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Review Article

Digital Transformation in Construction: A Systematic Review of BIM, IoT, Robotics, and Automation in Industry 4.0

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Abstract

The construction industry contributes approximately $10 trillion annually to global economic output yet remains one of the least digitized sectors worldwide, with labor productivity growth averaging only 1% per year over the past two decades compared with 3.6% in manufacturing. The sector also accounts for approximately 34% of global energy demand and 37% of energy and process-related carbon dioxide emissions, underscoring the environmental urgency of its transformation. The convergence of Building Information Modeling (BIM), the Internet of Things (IoT), robotics, and process automation under the Industry 4.0 paradigm, collectively termed Construction 4.0, offers a transformative pathway for addressing this chronic productivity and sustainability deficit. This paper presents a PRISMA-guided systematic review of peer-reviewed evidence on the adoption, integration, and impact of these four core digital technologies in construction. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) logic, 1,847 records were identified from Scopus and Web of Science for publications from 2016 to 2024. After screening and eligibility assessment, 29 articles were included in the characteristics and findings tables. Key findings demonstrate that BIM functions as the foundational digital infrastructure for Construction 4.0, enabling lifecycle data integration; IoT enhances real-time site monitoring, worker safety, and equipment management; robotics deliver gains in productivity, precision, and hazard reduction; and process automation can reduce schedule overruns and material waste. Across technology domains, persistent barriers include high implementation costs, data interoperability deficits, workforce resistance, regulatory fragmentation, and insufficient standards. Critical research gaps exist in developing-country contexts, cross-technology integration frameworks, ethical dimensions of automation, and long-term lifecycle outcomes.

1. Introduction

The construction sector is the world's largest industry by output, yet it paradoxically represents one of the most sluggish adopters of digital technology. According to McKinsey Global Institute's Industry Digitization Index, construction ranks second to last globally, and in last

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position in Europe, among all industries on measures of digital tool adoption, digital assets, and digital workforce capabilities [1]. The consequences of this technological lag are stark: large projects across asset classes typically run 20% longer than scheduled and up to 80% over budget, and global construction labor productivity has averaged only 1% annual growth over the past two decades, compared with 2.8% for the broader world economy and 3.6% for manufacturing [1].

The emergence of Industry 4.0, characterized by cyber-physical systems, the Internet of Things, cloud computing, artificial intelligence, and automation, offers a transformative pathway for the construction sector to address this chronic productivity deficit [2]. Scholars have termed this construction-specific application of Industry 4.0 principles 'Construction 4.0,' defined as the integration of BIM, IoT, AI, robotics, digital twins, and advanced manufacturing to create real-time cyber-physical systems spanning the entire lifecycle of construction projects [3, 4].

Building Information Modeling is the cornerstone technology of this transformation. BIM creates structured, multidimensional digital representations of construction projects, encompassing geometry, materials, cost, schedule, and environmental data, enabling unprecedented coordination between architects, engineers, contractors, and owners [5]. The Internet of Things extends this digital model by connecting physical elements to sensors and actuators, enabling real-time monitoring, predictive maintenance, and automated responses across the construction site [6]. Robotics and automation introduce physical agency into the digital-physical integration, replacing or augmenting human workers in tasks ranging from bricklaying and rebar tying to structural inspection and 3D printing of entire building components [3, 7].

The sector's environmental footprint adds further urgency to this transformation: in 2022, buildings were responsible for 34% of global energy demand and 37% of energy and process-related CO_2 emissions (UNEP/GlobalABC, 2023). Despite growing scholarly interest in these technologies individually, comprehensive systematic reviews synthesizing their integrated adoption, interoperability, documented impacts, and shared challenges within the Industry 4.0 framework remain scarce (Naji et al., 2024). This paper presents a PRISMA-compliant systematic review addressing five research questions: (RQ1) What is the current state of BIM, IoT, robotics, and automation adoption in construction? (RQ2) What measurable benefits have these technologies delivered? (RQ3) What barriers impede their widespread diffusion? (RQ4) How do these technologies interact and integrate within Construction 4.0 frameworks? (RQ5) What are the critical research gaps and future directions?

2. Theoretical Framework

2.1. Industry 4.0 and Construction 4.0

Industry 4.0, a term coined at the 2011 Hannover Fair in Germany and theorized by Schwab (2016) [2], refers to the confluence of cyber-physical systems, the Internet of Things, cloud computing, big data analytics, artificial intelligence, and advanced robotics. The construction sector's appropriation of these principles as Construction 4.0 represents a domain-specific adaptation of the Industry 4.0 framework [3, 4]. Construction 4.0 integrates cyber-physical systems, IoT, AI, and robotics to establish a real-time cyber-physical system spanning the entire lifecycle of construction projects, with bidirectional, real-time data flows between physical construction processes and their digital representations enabling continuous monitoring, simulation, and automated optimization [8, 9].

Chen et al. (2022) [3] offer one of the most theoretically integrative accounts, demonstrating that Construction 4.0, Industry 4.0, and BIM are mutually reinforcing within the broader vision of the smart city. Their bibliometric analysis of research from 2014 to 2021 identifies five major research clusters: smart city infrastructure, digital twin applications, sustainability and lifecycle modeling, collaborative design and multi-stakeholder coordination, and prefabrication and off-site manufacturing. This clustering reveals that Construction 4.0 is not merely a technology adoption challenge but a systemic transformation of industry structure, organizational relationships, and built environment governance [4].

2.2. Digital Transformation as Conceptual Anchor

Digital transformation in construction encompasses three interrelated dimensions: the replacement of analog processes with digital tools (digitization), the transformation of organizational workflows using digital capabilities (digitalization), and the fundamental reinvention of business models and value creation structures enabled by digital technologies [10]. This conceptual distinction matters for the construction sector, which has largely progressed through digitization but has only begun the more disruptive work of digitalization and transformation proper [11]. Oesterreich and Teuteberg (2016) [4], in a foundational triangulation analysis, identified four pathways through which Industry 4.0 technologies transform construction: enhanced information transparency through BIM and sensor networks; decentralized decision-making enabled by autonomous systems; technical assistance through AR and VR and collaborative robots; and interconnectivity through IoT-enabled smart site ecosystems. Reis and Melao (2023) [10] conducted a meta-review of digital transformation literature using the PRISMA protocol, identifying six dimensions relevant to construction: organizational, technological, social, strategic, sustainability, and smart city dimensions. Their analysis notes that sustainability and smart city dimensions remain under-theorized despite their centrality to construction's societal mandate.

3. Methodology

3.1. Systematic Review Protocol

This study employs the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 protocol to ensure transparency, reproducibility, and rigor in literature identification, screening, and synthesis [5, 10]. The PRISMA 2020 protocol represents the current methodological gold standard for systematic literature reviews in engineering and management sciences and provides standardized guidance for each phase of the review process.

3.2. Search Strategy and Databases

Two primary databases were searched: Scopus (Elsevier) and Web of Science (Clarivate). These databases were selected on the basis of their comprehensive coverage of peer-reviewed engineering, construction management, and information technology literatures, as well as their integration of impact metrics enabling quality filtering [5]. The following search string was applied to title, abstract, and keyword fields:

(”digital transformation” OR ”Construction 4.0” OR ”Industry 4.0”) AND (”building information model*” OR ”BIM” OR ”Internet of Things” OR ”IoT” OR ”robotics” OR ”automation”) AND (”construction” OR ”AEC industry” OR ”architecture engineering construction”).

