Exploration of Digital Transformation Path of Construction Engineering Management in the Background of Smart Construction

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Abstract: Against the backdrop of the digital economy and new urbanization, the construction industry is accelerating its transition toward smart construction. The digital transformation of construction project management has become a critical pathway for driving high-quality industry development. Traditional management models suffer from issues such as information silos, fragmented processes, and low efficiency, rendering them inadequate to meet the demands for collaboration, precision, and intelligence in complex engineering projects. This paper explores digital transformation pathways for construction project management within the smart construction framework. It elucidates the essence and drivers of smart construction and digital transformation in construction project management, revealing how policy direction, technological advancement, and industry demands propel this shift. Practical transformation pathways are analyzed across three dimensions: digital platforms and information integration, intelligent technology-enabled construction management, and collaborative management with organizational transformation. It summarizes challenges encountered during transformation—including lack of standards, high cost investment, data security concerns, and talent shortages—and proposes corresponding countermeasures. Digital transformation not only enhances project management efficiency and resource allocation but also injects new momentum into the sustainable development of the construction industry. With the application of emerging technologies such as artificial intelligence, blockchain, and the metaverse, construction project management will advance toward a new phase of intelligence and smartization.

1. Introduction

With the advent of the digital economy era and the continuous advancement of new urbanization, the construction industry is undergoing a critical phase of transition from traditional extensive development to intelligent and refined practices[1]. As a product of the deep integration of information technology and the construction industry, smart construction not only reshapes the organizational methods and production models of engineering projects but also provides new pathways for upgrading construction project management[2]. For a long time, construction project management has primarily relied on traditional methods, suffering from issues such as scattered information, poor communication, and inefficient processes[3]. These limitations make it difficult to meet the demands of large-scale, complex projects for efficient collaboration and dynamic control[4]. Promoting the digital transformation of construction project management has become an inevitable choice for enhancing the industry's core competitiveness and achieving high-quality development[5]. Digital management leverages emerging technologies like big data, the Internet of Things, artificial intelligence, and cloud computing to achieve information integration and dynamic monitoring throughout the entire project lifecycle[5]. This effectively improves the quality, safety, cost, and schedule control of projects[6]. This paper aims to explore the essence, implementation pathways, and challenges of digital transformation in construction project management in light of smart construction trends, proposing corresponding countermeasures to provide insights for sustainable development and management innovation in the construction industry[7].

2. Smart Construction and the Essence & Drivers of Digital Transformation in Construction

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Project Management

Smart construction represents a new paradigm centered on informatization, digitization, and intelligence[8]. Its essence lies in achieving efficient collaboration and dynamic optimization throughout the project lifecycle through the deep integration of next-generation information technologies with the construction industry[9]. Compared to traditional construction, smart construction emphasizes data-driven decision-making and intelligent operations, encompassing the entire process from planning and design through construction implementation to operation and maintenance. It not only enhances project efficiency and quality but also plays a crucial role in energy conservation, emissions reduction, green construction, and workplace safety, serving as a key engine for the transformation and upgrading of the construction industry. Project Cost Control (Earned Value Method)

$$CPI=\frac{EV}{AC} \quad (1)$$

The digital transformation of construction project management is an inevitable requirement in the context of smart construction. Traditional management models often rely on manual experience and paper-based documentation, resulting in low information transmission efficiency and difficulty in achieving precise control over complex projects. Digital transformation, however, centers on data as the core resource. Through the development of digital platforms and the application of technological tools, it enables real-time information sharing, dynamic tracking, and intelligent analysis, thereby elevating the scientific rigor and precision of project management. Its essence encompasses not only technological application but also systemic restructuring of organizational models, management processes, and even the industry ecosystem[10].

The primary drivers propelling the digital transformation of construction project management stem from national policies and industry development needs. In recent years, China has successively introduced multiple policies and standards explicitly setting development goals for advancing construction informatization and smart construction, providing institutional safeguards for industry transformation. As project scales grow increasingly large and engineering complexity continues to rise, the urgent demands from owners, contractors, and regulatory bodies for efficient collaboration and transparent management further accelerate the practical implementation of digital transformation.

