ISSN: 1813-4890

Carbon Reduction Method for High-Speed Railway Bridge Construction Based on Multi-Objective Optimization Theory

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Abstract

With the dual pursuit of low carbon and efficient construction in the high-speed rail bridge construction field, the application of carbon emission reduction optimization strategies has become crucial. This paper proposes a carbon emission reduction optimization scheme for high-speed rail bridge construction, which comprehensively considers various factors such as carbon emission sources during the construction process, construction progress, cost control, and quality, providing a scientific basis for the formulation of construction plans and aiding in achieving the goal of green construction. By analyzing and quantifying key parameters during the construction process, such as carbon emission intensity, material usage efficiency, and construction scheduling, and employing multi-objective optimization algorithms to evaluate and optimize these parameters comprehensively, the optimal construction strategy is ultimately generated. This scheme not only effectively enhances the precision of carbon reduction measures but also reduces the environmental impact during the construction process, offering strong technical support and decision-making reference for the sustainable development of high-speed rail bridge construction.

Keywords

High-speed rail bridge construction, multi-objective optimization theory, carbon reduction methods, low-carbon materials, green construction.

1. Introduction

With the increasingly severe issue of global climate change, the construction industry, as a major sector of energy consumption and carbon emissions, urgently needs to find innovative solutions to reduce carbon emissions. High-speed rail bridge construction, being a high-intensity and highly complex engineering project, primarily generates carbon emissions from the use of cement, steel, machinery, and energy consumption during the construction process. Therefore, it is particularly important to adopt effective carbon reduction strategies and optimize various decisions during the construction process. The carbon reduction method for high-speed rail bridge construction, based on multi-objective optimization theory, aims to minimize carbon emissions during construction while ensuring quality, progress, and safety, and has become one of the current research hotspots[1].

2. Overview of Multi-Objective Optimization Theory

Multi-objective optimization theory focuses on managing multiple conflicting objectives by constructing a multivariate objective function to find a dynamic equilibrium among them. In high-speed rail bridge construction, the core objectives include minimizing carbon emissions, optimizing construction progress, optimizing costs, and maximizing quality and safety. The

ISSN: 1813-4890

carbon emission reduction method for high-speed rail bridge construction, based on multi-objective optimization, requires a comprehensive consideration of the interactions between these objectives and the implementation of systematic strategies.

3. Multi-objective Optimization Method for Carbon Emission Reduction in High-Speed Rail Bridge Construction

3.1. Source Apportionment of Carbon Emissions

Material Usage: Cement production accounts for over 97% of the carbon emissions from concrete, and the energy consumption in the steel reinforcement smelting process is substantial;

Construction Machinery and Equipment: Large fuel-powered machinery (such as diesel cranes) are the primary sources of carbon emissions during the construction phase;

Energy Consumption and Transportation: Long-distance transportation of building materials and electricity use at construction sites (such as for concrete mixing);

Waste Disposal: Landfilling or reprocessing of construction waste (such as waste concrete and steel reinforcement) results in additional emissions.

3.2. Multi-objective Optimization Strategy

(1) Carbon Emission Minimization Strategies Material Selection and Usage Optimization: Carbon emissions can be reduced through the application of low-carbon substitute technologies and the use of circular materials. Utilizing mineral admixtures such as fly ash and slag to replace a portion of the cement reduces consumption; employing high-strength steel (such as HRB600) decreases the amount of steel required. Additionally, using recycled aggregates (recovered from waste concrete) instead of natural sand and gravel minimizes carbon emissions during resource extraction[2].

Efficient Machinery and Construction Techniques: The adoption of energy-efficient equipment, digital construction technologies, and prefabricated components can reduce energy consumption during the construction process, thereby lowering carbon emissions.

(2) Construction Schedule and Cost Optimization Construction Schedule Optimization: When calculating the total project duration, a key factor is understanding the duration of subsequent construction activities under uncertainty or incomplete information[3]. Efficient management of the construction timeline is achieved through the Critical Path Method (CPM) and parallel construction. Incorporating carbon reduction measures (such as commissioning electric machinery) into critical nodes of the construction plan also aids in optimizing resource allocation. Project managers can determine the total project duration based on the critical path, enhancing overall resource utilization, reducing unnecessary resource idling and waste, and lowering project costs. Cost Control: For example, high-efficiency water reducers, despite their relatively high procurement cost, can significantly reduce cement usage and improve construction efficiency, thus lowering overall costs. Cost reduction can also be achieved through the centralized procurement of low-carbon materials (such as bulk purchasing of recycled aggregates), ensuring both project quality and the achievement of carbon emission reduction goals.