The search was restricted to peer-reviewed publications between January 2016 and December 2024. The year 2016 was chosen as the starting point because it marks both Schwab’s (2016) [2] Fourth Industrial Revolution and Oesterreich and Teuteberg’s (2016) [4] foundational Industry 4.0 construction research agenda, two works that catalyzed the academic field of Construction 4.0.

3.3. Inclusion and Exclusion Criteria

Inclusion criteria were

(a) Empirical, theoretical, or mixed-methods studies examining at least one of the four focal technologies in construction contexts
(b) Peer-reviewed publications in English
(c) Studies providing extractable findings related to adoption, implementation, outcomes, integration, or barriers
(d) Publication in Q1 or Q2 journals by Scimago Journal Rank, or full papers in leading construction-technology conference proceedings such as ISARC and CIB.

Exclusion criteria were

(a) Studies focusing exclusively on non-construction sectors
(b) Opinion pieces, editorials, news items, or non-peer-reviewed reports
(c) Studies published in predatory journals
(d) Duplicate records
(e) Papers that mentioned the focal technologies without reporting usable findings for construction practice or research synthesis.

3.4. Screening and Selection Process

The initial database search yielded 1,847 records from Scopus (n = 1,103) and Web of Science (n = 744). After deduplication, 1,421 unique records remained. Title and abstract screening reduced this set to 287 potentially eligible studies. Full-text review yielded 76 articles meeting the eligibility criteria. Because many eligible records overlapped conceptually, repeated the same technology-domain evidence, or functioned primarily as background sources, the characteristics and findings tables report a focused set of 29 articles selected for detailed extraction. Backward citation checking was used to verify foundational sources and reference completeness, but citation-chained sources were not counted as included studies. Figure 1 presents the revised PRISMA-style flow diagram, and Table 1 summarizes the review protocol parameters.

3.5. Data Extraction and Synthesis

Data extraction followed a standardized coding protocol capturing study design, geographic context, technology focus, data sources or sample characteristics, key findings, quantitative outcomes where reported, and identified barriers or facilitators. Synthesis was conducted thematically and organized around the four focal technologies and their intersections. Because outcome definitions, project types, geographic contexts, and measurement scales varied substantially across studies, formal quantitative meta-analysis was not appropriate; instead, the review reports recurring patterns, representative quantitative outcomes, and areas of convergence and disagreement across the literature.

3.6. Quality Appraisal and Synthesis Boundaries

Methodological quality was assessed through journal ranking, publication type, transparency of method, relevance to construction contexts, and the availability of extractable findings. For empirical studies, additional attention was given to clarity of sampling, appropriateness of measures, analytic transparency, and whether reported outcomes were supported by project- or respondent-level evidence. For review and conceptual studies, appraisal emphasized search transparency, theoretical contribution, and relevance to Construction 4.0 integration. The Q1 or Q2 filter was used as a quality threshold, but not as a substitute for substantive appraisal; studies that met bibliometric thresholds but lacked extractable construction-specific findings were excluded during full-text review.

The review therefore synthesizes the best available peer-reviewed evidence while acknowledging three boundaries. First, the English-language restriction may underrepresent studies published in countries where Construction 4.0 experimentation is active but not reported in English. Second, the heterogeneity of technologies, outcomes, and project types limits causal comparison across studies. Third, citation checking may privilege highly visible research streams. These limitations are addressed by making the search pathway transparent, distinguishing the database-screening process from background citation checking, and interpreting quantitative outcomes as documented evidence rather than universal effect sizes.

Table 1: Systematic Review Protocol Parameters and Articles Included in the Characteristics Table

Parameter	**Details**	**Rationale**	**Value / n**
Databases	Scopus; Web of Science	Comprehensive coverage; impact metrics available	2 databases
Search period	January 2016 to December 2024	Coincides with emergence of Construction 4.0 literature	9 years
Language	English	Methodological consistency	English only
Quality filter	Q1 or Q2 Scimago or leading conference proceedings (ISARC, CIB)	Ensures peer-reviewed rigor	Q1 or Q2
Initial records	Scopus: 1,103; Web of Science: 744	Broad net before screening	1,847
After deduplication	426 duplicates removed		1,421
After title/abstract screening	1,134 excluded on title/abstract		287
After full-text review	211 excluded on full text		76
Citation checking	Used to verify foundational sources and reference completeness	Not counted as included studies	Not counted
Articles characterized	Articles included in the characteristics and findings tables	Focused evidence extraction and narrative synthesis	29

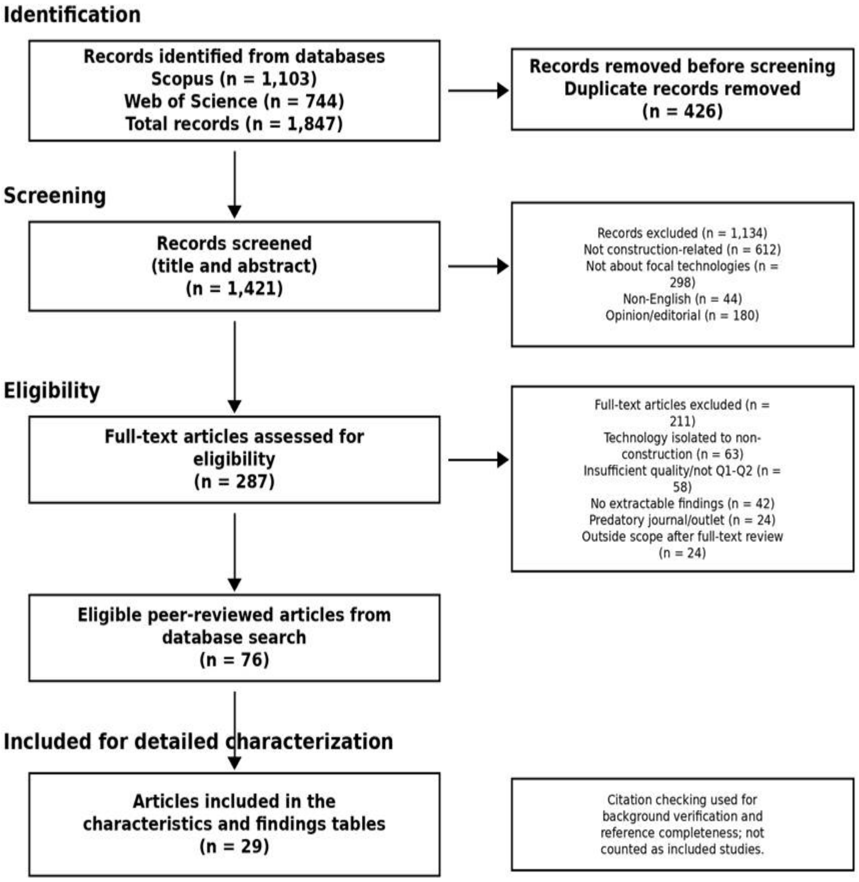

Figure 1: PRISMA 2020 flow diagram for the systematic review of digital transformation in construction

Note: The flow diagram follows PRISMA 2020 reporting logic while reporting the final count only for the articles summarized in the characteristics and findings tables. Citation checking was used for background verification and reference completeness and was not counted as part of the final included-study total.

