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Study on lifecycle management of high-speed rail catenary system under the MDD-APC theory

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Abstract

Purpose – The rapid development of China's railway construction has led to an increase in data generated by the high-speed rail (HSR) catenary system. Traditional management methods struggle with challenges such as poor information sharing, disconnected business applications and insufficient intelligence throughout the lifecycle. This study aims to address these issues by applying building information modeling (BIM) technology to improve lifecycle management efficiency for HSR catenary systems.

Design/methodology/approach – Based on the lifecycle management needs of catenary engineering, incorporating the intelligent HSR "Model-Data Driven, Axis-Plane Coordination" philosophy, this paper constructs a BIM-based lifecycle management framework for HSR catenary engineering.

Findings – This study investigates the full-process lifecycle management of the catenary system across various stages of design, manufacture, construction and operation, exploring integrated BIM models and data transmission methods, along with key technologies for BIM model transmission, transformation and lightweighting.

Originality/value – This study establishes a lossless information circulation and transmission system for HSR catenary lifecycle management. Multi-stage applications are verified through the construction of the Chongqing–Kunming High-Speed Railway, comprehensive advancing the intelligent promotion and high-quality development of catenary engineering.

Keywords Intelligent HSR, Catenary system, Lifecycle management, Building information modeling (BIM), Data circulation

Paper type Research paper

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1. Introduction

The high-speed rail (HSR) catenary system, as a critical part of electrified railway infrastructure, is integral not only to the safe and stable operation of trains but also to the transportation efficiency and economic performance of the railway network. In recent years, the wide application of building information modeling (BIM) in specialized construction fields such as railway bridges, tunnels and subgrade projects has significantly enhanced traditional railway infrastructure projects in areas of progress control and quality management. Consequently, BIM technology has been progressively extended to other engineering domains, including station building and catenary engineering (Li, Liu, & Shao, 2023). Through the creation of comprehensive, virtual models that fully mirror physical structures, BIM enables precise modeling, information sharing, business collaboration and management across the entire lifecycle of physical assets, yielding notable benefits in practical applications (Liu, Jiang, Lyu, & Li, 2024; Wang, 2015). The management of high-speed rail catenary system spans multiple stages, including design, manufacture, construction and operation. However, existing BIM model applications for catenary systems are limited to isolated applications within individual project stages, lacking continuity of data and models across the entire lifecycle (Jin & Li, 2021). This limits the realization of comprehensive efficiency and value of BIM technology, the primary reasons of which can be summarized as follows:

First of all, the HSR catenary system generates and accumulates vast amount of data and information during the design, manufacture, construction and operation stages. However, the overall utilization of the data remains limited, causing significant problems such as disrupted data flow across different stages of the system's lifecycle and insufficient data sharing and integration. This underscores the urgent need to establish a traceable data transmission mechanism that links all stages of the entire lifecycle of catenary engineering.

Secondly, there are issues of repeated modeling and low relevance between models and business operations during the transmission of catenary engineering models from the design stage to the construction stage. This leads to the design delivery model failing to meet the parametric requirements of the BIM model during the manufacture and construction stages. Therefore, it is necessary to establish model reuse standards across stages to reduce the redundant development of BIM models.

Besides, the process of integrating engineering structural geometry and non-geometry information, such as material information, into the various stages of catenary system projects, from design to manufacture, construction and operation, presents significant complexity. A unified data standard is yet to be established for both geometric information of engineering structures and non-geometric information such as material data, across different stages of the project (Meng, 2019). A standardized platform for design, review and visualization has yet to be established, insufficient to provide a data foundation that supports efficient collaboration and seamless transmission throughout the entire lifecycle of catenary engineering.

Finally, during the operation stage of catenary engineering, it is challenging to integrate and utilize data from previous stages, leading to the risk of data silos. It is essential to extend the downstream business flow interface on the basis of the data and model transmission flow between design and construction stages, thereby enabling the sharing and integration of catenary models and data across all stages.

To address the issues outlined above, based on the catenary system BIM technology combined with the intelligent high-speed rail "Model-Data Driven, Axis-Plane Coordination" (MDD-APC) lifecycle management philosophy, this paper proposes an intelligent management approach for the HSR catenary system, spanning the entire chain from design, manufacture, construction to operation (Wang, 2022). Through the research of key technologies during lifecycle management of HSR catenary system such as integrated transmission method for BIM models and data; transmission, transformation and lightweighting of BIM models, a BIM-based HSR catenary model-data integration platform is established. The goal is to achieve seamless integration and efficient transmission of data and models across all stages, thereby enhancing management efficiency and optimizing resource allocation. This research provides a scientific basis and technical support for the management and maintenance of HSR catenary system, promoting the overall intelligence of HSR catenary system.

2. In-depth study of the MDD-APC theory in the lifecycle management of the catenary system

The "Model-Data Driven, Axis-Plane Coordination" (MDD-APC) theoretical approach is applicable not only at the macro level for optimizing intelligent HSR overall efficiency by enabling interdisciplinary collaboration across construction, equipment and operation (Wang, 2021), but also for achieving comprehensive lifecycle optimization within individual disciplines, such as the catenary system, as shown in Figure 1.

