Research on Optimization of Municipal Road Construction Management under Intelligent Construction Environment

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Abstract: Aiming at the shortcomings of traditional municipal road construction management mode in efficiency, quality, safety and environmental protection, and the challenges faced by intelligent construction technology in integration, coordination and scene adaptation, this paper puts forward a closed-loop management framework of "perception-simulation-optimization-control" based on digital twin technology. The framework integrates multi-source heterogeneous data such as BIM, IoT (Internet of Things) and Management Information System (MIS) to build a high-fidelity digital twin model and realize dynamic virtual mapping of the physical construction site. On this basis, a dynamic scheduling optimization model is established, which can deal with uncertainty, so as to realize the multi-objective collaborative optimization of construction cost, machinery idle rate and carbon emission. Case study shows that the model can effectively reduce the idle rate of machinery, shorten the construction period, control costs and reduce carbon emissions, and provide a feasible practical path for the digital and intelligent transformation of municipal road construction management.

1. Introduction

With the continuous expansion of the scale of urban roads in China, the traditional municipal road construction mode faces severe challenges in terms of efficiency, quality, safety and environmental protection. The problems such as high idle rate of machinery, high rework cost, frequent accidents and high carbon emissions are prominent. With the rapid development of intelligent construction technology in the world, the application of BIM and IoT (Internet of Things) is becoming more and more popular, and China's policies have clearly put forward the development goal of intelligent construction, so it is extremely urgent to promote the digital and intelligent transformation of municipal road construction management [1].

Although intelligent construction has made a breakthrough in single-point technologies such as BIM simulation and UAV inspection, it faces three major faults: insufficient interaction between IoT and BIM data, serious information isolated island of the participants, and difficulty in adapting the industrialized intelligent mode to the complex environment of municipal roads, which restricts technical integration, management collaboration and scene adaptation. This study combines complex system theory with digital twin technology, and puts forward a closed-loop management framework of municipal road construction perception, simulation and optimization; A dynamic scheduling model based on multi-source heterogeneous data fusion is established to fill the gap in uncertainty processing in existing research.

2. Construction management optimization model construction

2.1 Overall framework

In order to solve the "three faults" problem, this study constructs a closed-loop management framework of "perception-simulation-optimization-control". The framework takes the digital twin of municipal road construction as the core, and realizes management optimization through four

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levels as shown in Figure 1.

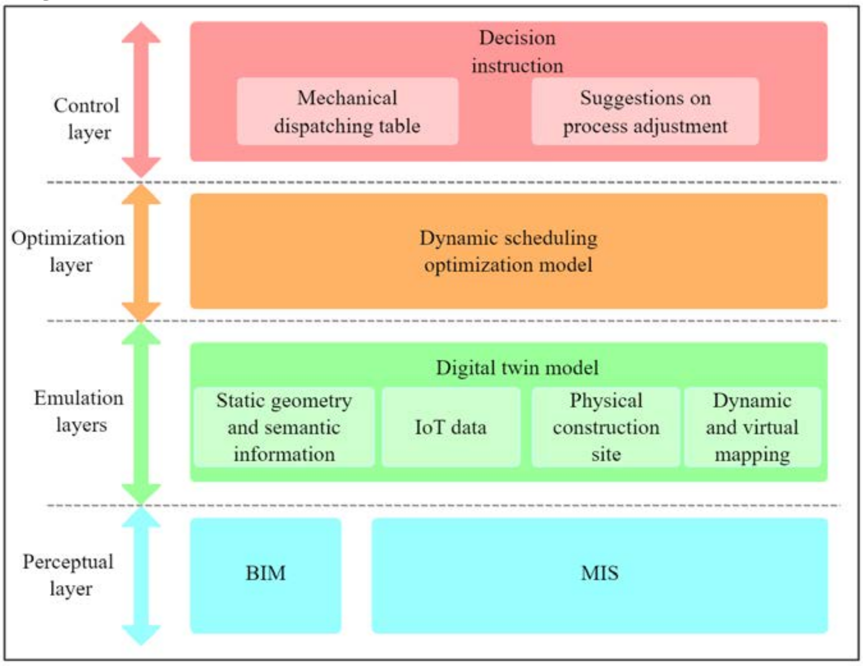

Figure 1 Closed-loop management model based on digital twinning

The perception layer comprehensively utilizes the data of BIM, IoT devices and management information systems (MIS), and carries out preliminary cleaning and integration through the edge computing gateway to build a multi-source heterogeneous database [2]. This layer aims to break the "information island".

