Research on BIM-Based Intelligent Construction System Integration and Its Application in Civil Engineering

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Abstract. This paper introduces the core role of BIM technology in intelligent construction systems, and analyzes its information flow, collaborative work and data visualization functions in the project life cycle. Then, an integrated model based on the K-means clustering algorithm is proposed to optimize resource scheduling and task allocation during the construction process. By clustering data from different construction scenarios, the model can automatically identify and optimize resource allocation, improve construction efficiency and project progress. Again, this paper constructs a multi-dimensional algorithm framework, covering key steps such as data preprocessing, feature extraction, and cluster analysis. Through simulation experiments, the application effect of the integrated system in actual civil engineering is evaluated. The experimental results show that the K-means clustering algorithm can effectively improve the accuracy and real-time performance of resource allocation, significantly reduce resource waste during construction, optimize construction progress, and the model has good robustness and adaptability. The data analysis results also prove the wide applicability of the system in different construction site environments.

Keywords: BIM, intelligent construction system, integration, civil engineering, K-means clustering algorithm.

1. Introduction

With the rapid development of information technology and intelligent technology, the construction industry is gradually transforming towards digitalization and intelligence. BIM can improve the visualization management, collaborative work and data analysis capabilities of construction projects through digital three-dimensional models and information integration, and has become an indispensable tool for the modern construction industry. However, with the continuous increase in the scale and complexity of construction projects, traditional BIM applications can no longer fully meet the needs of resource optimization and intelligence in project management and construction. Therefore, how to integrate BIM technology through intelligent construction systems and combine it with modern optimization algorithms to improve the resource allocation efficiency and construction management accuracy of civil engineering projects has become a hot topic in current research.

BIM technology creates a digital three-dimensional model of the building and integrates relevant information from various stages of the project on a single platform, which can promote information sharing and collaborative work in the design, construction and operation stages [1]. In the field of civil engineering, BIM technology can not only provide a visual design solution for the project, but also effectively improve resource management, construction scheduling and progress monitoring. However, traditional BIM systems mainly focus on information display and design, and often ignore the dynamic resource management and intelligent scheduling issues in the construction process [2].

The core goal of the intelligent construction system is to achieve automation of the construction process, optimal allocation of resources and precise control of project progress through intelligent data analysis and algorithm optimization [3]. Machine learning and data mining methods such as K-means clustering algorithm, genetic algorithm and particle swarm optimization algorithm are widely used in intelligent construction systems to solve the problems of resource waste, construction delay and quality control in traditional construction methods. Some scholars have proposed a BIM-based construction information management platform, which integrates construction resources, construction progress and quality information, realizes the visualization and information sharing of project management, and greatly improves the collaborative efficiency of the project [4]. Some scholars have designed an intelligent resource scheduling system for construction projects based on the BIM model, using machine learning algorithms to optimize the configuration of construction resources, reduce construction costs, and improve resource utilization.

Some scholars have proposed an intelligent construction system combined with the K-means clustering algorithm, which can automatically cluster and schedule resources according to the real-time data of the construction site, thereby improving construction efficiency and reducing unnecessary waste of resources [5]. Studies have found that the application of the K-means clustering algorithm in civil engineering projects can effectively identify the usage patterns of various resources in the construction process and perform automatic optimization based on these patterns. Some scholars have further explored the possibility of combining BIM with artificial intelligence technology, and proposed to predict and analyze construction project data through deep learning algorithms to provide decision support for resource scheduling and schedule scheduling during the construction process.

This paper proposes an integrated model of intelligent construction system based on BIM. This model combines the K-means clustering algorithm with BIM technology, and uses algorithms to intelligently schedule and optimize the resources in the construction process [6]. In the design part, this paper first analyzes the role of BIM technology in civil engineering, especially its application in the construction stage, and clarifies its advantages in project resource management and construction progress control. Secondly, combined with the K-means clustering algorithm, cluster analysis is performed on the resource data at the construction site to achieve automatic optimization of construction resources.

2. Technical framework for integration of BIM and intelligent construction system

2.1. Integration method of BIM and data model

Dynamically integrating real-time sensor data at the construction site with static information in the BIM model is an important step to achieve full-process monitoring. For example, field sensors can collect data such as temperature, humidity, vibration, etc. in real time, and equipment sensors can provide information on the working status of the equipment [7]. By integrating this data into the BIM model, project managers can monitor the construction process in real time in a virtual environment and promptly discover problems in the construction process, such as equipment failures and construction delays. This integration can not only help project managers better control the real-time status of the construction site, but also provide basic data support for later operation and maintenance.

