ISNN 3030-3907

2026
JUNE
ISSUE - 6
VOLUME -8

DEVELOPMENT OF SCIENCE

scientific journal



Development of science

Ilmiy jurnal

IYUN 2026
Issue - 6, VOLUME – 8

ISSN 3030 -3907

Ilmiy jurnal OAK rayosatining 2024 yil 27 sentabrdagi 361-son qaroriga asosan 02.00.00 kimyo fanlari hamda 2025 yil 12 fevral 367- son qaroriga asosan 05.00.00 texnika fanlari bo‘yicha falsafa doktori (PhD) va fan doktori (DSc) ilmiy darajasiga talabgorlarning dissertatsiya ishlari yuzasidan dissertatsiyalari asosiy ilmiy natijalarini chop etish tavsiya etilgan milliy ilmiy nashrlar ro‘yxatiga kiritilgan.

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ISSN 3030-3907

Development of science ilmiy jurnali 2024 yil 15 aprel kuni №256445 sonli guvohnoma bilan Davlat ro‘yxatidan o‘tgan.

To‘plam elektron ko‘rinishda (pdf formatida) mualliflarga taqdim etiladi. To‘plamga kiritiladigan maqolalarning mazmuni, ulardagi statistik ma’lumotlar va me’yoriy hujjatlarning to‘g‘riligiga hamda har qanday fikr - mulohazalarga mualliflarning o‘zlari mas’ul hisoblanadilar. Talablarga javob bermaydigan maqolalar to‘plamga kiritilmaydi. Tashkiliy qo‘mita maqola matnini qisqartirish, qisman tuzatish kiritish, seksiyalarga joylashtirish huquqiga ega.

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SMART CONSTRUCTION MANAGEMENT: INTEGRATING ARTIFICIAL INTELLIGENCE, BIM, AND DIGITAL TWINS FOR SUSTAINABLE INFRASTRUCTURE

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Abstract. The construction industry stands at the intersection of three transformative digital technologies—artificial intelligence (AI), Building Information Modeling (BIM), and digital twins—whose convergence is redefining how infrastructure is planned, delivered, and operated. This paper develops an integrated analytical framework of Smart Construction Management (SCM), in which AI provides cognitive capability, BIM delivers structured semantic representation, and the digital twin establishes a continuous link between the physical asset and its computational counterpart. Drawing on a structured review of peer-reviewed literature published between 2016 and 2024 and on industry reports, the study identifies the architecture of SCM systems, maps AI techniques to BIM-based functions, and quantifies expected performance gains across schedule, cost, safety, productivity, energy, and rework dimensions. The analysis shows that integrated AI–BIM–digital-twin systems are associated with reported productivity gains of 15–50 %, schedule reductions of 10–25 %, safety incident reductions of 20–35 %, and energy-efficiency improvements of 10–25 %. Implementation challenges related to data, organization, ethics, and cybersecurity are critically discussed, and concrete recommendations are proposed for construction firms, engineers, universities, and regulators. The article concludes that SCM constitutes a structural shift toward a data-driven, automated, and sustainable model of infrastructure development.

Keywords: smart construction management, artificial intelligence, Building Information Modeling, digital twin, predictive analytics, sustainable infrastructure, computer vision, Industry 4.0.

Аннотация. Строительная отрасль находится на пересечении трёх трансформирующих цифровых технологий — искусственного интеллекта (ИИ), информационного моделирования зданий (BIM) и цифровых двойников, — конвергенция которых коренным образом меняет подходы к планированию, реализации и эксплуатации инфраструктурных объектов. В данной работе разработана интегрированная аналитическая концепция интеллектуального управления строительством (IУС), в рамках которой ИИ обеспечивает когнитивные возможности, BIM формирует

