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Comprehensive analysis of digital technology applications in construction site management

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Abstract. This study examines the transformative impact of digital technologies on construction site management in the Russian Federation. Using a multi-method research approach incorporating content analysis, comparative assessment, systems analysis, and SWOT evaluation, the research investigates how Building Information Modeling (BIM), Internet of Things (IoT) architecture, cloud computing, and artificial intelligence applications reconfigure traditional construction processes. Findings demonstrate that smart construction sites implement informatization across four critical dimensions: personnel management, machinery administration, material resource coordination, and construction target optimization. Comparative analysis reveals significant advantages of technology-enhanced approaches over conventional methods, particularly in multi-location collaborative workflows, simulation modeling, construction process visualization, and remote monitoring capabilities. The SWOT analysis identifies initial capital investment requirements, specialized workforce development, and systems integration complexities as primary implementation challenges. The research concludes that smart construction sites represent an evolutionary progression in the construction industry, with implementation effectiveness directly correlating to organizational digital maturity, ultimately establishing unprecedented levels of construction production efficiency and operational safety.

Keywords: Big data analytics, smart construction sites, BIM modeling, construction management, cloud computing, construction digitalization

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1. INTRODUCTION

According to recent statistical analysis, the Russian Federation's construction sector has demonstrated substantial growth, with over 97,625 buildings and structures under active development by the conclusion of 2023 [1]. As a fundamental pillar of the national economy, the construction industry has exhibited consistent expansion in both scale and technological capabilities in recent years. This exponential growth has concurrently generated numerous engineering projects characterized by

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technical complexity, substantial scale, and extended implementation timelines, progressively intensifying the challenges and requirements associated with construction site management. The contemporary construction landscape necessitates more sophisticated information exchange mechanisms between diverse stakeholders and operational processes. However, conventional construction methodologies and site management frameworks have proven markedly insufficient to address the demands of this rapidly evolving industry, presenting significant operational challenges. The complexity inherent in construction project production elements has resulted in disorganized site conditions, representing a substantial impediment for traditional construction operations. Furthermore, contemporary construction environments typically manifest excessive energy consumption patterns, significant environmental contamination, elevated accident frequencies, and suboptimal operational efficiency [2]. In response to these challenges and to enhance traditional site conditions, improve construction environments, and mitigate safety incidents among construction personnel, the paradigm of "smart construction sites" has emerged as a viable solution.

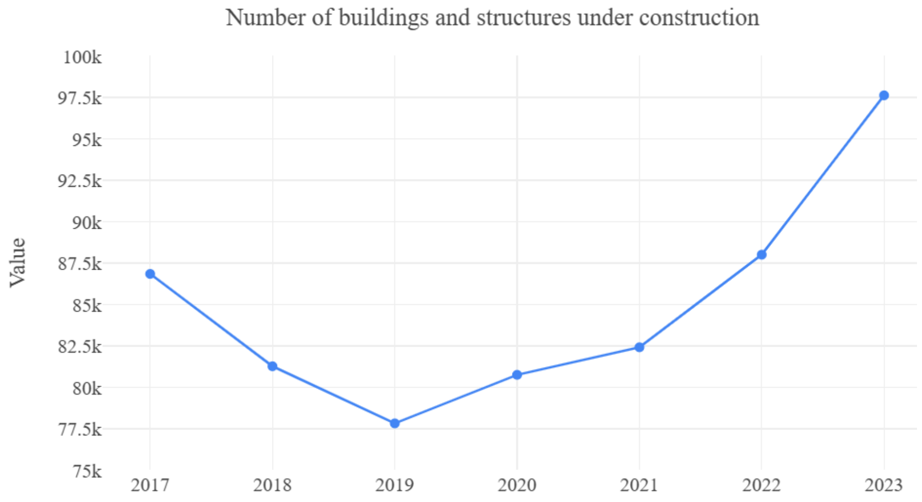

Fig. 1. Number of Buildings and Structures Under Construction in Russia, 2017-2023.