In actual operation, the standards and formats of data exchange are the prerequisites for ensuring the smooth integration of BIM with other information systems. At present, the industry generally adopts open standard file formats, such as IFC and BIM 360, to ensure data interoperability between different systems [8]. The IFC standard is widely used in cross-platform data exchange of BIM models. It allows different building information management software to exchange data and ensures that all parties can share a unified data set. As a cloud platform, BIM 360 can integrate real-time data from construction sites with BIM models, providing a collaborative working environment across departments and regions.

By adopting standardized data exchange interfaces, BIM models can be seamlessly connected with on-site data flows, construction plans, equipment management and other systems to form an information-integrated closed-loop system [9]. This integration method can reduce human intervention, improve the accuracy and timeliness of information transmission, and ensure that every link in project management can obtain timely and accurate data support.

2.2. Management and optimization of intelligent information flow

In the intelligent construction system, the information flow mechanism mainly includes data collection, information transmission, processing and feedback. By integrating BIM models and on-site sensor data, project managers can obtain real-time information on construction progress, equipment status, personnel safety and other aspects [10]. In addition, the intelligent construction system can also analyze the dynamic data of the construction site in real time and adjust the construction plan or resource allocation based on the analysis results. For example, when the system detects equipment failure or construction delay, it can immediately send early warning information to project managers through the feedback mechanism so that timely measures can be taken.

The intelligent construction system is not only an information integration platform, but also a decision support system. By analyzing a large amount of construction data, it can help project managers identify potential problems and make decisions. Using K-means clustering algorithm to classify and cluster construction data is one of the commonly used data analysis methods in intelligent construction systems. K-means clustering algorithm can cluster different types of data (such as budget data, progress data, quality data, etc.) in the construction process, thereby helping managers identify potential risks of construction progress, cost overruns or quality problems.

3. Application of K-means clustering algorithm in intelligent construction system

3.1. Principle and overview of K-means algorithm

Given a data set containing N samples, the K-means algorithm divides the data set into K clusters so that the samples within each cluster have the smallest variance and the differences between clusters are as large as possible. Suppose the data set is $D = \{x_1, x_2, \ldots, x_N\}$, each sample x_i is a d-dimensional vector, and the K-means algorithm performs clustering through the following steps: Randomly select K initial cluster centers $\mu_1, \mu_2, \ldots, \mu_K$.

For each sample x_i, assign it to the nearest cluster C_k according to its distance to each cluster center.

$$C_k = \{x_i \mid \|x_i - \mu_k\| \leq \|x_i - \mu_j\|, j \neq k\} \quad (1)$$

Update the center point of each cluster, making the center of each cluster the mean of all points in the cluster:

$$\mu_k = \frac{1}{|C_k|} \sum_{x_i \in C_k} x_i \quad (2)$$

Repeat steps 2 and 3 until the cluster division no longer changes.

3.2. Application example of K-means algorithm in intelligent construction

Suppose this article has a construction site containing multiple sensor data, the data set is $D = \{d_1, d_2, \ldots, d_N\}$, where each data point $d_i = (t_i, h_i, p_i)$ contains information such as temperature, humidity and personnel flow. By clustering these data using the K-means algorithm, the characteristic data of different construction stages can be identified to judge the progress of the project. The construction progress clustering formula based on the K-means algorithm can be expressed as:

$$C_k = \arg\min_{\mu_k} \sum_{i=1}^{N} \|d_i - \mu_k\|^2,\ \mu_k = \frac{1}{|C_k|} \sum_{d_i \in C_k} d_i \quad (3)$$

In the construction process, resource scheduling is one of the core elements to ensure the smooth progress of construction. The K-means clustering algorithm can effectively cluster resources such as construction materials, equipment, and labor, thereby achieving the optimal allocation of resources. For example, assuming that there is multiple equipment (such as cranes, concrete mixers, etc.) and many workers in a construction project, this paper can use the K-means algorithm to cluster these resources according to demand and frequency of use, thereby optimizing scheduling.

$$C_k = \arg\min_{\mu_k} \sum_{i=1}^{N} w_i \|r_i - \mu_k\|^2,\ \mu_k = \frac{1}{|C_k|} \sum_{r_i \in C_k} w_i r_i \tag{4}$$

w_i represents the importance weight of the resource, and r_i is the feature vector of the i resource. Through cluster analysis, the system can dynamically adjust the deployment of equipment and labor according to resource usage, thereby achieving optimal resource allocation.