Beyond external drivers like policy and demand, technological progress is another key catalyst. The rapid development and application of emerging technologies such as big data, the Internet of Things (IoT), cloud computing, artificial intelligence (AI), Building Information Modeling (BIM), and blockchain provide rich tool support for construction project management. These technologies enable the collection, transmission, and analysis of multi-source data, enhance visualization and controllability at construction sites, and offer predictive and decision-making support for project management. The concept of green and low-carbon development is also accelerating the industry's shift toward digitalization and intelligence, enabling the construction sector to achieve economic benefits while balancing social and environmental benefits, showed in Figure 1:

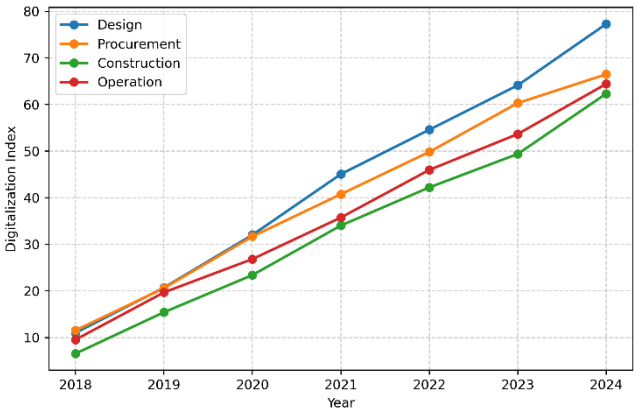

Figure 1 Digitalization Index trends across project phases

3. Practical Pathways for Digital Transformation in Construction Project Management

The digital transformation of construction project management is not merely a one-dimensional technological replacement but a systematic endeavor encompassing platform development, technology application, and organizational change. Its core objective is to leverage digital means to drive information integration across the entire project lifecycle, intelligent control of construction processes, and efficient collaboration among multiple stakeholders, thereby achieving comprehensive optimization of quality, schedule, cost, and safety. Within this process, digital platforms and information integration form the foundation, while intelligent technologies empowering construction management serve as the key enabler. Collaborative management and organizational transformation provide the institutional support and management pathways ensuring the effective implementation of these three elements. Interconnected and mutually reinforcing, they collectively constitute the practical logic of digital transformation in construction project management.

3.1 Digital Platforms and Information Integration

Digital platforms serve as the foundational support for construction project management transformation. Their core function lies in leveraging information technology to connect all stages of the project lifecycle, enabling centralized data storage, unified management, and efficient utilization. Under traditional models, design, construction, supervision, and operations often form “information silos” with inconsistent data standards, resulting in inefficient information transfer. Digital platforms overcome this by establishing unified data interfaces and standardized information exchange mechanisms. This facilitates data interoperability across different phases and stakeholders, providing a systematic, holistic perspective for project management. Project Schedule Performance

$$SPI=\frac{EV}{PV} \quad (2)$$

In construction practice, the integrated application of BIM technology and CIM platforms offers a key solution for information integration. BIM models enable three-dimensional visualization and data representation of design information, supporting construction simulation and schedule control. CIM platforms integrate building information with city-level data, providing macro-level support for regional construction management. This combination not only enhances internal information sharing within projects but also enables cross-project and cross-regional collaborative management.

The application of cloud computing and big data technologies further strengthens the digital platform's information processing and analytical capabilities. Through cloud storage and computing, projects enable real-time remote access and collaborative operations across multiple parties, transcending temporal and spatial constraints. Big data analytics dynamically monitors and forecasts trends in progress, cost, quality, and safety data during construction, providing scientific decision support for managers. This data-driven management model shifts construction project management from experience-based reliance toward intelligent and refined approaches.

Information integration is not solely a technical challenge but also involves establishing standards, specifications, and institutional frameworks. Current industry challenges include incompatible data interfaces and inconsistent standards, hindering platform interoperability and information sharing. While advancing digital platform development, unified data standards and information management protocols must be established. Cross-departmental and cross-enterprise collaboration mechanisms should be created, alongside strengthened information security frameworks. Only through the coordinated advancement of technology, standards, and management systems can the full potential of digital platforms and information integration be realized, laying a solid foundation for the comprehensive digital transformation of construction project management. Risk Index in Construction Management

$$R = P \times I \quad (3)$$

3.2 Empowering Construction Management with Intelligent Technologies

During the digital transformation of construction project management, the widespread application of intelligent technologies has opened new possibilities for refined and dynamic management of construction processes. Compared to traditional management methods reliant on manual experience, intelligent technologies enable real-time data collection, transmission, and analysis, significantly enhancing transparency and controllability at construction sites. Through the integrated application of

technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data, construction management is progressively advancing toward a new phase characterized by intelligent perception, predictive alerts, and scientific decision-making.