The concept of a "smart construction site" encompasses the comprehensive integration of hardware and software systems at construction locations through advanced technological implementations to achieve informatization, intelligence, and visualization in site management, thereby facilitating a transformative shift in operational paradigms [3]. The development trajectory of smart construction sites is fundamentally dependent on sophisticated information technologies, including Internet of Things (IoT) architecture, internet connectivity, Building Information Modeling (BIM), cloud computing infrastructure, big data analytics, and artificial intelligence applications. These technological components endow construction environments with enhanced perceptual capabilities—specifically, the autonomous, accurate, and real-time collection of operational data. Simultaneously, cloud-based computational systems conduct instantaneous analysis and processing of the acquired data, following which artificial intelligence algorithms support construction managers in optimized decision-making processes. The establishment of intelligent construction environments provides comprehensive site management solutions for all industry stakeholders, enabling the digital transformation of operational workflows at construction locations. Through the systematic collection and organization of diverse information streams and datasets from construction sites, these integrated systems generate valuable information repositories for construction enterprises. The implementation of smart construction sites is strategically oriented toward enhancing site management efficiency, achieving environmentally sustainable construction practices, improving safety protocols and environmental management systems, and ensuring superior engineering quality standards [4].

The technological foundation supporting smart construction sites can be systematically classified into three primary categories: digitalization technologies, networking infrastructures, and intelligent systems [5].

Digitalization technologies encompass the methodologies and systems for storage, transmission, analysis, and processing of information carriers (textual documents, visual representations, etc.) in encoded digital formats. These technologies primarily include Building Information Modeling (BIM) and big data analytics. BIM technology originated from the building computer simulation system conceptualized by Dr. Chuck Eastman from the United States in the 1970s. The National BIM Standard (NBIMS) of the United States articulates the fundamental attributes of BIM through three distinct perspectives: 1) BIM constitutes a digital representation of the physical characteristics and functional properties of construction projects; 2) BIM represents a shared knowledge repository encompassing comprehensive information throughout the project lifecycle, providing authoritative references for management decision-making; 3) BIM embodies a collaborative process wherein project participants across different implementation phases insert, extract, update, and modify information to achieve coordinated operational workflows [6]. Based on these distinctive attributes, BIM technology demonstrates applicability across multiple phases throughout the entire lifecycle of construction projects. Initially, geometric specifications, physical properties, process parameters, and other relevant building information are collected and integrated by various specialized entities to construct a comprehensive BIM visualization model, establishing a structured database for the efficient storage and management of diverse information categories [7]. As project implementation progresses, all participants continuously augment and update information within the BIM framework, facilitating seamless information transfer and collaborative sharing. Big data constitutes information collections of a magnitude that exceeds the capabilities of conventional database tools for acquisition, storage, management, and analytical processing, as defined by McKinsey & Company. In comparison with traditional data structures, big data exhibits four characteristic dimensions: 1) Volume: The extensive scale of information represents the most fundamental characteristic of big data, with exponential growth in data accumulation rates; 2) Variety: Data classifications extend beyond structured formats to encompass semi-structured and unstructured information, including visual images, video content, audio recordings, web-based resources, and additional formats, with increasingly diversified data origins; 3) Velocity: The accelerated generation and circulation of information imposes heightened requirements on big data processing timeliness, necessitating real-time analytical capabilities and efficient data processing methodologies; 4) Value: Substantial information volumes result in relatively diminished value density, requiring sophisticated analytical techniques and data mining methodologies to extract relevant information, transform it into actionable knowledge, and leverage potential value propositions.

Networking infrastructure refers to the interconnection of previously isolated entities, objects, services, and terminal devices, enabling comprehensive resource sharing among system users [8]. Networking technologies primarily encompass Internet architectures, IoT frameworks, cloud computing platforms, cyber-physical systems, and related innovations. The conceptual foundation of IoT originated from the network wireless radio frequency identification system proposed by the Auto-ID Center at the Massachusetts Institute of Technology in the late 20th century. IoT architecture establishes connectivity between diverse information sensing apparatuses and internet infrastructure, creating advanced intelligent sensing networks that facilitate communication interfaces between humans and objects, as well as autonomous object-to-object interactions. Supported by intelligent computational algorithms and connectivity technologies, IoT enables real-time acquisition of object or process information, implementing multiple functional capabilities including automatic identification, spatial positioning, continuous monitoring, and progressive tracking [9]. Cloud computing technology represents a computational paradigm providing extensive processing resources through networked infrastructure. The National Institute of Standards and Technology in the United States conceptualizes cloud computing as a resource utilization model enabling users to access consolidated shared computational resources (including storage facilities, application software, etc.) through internet connectivity irrespective of temporal or spatial constraints. Cloud computing technology integrates distributed computational systems with internet infrastructure, representing a revolutionary approach to computational service delivery. The implementation of cloud computing's robust data storage capabilities and accelerated processing capacities, in conjunction with big data analytics, BIM frameworks, and complementary technologies, can effectively facilitate the integrated management of extensive data generated throughout engineering project lifecycles [10].