3.3. Optimization and improvement of K-means algorithm

The K-means++ algorithm solves the problem of K-means being sensitive to the initial cluster center by optimizing the selection process of the initial cluster center. The basic idea is to avoid the instability of clustering results by increasing the distance between the initial cluster centers. The improved formula of the K-means++ algorithm is as follows:

$$D(x) = \min_{c \in C} \parallel x - c \parallel^2,\ C = \{c_1, c_2, \dots, c_K\} \tag{5}$$

Among them, $D(x)$ represents the distance from the sample point x to the nearest cluster center. The algorithm improves the stability and accuracy of the clustering effect by selecting points with a large distance from the existing cluster center as the new initial cluster center.

The data in construction projects often contain multiple dimensions, such as time, space, personnel, equipment, materials, etc. The traditional K-means algorithm mainly processes two-dimensional data or low-dimensional data, but in the scenario of multi-dimensional data, the efficiency and effect of the algorithm may be greatly reduced. Therefore, in multi-dimensional data analysis, the K-means algorithm can be improved by adopting a weighted distance metric (such as Mahala Nobis distance) to adapt to the complex needs of construction project management. The weighted K-means clustering formula for multi-dimensional data can be expressed as:

$$C_k = \arg\min_{\mu_k} \sum_{i=1}^{N} \|\Sigma^{-1}(d_i - \mu_k)\|^2 \tag{6}$$

Σ^{-1} is the inverse matrix of the covariance matrix of the data, which can weight different dimensions of the data to improve the clustering effect.

4. Case study of integration of BIM and intelligent construction system

The combination of BIM and intelligent construction systems, especially in terms of construction progress, cost control and quality monitoring, provides more accurate solutions. Based on actual civil engineering project cases, this study explores the integrated implementation of BIM technology and intelligent construction systems and their effect evaluation, focusing on the application of K-means algorithm in construction management, and analyzing its effects in optimizing construction progress, resource scheduling and risk management.

4.1. Case Selection and Background

This study selected a large-scale urban viaduct construction project as a case. The project is about 12 kilometers long, spanning several major urban traffic arteries, and the construction period is 5 years. Due to its special geographical location and complex construction environment, the project faces high technical requirements and great challenges [11]. The project area is busy with traffic, the construction site environment is tense, and the construction process requires coordination of multiple resources. Especially in the design and construction of the viaduct, it is necessary to avoid excessive interference with existing traffic and ensure the safety of surrounding residents. Some special building materials required for the project are difficult to obtain in time, especially in terms of imported materials, which may affect the construction progress. The project involves multiple construction tasks and working surfaces, which require precise scheduling and coordination. How to optimize resource allocation, reduce construction waste, and ensure that the construction period is completed on time is the challenge faced by this project.

4.2. Integrated Implementation and Technology Application

In this project, BIM technology is fully applied to multiple links such as design, construction, and monitoring. By building a three-dimensional BIM model, all parties in the project can conduct a full range of virtual display and analysis of the construction site, discover potential problems in time, and take measures in advance [12]. In addition, the combination of BIM and intelligent construction system, especially the collection of real-time data on the construction site through the Internet of Things technology, further improves the transparency and control accuracy of construction. The real-time monitoring system includes monitoring of construction progress, environmental factors, equipment operation status, etc. The data is transmitted to the integrated system through sensors and cloud platforms, and project managers can obtain data in real time and make decisions. These real-time data are combined with static data in the BIM model (such as design drawings, construction plans, etc.) to form a complete digital project management system. In order to improve the efficiency and accuracy of construction management, this study introduced the K-means clustering algorithm and applied it to multiple key links of the project.

4.3. Case results and effect evaluation

During the implementation of the project, the integration of BIM and intelligent construction system effectively improved construction efficiency, optimized resource scheduling, reduced costs, and improved construction quality and safety. By comparing the construction efficiency, cost control, quality monitoring and other indicators of the project before and after integration, the superiority of the integrated solution was verified.