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структурированное семантическое представление данных, а цифровой двойник устанавливает непрерывную связь между физическим объектом и его вычислительной моделью. На основе систематического обзора рецензируемой литературы, опубликованной в период с 2016 по 2024 год, а также отраслевых отчётов в исследовании определены архитектура систем ИУС, выполнено сопоставление методов ИИ с функциями на основе BIM, а также дана количественная оценка ожидаемых улучшений показателей в части сроков, стоимости, безопасности, производительности, энергопотребления и переделок. Анализ показывает, что интегрированные системы ИИ–BIM–цифровой двойник обеспечивают рост производительности на 15–50 %, сокращение сроков выполнения работ на 10–25 %, снижение числа инцидентов, связанных с охраной труда, на 20–35 %, а также повышение энергоэффективности на 10–25 %. Подробно рассматриваются проблемы внедрения, связанные с данными, организацией, этикой и кибербезопасностью, и формулируются конкретные рекомендации для строительных компаний, инженеров, университетов и регуляторов. В статье сделан вывод о том, что ИУС представляет собой структурный сдвиг в сторону информационно-управляемой, автоматизированной и устойчивой модели развития инфраструктуры.

Ключевые слова: интеллектуальное управление строительством, искусственный интеллект, информационное моделирование зданий, цифровой двойник, предиктивная аналитика, устойчивая инфраструктура, компьютерное зрение, Индустрия 4.0.

Annotatsiya. Qurilish sanoati uchta transformatsion raqamli texnologiyaning — sun’iy intellekt (SI), binolarni axborot modellashtirish (BIM) va raqamli egizaklar — kesishmasida joylashgan bo‘lib, ularning integratsiyasi infratuzilmani rejalashtirish, qurish va ekspluatatsiya qilish usullarini tubdan o‘zgartirmoqda. Ushbu maqolada intellektual qurilish boshqaruvi (IQB) integrallashgan analitik konsepsiyasi ishlab chiqilgan: unda SI kognitiv imkoniyatlarni ta'minlaydi, BIM tuzilgan semantik ma'lumotlar ifodasini shakllantiradi, raqamli egizak esa jismoniy ob'ekt va uning hisoblash modeli o‘rtasida uzluksiz bog‘liqlikni o‘rnatadi. 2016–2024 yillar oralig‘ida nashr etilgan peer-review adabiyotlarining tizimli sharhi va tarmoq hisobotlari asosida tadqiqotda IQB tizimlarining arxitekturasi aniqlanib, SI usullari BIM-ga asoslangan funksiyalar bilan mos holda ko‘rsatilgan, shuningdek jadval, narx, xavfsizlik, mahsuldorlik, energiya sarfi va qayta ishlash ko‘rsatkichlari bo‘yicha kutilayotgan takomillashtirish miqdori baholangan. Tahlil shuni ko‘rsatadiki, integrallashgan SI–BIM–raqamli egizak tizimlari mahsuldorlikni 15–50 % ga oshirishi, ish muddatlarini 10–25 % ga qisqartirishi, mehnat xavfsizligiga oid hodisalarni 20–35 % ga kamaytirishi va energiya

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samaradorligini 10–25 % ga yaxshilashi bilan bog‘liq. Ma'lumotlar, tashkilot, etika va kiberxavfsizlik bilan bog‘liq joriy etish muammolari batafsil muhokama qilinib, qurilish firmalari, muhandislar, universitetlar va tartibga soluvchilar uchun aniq tavsiyalar taklif etilgan. Maqola xulosasida IQB infratuzilma rivojlanishining ma'lumotlarga asoslangan, avtomatlashtirilgan va barqaror modeliga tomon tarkibiy siljishni ifodalashi ta'kidlanadi.

Kalit so‘zlar: intellektual qurilish boshqaruvi, sun’iy intellekt, binolarni axborot modellashtirish, raqamli egizak, prognozli tahlillar, barqaror infratuzilma, kompyuter ko‘rish, Sanoat 4.0.

1. INTRODUCTION.

The construction sector accounts for approximately 13 % of global gross domestic product and consumes nearly 36 % of global energy and 39 % of CO_2 emissions associated with the built environment, yet its productivity growth has averaged only about 1 % per year over the past two decades [World Economic Forum, 2018: 8]. This persistent gap between economic weight and operational performance has long been explained by the industry’s fragmented value chain, project-based organization, and limited digital integration. As infrastructure demand accelerates—driven by urbanization, climate adaptation, and the renewal of aging assets—the inability of traditional management practices to deliver projects on time, within budget, and within ecological limits has become a strategic concern for both governments and private investors.