Intelligence encompasses attributes that address diverse human requirements through the investigation and simulation of human cognitive processes, enabling objects to demonstrate perceptual awareness, learning adaptability, self-regulation, and autonomous decision-making capabilities [11-12]. Intelligent technologies primarily include artificial intelligence frameworks, robotics applications, and related innovations. Artificial intelligence constitutes a multidisciplinary domain encompassing diverse research areas, designed to enable computational systems to simulate sophisticated human cognitive processes including judgment formulation, logical reasoning, and knowledge acquisition, thereby extending human intellectual capabilities. Artificial intelligence technology encompasses multiple specialized domains, including machine learning algorithms, artificial neural networks, pattern recognition systems, computer vision technologies, natural language processing methodologies, and expert system frameworks. Among these diverse components, machine learning represents the core technological foundation of artificial intelligence [13-14]. The methodological approach in machine learning involves training computational systems to execute continuous calculations and iterative learning processes using substantial input datasets, synthesizing and inferring patterns and experiential knowledge, thereby acquiring corresponding human expertise or operational capabilities [15].

Based on the aforementioned theoretical foundations and technological infrastructure, it is evident that smart construction sites represent a transformative site management paradigm that synthesizes engineering project management methodologies with contemporary information technologies, constituting a comprehensive digital transformation of traditional construction environments [16]. The intelligent production ecosystem and management framework of construction sites leverage emerging information technologies including BIM integration, IoT architecture, and artificial intelligence applications, permeating throughout the construction production cycle, project objective management processes, and business information workflows. This integration ultimately achieves sophisticated coordination among all project elements, implementation phases, and stakeholders, while enabling intelligent production methodologies and data-driven decision-making processes within construction environments [17].

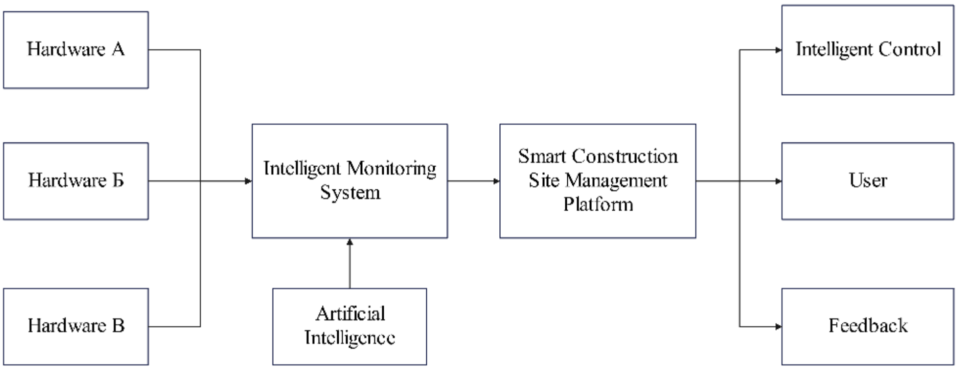

Fig. 2. Information Flow Architecture in Intelligent Monitoring Systems for Construction Sites.

2. METHODS AND MATERIALS

The formulation of well-balanced decisions and enhancement of managerial judgment accuracy in practical applications necessitates the utilization of multiple complementary methodological approaches – fundamentally, the adoption of a comprehensive analytical framework. This research is structured upon this methodological principle, employing a multi-method design incorporating content analysis, comparative analysis, systems analysis, and SWOT analysis techniques.

The study's documentary foundation comprises scholarly publications from academic repositories and peer-reviewed journals (specifically from databases including e-LIBRARY, Scopus and Young Scientist, supplemented by international academic publications) published from 2018 to the present. This temporal restriction was methodologically justified by the rapidly evolving nature of technological innovations in the construction domain, wherein contemporary publications offer the most relevant technological paradigms and current implementation practices. Through systematic content analysis, substantial textual corpora were assembled for subsequent analytical categorization and thematic synthesis.