The simulation layer drives the digital twin model of the construction site based on the fused high-fidelity data. This model not only contains the static geometric and semantic information provided by BIM, but also integrates the real-time data of IoT, thus realizing the dynamic and virtual mapping of the physical construction site [3-4]. This layer solves the problem of insufficient data interaction between IoT and BIM.

The optimization layer is the core of this model. Based on the real-time state reflected by digital twins, the dynamic scheduling optimization model is embedded. The model can deal with the uncertainty in the construction process, and output the optimization scheme of resource scheduling and process arrangement periodically or triggered. This layer directly responds to the challenge of "open complex environment".

The control layer pushes the decision instructions generated by the optimization layer to the handheld terminal or mechanical control system of the site management personnel to guide the construction activities in the physical world. The execution results are captured by the perception layer again, forming closed-loop feedback, thus realizing continuous optimization of management.

2.2 Dynamic scheduling optimization model based on multi-source data fusion

Establish a dynamic scheduling model that can deal with uncertainty. Under the constraints of time limit for a project (T), quality and safety, multi-objective dynamic collaborative optimization such as construction cost (C), machinery idle rate (I) and carbon emission (E) can be realized [5-6]. This is a typical multi-objective optimization problem.

Considering the linear and segmented characteristics of municipal road construction, it is modeled as a multi-objective, multi-stage and constrained resource dynamic scheduling problem [7]. A comprehensive objective function in the form of weighted summation is constructed, which is convenient to solve and reflects the multi-objective characteristics.

$$\text{Minimize } Z = \omega_1 \frac{C_t}{C_0} + \omega_2 \frac{I_t}{I_0} + \omega_3 \frac{E_t}{E_0} \quad (1)$$

Where Z is the target value of comprehensive optimization, and the smaller the value, the better the scheme. C_t is the actual cost in the calculation period. Including machinery rental fees, labor costs, extra costs caused by delay or rework, etc. C_t = ∑ (machine shift fee × service time+manual shift fee × working hours+penalty cost). C_0 is the benchmark planned cost.

I_t is the comprehensive mechanical idle rate in the calculation period. I_t = (∑ (total available time of machinery-actual working time of machinery)/∑ total available time of machinery. Real-time calculation through IoT data. I_0 is the benchmark idle rate.

E_t is the estimated carbon emission during the calculation period. Based on IoT data such as mechanical fuel consumption and power consumption, it is estimated by multiplying them by emission factors. E_t = ∑ (mechanical fuel consumption × fuel emission factor+power consumption × power emission factor). E_0 is the benchmark emission.

$\omega_1, \omega_2, \omega_3$ is the weight coefficient of cost, idle rate and carbon emission respectively, and satisfies $\omega_1 + \omega_2 + \omega_3 = 1$. The weight can be set by the management according to the actual priority of the project.

The model needs to be optimized under the constraint of dynamic updating to ensure that the total construction period of the project does not exceed T specified in the contract, that is, the sum of the duration of key processes meets $\sum t_k \le T$; Each process must follow the established logical order, and the start time S_j of the subsequent process j should not be earlier than the end time ($S_i + D_i$) of the immediately preceding process i ; At the same time, the demand for all kinds of resources at any time $R_n(t)$ must not exceed the real-time available resources $R_{n_{available}}(t)$; In addition, it is necessary to avoid the spatial conflict in the construction process, and carry out real-time collision detection through the digital twin model to ensure that the construction areas working at the same time do not interfere with each other in space.

The mechanism of uncertainty handling and dynamic optimization is introduced, and the traditional static mode of making full-cycle plan at one time is abandoned, and rolling cycle optimization strategy is adopted instead [8]. The model senses the state of the construction site in real time through digital twins, and automatically triggers re-optimization when significant deviation or sudden abnormal events are detected. The triggering conditions include: the deviation between the actual progress and the planned progress exceeds the threshold Δ_1, the key mechanical equipment fails, the environmental parameters exceed the safety threshold Δ_2 or Δ_3, and the delay of the arrival time of important materials exceeds Δ_4. This event-driven response mechanism ensures that the construction plan can adapt to the site changes in time, and improves the feasibility and robustness of the plan.