Three technological forces are converging to address this challenge. Artificial intelligence introduces predictive, perceptual, and generative capabilities that can be applied across the construction lifecycle [Pan & Zhang, 2021: 3]. Building Information Modeling provides a structured, semantically rich digital representation of the built asset, enabling collaboration and data interoperability among project participants [Eastman et al., 2018: 34]. Digital twins establish a real-time, bidirectional link between the physical site and its computational replica, transforming static models into living systems [Sacks et al., 2020: 6]. Although each technology has been studied separately, their integration into a coherent management paradigm—here termed Smart Construction Management (SCM)—has received comparatively little systematic treatment.

The objective of this article is therefore to construct an analytical framework for SCM and to evaluate its theoretical, technical, and practical implications for sustainable infrastructure development. The paper contributes to the literature by (i) articulating the conceptual architecture of SCM, (ii) mapping AI techniques to BIM-enabled functions, (iii) describing a four-layer digital-twin architecture for construction, (iv) synthesizing reported performance benefits, and (v) formulating actionable recommendations for industry stakeholders.

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2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Three intersecting research streams underpin the present study. The first concerns BIM as the digital backbone of construction. Eastman and colleagues argue that BIM functions as a single source of truth that supports collaboration, simulation, and lifecycle management [Eastman et al., 2018: 34]. Subsequent work has extended BIM into 4D (time), 5D (cost), and 6D (sustainability) dimensions, while emphasizing that the value of BIM grows non-linearly with the level of process integration.

The second stream addresses AI in construction engineering and management. Bilal and colleagues describe construction as a data-rich but information-poor sector and identify big-data analytics as a precondition for AI-based decision-making [Bilal et al., 2016: 503]. Pan and Zhang provide a systematic mapping of AI techniques to construction problems and observe that machine learning, computer vision, and natural language processing dominate current applications [Pan & Zhang, 2021: 11]. Akinosho and colleagues add that deep-learning architectures—particularly convolutional and recurrent networks—are increasingly used for visual inspection and time-series prediction tasks [Akinosho et al., 2020: 4].

The third-stream concerns digital twins. Tao and colleagues define the digital twin as a continuously updated virtual representation of a physical entity, characterized by bidirectional data flow and embedded analytics [Tao et al., 2019: 2406]. Boje and colleagues translate this concept to construction by emphasizing the need for semantic interoperability between BIM and the twin [Boje et al., 2020: 5], and Sacks and colleagues propose a maturity model from static BIM to closed-loop digital twins [Sacks et al., 2020: 11]. Zhang and colleagues, in a more recent contribution, refine the level-of-development requirements for construction-site digital twins and identify the lack of integration with AI as the principal research gap [Zhang et al., 2022: 4].

The literature converges on the recognition that AI, BIM, and digital twins each unlock partial value, while their integration produces transformative results. The conceptual framework of this paper is therefore built on the assumption that SCM emerges precisely at the intersection of these three domains, supported by an underlying layer of IoT-enabled data acquisition.

3. RESEARCH METHODOLOGY.

The study employs a qualitative analytical methodology grounded in a structured review of secondary sources. A search was conducted in Scopus, Web of Science, and ScienceDirect for publications dated between January 2016 and June 2024 using combinations of the keywords “artificial intelligence”, “machine learning”, “BIM”, “digital twin”, “smart construction”, “predictive analytics”, and

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"sustainable infrastructure". After removing duplicates and screening for thematic relevance, peer-reviewed articles, monographs, and authoritative industry reports were retained for analysis.

The selected sources were thematically coded along three axes: (i) AI technique, (ii) BIM or digital-twin function, and (iii) reported performance outcome. Coded findings were synthesized into the conceptual framework presented in Section 4 and into the comparative tables in Sections 5–8. The methodological choice is appropriate for a conference paper aimed at scientific synthesis: it enables identification of convergent patterns across heterogeneous sources, formal comparison of technological approaches, and grounded formulation of practical recommendations.