The systems methodology implemented in the subsequent analytical phase facilitated the construction of a coherent structural framework from the diverse theoretical propositions regarding artificial intelligence implementation in construction environments. This framework established the foundation for more granular examination. The methodological value of employing a systems approach is further substantiated in the scholarly work of Lavrichenko [18]. The analytical procedure involved the identification and selection of the most promising and technologically feasible applications of artificial intelligence within the construction industry, followed by the systematic organization of these applications according to their functional implementation across the construction project lifecycle—from initial design conceptualization through to operational facility management.

Building upon the aforementioned analytical foundation, a comparative assessment was conducted between conventional construction site management paradigms and intelligent construction environments. This was followed by a comprehensive SWOT analysis examining the current implementation status and developmental trajectories of smart construction sites, culminating in the formulation of evidence-based recommendations to enhance their developmental prospects. The granular analytical methodology employed enables the identification and exploration of implementation considerations, operational characteristics, and potential outcomes—establishing a substantive framework for subsequent research initiatives.

The predominant utilization of qualitative methodological approaches in this research is methodologically aligned with the innovative nature and technical complexity of the studied phenomena, as standardized quantitative metrics continue to evolve alongside these emerging technologies. This methodological orientation corresponds with established research paradigms for investigating emergent technological systems in dynamic implementation environments.

3. RESULTS AND DISCUSSION

The management system of a smart construction site implements informatization across four essential operational dimensions: personnel management, machinery administration, material resource coordination, and construction target optimization.

In the domain of personnel management, integrated information systems interfaced with appropriate hardware infrastructure facilitate comprehensive worker identification through biometric registration systems, generating precise workforce rosters and utilizing digital knowledge repositories for safety education dissemination. Smart technological components embedded within workers' protective equipment collect and transmit operational data through strategically positioned sensing devices throughout the construction environment. Through continuous positional monitoring, the system provides automated notifications when personnel enter designated high-risk zones or operate without appropriate safety equipment, substantially enhancing workplace safety metrics. Advanced protective equipment with embedded sensors provides precise monitoring of workforce distribution patterns and individual attendance data, offering scientifically validated operational management intelligence and decision-making support for site administrators. This approach advances personnel management practices beyond traditional administrative paradigms.

In the sphere of machinery and equipment administration, data integration between mechanical equipment management systems and the smart construction site management platform enables comprehensive remote monitoring capabilities for critical equipment such as hoists and tower cranes. The construction hoist safety monitoring system, developed through the integration of IoT sensor networks, embedded computational systems, data acquisition and fusion methodologies, wireless transmission protocols, and remote data communication infrastructure, implements biometric authentication protocols--allowing only properly authenticated operators with verified credentials to activate and control the equipment. The system provides real-time visualization of hoist operational parameters, automatically activating multi-sensory notification systems when operational anomalies occur, such as load threshold exceedance, access point malfunctions, or proximity to operational boundaries, thereby ensuring optimal functional performance and operational safety of vertical transportation systems. The tower crane management system, established through the convergence of IoT sensing technology, wireless communication infrastructure, big data analytics, and cloud storage architecture, continuously monitors critical safety parameters including load measurements, operational angles, height parameters, and environmental conditions such as wind velocity, transmitting this data to centralized platforms and secure cloud repositories. During the tower crane layout coordination phase, Building Information Modeling (BIM) technology facilitates advanced simulation and analytical assessment of tower crane positioning and height configurations, enabling comprehensive evaluation of coverage radii and potential spatial interference conflicts. This proactive approach substantially enhances material transportation efficiency while ensuring uninterrupted construction workflow progression. During multi-crane operations, the system implements automated operational constraints through integrated sensor networks, providing advance notifications to crane operators about potential operational conflicts. When tower cranes approach predetermined proximity thresholds, the system initiates automated response protocols and implements directional control limitations, permitting movement exclusively within verified safe operational parameters. During crane operations, dynamic camera systems with adjustable viewing parameters provide enhanced visual feedback to operators through cabin-mounted display systems, enabling precise hook visualization and facilitating accurate operational control [19]."

