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Integration of BIM and Emerging Information Technologies: Paths and Challenges for Driving Intelligent Construction Management

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Abstract. The convergence of core and emerging technologies increasingly drives the digital transformation of the construction industry. This paper systematically explores the integrated application of Building Information Modeling (BIM) with technologies like Artificial Intelligence (AI), the Internet of Things (IoT), big data, and Augmented/Virtual Reality (AR/VR) in construction management, alongside the inherent challenges. Findings indicate that BIM-AI integration facilitates design optimization, error detection, and progress tracking; BIM-IoT combination enables dynamic monitoring via a “virtual model + real-time data” paradigm; big data analytics empower BIM for progress correction and risk early-warning; and AR/VR technologies significantly enhance model visualization and immersive collaboration. These integrations collectively enhance decision-making, risk control, and operational efficiency throughout the project lifecycle. However, major challenges persist, including data heterogeneity between BIM and IoT, non-standardized data hindering AI training, and technical bottlenecks in BIM-AR/VR model conversion and rendering. To overcome these barriers and harness the full potential of integrated BIM, this study proposes systematic countermeasures, including a general data fusion framework, semantic standardization, cloud-edge computing, and an intermediate conversion layer. The study further identifies the development of digital twin systems as a key future direction to achieve multi-source data closed-loop interaction. This evolution is envisioned to propel the construction industry toward unprecedented levels of intelligence and management refinement.

Keywords: Building Information Modeling (BIM); Construction Management; Digital Twin; Data Integration; Information Technology Integration.

1. Introduction

The world construction industry is the very pillar of global economic growth. At present, China's construction industry is a flagship industry of the national economy. The industry is transforming from a stage of rapid growth to a stage of high-quality growth. However, the old-fashioned construction management model also has a lot of issues. Firstly, the management system is comparatively underdeveloped and has very poor quality and efficiency in management work. Secondly, a shortage of construction staff and construction materials has constrained the overall level of project management. Thirdly, the construction safety management implementation is sluggish, the risk warning is deferred, and the awareness and investment in construction safety are inadequate [1]. The above issues not only severely limit the efficiency of construction management but also threaten the final benefits and quality of engineering projects.

Herein lies the potential of building information modeling (BIM) technology to resolve these perennial challenges in the construction management process for building projects. BIM technology materializes management content through three-dimensional models. Enable managers to observe, analyze, study, and coordinate various management tasks from an overall perspective. Enhance the quality of engineering information management at the same time [2]. BIM collects project data, detects project conflicts, estimates project costs, and integrates with on-site data management tools, FDMTs. Improved the efficiency of construction project management [3]. Despite these advantages, the standalone application of BIM is not without its limitations. However, BIM technology still has many shortcomings. Compared to physical models and sketch designs.

BIM has shortcomings in terms of timeliness and accuracy. BIM cannot cover all methods of collecting, constructing, and modifying building information. In other words, BIM still needs development in data collection. In addition, employees' understanding of BIM is also a factor affecting construction management. These constraints of BIM can, however, be resolved by integrating it with the latest information technologies. The IoT and big data have increased the data collection capacity of BIM. Error correction in BIM is assisted by AI while processing powers are increased. Users are better able to comprehend BIM content through the use of VR/AR and integrating these latest information technologies with BIM. Have been able to drive the construction management operation [4] successfully.

This paper endeavored to explore the channels for profound integration of BIM with new information technologies (AI, IoT, Big Data, AR/VR), summarise the major obstacles blocking such integration, and advance countermeasures in a systematic way. Through such efforts, this work attempts to provide both theoretical contributions and practical guidelines for maximizing construction management efficiency, guaranteeing project quality and security, and triggering the digitalization of the construction industry.

2. Applications of BIM combined with New Information Technologies

2.1. AI-BIM Integration for Construction Management

Artificial Intelligence (AI) is a technology aimed at making machines able to perform defined tasks very quickly. Its essence is that it lets machines utilize data and computation to learn and resolve issues autonomously, and this technology has a close relationship with BIM's content [5]. If these two technologies are utilized together, construction management is efficient and precise. The idea is that these technologies optimize visualization and coordination. Specifically, BIM gives a whole 3D model of the project, and AI examines this information to identify conflicts and errors. Together, they help identify errors and track construction progress [6]. Portuguese Betar company utilized 3D technology, BIM, and AI to explore bridge defects. The project utilized AI's deep learning image repositories to attain automatic detection of bridge structural irregularities [7]. Apart from such particular utilization, the research front is broadening towards overall systems. In recent research studies, the integration of the BIM–AI systems with digital twins, blockchain, and human–machine intelligence has been a promising area that holds promise and provides overall data support throughout the whole construction lifecycle [8].