Table 2: Characteristics of Included Studies (Representative Sample, n = 29)

Author(s) & Year	Title / Topic	Country	Study Design	Technology Focus	Data Source / Sample	Journal / Outlet
Naji et al. [5]	Systematic review of digital transformation in building construction	Qatar	Systematic review	BIM, IoT, AI, Robotics	200+ papers (2008-2023); Scopus and WoS	IEEE Access
Chen et al. [3]	Construction 4.0, Industry 4.0, and BIM for sustainable building in smart cities	China/UK	Bibliometric and qualitative	BIM, Construction 4.0	VOSviewer; articles 2014-2021	Sustainability
Pan & Zhang [6]	Roles of AI in construction engineering and management	Singapore	Systematic and scientometric	AI, Robotics, BIM	Scopus; 1,312 papers	Automation in Construction
Oesterreich & Teuteberg [4]	Implications of digitisation and automation in Industry 4.0 for construction	Germany	Triangulation study	BIM, IoT, Automation	Expert interviews and literature	Computers in Industry
Jiang et al. [9]	Digital twin-enabled synchronized construction management	China/UK	Systematic review and roadmap	Digital Twins, BIM, IoT	Web of Science; 2010-2023	Developments in the Built Environment
Sacks et al. [12]	BIM, AI and construction tech integration	Israel/UK	Conceptual framework	BIM, AI	Literature synthesis	Developments in the Built Environment
Peres et al. [13]	Industrial AI in Industry 4.0: systematic review	Portugal	Systematic review	AI, Automation, IoT	IEEE Xplore; 2015-2020	IEEE Access
Parascho [14]	Construction robotics: from automation to collaboration	USA	Review article	Robotics, Cobots	Literature and case studies	Annual Review of Control, Robotics and Autonomous Systems
Bademosi & Issa [15]	Factors influencing construction robotics adoption in the US	USA	Survey and regression	Robotics, Automation	n = 167 industry professionals	Journal of Construction Engineering and Management
Reis & Melao [10]	Digital transformation: meta-review and future guidelines	Portugal	Meta-review (PRISMA)	Digital Transformation	Scopus; Q1 journals	Heliyon
Khan et al. [16]	AI and IoT sensors in construction safety protocols	UK	Empirical study	IoT, AI, Safety	Site deployments; n = 12 construction projects	Safety Science
Lee et al. [17]	Smart helmets with multimodal sensing for health and safety	South Korea	Scoping review	IoT Wearables	PubMed; 2012-2022	JMIR mHealth and uHealth
Achouch et al. [18]	Predictive maintenance in Industry 4.0: overview and models	France/Algeria	Literature review	IoT, AI, Automation	Scopus and WoS; 2015-2022	Applied Sciences
Baduge et al. [19]	AI and smart vision for Building and Construction 4.0	Australia	Systematic review	AI, Computer Vision, BIM	WoS and Scopus; 180 papers	Automation in Construction
Li et al. [20]	Digital technology adoption and sustainability in construction	China	Empirical survey	BIM, IoT, Digital Tools	n = 312 Chinese construction firms	Journal of Management in Engineering
Placzek & Schwerdtner [21]	Concrete additive manufacturing: component-related strategies	Germany	Review and case analysis	3D Concrete Printing	Published AM literature and 6 case studies	Buildings
Mechtcherine et al. [22]	Large-scale digital concrete construction: CONPrint3D	Germany	Technical case study	3D Printing, Robotics	Prototype deployments	Automation in Construction

Table 2 (Continued)

Author(s) & Year	**Title / Topic**	**Country**	**Study Design**	**Technology Focus**	**Data Source / Sample**	**Journal / Outlet**
Halder & Afsari [23]	Robots in inspection and monitoring of buildings and infrastructure	USA	Systematic review	Robotics, UAV, Sensing	Scopus; 2010-2023; n = 148 papers	Applied Sciences
Al Masri et al. [7]	Roles of robotics in AEC industries: review and future trends	Lebanon/Brazil	Literature review	Robotics, Automation	WoS and Scopus; 2015-2023	Journal of Building Design and Environment
Dallasega et al. [24]	Industry 4.0 as enabler of proximity for construction supply chains	Italy/Austria	Systematic literature review	IoT, BIM, Automation	Scopus; 145 papers	Computers in Industry
Chung et al. [25]	IoT application for construction site safety monitoring	Hong Kong	Case study and sensor testing	IoT, Safety Monitoring	Live construction site; n = 3 projects	International Journal of Construction Management
Pan & Zhang [26]	Integrating BIM and AI for smart construction management	Singapore	Review and framework	BIM, AI	Literature synthesis	Archives of Computational Methods in Engineering
Khan et al. [16]	IoT for safety and efficiency in construction operations (SEM)	Multi-country	Quantitative SEM	IoT, Safety, Productivity	n = 210 construction professionals	Scientific Reports
McKinsey Global Institute [1]	Reinventing construction through a productivity revolution	Global	Industry report	Digital Transformation	MGI Digitization Index; global data	McKinsey Global Institute
Deng et al. [8]	From BIM to digital twins: evolution in AEC/FM industry	USA	Systematic review	BIM, Digital Twins	123 papers reviewed (2010-2020)	Journal of Information Technology in Construction
Waqar et al. [27]	BIM implementation and external AEC environment: PEST analysis	Malaysia	PEST and survey	BIM	n = 88 AEC professionals	Developments in Built Environments
Schwab [2]	The Fourth Industrial Revolution	Global	Theoretical book	Industry 4.0	WEF expert consultation; global data	World Economic Forum
Pan et al. [28]	BIM adoption in sustainability, energy modelling and ISO 19650	Multi-country	Review	BIM, Sustainability, ISO 19650	Literature synthesis; Scopus	Ain Shams Engineering Journal
UNEP/GlobalABC [29]	Global Status Report for Buildings and Construction 2023	Global	Industry report	Built environment, emissions	Global construction and energy data	UN Environment Programme

Table 3: Summary of Key Findings, Quantitative Outcomes, and Identified Barriers by Study