In the design phase, a unified BIM collaborative design platform is established, with standards for plugin tools, family library management, component attribute definitions and model upload formats. This platform enables iterative comparisons across different stages, such as feasibility reports, preliminary design and construction drawing design, facilitating dynamic optimization of the design solutions.

In the manufacture stage, based on BIM design delivery models, catenary components suitable for intelligent production (such as cantilevers and droppers) undergo further detailed processing. BIM models and relevant data are input into the intelligent production system, enabling remote automated production control. Therefore, intelligent production line equipment can achieve functions such as automatic pre-assembly data recognition, automatic pipe feeding, automatic length cutting and drilling, automatic spray coding and marking, automatic part positioning, automatic part fastening, and automatic product unloading and stacking. Meanwhile, production data can be fed back into the construction management system.

In the construction stage, based on BIM manufacture delivery model, this approach focuses on data refining in areas of quality, safety, progress, investment, control and environmental protection. It explores multi-dimensional data collaboration, prompts the relationship mapping between BIM models and construction progress and automatic generation of detailed "one pole, one file" data of the catenary system. Additionally, intelligent installation equipment is developed and utilized, ensuring synchronization between BIM model, data and smart installation devices. This improves the installation efficiency of catenary system key components, including poles, wire supports, cantilevers and droppers.

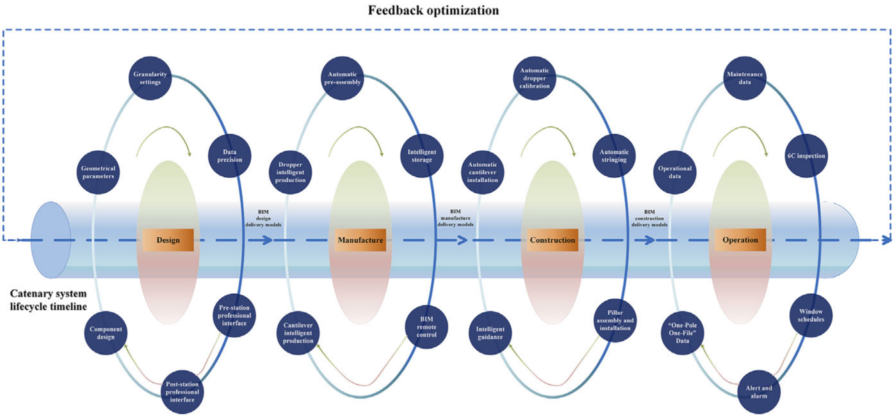


Figure 1. Lifecycle management of the high-speed rail catenary system based on the MDD-APC theory.
Source: Authors' own work

In the operation stage, data interfaces are established to integrate the detailed catenary "one pole, one file" data with maintenance data. This allows for the seamless fusion of various data sources, such as window schedules, operational data, 6C data, defect databases, overpass bridge/line data, alert data and maintenance data through the "one pole, one file" data, which is then used to update operation models, facilitating data integration across the design, construction and operation stages. This enables applications such as monitoring, testing, inspection and maintenance activities.

In this approach, "Model" refers to the representation models and mechanism models utilized throughout the lifecycle management of the catenary system at different stages. The representation models consist of BIM models of the catenary components and units tailored to the delivery requirements of different stages, as well as Geographic Information System (GIS) models that are integrated and displayed together with those BIM models. The mechanism models are the algorithmic analysis models employed for computational verification, evaluation, inspection, monitoring and early warning functions during these stages. The term "Data" corresponds to data relevant to the catenary system in different stages, such as the information parameters of catenary components in the design stage, material parameters in the manufacture stage, installation information parameters in the construction stage, and inspection and monitoring data in the operation stage. These data can be primarily categorized into the forms of static data and dynamic data. "Axis" is the timeline through the four stages of the catenary system's lifecycle. "Plane" refers to the business scenarios associated with the catenary system at different stages.

"Model-Data Driven" refers to integrating representation models, mechanism models and dynamic/static data in different stages of the lifecycle management of the catenary system to establish integrated transmission, thereby facilitating model and data forward transmission and feedback optimization of the catenary system during the entire lifecycle from design to manufacture, construction and operation. "Axis-Plane Coordination" indicates that under the influence of "Model-Data Driven" methodology, effective linkage of upstream and downstream data is established in business scenarios at various stages, addressing the requirements for data sharing between upstream and downstream stages, thereby reaching optimal efficiency of entire lifecycle management.

3. Architecture of model-data integration platform for lifecycle management of the catenary system

To achieve forward transmission and feedback optimization of models and data in the lifecycle management of HSR catenary systems and improve overall efficiency, this approach applies the HSR MDD-APC theory and integrates the models and data from the design, manufacture, construction and operation stages of the catenary system into a model-data integration platform for management and empowerment. The platform is structured vertically into four layers: the model-data aggregation layer, the model-data storage layer, the model-data processing layer and the analysis application layer (Wang, Wang, Li, & Lu, 2024b), as illustrated in Figure 2.

