 27.89% (time) and 18.4% (carbon)
Waqar et al. [9]	Regression model (70 observations)	$R = 0.628$; $R^2 = 0.386$; ANOVA significance 0.00656
Li et al. [14]	Accuracy of risk prediction (1,300 records)	98.88%
Rocha et al. [5]	Waste and emissions	About 40% of materials and about 28% of the energy footprint quoted
Cheng et al. [24]	Share of papers by digital twin loop topic	DfMA 26.5%; integration 19.4%; analysis 13.8%; acquisition 10.4%; decisions 8.1%
Fan et al. [6]	Articles by phase	Design 54; production 50; construction 50; operation and maintenance 19
Chea et al. [16]	Examples at scale	Pilbara automated freight rail, US$940 million (2019); seven-storey steel frame (2012)
Pasquire et al. [10]	UK offsite market share	About 2% in 2004

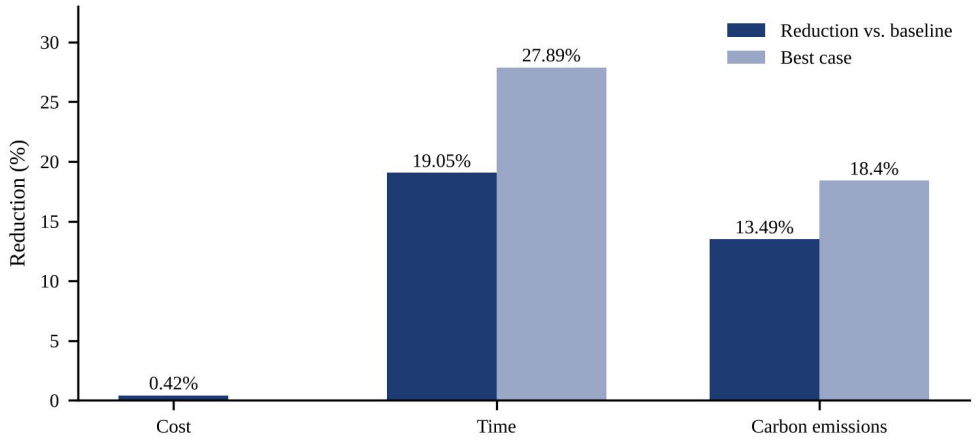


Figure 6: Reductions achieved by the ant colony optimisation of Xu et al. [15].

Table 4 compares the studies that developed or tested a system. A clear pattern emerges: each study joins at least two technologies, and BIM is the common element in most of them. The studies also differ in how far they have moved from concept to practice. The platform of Lu et al. and the IoT system of Zhao et al. were applied to real projects [12, 13], the bridge system of Fawad et al. was validated by field load tests [23], the optimisation of Xu et al. was applied to a building model [15] and the welding tests of Lund et al. covered three joint types [17].

Table 4: Comparison of case-based and experimental studies.

Study	Application	Technologies	Outcome
Fawad et al. [23]	SHM of a 600 m bridge	BIM, FEA, visual programming, Arduino-based IoT	Remote management; online visualisation; reliable data for sensor calibration
Lu et al. [13]	Prefabricated metro station (Jinan Metro Line 8)	Digital twin, SERIC, BIM, IoT	Better progress, safety and quality control; real-time risk warning
Zhao et al. [12]	Monitoring of precast components	RFID, LoRa, strain sensors, cloud BIM	Reliable data; accurate component location; monitoring during installation
Li et al. [14]	Construction risk management	BIM, TabNet, Bayesian network, LSTM, Monte Carlo	98.88% accuracy; BIM dashboards for risk monitoring
Henao-Rios et al. [22]	3D-printed house	BIM, Dynamo scripts for Revit	Faster component design and manufacturing
Lund et al. [17]	Multi-robot welding	Robots, digital twin, optical sensors, FEA	Reduced angular misalignment within tolerance
Xu et al. [15]	Selection of prefabricated and cast-in-place components	Ant colony algorithm	Lower time, carbon and cost
Zhou et al. [26]	Prefabricated building construction	Digital twin, BIM	Real-time monitoring and prediction of component damage

The same barriers appear in many of the papers, which suggests that they are structural problems of the sector and not features of single projects (Table 5). Technical barriers such as interoperability and standards are closely linked with organisational ones such as skills, cost and resistance to change. Olanipekun and Sutrisna show that collaboration is the consideration that supports most enablers and counters several barriers [1], which suggests that organisational measures may be as important as technical ones.

Table 5: Main barriers reported and remedies suggested.

