Technological Innovation and Development Trends in Smart Building and Construction: with Harbin Grand Theatre as an interpretive case

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Abstract: This paper takes the Harbin Grand Theatre as a systematic literature-based case analysis to examine the application of parametric design and digital collaborative technologies in its design and construction process, and to analyze its technological position within the development of smart buildings. The study shows that the Harbin Grand Theatre mainly represents a stage of digital-assisted construction centered on parametric modeling and digital collaboration. Its "smartness" is reflected more in the control of complex forms and the improvement of construction coordination efficiency, rather than in the application of fully developed intelligent systems. On this basis, the paper distinguishes the technical logic between digital-assisted construction and intelligent system design, and points out that smart buildings should be understood as an evolving system process throughout the entire building life cycle, supported by digital foundations. This research provides a reference for understanding the gradual transition of complex public buildings from digital design to smart building development.

1 Introduction

With the continuous development of digital design tools, intelligent construction technologies, and sustainable design concepts, smart buildings are gradually shifting from isolated technical applications toward a systematic transformation of design and construction paradigms. [1] Smart buildings are no longer evaluated solely by the level of equipment automation or intelligence, but instead emphasize the integrated coordination of environmental response, functional organization, and cultural expression throughout the entire process of design, construction, and operation.

Located in the Songhua River wetland area of Songbei District, Harbin, the Harbin Grand Theatre is characterized by an architectural form inspired by the imagery of ice and snow, representing a combination of cold-region culture and contemporary architectural technology. During its design and construction, the project adopted parametric design methods, complex curved structural control, and BIM-based collaborative construction techniques. [2] These practices have been systematically discussed in academic journals. Therefore, this paper adopts a systematic literature-based case analysis approach, drawing on existing academic literature to summarize the digital design characteristics of the Harbin Grand Theatre and to compare them with current definitions of intelligent systems in smart building research.

Given the lack of access to primary design documents, this study focuses on secondary sources to reconstruct the technological logic and development stage of the project.To ensure that the analysis is grounded in documented technological practices rather than subjective interpretation, the priority is given to sources that explicitly discuss design methods, construction technologies, or system-level concepts. As a literature-based analytical study, this research is constrained by the availability and scope of published sources. The findings should therefore be understood as analytical positioning results.

2 Methodological Value of Parametric Design in Complex Architecture

Parametric design is one of the most representative methods for generating and controlling complex architectural forms in contemporary practice. Its core value does not lie in producing a specific form, but in establishing parametric relationships that allow complexity to remain controllable under multiple constraints.[3] Compared with traditional drawing-centered design processes, parametric design emphasizes the early expression of design logic, enabling geometric relationships, structural conditions, environmental factors, and functional requirements to be handled collaboratively within a unified model system.

The continuous and fluid architectural form of the Harbin Grand Theatre is intuitively understood as a result of natural generation.[4] However, from a methodological perspective, the design relies on digital modeling tools to systematically manage curvature continuity, overall mass control, and variations in local components. This approach reflects a design strategy that achieves coordination between the whole and the parts through parametric adjustment.

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It should be noted that some studies have introduced fractal theory to interpret the formal characteristics of the Harbin Grand Theatre. For example, Zheng et al. (2025) applied fractal analysis tools such as the box-counting dimension to conduct quantitative studies of the building form.[5] However, such analyses are mainly post-design interpretations, and there is no evidence that fractal theory was adopted as a generative method during the actual design process. Therefore, in this paper, fractal theory is treated as a supplementary analytical perspective rather than a core design methodology.

In comparison, parametric design more accurately reflects the practical design characteristics and technological stage of the Harbin Grand Theatre. Through parametric models, the design team was able to maintain overall formal coherence and flexibility while meeting multiple requirements related to structural safety, construction feasibility, and spatial performance. This parameter-based design approach provided an important foundation for coordination between design and construction in complex architecture, and also created conditions for the later integration of smart building technologies.