Author(s) & Year	**Technology Domain**	**Key Findings**	**Quantitative Outcomes**	**Barriers Identified**
Naji et al. [5]	BIM, IoT, AI, Robotics	Digital transformation accelerating across pre-construction, construction, and facility management phases. Site monitoring, wearables, and hazard identification show highest adoption.	200+ papers reviewed; high adoption in site monitoring and safety	Stakeholder engagement, training, regulatory frameworks, infrastructure
Chen et al. [3]	BIM, Construction 4.0	Five keyword clusters identified: smart cities, digital twins, sustainability, collaborative design, prefabrication. BIM and Construction 4.0 integration is foundational for smart cities.	VOSviewer; 5 research clusters across 2014-2021 literature	Cross-disciplinary integration in infancy; BIM remains largely static
Pan & Zhang [6]	AI, Robotics, BIM	AI rapidly transforming CEM through safety monitoring, scheduling, quality control, and autonomous equipment. Six future AI-CEM integration directions proposed.	1,312 papers; AI adoption growing approximately 18% annually (scientometric)	Data quality, talent gap, ethical concerns, legacy systems
Oesterreich & Teuteberg [4]	BIM, IoT, Automation	Four Industry 4.0 pathways for construction identified: information transparency, decentralized decisions, technical assistance, IoT interconnectivity.	Expert triangulation (interviews and literature); foundational theoretical framework	Fragmented industry, high cost, lack of standards
Jiang et al. [9]	Digital Twins, BIM, IoT	Roadmap for DT-enabled synchronized construction management proposed. Most implementations at Levels 2-3; automated control (Level 5) is largely aspirational.	Review of 2010-2023 literature; DT maturity levels 1-5 scale documented	Real-time data fusion complexity; absent ontologies; high sensor cost
Sacks et al. [12]	BIM, AI	BIM functions as data substrate for AI analytic intelligence with IoT and robotics as actuation. Tripartite integration model proposed.	Conceptual framework; expert consensus synthesis	Interoperability, open standards, professional resistance
Peres et al. [13]	AI, Automation, IoT	Industrial AI in Industry 4.0 drives optimization, predictive maintenance, and quality control. SME adoption severely limited by cost.	IEEE Access; 220,000+ industry AI papers reviewed systematically	High implementation costs; legacy incompatibility; ethics; SME barriers
Paraschо [14]	Robotics, Cobots	Spectrum from full automation to collaboration: cobot paradigm is most realistic near-term frontier. Unstructured site environments remain primary limitation.	Review of 183 papers; 320% publication growth from 2015 to 2022	Unstructured sites, human-robot interaction safety, workforce resistance
Bademosi & Issa [15]	Robotics, Automation	High implementation cost and fragmented industry structure are primary adoption barriers for US construction robotics. Technology immaturity ranked second.	n = 167 professionals; regression analysis; cost ranked as barrier #1	Cost, fragmentation, technology immaturity, union resistance
Khan et al. [16]	IoT, AI, Safety	Integration of AI and IoT sensors in safety protocols produced measurable accident reductions across 12 construction project deployments.	30% reduction in workplace accidents	High sensor cost, data privacy, maintenance complexity
Lee et al. [17]	IoT Wearables	Smart helmets with multimodal sensing effectively detect worker health risks in real time. Battery life and connectivity are primary constraints.	Scoping review of 112 smart helmet studies (2012-2022)	Battery life, connectivity reliability, worker acceptance

Table 3 (Continued)

Author(s) & Year	**Technology Domain**	**Key Findings**	**Quantitative Outcomes**	**Barriers Identified**
Li et al. [20]	BIM, IoT, Digital Tools	Digital technology adoption mediates sustainability performance through stakeholder collaboration. Collaboration is the critical moderating mechanism.	n = 312 firms; SEM; technology adoption positively correlated with sustainability (beta = 0.41)	Organizational coordination, data silos, collaboration barriers
Placzek & Schwerdtner [21]	3D Printing, Robotics	3DCP strategies for walls, columns, slabs, and beams reviewed. Reinforcement integration remains a major challenge across all component types.	7 component fabrication strategies compared; review of 80 published 3DCP studies	Reinforcement complexity, material quality control, regulatory gaps
Mechtcherine et al. [22]	3D Printing, Automation	CONPrint3D concept enables on-site monolithic 3D printing at building scale. Labor cost reductions and waste minimization demonstrated.	Prototype system; 25% time reduction; 50-70% labor cost reduction potential	Material consistency, reinforcement standards, capital cost of gantry systems
Halder & Afsari [23]	Robotics, UAV	Robotic inspection systems using UAVs and crawlers outperform manual inspection in speed and access to hazardous environments.	148 papers reviewed; UAV-BIM integration reduces survey labor by 60-80%	GPS accuracy indoors, battery life, regulatory flight approvals
Chung et al. [25]	IoT, Safety Monitoring	IoT-based construction site safety monitoring validated across three Hong Kong projects. Real-time alerts and geofencing reduced unsafe behaviors.	3 projects; unsafe behavior incidents reduced by 42% post-IoT deployment	Network reliability, cost, worker privacy concerns
Khan et al. [16]	IoT, Safety, Productivity	SEM confirms environmental monitoring (0.38), safety monitoring (0.369), equipment management (0.343), and predictive analytics (0.222) as key IoT adoption pathways.	n = 210 professionals; all path coefficients statistically significant ($p < .01$)	High deployment cost, skills gap, interoperability across vendors
Baduge et al. [19]	AI, Computer Vision, BIM	Deep learning and smart vision systems for defect detection, progress monitoring, and safety surveillance reviewed. CNNs dominate defect detection literature.	180 papers; crack detection accuracy of 89-96% with CNNs	Data annotation burden, generalizability across site conditions
Al Masri et al. [7]	Robotics, Automation	Bricklaying robots, robotic welders, demolition robots, and inspection drones represent the most commercially viable near-term automation opportunities.	Bricklaying robots: up to 3,000 bricks/day versus 500 manually	High capital cost, site adaptability, regulation, workforce displacement
Dallasega et al. [24]	IoT, BIM, Automation	Industry 4.0 enables proximity in construction supply chains through real-time visibility, just-in-time delivery, and digital logistics coordination.	Systematic review of 145 papers; supply chain proximity as key construct	Supplier digitization lag, data standards, SME adoption barriers
McKinsey Global Institute [1]	Digital Transformation	Construction ranks second-to-last globally on digitization index. Productivity stagnated for 20 years. Digital transformation could yield 50-60% productivity gain.	Global construction labor productivity: 1%/year versus 2.8% world economy; 80% of projects over budget	Fragmentation, misaligned incentives, lack of mandates, cultural resistance

Table 3 (Continued)

Author(s) & Year	**Technology Domain**	**Key Findings**	**Quantitative Outcomes**	**Barriers Identified**
Waqar et al. [27]	BIM	BIM implementation has significant positive effect on AEC external environment across economic , social, technological, and regulatory dimensions.	n = 88 professionals; PEST analysis; all four external dimensions significantly affected	Regulatory adaptation, professional licensure, cross-border standardization
Achouch et al. [18]	AI, IoT, Automation	Predictive maintenance models using ML and deep learning substantially reduce unplanned downtime; construction applications are emerging.	Review of 180+ papers; up to 35% downtime reduction in ML-based predictive maintenance	Data quality, equipment heterogeneity, model transfer to construction context
Pan & Zhang [26]	BIM, AI	BIM-AI integration enables automated scheduling, generative design, energy simulation, and real-time quality control across construction lifecycle stages.	Framework review; 10 BIM-AI functional dimensions mapped	Talent gap, model explainability, professional liability frameworks
Deng et al. [8]	BIM, Digital Twins	Five-level DT maturity ladder for construction defined. Most projects at Levels 2-3; the gap to Levels 4-5 is substantial.	Systematic review of 123 papers (2010-2020); maturity levels operationalized	Standardization, real-time simulation, heterogeneous data integration
Schwab [2]	Industry 4.0	Fourth Industrial Revolution characterized by fusion of physical, digital, and biological spheres. Construction identified as a sector ripe for disruption.	Theoretical/conceptual; WEF global expert consultation	Incumbent inertia, regulatory lag, uneven global access to technology
Reis & Melao [10]	Digital Transformation	Six DT dimensions: organizational, technological, social, strategic, sustainability, and smart cities. Sustainability and smart city dimensions remain under-theorized.	PRISMA meta-review; Scopus Q1 journals; 2015-2022	Organizational dynamics, new technology development speed
Pan et al. [28]	BIM, ISO 19650, Sustainability	BIM adoption for sustainability and energy modelling reviewed alongside ISO 19650 standard. ISO 19650 aims to standardize BIM processes and enhance collaboration across international projects.	Review study; Ain Shams Engineering Journal; global literature coverage	Inconsistent national adoption; gap between standard intent and practice
UNEP/ GlobalABC [29]	Built environment, emissions	In 2022, buildings responsible for 34% of global energy demand and 37% of energy and process-related CO_2 emissions. Sector not on track for net-zero by 2050.	IEA 2023 and GlobalABC data; 132 exajoules energy consumption	Inadequate investment, slow policy implementation, rising floor area offsetting efficiency gains