Barrier	Reported in	Remedy suggested in the studies
Data interoperability and standards	[1, 4, 19, 25, 27]	Open data standards and tools; common rules and better data exchange; standardisation
High cost and ROI uncertainty	[1, 18, 27]	Value and lifecycle planning; cost optimisation with digital twins
Skill gaps and training	[5, 8, 18, 27]	Training, clear guidelines and good data; knowledge and experience of professionals
Organisational resistance and fragmentation	[1, 11, 18]	Changes in structures, processes and business models; collaboration
Logistics and regulation	[5, 7]	Not specified; identified as limits to wider adoption
Data governance, privacy and security	[4, 24, 25, 29]	Data governance; leadership commitment; blockchain security
Limited validation in practice	[9, 17, 19]	More practical studies; larger samples and more joint types

Across the papers there is a common direction of development, from isolated tools to connected systems and then to predictive and cognitive ecosystems. Early work used CAD and BIM for individual design tasks. Later work connected BIM with IoT so that the model could receive data from the factory and the site [12, 13]. Digital twins then closed the loop with two-way feedback [24], and the newest studies add AI, blockchain and autonomous systems for prediction, security and decision-making [14, 25]. Figure 7 summarises this convergence: prefabrication provides the physical process, BIM the information backbone, IoT the connectivity, digital twins the real-time monitoring, and AI and automation the intelligence.

[Figure 7: Integrated framework of prefabrication and digital technologies synthesised from the reviewed studies.]

Placeholder – Layered framework: prefabrication (physical process) → BIM (information backbone) → IoT (connectivity) → digital twins (real-time monitoring) → AI and automation (intelligence).

Figure 7: Integrated framework of prefabrication and digital technologies synthesised from the reviewed studies.

The evidence also shows that benefits are largest where technologies are combined. Nozari et al. report that BIM, AI and IoT together give better results than a single tool [18], Lu et al. identify BIM as the collaborative platform for integrating other digital tools [3], and Keles et al. find BIM at the core of most integrations [4]. At the same time, no study covers the whole lifecycle with one integrated system [2, 19], and the operation and maintenance phase is the least studied [6]. This is the main gap addressed in the next section.

RESEARCH GAPS AND FUTURE SCOPE

The following gaps were identified from the reviewed papers:

- Operation and maintenance is the least studied phase of industrialised construction, and occupant experience is often overlooked [6].
- No single system combines BIM, digital twins, IoT, AI and blockchain across the whole lifecycle [2, 4].
- Data interoperability and standards are weak; the current IFC standard gives limited support for prefabrication [6, 19].
- Many digital twin models serve specific building types and are not general enough for a wide range of projects [6, 19].
- Real-project testing and experimental validation are limited, and several studies rely on models, surveys or a few cases [9, 15, 17].
- Circularity studies concentrate on reducing, reusing and recycling, while refusing and rethinking are less developed, and business models and policy support remain weak [30].
- Cost, skills, training and organisational resistance still slow adoption [11, 18, 27].

On this basis, the following directions are suggested for future work:

- Greater attention to lifecycle integration and to operation and maintenance, including digital twins that simulate the experience of occupants [6].
- Development of integrated systems that combine BIM, digital twins, IoT, AI and blockchain [2, 4].

- Promotion of open data standards, better information sharing and smart operation and maintenance, with training and clear guidelines to close skill gaps [6, 18, 27].
- Improvement of the long-term performance, simulation and resilience of prefabricated buildings, including seismic risk [6, 27].
- Development of circular business models and policy support, backed by material passports and IoT tracking [4, 30].
- More real-project testing and experimental validation of digital tools [17, 19].
- Combination of robotics with 3D printing to automate assembly and support mass customisation [6, 10].

CONCLUSION

This paper reviewed thirty published studies on the use of digital technologies in prefabricated and industrialised construction. Prefabrication and modular construction reduce construction time, cost and waste and improve quality and safety, but their success depends on planning, knowledge, logistics and regulation [5, 7–9]. Digitalisation is necessary for sustainability, efficiency, safety and productivity, yet technology alone is not enough, and organisational change, collaboration and training are also required [1, 11, 18]. BIM is the backbone of the digital environment, digital twins and IoT add real-time two-way information, robotics and 3D printing extend automation, and AI supports prediction and optimisation [3, 14, 16, 24].

The reported results are encouraging: one optimisation study shows time savings of up to 27.89% and carbon savings of up to 18.4% [15], and case studies show better progress, safety and quality control [12, 13]. Circular construction can be supported by modularity, reversible joints, material passports and IoT tracking [4, 30]. Barriers such as data interoperability, standards, cost, skills and resistance to change remain, and the operation and maintenance phase and real-project validation need more research [6, 19]. Overall, the best results are obtained when prefabrication is integrated with BIM, digital twins, AI, IoT and automation. Such integration can make construction faster, safer, more cost-effective and more sustainable, and the gaps identified here indicate where future work should be directed.

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