3 Practical Application of Digital Design and Construction Collaboration

At the construction level, the Harbin Grand Theatre, completed in 2015, represents an early exploration of digital collaboration in complex public buildings in China. Existing studies indicate that three-dimensional model-based collaborative design methods were introduced during the structural design and façade construction stages, significantly improving the precision of fabrication and installation for complex curved components. [6]These methods show clear continuity with the BIM-based collaborative construction concepts widely discussed in recent years. The construction phase of the Harbin Grand Theatre mainly relied on three-dimensional digital models, coordinated structural detailing, and digital transmission of construction information. The primary objective was to address the feasibility challenges of complex curved architecture in terms of structural safety, component fabrication, and on-site installation. The "smartness" at this stage was mainly reflected in improved design and construction efficiency, as well as enhanced interdisciplinary collaboration. However, these technologies remained focused on supporting the delivery of the building itself and did not extend to intelligent functions such as real-time environmental monitoring, automated control, or adaptive building management during operation.

4 From Case to Trend: Evolution from Digital Assistance to Intelligent Systems

4.1 Conceptual Distinction between Digital-Assisted Construction and Intelligent Building Systems

To clarify the technological position of the Harbin Grand Theatre within the development of smart buildings, it is necessary to distinguish between digital-assisted construction and intelligent building systems at the system level. Digital-assisted construction refers to the application of digital tools such as parametric modeling, computational simulation, and digital fabrication to support architectural form generation, structural coordination, and construction control. These technologies primarily enhance precision and efficiency during the design and construction phases, with digital models functioning as representational and coordination tools.

In contrast, intelligent building systems integrate real-time sensing, data processing, feedback mechanisms, and adaptive control strategies that operate throughout the building life cycle. In such systems, digital models are embedded within operational frameworks, enabling continuous environmental regulation and system-level responsiveness during use. As shown in Table 1, digital-assisted construction and intelligent building systems differ significantly in lifecycle coverage, sensing capability, feedback mechanisms, and the role of digital models. Based on this distinction, the Harbin Grand Theatre can be identified as a representative case of advanced digital-assisted construction rather than an intelligent building system.

Table 1. Comparison between Digital-Assisted Construction and Intelligent Building Systems

Analytical Dimension	Digital-assisted Construction	Intelligent System
Lifecycle coverage	Design & construction	Full lifecycle
Real-time sensing	Not required	Core requirement
Feedback & adaptation	No	Yes
Role of digital model	Static	Dynamic

4.2 Digital-Assisted Construction as a Prerequisite for Intelligent Building Systems

Although digital-assisted construction does not itself constitute an intelligent building system, it provides the technological foundation upon which intelligent building applications can be developed. Intelligent buildings rely on structured digital representations, interoperable data environments, and integrated system architectures to support real-time monitoring and adaptive operation. These capabilities are rarely achievable without a prior digital foundation established during design and construction. Digital models created through BIM and other design tools enables sensor integration, data aggregation, analytics, and control logic in later operational systems.

Some smart building projects confirm this dependency. For example, studies on digital twin platforms for building performance monitoring and optimization done by Li et al. (2025) show that real-time operational intelligence depends on the integration of sensor data, building simulations, and computational models. These integrated systems are typically built upon comprehensive digital building representations developed during the design and construction phases.[7]Another research done by Almatared et al.(2024) on digital twin－based management frameworks for smart buildings also shows that digital structures created early in a building’s lifecycle, such as sensor maps and simulation links, are indispensable for later operational applications like fire safety management, real-time hazard detection, and integrated facility controls. [8]Such frameworks extend beyond design efficiency goals to support holistic building intelligence in use. Although these studies focus on digital twin applications rather than the Harbin Grand Theatre itself, they demonstrate a common technological principle: intelligent building systems rely on digital information structures established during earlier design and construction stages. This supports the interpretation that digital-assisted construction should be regarded as a prerequisite rather than an equivalent to intelligent building systems.

From this perspective, intelligence extends digital design into the operational domain. It is the structured digital base established through digital-assisted construction that enables the building to evolve into an intelligent system over time.

4.3 From Digital-Assisted Construction to Intelligent Building Systems

From the development process of architectural technology over the past two decades, the role of digital technology in architecture has undergone a continuous evolution from "geometric representation" to "information management", and further to "intelligent operation". Accordingly, the role of digital models throughout the building life cycle has continuously expanded.