1) Effect analysis: construction efficiency

Table 1 shows the comparative data of construction efficiency before and after integration. After integrating BIM with the intelligent construction system, the project's construction efficiency has been significantly improved, especially in terms of resource scheduling and construction progress management [13]. After integrating BIM with the intelligent construction system, all stages of the construction progress were generally completed ahead of schedule, and the overall project duration was shortened by about 16.7%, mainly due to the precise integration and scheduling optimization of real-time data and BIM models.

Table 1. Construction efficiency comparison

Project phases	Construction progress using traditional management methods (d)	Construction progress after BIM integration (d)	Finished ahead of schedule (%)
Design phase	45	35	22.2
Construction preparation phase	60	50	16.7
Construction phase	180	150	16.7
Commissioning and completion phase	70	60	14.3

2) Effect Analysis: Cost Control

Table 2 shows the comparison of project cost control before and after integration. After the introduction of BIM and intelligent construction system integration, the cost of the project was effectively controlled, especially in terms of resource utilization and material procurement. By introducing BIM and intelligent construction system integration, the overall cost of the project decreased by about 12.5%. Among them, the cost savings in resource scheduling and quality control were the most significant, thanks to the precise analysis and real-time scheduling of data.

Table 2. Comparison of cost control

Project phase	Traditional cost (RMB 10,000)	Cost after BIM integration (RMB 10,000)	Cost savings (%)
Design phase	200	180	10
Construction phase	800	700	12.5
Resource scheduling	120	100	16.7
Quality control	100	80	20

3) Effect Analysis: Construction Quality

Figure 1 shows the data changes of construction quality monitoring before and after integration. By monitoring the real-time data during the construction process, the system can promptly detect and correct quality problems in the construction, such as abnormal equipment operation, unqualified materials, etc., thereby ensuring the construction quality.

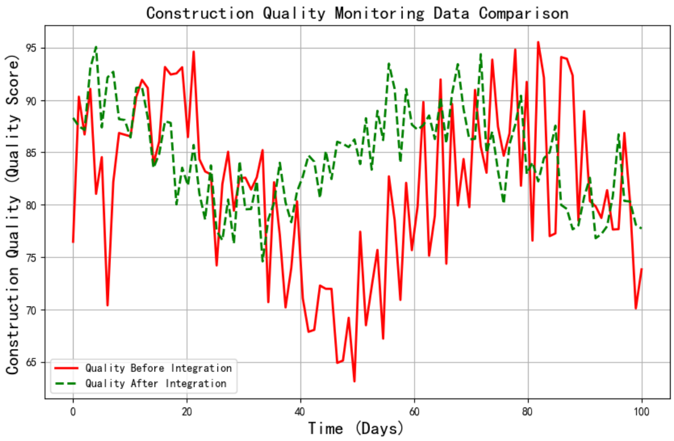

Figure 1. Comparison of construction quality monitoring data

Figure 1 shows that the integrated BIM and intelligent construction system can detect quality problems in the construction process timelier, and ensure that the construction quality meets the design standards by adjusting the construction plan in real time.

4) Effect analysis: risk management

Figure 2 shows the application of K-means clustering algorithm in risk management. By clustering sensor data from different areas of the construction site, the system can identify potential risk areas and issue warnings in time.