(3) Carbon Reduction and Quality Quality Control: Ensuring engineering quality through digital testing and material performance verification.Use advanced technologies such as drone patrols and laser scanning to monitor the construction process in real-time. For low-carbon materials like mineral admixture concrete, ensure their strength and durability meet design requirements by combining laboratory performance tests with on-site sampling inspections, guaranteeing the structure remains stable and reliable over time.

ISSN: 1813-4890

4. Key Technologies for Concrete Emission Reduction

4.1. Concrete Material Emission Reduction Technology

4.1.1. Low Mix Design

(1) Application of Water Reducers Admixtures are essential components in concrete or mortar, and their proper addition before or during mixing can significantly enhance the workability of fresh concrete while ensuring strength and durability. They also help reduce cement consumption, offering both economic and environmental benefits. Water reducers are classified into three categories based on their effectiveness: ordinary, high-efficiency, and high-performance (e.g., polycarboxylate-based). Polycarboxylate ether (PCE) is one of the most extensively used admixtures in the construction industry, capable of improving the dispersibility of high-performance concrete suspensions, thereby enhancing its rheological properties and workability [4]. Therefore, the appropriate selection of water reducers not only improves concrete performance but also achieves a balance between economic savings and environmental protection.

(2) Compound Technology of Mineral Admixtures The compound technology of mineral admixtures is a key approach to achieving low-carbon concrete. By incorporating industrial solid wastes such as fly ash (e.g., 20%) and slag (e.g., 30%) to partially replace cement, carbon emissions from concrete production can be significantly reduced. Research indicates that this blending method can cut carbon emissions by approximately 25%. Zhang D et al. investigated the effects of varying amounts of fly ash and slag powder in coal gangue shotcrete. Their findings revealed that a low substitution rate of fly ash effectively improved the pore structure [5]. However, when applying this compound technology, it is crucial to carefully control the total proportion of blended materials to prevent any adverse impact on the early strength of concrete.

4.2. Plant-mixed concrete machinery emission reduction technology

The key mechanical emission reduction technologies for plant-mixed concrete focus on optimizing the machinery and equipment used in the production process, as well as their operation methods, to reduce carbon emissions and enhance production efficiency[6].

Equipment upgrades: High-efficiency energy-saving mixers help lower energy consumption. Additionally, the integration of automated systems reduces errors from manual operations, minimizes material waste, and improves both production efficiency and product quality.

Energy substitution: Replacing diesel-powered loaders with fully electric models enables zero-emission operation, with each unit cutting CO_2 emissions by approximately 20 tons annually, significantly reducing the carbon footprint. Furthermore, installing photovoltaic power systems at mixing plants harnesses solar energy to meet electricity needs for lighting and control systems, decreasing dependence on conventional power sources and further reducing carbon emissions.

4.3. Intelligent Concrete Mixing Plant: A Case Study in Reducing Carbon Emissions

(1) Concrete Cloud Connection System The Concrete Cloud Connection System is an intelligent management and control system specifically designed for concrete production. By integrating hardware and software, it enables full-process intelligent management of concrete production[7]. Operating Procedure: On-site technicians submit concrete task orders through the WeChat Official Account. After laboratory staff review the mix proportions, the control center arranges production based on the review results. Mixing plant operators produce concrete according to the specified mix proportions and use the information tracking system to

monitor production progress in real time, ensuring proper allocation of construction personnel and scheduling, see Fig. 1.