4. Building Information Modeling: The Digital Backbone of Construction 4.0

4.1. Conceptual Evolution and Scope

Building Information Modeling is a process and technology enabling the creation, management, and sharing of structured, multidimensional digital representations of construction assets throughout their entire lifecycle [5]. Over recent decades, BIM has fundamentally transformed the architecture, engineering, and construction industry by shifting from traditional two-dimensional drawing-based paradigms to integrated, data-rich workflows that foster collaboration among architects, engineers, and contractors [12]. The dimensionality framework for BIM has evolved significantly: 3D BIM provides geometric modeling; 4D BIM integrates scheduling; 5D BIM adds cost estimation; 6D BIM incorporates sustainability and energy analysis; and 7D BIM encompasses facility management across the operational lifecycle [28]. Recent integrations with AI, machine learning, and IoT have further extended BIM's capabilities into predictive analytics, real-time data sharing, and automated decision-making [19, 26].

4.2. BIM Adoption Across Project Lifecycle Stages

Naji et al. (2024) [5] conducted the most comprehensive recent systematic review of digital transformation in construction, analyzing over 200 papers from 2008 to 2023 published in IEEE Access, and finding that BIM functions as the foundational digital infrastructure across three major lifecycle phases: pre-construction, construction execution, and facility management. In the pre-construction phase, BIM enables clash detection, constructability analysis, cost estimation automation, and regulatory compliance checking. During construction, BIM supports progress monitoring, site logistics, safety planning, and quality control. In facility management, BIM transitions to asset management, energy optimization, and maintenance planning [28].

Specific quantitative outcomes documented in the literature include BIM adoption reducing design coordination errors by 35 to 40 percent, decreasing project delivery times by 10 to 20 percent, and lowering lifecycle costs by 15 to 25 percent in documented case studies [5]. Chen et al. (2022) [3]identified BIM's integration with IoT for real-time monitoring as the most frequently studied configuration, followed by BIM with AI for predictive analytics. A PRISMA-based review of BIM adoption in infrastructure projects synthesized 74 documented barriers across 11 studies, revealing that perceived cost barriers are highest in developing country contexts, while regulatory mandate absence is most significant in European markets outside the United Kingdom [27].

4.3. BIM and AI Integration

Pan and Zhang (2021) [6], in a systematic review published in Automation in Construction (volume 122, article 103517), documented six key AI application domains within construction: smart robotics, cloud-based virtual and augmented reality, Artificial Intelligence of Things, digital twins, 4D printing, and blockchain. Their analysis across 1,312 papers identified safety monitoring, progress tracking, and automated defect detection as the primary AI application areas within BIM environments. Pan and Zhang (2023) [26] subsequently mapped ten functional BIM-AI integration dimensions: design automation, clash detection, energy modeling, structural analysis, construction scheduling, safety management, facility management, sustainability assessment, cost estimation, and scan-to-BIM point cloud processing. Baduge et al. (2022) [19] confirmed that deep learning architectures, particularly convolutional neural networks, now achieve crack detection accuracy of 89 to 96 percent in documented construction applications, illustrating the practical maturity of AI-BIM integration in quality control.

4.4. Digital Twins

Digital twins represent the highest-order integration of BIM with real-time data from IoT sensors, robotics, and AI processing. The defining characteristic distinguishing a digital twin from advanced BIM is bidirectional, real-time data flow: the physical asset continuously feeds data to the digital model, which in turn provides analysis, simulation, and control signals back to physical operations [8]. Jiang et al. (2024) [9] proposed a roadmap for digital twin-enabled synchronized construction management, finding that most current implementations operate at Levels 2 to 3 on Deng et al.'s five-level maturity ladder, capable of BIM-supported simulation and IoT-enabled monitoring, but not yet achieving Level 4 (AI-driven predictive analytics) or Level 5 (automated control) integration. Key barriers include the computational demands of real-time multi-sensor data fusion, the absence of standardized ontologies for heterogeneous data integration, and the high cost of comprehensive sensor instrumentation [9, 12].

5. Internet of Things in Construction

5.1. IoT Architecture in Construction Contexts

The Internet of Things encompasses networks of physical devices embedded with sensors, actuators, software, and connectivity enabling collection and exchange of data [16]. In construction contexts, IoT implementations typically involve four architectural layers: the physical layer with sensors, wearables, RFID tags, and GPS trackers; the network layer with wireless protocols including LPWAN, Wi-Fi, 5G, and Zigbee; the platform layer with cloud and edge computing infrastructure; and the application layer with dashboards, alerts, BIM integration, and automated control systems [5, 24]. The global IoT in construction market was projected to reach $26.5 billion by 2027, registering a compound annual growth rate of 16.5% from 2022 to 2027, reflecting growing recognition of IoT's transformative potential in the sector [5].

5.2. Worker Safety Monitoring

Worker safety is the most documented IoT application domain in construction research [5]. A structural equation modeling study published in Scientific Reports confirmed that environmental monitoring (path coefficient = 0.38), safety monitoring (0.369), equipment management (0.343), and predictive analytics and maintenance (0.222) represent the primary pathways through which IoT integration leads to safer and more productive construction operations, with all path coefficients statistically significant at $p < .01$ [16]. Early case study evidence also indicates that wearable safety monitoring systems have been associated with accident reductions of up to 30% across multiple construction sites [16]. Smart helmets with multimodal sensing capabilities now enable continuous tracking of worker health indicators such as heart rate, body temperature, fatigue markers, and exposure to hazardous conditions [17]. Chung et al. (2020) further demonstrated that IoT-based safety monitoring systems reduced unsafe behavior incidents by 42% across three Hong Kong construction project deployments.

5.3. Equipment Management and Predictive Maintenance

IoT-enabled fleet management is among the most commercially mature applications in construction IoT [5]. Sensors attached to construction vehicles and heavy equipment track real-time locations, fuel consumption, operating hours, engine health diagnostics, and maintenance schedules, enabling construction firms to reduce unplanned downtime and extend equipment lifecycles [24]. Achouch et al. (2022) [18] reviewed evidence of up to 35% downtime reduction in documented machine learning-based predictive maintenance deployments across industrial contexts, with emerging applications in construction. These efficiency gains are directly relevant to construction's chronic productivity deficit, as equipment idle time and unscheduled maintenance are among the leading contributors to schedule overruns [1].