4. THE SMART CONSTRUCTION MANAGEMENT ECOSYSTEM.

Smart Construction Management can be defined as the systematic orchestration of artificial intelligence, Building Information Modeling, and digital twins, supported by an underlying layer of IoT-enabled data acquisition, to deliver infrastructure projects with measurable improvements in productivity, cost, safety, and sustainability. Figure 1 illustrates the conceptual architecture of this ecosystem.

Figure 1. Conceptual framework of Smart Construction Management

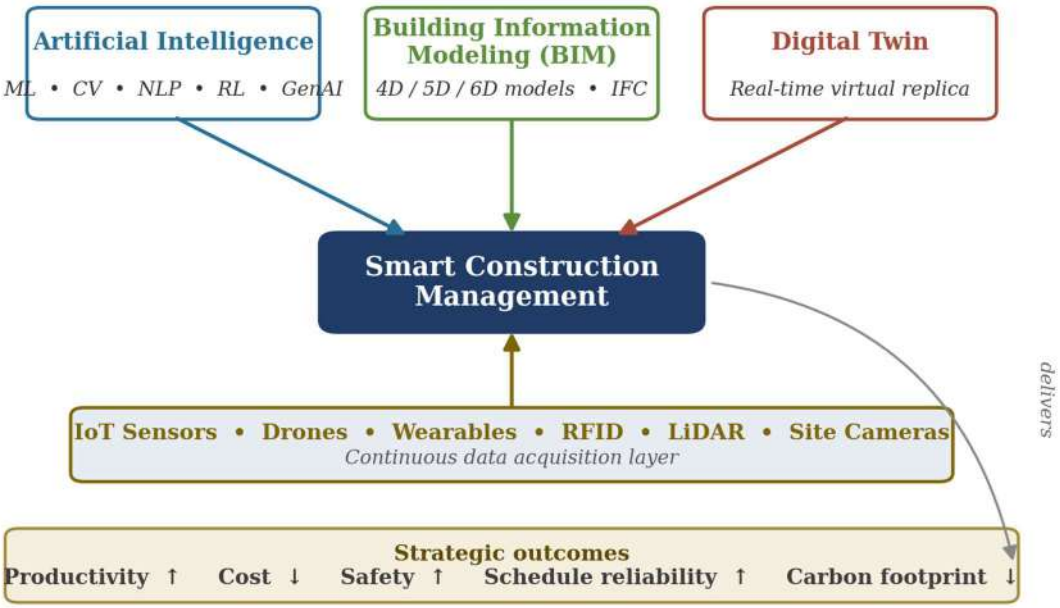


Figure 1. Conceptual framework of Smart Construction Management.

Three observations follow from this architecture. First, AI is not a stand-alone solution but a cognitive capability that derives its power from BIM-based semantic structure and from the temporal continuity provided by the digital twin. Second, the data acquisition layer—comprising IoT sensors, drones, wearables, RFID tags, LiDAR scanners, and site cameras—functions as the sensory

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infrastructure of SCM, transforming an opaque construction site into a continuously observable system. Third, the strategic outcomes of SCM are inseparable from one another: gains in productivity reinforce safety, while improved sustainability supports long-term cost competitiveness.

5. AI–BIM INTEGRATION: CAPABILITIES AND APPLICATIONS.

The integration of AI with BIM transforms the federated model from a static container of design information into an active analytical environment. Table 1 maps the principal AI techniques to their construction applications and to the corresponding BIM-integration mechanisms.

Table 1.

AI techniques and their integration with BIM in Smart Construction Management.