The deployment of IoT technology on construction sites enables real-time sensing and monitoring of critical elements such as project progress, safety, and quality. Devices like sensors, drones, and RFID systems collect multidimensional data—including temperature, humidity, vibration, and displacement—and transmit it wirelessly to management platforms. Managers leverage this data for visual monitoring of on-site operations, promptly identifying anomalies and implementing corrective actions to effectively mitigate safety risks and boost construction efficiency.

Artificial intelligence plays a vital role in decision support and risk warning. Through machine learning and deep learning algorithms, AI performs pattern recognition and trend analysis on historical project data to predict potential delays in construction schedules and risks of cost overruns. AI technology also provides support in image recognition and unmanned equipment scheduling—for instance, using computer vision to automatically identify construction defects or employing intelligent algorithms to optimize resource allocation, thereby achieving automation and intelligence in construction management, showed in Figure 2 :

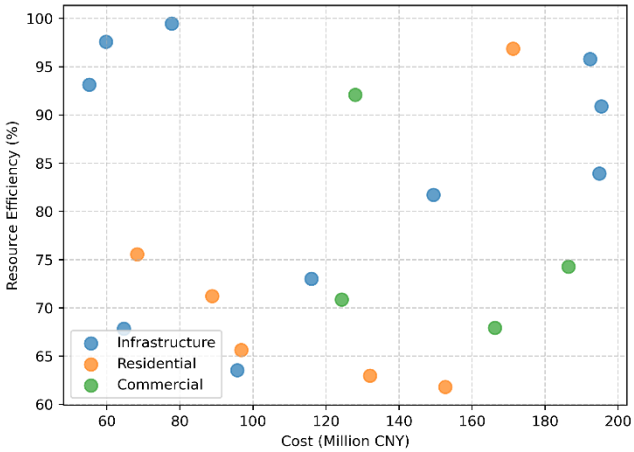

Figure 2 Resource efficiency vs cost over multiple projects

Big data analytics further enhances the scientific rigor of construction management. By integrating and analyzing progress, cost, and quality inspection data, managers gain real-time visibility into project status, identify potential issues, and formulate optimization strategies. Data mining and visualization technologies not only improve planning accuracy but also provide robust support for refined control and long-term decision-making. It is noteworthy that the effective application of intelligent technologies must be integrated with management systems and personnel capabilities to fully realize their value. While advancing the intelligent transformation of construction management, emphasis should be placed on technical training and organizational structure optimization to ensure intelligent technologies are embedded throughout all phases of construction management and continue to deliver sustained benefits. Resource Allocation Optimization (simplified)

$$\min Z = \sum_{i=1}^{n} c_i x_i \quad \text{s.t.} \quad \sum_{i=1}^{n} a_{ij} x_i \leq b_j \qquad (4)$$

3.3 Collaborative Management and Organizational Transformation

Construction projects typically involve multiple stakeholders, including owners, designers, contractors, supervisors, and suppliers. Under traditional management models, communication efficiency among parties is low, collaboration costs are high, and decision-making delays and resource wastage are common. Digital transformation provides new tools and platforms for collaborative management. Unified information systems and shared data resources enable efficient collaboration and real-time communication among multiple entities. This data-driven collaborative management model enhances overall project efficiency, reduces rework and conflicts, and safeguards the smooth progression of construction projects.

In practice, the integration of new project management models—such as EPC (Engineering, Procurement, and Construction) and IPD (Integrated Project Delivery)—with digital technologies is driving profound transformations in construction management. Through BIM collaboration platforms, design and construction teams can share and dynamically update plans in real time, eliminating information distortion and delays. Digital management systems empower owners to monitor construction progress and quality status instantly, enabling more proactive and informed decision-making. This collaborative approach not only streamlines workflow integration but also enhances project governance transparency and controllability.