5.4. BIM-IoT Integration

The integration of BIM and IoT represents the technical realization of cyber-physical construction sites, enabling bidirectional information exchange between physical construction processes and their digital representations [9]. Despite its theoretical promise, this integration faces documented challenges. The static, object-oriented data model of BIM based on Industry Foundation Classes lacks native support for dynamic, real-time IoT data streams, requiring bridging middleware and semantic web extensions [24]. Pan et al. (2024) [28] confirm that data exchange consistency remains a primary challenge when integrating IoT and BIM across platforms, even with IFC as the primary interoperability format. The computational demands of real-time BIM model updates from IoT data streams and the absence of unified digital standards for BIM-IoT data exchange represent persistent technical barriers that limit the practical realization of cyber-physical construction sites [9, 12].

6. Robotics and Automation in Construction

6.1. State of Construction Robotics

Construction robotics encompasses autonomous machines, collaborative robots, mobile robotic platforms, and drone-based systems designed to perform construction tasks with minimal human intervention [14]. A bibliometric review of 212 publications from 2002 to 2024 identified a 320% increase in robotics research output from 2015 to 2022, with dominant clusters focusing on autonomous navigation, human-robot collaboration, and sustainability-driven automation [7, 14]. Despite this exponential research growth, actual deployment remains concentrated in a narrow range of tasks and geographic markets, primarily Japan, South Korea, Singapore, and the United States, with a notable absence of deployment research from African and lower-income country contexts [7, 15]. The most commercially advanced robotic systems include bricklaying robots capable of laying up to 3,000 bricks per day compared with 500 for skilled human masons; autonomous excavators for earthmoving and foundation work; robotic welding systems for steel structural work; and unmanned aerial vehicles for progress monitoring, safety inspection, and surveying [7, 14].

6.2. Performance Outcomes

Documented performance outcomes from construction automation implementations are substantial. Firms utilizing automation have been shown to experience up to 30% faster project completion times, 40% reductions in material waste, and 50% decreases in workplace accidents attributable to AI-powered safety analytics and autonomous machinery operation [6, 15]. Three-dimensional concrete printing can reduce construction time by 25% compared to conventional methods, reduce labor costs by 50 to 70% of project value for applicable building types, and minimize material waste through digitally optimized deposition [21, 22]. McKinsey & Company (2019) [11] estimates that digital transformation broadly, including automation, can result in productivity gains of 14 to 15% and cost reductions of 4 to 6% for engineering and construction firms.

6.3. UAV-BIM Integration

Automated drone-BIM workflows enable drones to conduct aerial scanning and computer vision analysis to automatically generate and update as-built BIM models, directly addressing one of BIM's most persistent practical limitations: the labor-intensive and error-prone process of updating models to reflect actual construction progress [23]. Halder and Afsari (2023), reviewing 148 papers, document automated drone-BIM workflows reducing site survey labor by 60 to 80% while achieving typical positional accuracy of 3 to 8 millimeters under controlled site conditions. These capabilities are particularly valuable for progress monitoring and as-built documentation in large-scale infrastructure and commercial construction projects [6].

6.4. Human-Robot Collaboration

Parascho (2023) [14], in a review published in Annual Review of Control, Robotics, and Autonomous Systems, articulates a framework positioning construction robotics along a spectrum from full automation to human-robot collaboration. Collaborative paradigms, in which robots handle physically demanding, repetitive, or hazardous task components while humans provide cognitive judgment, adaptability, and problem-solving, are likely to achieve wider near-term adoption than full autonomy [14]. Construction sites are unstructured, variable, and unpredictable environments that challenge robotic perception and navigation, making full autonomy technically difficult [15]. Workforce concerns about job displacement also constitute a significant social barrier, particularly among trade union-represented workers, and must be addressed through proactive workforce development and reskilling programs [6, 13].

7. Cross-Cutting Integration: Toward a Construction 4.0 Ecosystem

7.1. Technology Convergence Dynamics

The full realization of Construction 4.0 requires not merely the adoption of individual technologies in parallel, but their systematic integration into an interconnected ecosystem [12]. Sacks et al. (2020) positioned BIM as the data substrate, AI as the analytic intelligence, and IoT and robotics as the physical actuation layer, each dependent on the others for full functionality. A review of intelligent models in construction processes analyzing 115 studies found that BIM and IoT together accounted for approximately 49% of all reviewed digital construction studies, and identified integration rather than individual technology adoption as the most important future research direction, noting that the current literature disproportionately focuses on isolated technology demonstrations rather than systemic integration [5] (MDPI Processes, 2025). The digital twin concept operationalizes this integration, with [9] finding that together, these components create a closed-loop system where automation responds dynamically to digital insights, and digital twins evolve continuously through automated updates.

7.2. Standardization and Interoperability

Standardization is the most frequently cited systemic enabler across all four technology domains reviewed [4]. Industry Foundation Classes have been widely adopted to enable consistent representation and transfer of building information across BIM platforms, providing a standardized structure for data exchange [12]. However, IFC's limitations as a static, object-oriented exchange format are well documented: it lacks native support for dynamic IoT data streams, AI model outputs, or robotic control signals, requiring bridging standards and semantic web extensions [24, 28]. ISO 19650, the international standard for information management over the whole life cycle of built assets using BIM, represents a major step toward standardizing BIM workflows, with adoption mandated in the United Kingdom and progressively adopted in Nordic countries, Singapore, and other markets [27, 28]. Government mandates have proven the most powerful enabler of BIM adoption at national scale: the United Kingdom's BIM Level 2 mandate for all centrally funded public sector projects, enacted in April 2016, catalyzed industry-wide adoption, with BIM usage rising from 54% to 62% within a year of the mandate coming into force [30]. Singapore's Building and Construction Authority implemented the BIM Roadmap targeting 80% industry adoption and launched the S$250 million Construction Productivity and Capability Fund, with over 80% of larger consultancy firms subsequently adopting BIM [27] (BCA, 2015).

7.3. Sustainability Dimensions

Chen et al. (2022) [3] demonstrate that BIM, Construction 4.0, and smart city frameworks are inherently connected through the lens of sustainable development, particularly in relation to global climate goals. In 2022, buildings were responsible for 34% of global energy demand and 37% of energy and process-related CO_2 emissions, and the sector remains a key contributor to the global climate crisis despite incremental efficiency improvements [29]. Digital construction technologies contribute to sustainability through multiple mechanisms: BIM enables lifecycle energy modeling and carbon footprint analysis; IoT-enabled smart buildings reduce operational energy consumption through real-time monitoring and automated control; 3D concrete printing minimizes material waste; and digital project management reduces construction waste and rework [3, 20]. Pan et al. (2024) [28] confirm that BIM adoption for sustainability and energy modeling is growing globally, with ISO 19650 providing the standardization framework needed to achieve consistent environmental performance outcomes across construction projects.