AI technique	Primary function	Construction application	BIM integration	Maturity
Machine learning (supervised)	Prediction	Cost estimation, schedule forecasting, risk classification	Feature extraction from 5D BIM	High
Deep learning / CNN	Perception	Defect detection, progress monitoring, PPE detection	4D BIM vs as-built comparison	High
Natural language processing	Document understanding	Specification analysis, contract review, RFI classification	Semantic linking to BIM elements	Medium
Reinforcement learning	Sequential decision	Resource allocation, schedule optimization	Generative scheduling on BIM	Medium
Generative AI / GANs	Design generation	Layout exploration, alternative geometries	Generative BIM modelling	Emerging
Knowledge graphs / ontologies	Reasoning	Code compliance, clash interpretation	Semantic enrichment of IFC	Emerging

ISSN 3030-3907

Two patterns emerge from the table. First, the most mature applications—machine learning for prediction and computer vision for perception—are precisely those whose value scales with the volume of structured BIM and sensor data that is now routinely collected on large projects. Second, generative AI and knowledge-graph reasoning are still emerging but hold particular promise for early-design exploration and automated regulatory compliance, two functions that have historically resisted automation.

6. DIGITAL TWIN ARCHITECTURE FOR CONSTRUCTION.

A construction digital twin is a continuously updated virtual replica of a project, fed by sensor data and analytical models, that supports real-time monitoring, predictive maintenance, and what-if scenario testing throughout the asset lifecycle [Boje et al., 2020: 7; Zhang et al., 2022: 4]. Figure 2 presents a four-layer architecture that integrates the physical site, the data acquisition infrastructure, the modelling and analytics core, and the service-oriented decision layer.

Figure 2. Four-layer architecture of a construction Digital Twin

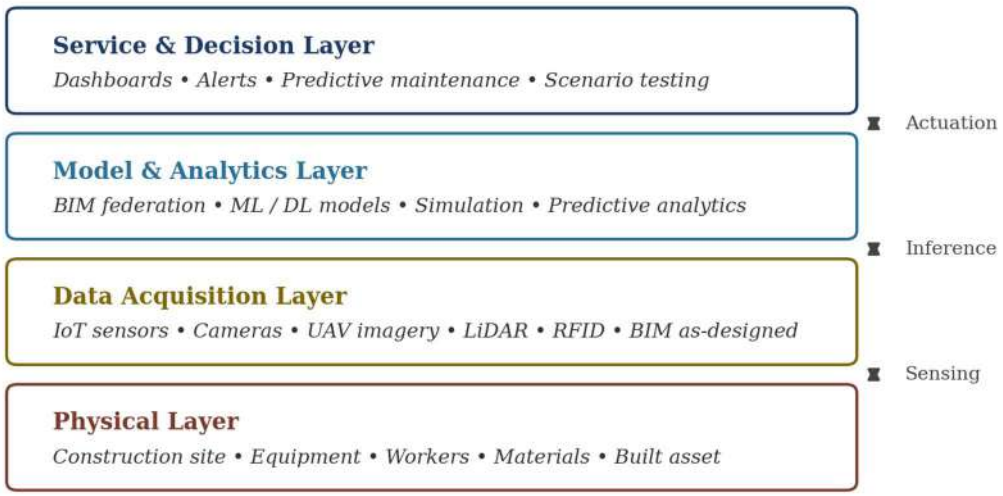


Figure 2. Four-layer architecture of a construction Digital Twin.

The maturity of digital-twin implementations varies considerably across the industry. Table 2 proposes a five-level maturity model, derived from the digital-twin literature, that links data flow, modelling capability, and the role of AI.

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Table 2.

BIM–Digital Twin maturity model in Smart Construction Management.

Level	Designation	Data flow	Primary capability	AI role
0	Pre-digital	None / paper-based	2D drawings	None
1	Static BIM	Manual export	3D federated model	Limited (rule checks)
2	Connected BIM	Periodic sync	4D / 5D simulation	Predictive analytics on BIM data
3	Living digital twin	Bidirectional, near-real-time	Real-time monitoring & alerting	Embedded ML inference
4	Autonomous twin	Closed-loop control	Self-optimizing systems	Autonomous decision-making with human oversight

The maturity model highlights a key managerial insight: the marginal value of digital-twin investment grows discontinuously across levels. Moving from Level 1 to Level 2 yields incremental analytical benefits, but the transition from Level 2 to Level 3 unlocks qualitatively new capabilities such as live risk identification and predictive maintenance. Most large contractors today operate between Levels 2 and 3, with Level 4 implementations remaining experimental and confined to large public-infrastructure programmes.