2.2. BIM-IoT Integration for Construction Control

The fusion of BIM and the Internet of Things (IoT) constitute a highly effective construction control mode by connecting the digital design and the real world. BIM models contain rich component information and unify geometric, spatial, and attribute information, thus converting physical building components into digital entities highly faithful to information. IoT devices, meanwhile, offer continuous real-world data such as temperature and equipment status [9]. This fusion defines a cyber-physical connection between the fixed virtual model and variable real-time data, thus transforming construction supervision and making it possible to take proactive control. In a real scenario, BIM creates a digital model covering the schedule, cost, and standards, while IoT sensors are used to monitor the condition of the materials, equipment, and environmental conditions. For instance, building materials could be implanted with RFID tags, and the RFID reader could accurately document the information of storage, utilisation, and transportation [10].

2.3. BIM and Big Data Analytics for Project Control

The strength of BIM is further enhanced when utilized in combination with big data analysis so that insights may be drawn from the enormous datasets produced during the course of a construction project. It remains a major challenge to maintain the legitimacy and verifiability of data when the volume of data escalates. In implementing big data, data interfaces between various systems have to be coordinated by the managers so that information moves smoothly [11]. The integration of BIM and big data here combines digital building models with voluminous datasets of duration/progress, quality, safety, and cost. This permits real-time tracking, early warning of possible issues, and the efficient utilisation of resources. In cost management, BIM, aided by big data infrastructure, has the capability to predict possible issues ahead of time and avoid unnecessary expenditures so that better project control decisions are available for informed decisions [12].

2.4. BIM with AR and VR for Visualization and Collaboration

AR and VR provide mutually supplementary visual capabilities for BIM data interaction. AR superimposes digital data over the real world, while VR places users in a complete virtual world [13,14]. With advancing technologies, combining AR/VR and BIM has attracted ever more interest. An excellent example is that of combining Autodesk BIM 360 Docs and the AR/VR platform Wild to create immersive on-site collaboration and on-site visualisation [15]. With AR-based applications, on-site staff are able to carry out on-site inspections or report defects using interactive 3D models directly superimposed over the construction site. With VR, which is most commonly utilized for design and visualisation purposes, first-person experience and editing of BIM models are provided for the end-user [16]. Beyond this, AR–BIM in the 4D dimension allows real-time comparison between planned and constructed work to date and provides the engineer with a real-time and immediate view of project implementation.

AR and VR together transform BIM from a fixed design program into an interactive form of experience, communication, and verification.

3. Challenges in Integrating BIM with Emerging Technologies

After evaluating the applications, the current chapter critically discusses the key challenges jeopardizing the in-depth integration of BIM with major emerging technologies. The analysis is organized around the three key domains of IoT interoperability, AI data preparation, and AR/VR technical efficiency.

3.1. Data Interoperability Challenges in BIM-IoT Integration

The combination of BIM and IoT, the basis for a smart building, indeed encounters the inherent inconsistency between static design data and real sensing data. There is a significant difference between data sources for BIM and IoT, which is observable in real operation. Such inconsistency dominates mainly in the facet of a data interoperability barrier rooted in inherent differences between underlying protocols and data structures. However, most of the BIM software is based on proprietary standards. For example, the core data interaction in Revit is based on the BIM360/Autodesk Construction Cloud (ACC) platform. The differences in bottom protocol and data format are the reason why BIM applications are difficult to analyze and utilize the data from IoT devices directly. Although relevant practitioners in the industry have made many efforts to standardize data, there is still no recognized unified data modeling and transfer standard. Consequently, in actual projects, different suppliers often provide different data support, which means that BIM data, equipment data, and operation and maintenance data are stored in different systems, and the data cannot be interconnected, hindering the integration process. On the other hand, the data information of the BIM model is basically geometric and material, while IoT mainly contains physical quantity readings with time. To integrate BIM models with IoT, it is necessary to enable BIM models to process and respond to IoT data.