In order to meet the challenge of high complexity computation (NP-Hard problem) brought by dynamic re-optimization, the model adopts efficient meta-heuristic algorithm to solve it quickly [9]. Through iterative optimization, the fitness function (that is, the above-mentioned objective function Z) tends to be optimal, so that the optimal or near-optimal construction scheduling scheme can be continuously generated under the dynamic constraint environment.

2.3 Data fusion method

In order to support the above optimization model, it is necessary to fuse multi-source heterogeneous data. Based on BIM and GIS data, provide road design model and geographical environment information as spatial benchmark; The GPS and sensor data collected by IoT equipment are denoised and smoothed by Kalman filter and other algorithms to realize accurate real-time perception of the position and state of machinery and personnel; The construction progress data is automatically compared with BIM model by using the orthophoto images regularly obtained by drones and combining with computer vision technology, and the earthwork volume and the completion ratio of structures are calculated to realize the automatic identification and update of progress; Finally, all the data are integrated into the BIM coordinate system and stored in the spatio-temporal database under a unified spatio-temporal benchmark, forming high-precision, real-time synchronized fusion data, providing reliable data input for digital twins and dynamic optimization models.

3 Case empirical study

In order to verify the practical application effect of the intelligent construction management optimization model constructed in this study, this study selects a "comprehensive renovation project" in a city in East China as an empirical case. The total length of the project is 2.5 kilometers, and the construction content covers subgrade treatment, pipeline laying, water-stable layer and asphalt pavement paving, etc. The environment is complex, the construction period is tight and the environmental protection requirements are high. The project is divided into two experimental sections:

Control group (K0+000-K1+250): Traditional construction management methods, relying on experience to make static plans, and communicating through manual reports.

Experimental group (K1+250-K2+500): Deploy the intelligent construction management system proposed in this study. Data are collected by IoT devices such as UAV, mechanical GPS and intelligent yard, and connected to the digital twin platform based on BIM to run the dynamic scheduling optimization model constructed in Chapter 2 (the optimization period is one day).

After a three-month construction period, the key performance indicators (KPI) of the two groups were compared and analyzed, and the results are shown in Table 1 below. The experimental group using intelligent optimization model is significantly better than the control group using traditional methods in KPI: the average mechanical idle rate is reduced from 28.5% to 15.2%, which is 46.7%; The deviation rate of construction period is improved from 12.3% delay to only -1.8%, and the overall progress control ability is improved by 14.1%; The proportion of rework cost decreased by 68.8%, from 4.8% to 1.5%; At the same time, the carbon emission per unit output value decreased from 1.82 t/ 10,000 yuan to 1.61 t/ 10,000 yuan, with a decrease of 11.5%, which fully shows that the intelligent optimization model has obvious advantages and practical application effects in improving resource utilization rate, ensuring construction period, controlling cost and promoting green construction.

Table 1 Comparison table of main performance indicators

Performance indicators	Control group (traditional method)	Experimental group (intelligent optimization model)	Enhancement/improvement range
Average mechanical idle rate	28.5%	15.2%	Decrease by 46.7%
Time limit deviation rate	+12.3% (delay)	-1.8% (almost on time)	14.1% improvement
Proportion of rework cost	4.8%	1.5%	Decrease by 68.8%
Carbon emission per unit output value	1.82 t/ ten thousand yuan	1.61 t/ ten thousand yuan	Decrease by 11.5%