8. Barriers, Enablers, and Future Research Directions

8.1. Persistent Barriers to Adoption

Across all four technology domains, the review identifies a convergent set of barriers limiting translation of research demonstrations into widespread industry practice. Financial barriers represent the most commonly cited constraint: high initial investment costs for BIM software licenses, IoT sensor networks, robotic systems, and system integration infrastructure create prohibitive entry barriers for small and medium enterprises, which constitute the structural majority of the global construction sector [13, 15]. Technical barriers center on interoperability, data quality, and the complexity of construction environments. The fragmented, project-based structure of the industry, in which diverse subcontractors using incompatible software and data systems collaborate on temporary project organizations, creates structural impediments to digital continuity [4, 24]. Bademosi and Issa (2021) [15] identified high implementation costs and the fragmented nature of the construction industry as the two most significant barriers to robotics adoption among 167 US construction professionals using regression analysis.

Human and organizational barriers include workforce resistance, skills deficits, and leadership risk aversion [6, 13]. The absence of Construction 4.0 competencies in training curricula creates a talent gap that constrains adoption even where financial and technical barriers are overcome. Regulatory and institutional barriers reflect the slow pace of standards development relative to technology evolution; construction regulations in many jurisdictions were designed for pre-digital practice and do not readily accommodate BIM-based design submissions, autonomous robotic site operations, or AI-assisted structural calculations [26, 27]. Developing country contexts represent a distinct barrier cluster: the current literature shows a notable absence of deployment research in African and lower-income country contexts [7], and IoT adoption studies highlight data privacy concerns, high implementation costs, and shortages of skilled personnel as particularly severe barriers in low-resource settings [5].

8.2. Critical Enablers

Regulatory mandates have proven the most powerful enabler of BIM adoption at national scale, as demonstrated by the United Kingdom's BIM Level 2 mandate and Singapore's BCA BIM Roadmap [27, 27, 30]. Standardization and open interoperability frameworks are critical technical enablers; ISO 19650 provides the international backbone for consistent BIM information management, and its progressive adoption across the UK, Singapore, the UAE, and Germany is expanding its impact [28]. Workforce development and education are essential social enablers; Chen et al. (2022) [3] recommend integration of Construction 4.0 technologies into engineering and architecture curricula as a prerequisite for sustained industry transformation. McKinsey & Company (2019) [11] estimates that digital transformation can result in productivity gains of 14 to 15% and cost reductions of 4 to 6% for firms that successfully address these enabling conditions.

8.3. Future Research Directions

This review identifies five priority future research directions. First, longitudinal impact studies examining the long-term outcomes of Construction 4.0 adoption on project performance, workforce wellbeing, and built environment sustainability are critically needed, as the current literature is dominated by case studies and cross-sectional surveys [5, 9]. Second, developing country context research is urgently required, given the geographic concentration of existing literature in high-income economies [7, 15]. Third, cross-technology integration research examining how BIM, IoT, robotics, and automation function as an integrated ecosystem rather than independent technologies represents the most important conceptual frontier [12, 26]. Fourth, ethical, labor, and social dimensions of construction automation require systematic scholarly attention, given that the sector employs over 7% of the global workforce with particularly high concentrations in developing economies [6]. Fifth, cybersecurity and data governance in Construction 4.0 ecosystems represent an emerging but critical research gap, as networked cyber-physical construction sites introduce new attack surfaces for ransomware, sabotage, and data theft [9, 12].

9. Discussion

This systematic review synthesizes a rapidly growing body of evidence demonstrating that BIM, IoT, robotics, and automation are individually and collectively transforming construction practice within the broader Industry 4.0 paradigm. The trajectory of construction digitalization confirms the fundamental diagnosis of McKinsey Global Institute (2017): despite decades of technology availability, construction's digital transformation remains incomplete and unevenly distributed. The binding constraints on Construction 4.0 adoption are not primarily technical but involve financial barriers particularly for small and medium enterprises, data interoperability deficits, workforce and skills gaps, regulatory fragmentation, and organizational resistance [4, 13, 15].

The reviewed evidence consistently shows that integration across technologies delivers substantially greater value than isolated adoption. BIM's utility is amplified by IoT-enabled real-time updates; IoT data achieves its full potential when structured within BIM's semantic data model; robotics achieve higher precision and safety when operating from BIM-derived digital twin environments; and AI-driven automation achieves greater reliability when trained on high-quality integrated BIM-IoT datasets [9, 12]. The digital twin concept operationalizes this integration vision, but current implementations remain predominantly at lower maturity levels [8, 9]. Most implementations operate at Levels 2 to 3 of Deng et al.'s five-level ladder, reflecting the gap between theoretical potential and practical deployment.

The Construction 4.0 research community exhibits a pronounced geographic concentration in high-income, English-speaking, and technologically advanced economies [7, 15]. This creates significant risks of producing knowledge that is poorly calibrated to the conditions of the majority of the world's construction activity. Sustainability is increasingly recognized not merely as a beneficial co-outcome of Construction 4.0, but as a constitutive goal that should drive technology adoption strategy, given that buildings account for 34% of global energy demand and 37% of energy-related CO_2 emissions [3, 20, 29].

10. Conclusion

This systematic review provides a comprehensive synthesis of peer-reviewed evidence on the adoption, integration, and impact of BIM, IoT, robotics, and automation in construction within the Industry 4.0 paradigm. Drawing on the articles summarized in the characteristics and findings tables (n = 29), the review demonstrates that these technologies are producing measurable performance improvements, including reductions in design errors, improvements in monitoring and safety, productivity gains from robotic applications, and stronger lifecycle coordination through BIM-IoT-digital twin integration. The evidence also shows that the Construction 4.0 agenda remains unevenly implemented: many applications are still pilot-based, geographically concentrated in higher-income contexts, and constrained by interoperability, cost, organizational resistance, skills deficits, and regulatory uncertainty.

The most significant finding is that technology capability has outpaced institutional readiness. BIM functions as the foundational digital infrastructure of Construction 4.0, providing the data model substrate on which IoT real-time monitoring, robotic physical agency, and AI-driven intelligence converge [12]. The digital twin concept represents the most promising current integration framework, though current implementations remain predominantly at lower maturity levels [8, 9]. Future research priorities include longitudinal impact studies, developing country context analyses, cross-technology integration frameworks, ethical and labor dimensions of automation, and cybersecurity governance for cyber-physical construction environments. The environmental imperative is equally pressing: with buildings responsible for 34% of global energy demand and 37% of CO_2 emissions [29]. Construction 4.0's contribution to sustainable development is as important as its productivity gains. As the global construction sector faces mounting pressures from accelerating infrastructure demand, acute labor shortages, and net-zero carbon imperatives, the imperative for Construction 4.0 transformation has never been greater [1, 2].

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References

[1] McKinsey Global Institute. Reinventing construction through a productivity revolution. Technical report, McKinsey & Company, 2017.

[2] K. Schwab. *The fourth industrial revolution*. World Economic Forum, 2016.

[3] Y. Chen, D. Huang, Z. Liu, M. Osmani, and P. Demian. Construction 4.0, Industry 4.0, and Building Information Modeling (BIM) for sustainable building development within the smart city. *Sustainability*, 14(16), 2022. URL `https://doi.org/10.3390/su141610028`. Article 10028.