The implementation of collaborative management also imposes new demands on organizational structures. Traditional hierarchical and compartmentalized management approaches are increasingly inadequate for project operations in the digital era. Digital transformation necessitates flatter, more flexible organizational structures to support efficient cross-departmental and cross-disciplinary collaboration. Management processes must similarly evolve from linear, sequential models to dynamic, multi-threaded interactions capable of adapting to rapidly changing project requirements in the digital environment.

Talent development and cultural transformation are critical enablers for collaborative management and organizational change. Digital transformation demands not only technological tools but also a workforce equipped with interdisciplinary knowledge, digital literacy, and innovation capabilities. Corporate culture must evolve from experience-driven to data-driven and collaboration-oriented, fostering knowledge sharing and cross-boundary cooperation. Only through the synergistic integration of technology, organization, and culture can collaborative management be effectively implemented, propelling construction project management from “digitalization” to “intelligentization”.

4.Challenges and Countermeasures in Digital Transformation

Although digital transformation in construction project management has become an inevitable trend for industry development, numerous challenges persist in its practical implementation. An incomplete industry-wide standard system leads to information silos and interface incompatibilities between different platforms and systems, limiting the full sharing and utilization of data. Digital transformation often requires substantial upfront investments, including hardware procurement, platform setup, and software maintenance, posing significant financial pressures for small and medium-sized construction enterprises and hindering widespread adoption. The construction industry's weak information technology foundation and insufficient understanding of digital transformation among some enterprises result in limited practical application effectiveness.

Data security and privacy protection issues are particularly prominent. As project management increasingly relies on cloud computing and IoT platforms, vast amounts of sensitive information must be stored and transmitted over networks. Without robust security measures, this creates significant risks of data breaches and security vulnerabilities. Significant disparities exist in IT capabilities and digital maturity across companies, creating a pronounced digital divide within the industry that hinders the formation of a unified, collaborative digital ecosystem. BIM Data Integration Metric

$$DI=\frac{\sum_{i=1}^{n} w_i d_i}{\sum_{i=1}^{n} w_i} \qquad (5)$$

Talent shortages also constitute a major bottleneck for digital transformation in construction project management. This transformation requires not only IT specialists but also hybrid professionals proficient in both engineering management and digital skills. The construction sector's talent pool remains predominantly traditional, with limited numbers possessing cross-disciplinary capabilities. This shortage impedes the effective implementation of digital technologies in corporate management practices.

To address these challenges, coordinated efforts across policy, technology, and organizational dimensions are essential. Accelerating the development of industry standards is crucial, including establishing unified data interfaces and information exchange protocols to promote interoperability between platforms. Additionally, governments should enhance policy and financial support by providing fiscal subsidies and technical guidance to lower the transformation barriers for small and medium-sized enterprises. Technologically, robust data security frameworks must be established to improve the safety

and stability of information systems. Enterprises should strengthen the development of multidisciplinary talent pools through university-industry collaborations, training programs, and talent recruitment, thereby solidifying the human capital foundation for digital transformation. Only through the combined effects of refined standards, policy support, technological safeguards, and talent supply can the digital transformation of construction project management achieve sustainable development.

5. Conclusion

Against the backdrop of smart construction, the digital transformation of construction project management has become an inevitable choice for driving high-quality industry development. This paper analyzes the essence and driving factors of smart construction and digital transformation in construction project management. It proposes a practical pathway grounded in digital platforms and information integration, centered on empowering construction management with intelligent technologies, and safeguarded by collaborative management and organizational transformation. Furthermore, it explores the primary challenges encountered during the transformation process and corresponding countermeasures. Research indicates that digital transformation not only enhances the informatization level and management efficiency of construction projects but also plays a significant role in safety control, cost management, and resource allocation, providing new momentum for the industry's green, intelligent, and sustainable development.

Looking ahead, as emerging technologies like artificial intelligence, blockchain, and the metaverse continue to mature and find practical applications, construction project management will advance toward a new era of intelligence and smart operations. Digital transformation is not merely a technological innovation process but a systemic endeavor involving organizational change and conceptual renewal, requiring concerted efforts and collaborative advancement from governments, industries, and enterprises. Only through the synergistic interaction of technology, systems, talent, and culture can construction project management achieve a comprehensive leap from traditional models to smart construction.

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