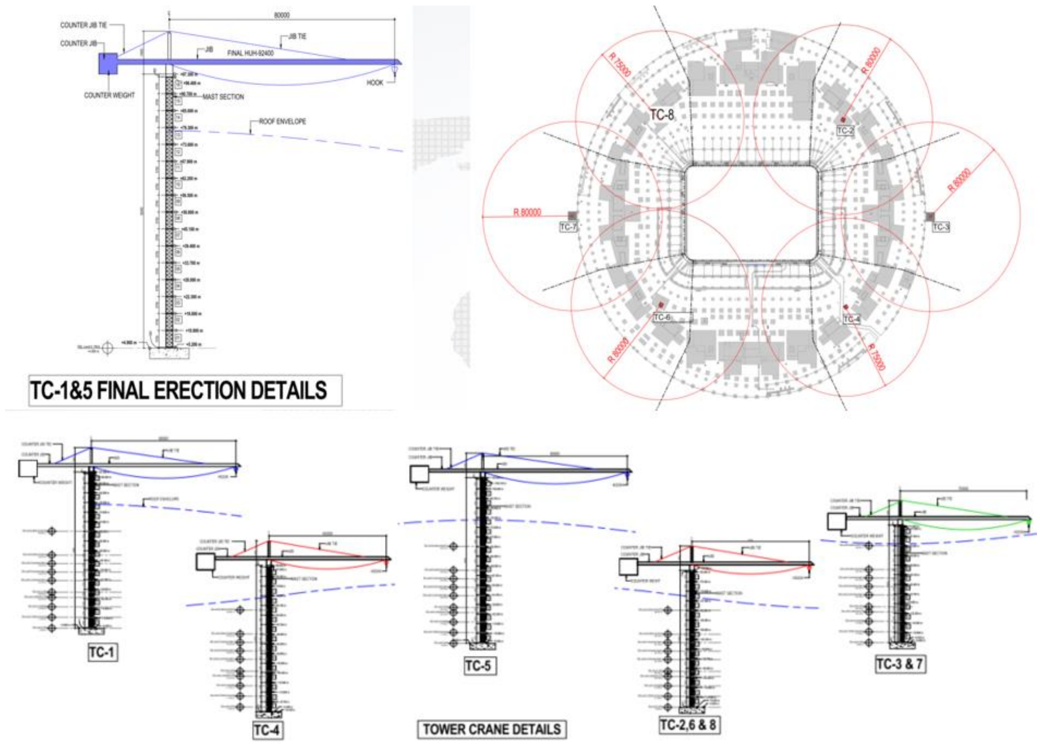

Fig. 3. Tower Crane Final Erection Details Illustrating Positioning Coordination, Operational Radius Analysis, and Installation Configurations for Multiple Tower Crane Arrangements.

In the realm of engineering material management, system-based accounting methodologies founded on hardware-collected data ensure exceptional data integrity and comprehensive verification capabilities for material transactions. The implementation of non-contact 3D laser scanning technology, integrated with sophisticated modeling software, significantly enhances this data integrity by facilitating precise volumetric analysis of material stockpiles at construction sites. Through the conversion of high-density point cloud data into computational models, this advanced approach enables detailed simulation and analytical modeling for earthwork excavation planning and material volume computation, yielding highly accurate measurements of required excavation volumes and on-site material quantities. The smart construction site management platform provides statistical analysis capabilities for on-site material resources, achieving standardized oversight of project material utilization. Through the material management system, projects maintain comprehensive inventory control from initial delivery through final disposition, promoting standardized weighing operations. This approach significantly enhances the operational efficiency and transactional accuracy of material management personnel and weighing station staff, advancing the economic performance metrics of enterprises and project divisions [20].

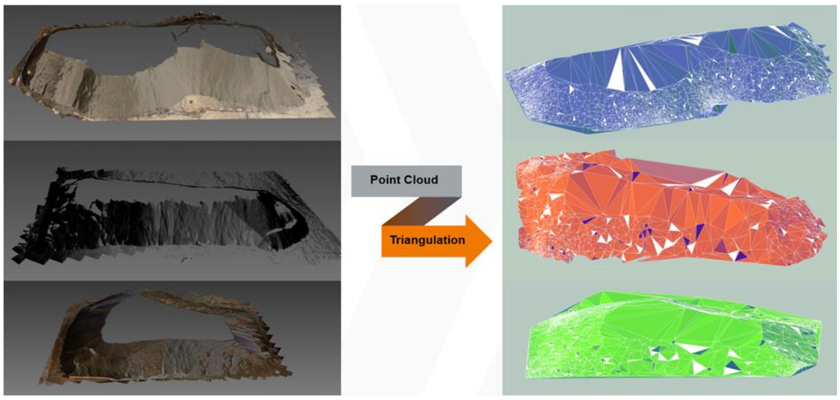

Fig. 4. Transformation process of construction material volume calculation utilizing 3D laser scanning: conversion from point cloud acquisition (left) to triangulated mesh models (right), demonstrating the computational workflow for precise volumetric analysis of stockpiled materials.