7. PERFORMANCE BENEFITS AND SUSTAINABILITY OUTCOMES.

The integration of AI, BIM, and digital twins delivers measurable improvements across multiple performance dimensions. Figure 3 synthesizes the ranges of improvement reported in the reviewed literature and in industry case studies.

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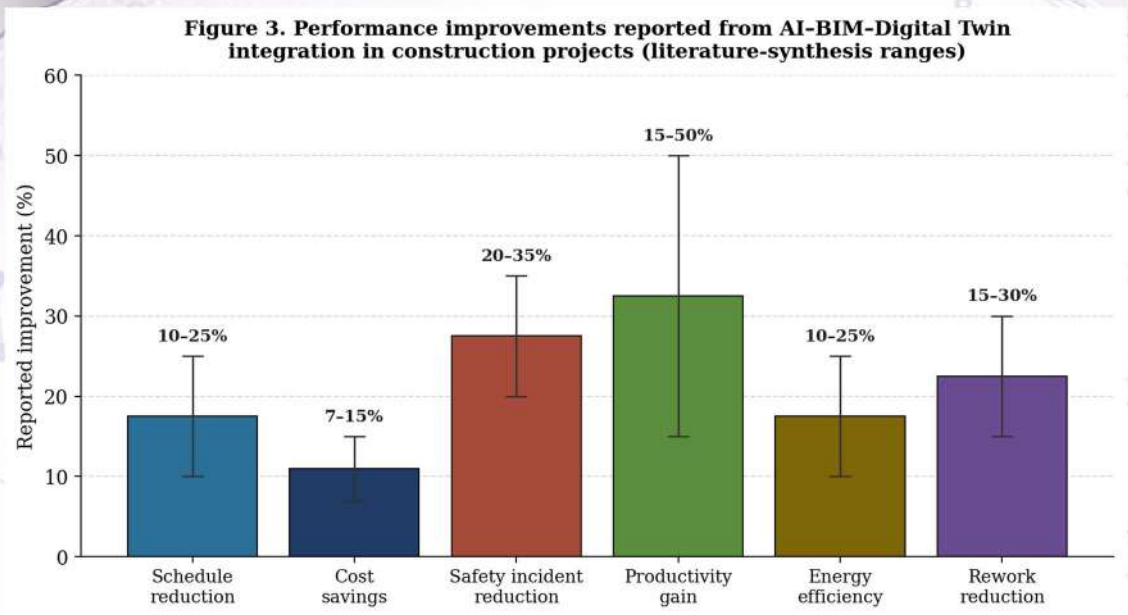


Figure 3. Performance improvements reported from AI–BIM–Digital Twin integration.

Productivity gains, ranging from 15 % to 50 %, are driven primarily by automated quantity take-off, intelligent scheduling, and the reduction of coordination losses across subcontractors [Pan & Zhang, 2021: 14]. Schedule reductions of 10–25 % and rework reductions of 15–30 % stem mainly from clash-detection and as-built monitoring against the BIM baseline. Safety improvements—incident reductions of 20–35 %—are linked to the deployment of computer-vision systems that monitor personal protective equipment, hazardous proximity, and unsafe postures in real time [Fang et al., 2020: 14].

Sustainability outcomes are equally significant. AI-driven energy simulation embedded in 6D BIM enables design teams to evaluate hundreds of envelope and HVAC configurations within hours, leading to operational-energy reductions of 10–25 % in reviewed case studies. Beyond the construction phase, digital twins support predictive maintenance and demand-response control, extending energy savings into the asset's operational life. When combined with embodied-carbon estimation and material-passport tracking, SCM thus becomes a critical enabler of low-carbon and circular construction practices.

8. IMPLEMENTATION CHALLENGES.

Despite these benefits, the adoption of integrated SCM systems faces substantial barriers. Table 3 organizes the principal challenges along six dimensions and proposes corresponding mitigation strategies.

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Table 3.