3.2. Data and Computational Challenges for AI in BIM

The effective application of AI in BIM, such as for design automation, is critically dependent on the availability of large volumes of high-quality training data—a requirement that current BIM practices often fail to meet. The major issues are a shortage of data and lower quality. It takes a great deal of quality data to train AI, and this is something that is absent in BIM models. The quality of a successful AI algorithm relies on the training data. Practically applied scenarios are represented by the same BIM platforms that are utilized by various entities. Data that is consistently transferred between various platforms often has problems due to inconsistencies, flaws, diverse formatting, and sometimes even discrepancies. On top of that, the absence of standardization for the data makes the problem worse. It is very hard to integrate the data and implement it across projects, given the absence of a standardisation for this data. Without the support of high-quality data, the training effects and reliability of AI models are severely diminished. The complex dataset composed of geometric and semantic information in BIM models makes it difficult for AI to process effectively. Due to the larger data volume of large projects, the challenges of AI are greater. Beyond data-related challenges, the computational intensity of AI training presents significant economic and technical barriers. In addition, training complex AI models requires extremely high hardware requirements and computational expense. This means high hardware investment, accompanied by huge energy costs and model optimization problems after training.

3.3. Technical Bottlenecks in BIM-AR/VR Integration

Although they could be immersive experiences, technically bringing detailed BIM models into AR/VR is full of technical roadblocks, and those roadblocks stem from model conversion and real-time rendering. However, there are many bigger roadblocks to perfectly transplanting large and complex BIM models onto mobile head-mounted displays with limited device performance. Bringing the two technologies together has serious technical roadblocks. BIM models have to be highly converted to run perfectly in AR/VR engines. That means translating BIM models (typically in proprietary formats such as RVT) to a "neutral" format such as IFC, then geometry simplification, then semantic data mapping—each of those steps risks data loss or corruption. That means exporting from a proprietary BIM platform, typically in a proprietary format, to IFC (Industry Foundation Classes), then performing lightweight processing on that. That's a time-consuming process, and there's no guarantee that all the data from the BIM model will be retained. It's very easy to lose data or corrupt the BIM model. After the conversion and processing, due to the huge number of components and details contained in the BIM model, it is difficult for AR/VR devices to perform real-time rendering smoothly because of hardware limitations. This can lead to problems such as low frame rates or even device freezes, making it completely impossible to put them into normal use. Optimizing these problems requires excessive time and labor. Currently, there is still no recognized end - to - end BIM - to - AR/VR architecture or standardized development tools in the industry. This means that projects that want to use the combination of these technologies need to pay an additional huge cost. At the same time, relevant developers can only explore and build data conversion and optimization on their own, resulting in low development efficiency. These combined bottlenecks significantly hinder the widespread adoption and practical utility of BIM-AR/VR integration in routine construction workflows.

4. Proposed Solutions and Implementation Strategies

4.1. A Multi-Level Framework for BIM-IoT Data Fusion

As Section 3.1 has revealed, the fundamental problem is that of data interoperability. A classic interdisciplinary challenge is integrating the Internet of Things (IoT) and Building Information Modeling (BIM). Multi-layered systems such as these are seldom amenable to single-layer solutions but are enhanced by a multi-level framework for reasoning that may bridge technical, semantic, and organizational disparities. Following this rationale, the subsequent discussion embraces a "general-to-specify" mode of analysis [17].

A multi-level framework encompasses the various major strategies. The initial step involves the establishment of a broadly applicable and extensible data fusion framework. Instead of relying on specific software or hardware platforms, the framework establishes a whole lifecycle of data that encompasses collection and preprocessing to integration and application, such that it permits flexible adaptation for a variety of construction scenarios.

The next steps are achieving data standardisation and semantic interoperability. Open data standards and interface protocols, also coupled with semantic web technologies and ontology-based modeling, are a good method that can enable the creation of a shared semantic environment. In these conditions, BIM elements and IoT sensor data can be semantically aligned and facilitate smooth and meaningful information exchange.

In the same way, data quality and reliability are highly significant for data fusion. Eliminating noise and aligning time stamps on the IoT systems and anomaly detection could lower data errors. Accordingly, model version control and information consistency management also need to be enforced for BIM systems. Managers could employ optimally designed mechanisms for data governance such that all the fused data remains accurate, complete, and traceable.

What's more, building a single Data Service Layer is also a vital step for practical integration. Acting as a bridge between multiple data sources can offer standardized APIs that support machine learning, simulation, and visualisation. This architecture allows for efficient data reuse and sharing, which then improves decision-making and project coordination.

Ultimately, reinforcing security and protection measures for privacy is also crucial for the combination of IoT and BIM. Data can be secured by encrypting it using blockchain technology and distributed database technology. Establish safe sharing protocols between systems and multi-owner environments. Implementing these two technologies can enhance the level of trust between different systems and their collaboration efficiency.