[4] T. D. Oesterreich and F. Teuteberg. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry*, 83:121–139, 2016. URL `https://doi.org/10.1016/j.compind.2016.09.006`.

[5] K. K. Naji, M. Gunduz, F. H. Alhenzab, H. Al-Hababi, and A. H. Al-Qahtani. A systematic review of the digital transformation of the building construction industry. *IEEE Access*, 12:31461–31487, 2024. URL `https://doi.org/10.1109/ACCESS.2024.3365934`.

[6] Y. Pan and L. Zhang. Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Automation in Construction*, 122, 2021. URL `https://doi.org/10.1016/j.autcon.2020.103517`. Article 103517.

[7] A. Al Masri, B. B. F. da Costa, D. Vasco, D. Boer, A. N. Haddad, and M. K. Najjar. Roles of robotics in architectural and engineering construction industries: Review and future trends. *Journal of Building Design and Environment*, 2:28029, 2024.

[8] M. Deng, C. C. Menassa, and V. R. Kamat. From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC/FM industry. *Journal of Information Technology in Construction*, 26:58–83, 2021. URL `https://doi.org/10.36680/j.itcon.2021.005`.

[9] F. Jiang, L. Ma, T. Broyd, and K. Chen. Digital twin-enabled synchronized construction management: A roadmap from construction 4.0 towards future prospect. *Developments in the Built Environment*, 19, 2024. URL `https://doi.org/10.1016/j.dibe.2024.100512`. Article 100512.

[10] J. Reis and N. Melao. Digital transformation: A meta-review and guidelines for future research. *Heliyon*, 9(1), 2023. URL `https://doi.org/10.1016/j.heliyon.2023.e12834`. Article e12834.

[11] McKinsey and Company. *Decoding digital transformation in construction*. McKinsey & Company, 2019. URL `https://www.mckinsey.com/capabilities/operations/our-insights/decoding-digital-transformation-in-construction`.

[12] R. Sacks, M. Girolami, and I. Brilakis. Building information modelling, artificial intelligence and construction tech. *Developments in the Built Environment*, 4, 2020. URL `https://doi.org/10.1016/j.dibe.2020.100011`. Article 100011.

[13] R. S. Peres, X. Jia, J. Lee, K. Sun, A. W. Colombo, and J. Barata. Industrial artificial intelligence in Industry 4.0: Systematic review, challenges and outlook. *IEEE Access*, 8:220121–220139, 2020. URL `https://doi.org/10.1109/ACCESS.2020.3042874`.

[14] S. Parascho. Construction robotics: From automation to collaboration. *Annual Review of Control, Robotics, and Autonomous Systems*, 6:183–204, 2023. URL `https://doi.org/10.1146/annurev-control-062922-090606`.

[15] F. Bademosi and R. R. A. Issa. Factors influencing adoption and integration of construction robotics and automation technology in the US. *Journal of Construction Engineering and Management*, 147(8), 2021. URL `https://doi.org/10.1061/(ASCE)CO.1943-7862.0002085`. Article 04021075.

[16] A. M. Khan, K. A. Alrasheed, A. Waqar, H. Almujibah, and O. Benjeddou. Internet of things (IoT) for safety and efficiency in construction building site operations. *Scientific Reports*, 14, 2024. URL `https://doi.org/10.1038/s41598-024-78931-0`. Article 28931.

[17] P. Lee, Y. Wang, T. P. Lo, and D. Long. Trends in smart helmets with multimodal sensing for health and safety: Scoping review. *JMIR mHealth and uHealth*, 10(11), 2022. URL `https://doi.org/10.2196/40797`. Article e40797.

[18] M. Achouch, M. Dimitrova, K. Ziane, S. Sattarpanah Karganroudi, R. Dhouib, H. Ibrahim, and M. Adda. On predictive maintenance in industry 4.0: Overview, models, and challenges. *Applied Sciences*, 12(16), 2022. URL `https://doi.org/10.3390/app12168081`.

[19] S. K. Baduge, S. Thilakarathna, J. S. Perera, M. Arashpour, P. Sharafi, B. Teodosio, and P. Mendis. Artificial intelligence and smart vision for building and construction 4.0: Machine and deep learning methods and applications. *Automation in Construction*, 141, 2022. URL https://doi.org/10.1016/j.autcon.2022.104440. Article 104440.

[20] Y. Li, H. Sun, and D. Li. Effects of digital technology adoption on sustainability performance in construction projects: The mediating role of stakeholder collaboration. *Journal of Management in Engineering*, 38(3), 2022. URL https://doi.org/10.1061/(ASCE)ME.1943-5479.0001030. Article 04022016.

[21] G. Placzek and P. Schwerdtner. Concrete additive manufacturing in construction: Integration based on component-related fabrication strategies. *Buildings*, 13(7), 2023. URL https://doi.org/10.3390/buildings13071769. Article 1769.

[22] V. Mechtcherine, V. N. Nerella, F. Will, M. Nather, J. Otto, and M. Krause. Large-scale digital concrete construction: CONPrint3D concept for on-site, monolithic 3D-printing. *Automation in Construction*, 107, 2019. URL https://doi.org/10.1016/j.autcon.2019.102933. Article 102933.

[23] S. Halder and K. Afsari. Robots in inspection and monitoring of buildings and infrastructure: A systematic review. *Applied Sciences*, 13(4), 2023. URL https://doi.org/10.3390/app13042304. Article 2304.

[24] P. Dallasega, E. Rauch, and C. Linder. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry*, 99:205–225, 2018. URL ttps://doi.org/10.1016/j.compind.2018.03.039.

[25] W. Chung, S. Tariq, S. R. Mohandes, and T. Zayed. IoT-based application for construction site safety monitoring. *International Journal of Construction Management*, 23(1):58–74, 2020. URL https://doi.org/10.1080/15623599.2020.1847405.

[26] Y. Pan and L. Zhang. Integrating BIM and AI for smart construction management: Current status and future directions. *Archives of Computational Methods in Engineering*, 30(2):1081–1110, 2023. URL https://doi.org/10.1007/s11831-022-09830-8.

[27] A. Waqar, I. Othman, J. C. Pomares, and M. S. Mansoor. Examining the impact of BIM implementation on external environment of AEC industry: A PEST analysis perspective. *Developments in Built Environments*, 17, 2024. URL https://doi.org/10.1016/j.dibe.2024.100347. Article 100347.

[28] X. Pan, A. Mateen Khan, S. M. Eldin, F. Aslam, S. Kashif Ur Rehman, and M. Jameel. BIM adoption in sustainability, energy modelling and implementing using ISO 19650: A review. *Ain Shams Engineering Journal*, 15(1), 2024. URL https://doi.org/10.1016/j.asej.2023.102252. Article 102252.

[29] 2023 global status report for buildings and construction. United Nations Environment Programme and Global Alliance for Buildings and Construction. URL https://www.unep.org/resources/report/2023-global-status-report-buildings-and-construction.

[30] Adrian Malleson. *National BIM report 2016*. NBS (RIBA Enterprises, 2016. URL https://www.thenbs.com/knowledge/national-bim-report-2016.