In construction target management, BIM technology enables comprehensive digital modeling of engineering projects integrated with temporal construction schedules for dynamic process simulation, providing accurate visual representations of project advancement. This capability facilitates proactive coordination across multidisciplinary domains including technological implementation, production workflows, financial allocation, quality assurance, and safety protocols, enhancing operational efficiency and supporting evidence-based management decisions [21]. During the installation phase of construction projects, augmented reality (AR) applications integrated with virtual reality technologies enable field personnel to utilize mobile devices for on-site scanning, synchronously displaying BIM models superimposed on physical environments to detect potential spatial conflicts and facilitate more precise, intuitive technical communication with construction workers. Concurrently, for quality assurance during construction, unmanned aerial vehicles equipped with high-magnification optical systems collect real-time imagery for cloud-based algorithmic analysis, providing immediate access to construction quality parameters including precise dimensional measurements and positional data.

Fig. 5. Implementation of Augmented Reality Technology in Construction: Site engineer utilizing tablet-based AR interface to overlay BIM models onto the physical construction environment, enabling real-time collision detection and enhanced visualization during the installation phase.

Compared with traditional construction site management methods, this approach demonstrates significant advantages in improving production efficiency and reducing personnel safety risks.

Table 1. Contrast the Effect of Traditional Site Management and Smart Site Management.

Comparison Elements	Traditional Site Management	Smart Site Management
Personnel Management	- Frequent inaccuracies in workforce statistics - One instance of labor dispute - Cases of work stoppage exist	- Real-time personnel information monitoring - Accurate attendance data - Scientific workforce arrangement
Equipment Management	- Untimely maintenance and repairs - Equipment failures leading to work stoppages - Low efficiency due to collisions in group operations - Cases of operational violations	- Online display of maintenance data - No mechanical equipment failures - Collision prevention system for group tower operations - Real-time online supervision with no violations
Materials Management	- Low efficiency in material acceptance with errors - Disorganized on-site material storage - Material waste occurs - Frequent discrepancies between material planning and actual site needs	- Full-process monitoring of material acceptance with problem tracing - High efficiency in electronic acceptance and inventory - Complete accuracy - Online material procurement - Scientific material planning
Information Management	- Incomplete information management - Low communication efficiency - Lack of information resource management concept	- Online information management - Information sharing - Cloud server data storage - Formation of enterprise data assets
Construction Objectives	- Mutual constraints between safety, progress, quality, cost, and environmental protection goals - Difficulty in comprehensive coordination - Frequent quality compromises and cost increases due to rushed schedules	- Comprehensive management of objectives through BIM simulation - Finding optimal balance points - Comprehensive intelligent site monitoring - Timely identification of safety hazards - Prompt environmental pollution control

The SWOT analysis of smart construction site management models aims to comprehensively grasp its competitive position and development potential in the current construction market through systematic identification and assessment of its Strengths, Weaknesses, Opportunities, and Threats. This strategic analytical methodology not only assists practitioners in clearly recognizing core competencies and vulnerable aspects but also facilitates understanding of development opportunities and potential risks emanating from the external environment.

Table 2. SWOT Analysis of Smart Construction Sites Implementation.

Analysis Dimensions	Specific Analysis Items
Strengths	1. Enhanced Construction Efficiency: Real-time monitoring and data analysis optimize workflows 2. Reduced Management Costs: Decreased need for manual inspection through remote management 3. Improved Safety: Smart warning systems for timely detection of construction hazards 4. Extreme Weather Adaptation: Remote monitoring reduces outdoor work in severe cold 5. Strong Industrial Foundation: Existing technical base for rapid development of localized solutions 6. Precise Material Management: Smart systems optimize material usage and inventory control
Weaknesses	1. High Initial Investment: Substantial costs for smart equipment and system deployment 2. Technical Talent Gap: Requirement for specialized IT professionals for system maintenance 3. Geographic Coverage Challenges: Vast territory increases network infrastructure costs 4. Complex System Integration: Coordination needed between multiple subsystems and vendors 5. Long Adaptation Period: Traditional workers require extensive additional training 6. High Maintenance Costs: Difficulty in maintaining smart equipment in extreme weather
Opportunities	1. Technological Innovation: Development of localized smart construction technologies 2. Market Demand: Increasing large-scale infrastructure projects requiring smart solutions 3. Talent Development: Promotion of construction IT professional training 4. Weather Management: Smart systems better suited for local climate conditions 5. Workforce Optimization: Technology upgrade addressing aging workforce challenges 6. Energy Efficiency: Smart systems optimize energy usage and reduce operational costs
Threats	1. Rapid Tech Evolution: Quick obsolescence of smart equipment and systems 2. Cybersecurity Risks: Smart systems vulnerable to network attacks 3. Traditional Mindset Resistance: Difficulty in changing conventional industry thinking 4. Standardization Challenges: Difficulty in unifying standards across different regions 5. Climate Challenges: Extreme weather affecting equipment stability 6. Market Competition: Competition from international smart construction solutions