4.2. Strategies for Data Standardization and Scalable AI Training

Those two primary challenges, non-uniform data standards and the high computational cost of training AI models, further inhibit BIM–AI integration. Following the work by Dagmar Kutá and Michal Faltejsek, the challenges are amenable to systematic rectification by joint developments of data governance, algorithm design, and industry-level coordination [18].

There is a need to address the absence of harmonized data standards. A real-world solution for this problem is the building of interoperability protocols across stages and across platforms. Using the techniques of the semantic web and ontology modeling, the engineer will be able to develop a common semantic base that guarantees the consistency of the meaning across various BIM environments. Using the adoption and propagation of open standards like IFC, CityGML, and gbXML further improves the interpretability of the BIM data by the AI mechanisms. On a larger level, the development of a shared "BIM–AI Data Dictionary" and the formulation of "Semantic Mapping Rules" will define a uniform manner for describing object attributes and behaviours that will advance the portability and transparency of the AI algorithms in the construction industry.

Once data standardisation is resolved, the computational cost challenge may be managed successfully using a scalable architecture. Scalability also addresses the otherwise high expense of training AI models. A cloud–edge hybrid architecture allows for large training to be done in the cloud, while smaller inference work is done near the edge devices requiring it. This configuration keeps computational load and power consumption to a minimum. Transfer learning and federated learning may also avoid redundancy by enabling the models to share knowledge between various projects. Additionally, open repositories of datasets for building construction and pretrained models will reduce the barrier to entry for small and medium enterprises while enabling greater participation in AI-enhanced construction.

4.3. Technical Solutions for Streamlined BIM-AR/VR Workflows

The combination of BIM and AR/VR technologies provides architectural design, construction, and operation work with an interactive visual experience. However, when implemented in real-life scenarios, they are likely to encounter technical issues such as highly complicated models, sluggish conversion of data, inadequate rendering capabilities, and non-uniform data. Based on this dilemma, this article will analyse the transmission of data from AR/VR to BIM, dissect a series of effective mechanisms and optimization schemes introduced by Chen et al. (2020), and condense the ensuing solutions [19].

The Intermediate Conversion Layer is effective for addressing eleven tricky data conversion and incompatible format issues. It establishes a universal intermediate format for data, which allows for automatic mapping between AR/VR engine data structures and BIM raw data. This minimizes the work that needs to be done manually and avoids loss of information. A lightweight IFC (Industry Foundation Classes) standard-based data model is also a handy tool for addressing these challenges. This model converts the semantic and geometric data in BIM automatically into object structures that a VR engine understands directly. This accelerates model conversion, besides reducing the risk of formatting or duplication model errors.

Meanwhile, to cope with huge models and inadequate rendering capabilities, engineers may employ Level of Detail (LOD) and data sharding rendering technologies. Under the export of BIM, the automatic algorithms calculate the priority of each element and its line-of-sight connection, and implement models of varied precision levels for varied regions. This guarantees the accuracy of key parts' visualisation while keeping the system's rendering workload down remarkably and enabling smooth real-time interaction.

Ultimately, the inconsistency between the AR/VR models and the base BIM also has to be eliminated. There is the possibility of geometric misalignment or loss of information when the conventional manually-guided import and conversion are employed. Suppose it opts for the automated detection system and confirms its geometric correctness and feature consistency upon the transmission of the data. In that case, it will be able to guarantee that the AR/VR model supplied will be the same as the original BIM data. This verification mechanism actually enhances the reliability and stability of integration.

5. Conclusion

This study has investigated the paths, challenges, and solutions for integrating BIM with emerging information technologies to drive intelligent construction management. The main findings and conclusions are summarized as follows. First, the integration of BIM and the Internet of Things result in BIM data, device data, and operation and maintenance data being stored in different systems, making the data unable to communicate with each other and hindering the integration process. Second, the combination of BIM and artificial intelligence makes AI somewhat weak in handling complex datasets composed of geometry, semantic information, and other elements in BIM models. For large-scale projects, the volume of data is even greater, posing an even bigger challenge to AI. Third, BIM integrated with AR/VR still does not have a recognized, end-to-end architecture or standardized development tools in the industry, resulting in low development efficiency. Fourth, the core of integration is to build a digital twin system that enables closed-loop interaction between the dynamic real-time data of IoT and the static models of BIM. Although there are technological and cost barriers, with the popularization of cloud platforms and standardized AI models, they will become the industry standard in the future. Finally, BIM is combined with various emerging technologies throughout the entire construction process management. Absorb and utilize its visualization, refinement, and dataoriented advantages in different construction processes to improve efficiency in engineering production. At the same time, it also ensures its safety and construction quality.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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