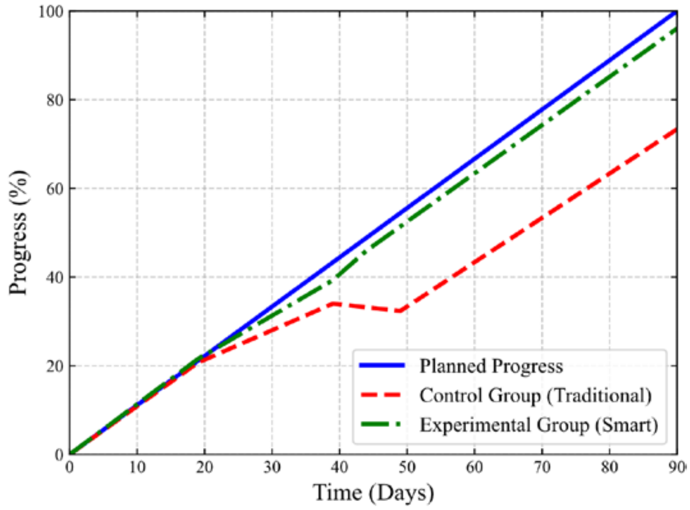

Figure 2 Comparison curve of construction progress

Figure 2 above shows the comparison of the planned progress, the actual progress of the control group and the actual progress of the experimental group. The progress curve of the control group continued to be lower than the planned baseline in the middle and late period (rework due to rainfall and a pipeline installation error). Although the progress curve of the experimental group fluctuated due to the same rainfall, the model dynamically adjusted the subsequent process (the original planned outdoor operation was adjusted to the installation of prefabricated components), and the progress quickly returned to the planned baseline, and finally it was almost completed on time.

The case study shows that the intelligent building optimization model proposed in this study shows remarkable effectiveness, synergy and sustainability in municipal road construction. The model can effectively cope with uncertain factors such as weather change and rework, and significantly reduce the idle rate of machinery, construction delay and rework cost through dynamic scheduling, which verifies its practical application value. The multi-source data fusion framework based on digital twins has successfully broken the "information island" of all parties involved in the construction, providing a solid data foundation for global optimization; At the same time, the model takes carbon emissions into the optimization goal, which improves efficiency and reduces costs while giving consideration to environmental benefits, which reflects the potential of intelligent construction to promote green construction, and fully proves that the model provides a practical path for solving the pain points of the industry and realizing the digitalization and intelligent transformation of municipal road projects.

4. Conclusion

The experimental group adopting the intelligent construction optimization model is significantly superior to the control group in key performance indicators such as average mechanical idle rate, construction period deviation rate, rework cost ratio and carbon emission per unit output value, which verifies the remarkable advantages and practical application effect of the model in improving resource utilization rate, ensuring construction period, controlling cost and promoting green construction. The case study further shows that the model can effectively cope with uncertain factors such as weather change and rework, realize global optimization through dynamic scheduling, break the information isolated island of all parties involved in the construction, and provide a practical path for the digital and intelligent transformation of municipal road engineering. To sum up, the intelligent construction optimization model proposed in this study not only improves the management efficiency and quality of municipal road construction, but also promotes green construction and sustainable development, and provides an effective solution to solve the pain points in the industry.

References

[1] Lu Zhanyang, Sun Tingting, Li Junji. Research on Quality Control Issues and Refined Management Measures of Municipal Road Construction[J]. Petrochemical Technology, 2025, 32(08): 437-438.

[2] Huang Dingwu. Exploration of Construction Management Strategies for Road Rainwater and Sewage Pipeline under Low-Carbon Background[J]. New Urban Construction Science and Technology, 2025, 34(07): 196-198.

[3] Wang Yang, Liu Xiang. Research on Safety Management Technology of Municipal Road Construction Site[J]. Guangdong Building Materials, 2025, 41(07): 152-155.

[4] Zhang Qian. Exploration of Quality Control and Safety Management Strategies in Municipal Road Engineering Construction[J]. Automotive Weekly, 2025, (08): 178-180.

[5] Huang Yangyang, Zhang Yanping, Hao Chao. Analysis of On-site Construction Technology and Application in Municipal Road and Bridge Construction[J]. Automotive Weekly, 2025, (08): 227-229.

[6] Tao Yu, Shi Tao, Ma Xiaomin. Research on Cost Control and Management of Municipal Road Construction Projects[J]. Chinese Construction, 2025, (07): 86-88.

[7] Chen Hui, Liu Hengxin, Li Juan. Analysis of Optimized Construction and Management Methods of Municipal Road Engineering[J]. China Residential Facilities, 2025, (06): 130-132.

[8] Zhou Biao. Research on the Application of Digital Technology in On-site Management of Municipal Road Construction[J]. New Urban Construction Science and Technology, 2025, 34(06): 129-131.

[9] Jin Hongwen. Research on Refined Management and Quality Control of Municipal Road Construction[J]. Times Automobile, 2025, (14): 163-165.