4. CONCLUSIONS

The conducted research on the influence of big data and artificial intelligence on construction site management models unequivocally demonstrates that the implementation of the "smart construction site" concept represents an inevitable evolutionary stage in Russia's construction industry. The analysis reveals that modern digital technologies—BIM modeling, Internet of Things, cloud computing, and artificial intelligence—fundamentally transform traditional approaches to construction process management, ensuring comprehensive informatization, intellectualization, and visualization of construction production. With over 97,000 construction objects across the Russian Federation, the optimization of management processes through digital technology integration becomes not merely desirable but critically essential for enhancing the industry's competitiveness.

Comparative analysis of traditional and intelligent construction management models convincingly evidences the significant advantages of the latter in personnel management, equipment management, material resource administration, and information flow control. The utilization of intelligent monitoring systems substantially reduces occupational injury risks, promptly identifies potentially hazardous situations, and prevents accidents. Simultaneously, the conducted SWOT analysis identified several substantial impediments to the large-scale implementation of smart technologies in Russia's construction sector, including high initial investments, qualified personnel deficits, and complexities in integrating various subsystems [22].

In-depth examination of the obtained results leads to the conclusion that the transformation of construction site management models exhibits a systemic character, affecting all aspects of construction production. Particularly noteworthy is that the effectiveness of intelligent management system implementation directly correlates with the digital maturity level of the construction organization as a whole. Companies possessing developed information infrastructure and data management culture demonstrate significantly higher returns on investments in smart technologies. This observation confirms the necessity of a comprehensive approach to construction digitalization, ranging from basic document flow processes to complex predictive analytics systems.

It is remarkable that the Russian construction complex possesses several unique characteristics that simultaneously create both challenges and opportunities for implementing intelligent management models. On one hand, significant territorial distribution of objects and extreme climatic conditions in several regions complicate the implementation and operation of high-tech equipment. On the other hand, these very factors render smart technology utilization particularly valuable, as they minimize the necessity for physical presence of specialists at remote sites and ensure continuous monitoring of construction processes under challenging weather conditions.

The research-identified tendency toward an ecosystem approach formation in construction site management deserves special attention. Analysis indicates that projects achieve maximum efficiency when digital technologies not merely automate individual processes but create a unified information environment ensuring seamless integration of all construction process participants—from designers and suppliers to builders and future facility operators. In this context, the necessity for developing not only technological but also organizational innovations directed at forming new interaction models between construction market participants becomes evident.

It is also interesting to note the transformation of the human factor role in construction digitalization conditions. Contrary to the widespread belief that automation leads to job reduction, the research indicates that smart technology implementation rather changes the labor character, shifting emphasis from routine operations to creative and analytical tasks requiring high qualification. This observation has important implications for the professional education system and personnel retraining organization in the construction industry.

Based on the conducted research, it appears expedient to develop a governmental program supporting intelligent technology implementation in construction, including initial investment subsidization and solution adaptation to Russian climatic conditions; concurrently, development of domestic software and hardware complexes with uniform national digitalization standards formation and systematic resolution of personnel issues through educational program modernization emphasizing digital competencies is necessary. The developmental perspective of smart construction sites in Russia prognosticates transition to fully integrated construction management ecosystems encompassing the entire life cycle of objects, where artificial intelligence will provide predictive analytics, while the synergy of BIM modeling, Internet of Things, and other digital technologies will create a qualitatively new level of construction production efficiency and safety, contributing to the enhanced competitiveness of the Russian construction industry in the global market.

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