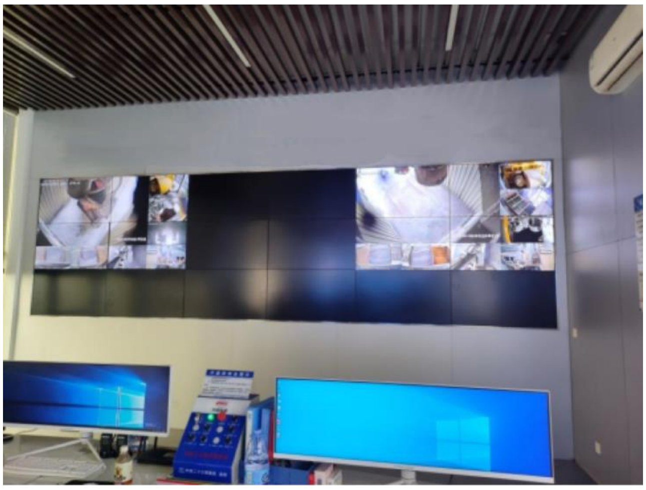

Fig. 1 Project Department Intelligent Concrete Mixing Station Cloud Management System

(2) Intelligent Material Acceptance System The intelligent material acceptance system enables comprehensive lean management of material entry and exit by leveraging IoT technology. It uses hardware installed around the weighbridge to intelligently monitor cheating behaviors and automatically collect precise data. By employing data integration and cloud computing technologies, it ensures real-time access to first-hand information[8]. Operation Process: When a material truck is ready to be weighed, the LED screen displays guidance information, while the outdoor camera captures images and automatically recognizes the license plate number. After the weighmaster selects the material details, the system automatically completes the weighing and data recording, then directs the driver to unload at the designated material warehouse. Once unloading is complete, the system automatically weighs the empty vehicle and records the data, achieving closed-loop management of the material acceptance process. User terminals include PC and mobile applications, enabling managers to monitor vehicle status in real time and perform remote dispatching and control through these interfaces, see Fig. 2.

Fig. 2 Application of Intelligent Material Acceptance System in Silos

The combined use of the Concrete Cloud Contact System and the Intelligent Material Acceptance System has enabled the intelligent and precise management of concrete production and material acceptance processes in high-speed rail bridge construction. This not only enhances construction efficiency and quality but also plays a crucial role in reducing carbon emissions. By streamlining production workflows and optimizing material management, it minimizes human intervention and material waste, boosts the utilization rates of materials and energy, and consequently cuts down on carbon emissions. Additionally, it facilitates the adoption and

ISSN: 1813-4890

management of low-carbon materials and technologies, driving the shift of high-speed rail bridge construction toward greener and more intelligent practices.

5. The Integrated Logic of Multi-Objective Optimization Applications

In the field of concrete engineering and construction, a series of integrated measures must be implemented to minimize carbon emissions, optimize construction schedules, reduce costs, and achieve a balanced multi-objective approach to quality and safety. Below is a detailed explanation of the key measures for each objective dimension and their synergistic benefits, see Table 1.

Table 1 Multi-objective Optimization: Goal Dimensions and Key Measures Synergy Benefits Table

Target Dimensions	Key Measures	Synergistic Benefits
Minimizing Carbon Emissions	Low-carbon materials, electric machinery, Intelligent processes, renewable energy	Reduce resource consumption, cut long-term environmental costs
Optimizing Construction Progress	BIM scheduling, prefabricated construction, critical path management	Shorten construction time, prevent delays due to emission reduction
Cost Optimization	Material savings, Improved equipment energy efficiency, smart management	Lower labor, energy costs while balancing investments in emission reduction
Quality and Safety	Digital monitoring, standardized processes, intelligent safety systems	Ensure project durability, mitigate operational risks

6. Conclusion

This paper develops a carbon reduction methodology based on multi-objective optimization theory to address the reduction of carbon emissions from high-speed railway bridges. By combining technological innovation with coordinated management, it successfully resolves the conflicts among traditional carbon emission reduction measures for high-speed railway bridges, significantly contributing to the realization of the "dual carbon" goals and the sustainable development of the construction industry.

Acknowledgements

This work was supported by the National Natural Science Foundation of China(No. U23A2046), the Sichuan Youth Sci-Tech Innovation Team Project(No. 2022JDTD0007), the Tianfu Ten Thousand Talents Program of Sichuan Province(No. 6580), and the Scientific Research Program Projects of China Railway Construction Corporation Limited(CRCC)(No. 2023-Q04).

ISSN: 1813-4890

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