During the early stage of digital design development, technologies such as parametric design and computer-aided modeling were mainly employed to address the difficulties associated with the design and construction of complex architectural forms. As the complexity of buildings continued to increase, digital modeling alone was no longer sufficient to satisfy engineering and construction requirements. Consequently, digital technology gradually shifted from geometric representation toward information organization. The development of Building Information Modeling (BIM), multidisciplinary collaborative design, and digital construction management enabled building models to incorporate not only spatial geometry but also structural, mechanical, electrical, construction, and material information. As a result, digital models gradually assumed the role of platforms for cross-disciplinary information sharing and construction coordination. The focus of digital technology therefore shifted from "how to design complex buildings" to "how to organize information for complex buildings", while digital models evolved from design tools into carriers of engineering information.

In recent years, with the development of digital twins, the Internet of Things (IoT), and artificial intelligence (AI), building digitalization has undergone another significant transformation. Digital models have gradually extended beyond the design and construction stages by continuously receiving data from sensors, building systems, and environmental monitoring during building operation, thereby constantly updating the operational status of buildings. This indicates that digital models have evolved from static design deliverables into dynamic information platforms. Their value is no longer limited to the period before construction is completed but increasingly lies in the long-term operation and management of buildings after they are put into use. Digital technology has therefore begun to span the entire process of building design, construction, and operation and maintenance, enabling information continuity throughout the whole building life cycle.

Within this framework, the Harbin Opera House represents a critical transitional case. It demonstrates the potential of digital-assisted construction in achieving highly complex architectural forms and structural systems, while also revealing the limitations of design-centered digital approaches.

4.4 Development Trends of Smart Buildings

The development trend of building digitalization indicates that the future competitiveness of smart buildings will no longer depend solely on the adoption of more digital technologies but rather on achieving information continuity throughout the entire building life cycle. Future digital models should not only support building design and construction but also remain continuously connected with building operation, facility maintenance, and subsequent renovation stages, thereby maintaining a unified data foundation and information logic throughout the entire life cycle.

In this process, digital twins will become a key technological medium connecting design and operation. By continuously collecting data related to the environment, energy consumption, equipment operation, and occupant activities through IoT devices, digital models can reflect the real-time status of buildings while utilizing artificial intelligence algorithms for energy consumption prediction, equipment fault warning, and operational optimization. This continuously updated information mechanism enables buildings to adjust management strategies according to actual operating conditions, thereby improving operational efficiency and resource utilization.

Meanwhile, the development objective of smart buildings is gradually shifting from simply pursuing automation toward comprehensive performance optimization. Future buildings should not only possess environmental sensing and automatic control capabilities but also achieve a dynamic balance among energy conservation, equipment maintenance, space utilization efficiency, and occupant comfort. Accordingly, the role of digital technology will gradually evolve from providing technical support to supporting building decision-making, enabling buildings to continuously optimize their operational performance based on accumulated data.

Considering the Harbin Opera House case, the project has already established a high-quality digital design foundation. If digital twin platforms, real-time sensing systems, and intelligent building management systems are further introduced in the future, its existing digital model will retain considerable expansion potential and can be extended to the stages of building operation and facility management, thereby realizing the transition from digital-assisted construction to a smart building.

5 Conclusion

This paper takes the Harbin Grand Theatre as a research object and explores its position and significance in the development of smart buildings through an analysis of digital technologies applied in its design and construction process. The study shows that the project primarily relied on parametric modeling and digital collaboration to address the challenges posed by complex forms and cold-region construction conditions, rather than being designed as an intelligent system-oriented building. As a result, it is more accurately positioned within the stage of digital-assisted construction rather than a mature smart building paradigm.

On this basis, the paper further distinguishes the differences in technical logic and application objectives between digital-assisted design and intelligent system design. The former focuses on improving controllability and collaboration efficiency during design and construction, addressing the question of how complex public buildings can be built. The latter shifts the technical focus toward building operation through sensing, data analysis, and feedback mechanisms, considering how buildings can be used efficiently and sustainably over the long term. The Harbin Grand Theatre occupies a transitional position between these two stages, with its digital model-centered information organization providing a realistic foundation for future intelligent system integration and upgrades.

In the future, smart building design should incorporate a holistic consideration of intelligent system evolution pathways at the design stage. While respecting existing technological conditions and construction realities, space should be reserved for sustainable upgrades such as digital twins, energy monitoring, and intelligent management systems. Through this gradual development model, smart buildings can truly evolve from conceptual technological integration into comprehensive systems oriented toward long-term operational and user value.

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