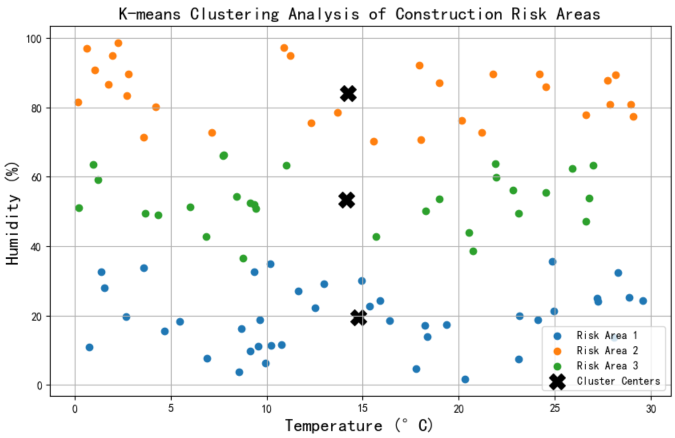

Figure 2. Risk early warning system

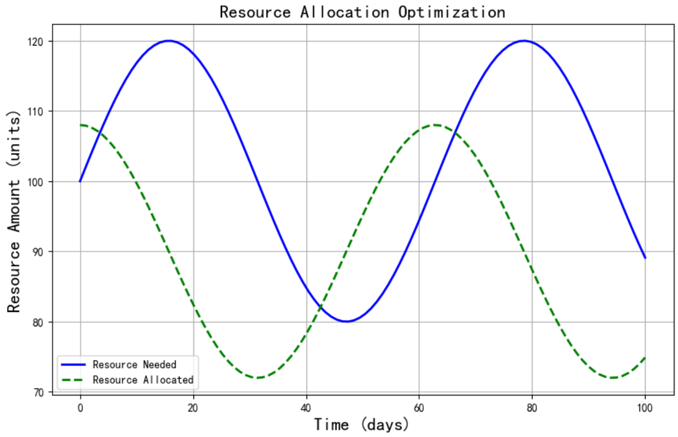

Figure 3. Resource scheduling optimization effect

Figure 3 shows the optimization effect of project resource scheduling after the integration of BIM and intelligent construction system. Through the combination of BIM model and real-time data of intelligent construction system, resource scheduling is accurately optimized. The figure shows the allocation of resources (such as building materials, equipment, and labor) at different time nodes and their matching degree with the construction progress. The integrated system can adjust resource allocation in real time, thereby ensuring the smooth progress of each stage of construction and reducing resource waste.

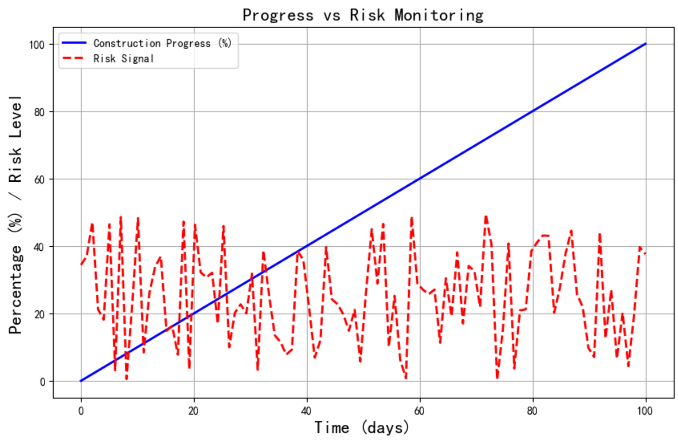

Figure 4. Real-time response of construction progress and risk monitoring

Figure 4 shows the real-time response of construction progress and risk monitoring after the integration of BIM and intelligent construction system. By monitoring the real-time data of the construction site, the system can automatically adjust the construction plan to ensure progress while optimizing risk management. The data in the figure shows the combination of construction progress and risk signals of real-time monitoring. When potential safety hazards occur, the system will immediately adjust the construction progress to avoid risks.

The real-time optimization of construction progress, cost and risk management combined with the K-means algorithm further improves the accuracy and efficiency of project execution. In the future, with the continuous advancement and innovation of technology, BIM and intelligent construction systems will play an increasingly important role in civil engineering project management, providing solid technical support for the digital transformation and intelligent management of the construction industry.

5. Conclusion

This study explores the integration of intelligent construction systems based on BIM (Building Information Modeling), proposes an optimization model combined with the K-means clustering algorithm, and verifies its application potential in civil engineering. The study shows that BIM, as the core technology of digital construction, can provide efficient information management and collaborative operation platform for civil engineering projects. The intelligent construction system further improves the accuracy of resource allocation, construction progress and quality control by integrating different calculation methods and algorithms. Through the application of the K-means clustering algorithm, the system can realize the automatic classification and optimization of construction site resources, significantly improving resource utilization and construction efficiency. The simulation results show that the integrated model has strong adaptability and robustness in actual engineering applications, can effectively cope with challenges in different construction scenarios, and optimize the overall progress management of the project. In addition, the real-time data analysis function of the system further enhances the controllability of the project, reduces unnecessary waste of resources, and improves the overall quality of the project.

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