Implementation challenges of Smart Construction Management and proposed mitigation strategies.

Dimension	Specific issue	Mitigation strategy
Data	Heterogeneous, fragmented, low-quality data across stakeholders	Common Data Environments (CDE), IFC and OpenBIM standards, structured ontologies
Technical	Limited interoperability among BIM, IoT, and DT platforms	Vendor-neutral APIs, open data schemas, modular DT architectures
Organizational	Cultural resistance, shortage of hybrid engineering–data-science skills	Change-management programmes, upskilling, hybrid project teams
Economic	High upfront investment, uncertain return on investment	Phased pilot-then-scale adoption, public incentives, shared digital infrastructure
Ethical / legal	Worker surveillance, privacy, algorithmic liability	Data-governance frameworks, anonymization, transparent accountability rules
Cybersecurity	Vulnerability of connected sites and digital twins	Zero-trust architectures, end-to-end encryption, audit trails, security-by-design

These challenges are interrelated. Insufficient data quality undermines the reliability of AI predictions, organizational inertia delays the adoption of even technically mature solutions, and unresolved ethical questions can erode the social legitimacy of digital monitoring. A coherent SCM strategy must therefore address all six dimensions simultaneously rather than treating them as isolated problems.

9. PRACTICAL RECOMMENDATIONS.

Based on the preceding analysis, the following recommendations are formulated for the principal stakeholder groups.

For construction companies:

—develop a long-term digital strategy that explicitly aligns AI investments with BIM, IoT, and digital-twin roadmaps;

—establish standardized data-collection protocols on every project to build the high-quality datasets required for reliable model training;

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—begin with high-value pilot applications such as predictive scheduling or computer-vision safety monitoring before scaling to enterprise deployments;

—incorporate sustainability key performance indicators into digital-twin dashboards to make environmental performance a managerial priority.

For engineers and project managers:

—acquire competencies in data analytics, BIM coordination, and the interpretation of machine-learning outputs;

—treat AI tools as decision-support systems and retain professional responsibility for engineering judgment;

—integrate AI-generated insights into existing project-management routines rather than running them as parallel processes.

For universities and researchers:

—update civil-engineering and construction-management curricula to include programming, data science, and AI fundamentals;

—encourage interdisciplinary research that combines construction engineering with computer science, ethics, and management;

—publish open construction datasets to accelerate reproducible research and benchmarking.

For governmental and regulatory institutions:

—develop normative frameworks governing data ownership, privacy, and algorithmic accountability in construction;

—incentivize SCM adoption through targeted subsidies, tax credits, and procurement preferences for digitally mature contractors;

—invest in national digital-twin platforms for critical public infrastructure and integrate AI-based monitoring into regulatory inspection regimes.

10. Conclusion and Future Outlook

This article has argued that the integration of artificial intelligence, Building Information Modeling, and digital twins constitutes the foundation of a new managerial paradigm—Smart Construction Management—capable of transforming construction from a traditional, labor-intensive activity into a data-driven, automated, safe, and sustainable system of infrastructure development. The conceptual framework presented in Section 4, the AI–BIM mapping in Section 5, the digital-twin architecture in Section 6, and the empirical evidence in Section 7 jointly substantiate the thesis that the value of these technologies grows non-linearly with their integration.

Realizing this potential requires coordinated action across the ecosystem. Companies must invest strategically in data infrastructure and pilot programmes; professionals must develop hybrid competencies; universities must modernize

ISSN 3030-3907

curricula and research agendas; and regulators must craft balanced frameworks for accountability, privacy, and innovation. Particular attention should be paid to ethical and organizational dimensions so that technological gains are not achieved at the expense of worker rights, professional responsibility, or system resilience.

Future research should focus on four priorities: explainable AI for engineering decision-making, robust learning under construction-specific data scarcity, secure and interoperable data sharing across project participants, and quantitative measurement of the long-term sustainability impact of SCM. If these directions are pursued with scientific rigour and ethical clarity, Smart Construction Management will not merely modernize the industry—it will redefine the very meaning of building infrastructure in the twenty-first century.

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