The bottom layer is the model-data aggregation layer. This layer aggregates data and models related to the catenary system in the design, manufacture, construction and operation stages. The design stage includes basic project information, geometric parameter information of catenary components, and preliminary project drawings and models. The manufacture stage involves pre-assembly and production control data of key components (such as cantilevers and droppers), along with corresponding detailed BIM models. The construction stage covers operational data and models during processes of cantilever intelligent installation, setting-out control and H-shaped pillar assembly. The operation stage consists of the as-built BIM models delivered after the construction of the catenary system and the maintenance data, which include inspection and monitoring data, maintenance window schedules, operational schedules and abnormal alerts.

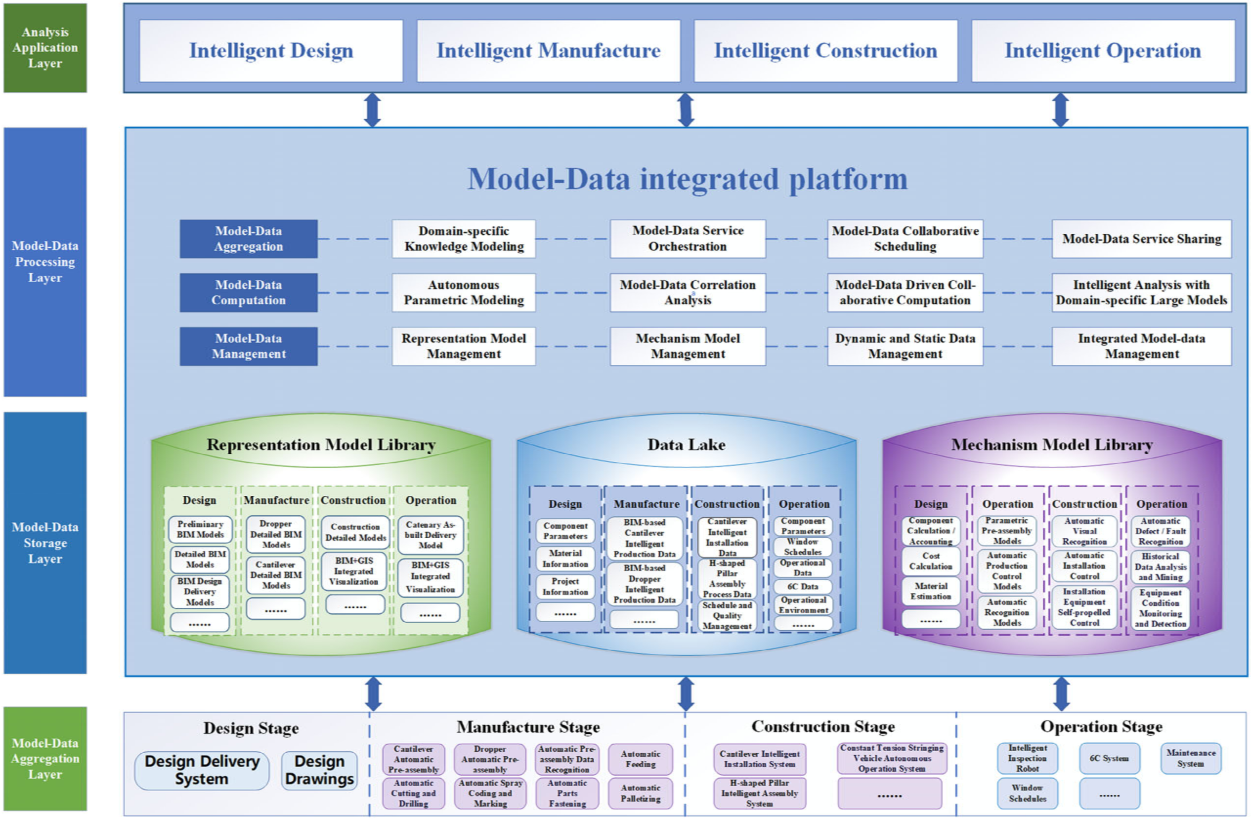


Figure 2. The architecture of the model-data integration platform for lifecycle management of the catenary system. Source: Authors' own work

Then follows the model-data storage layer. This layer organizes the aggregated data by their subject areas into representation model library, data lake and mechanism model library. The representation model library primarily contains preliminary BIM models created during the design stage based on drawing data and geometric parameters, detailed BIM models refined through processes such as inspections, conflict detection and computational verification, along with reviewed BIM design delivery models. It also holds detailed BIM models that support intelligent production of relevant components during the manufacture stage; detailed construction BIM models, lightweight BIM models of the catenary system for integrated visualization and GIS models of the project route during the construction stage; and the as-built BIM delivery model of the catenary system during the operation stage. The data lake is used for storage of data aggregated from different stages of the catenary system's lifecycle, such as the catenary system's basic parameter information, production material data, schedule management data, installation control data and maintenance data. The mechanism model library includes computational models and predictive analysis models developed in different stages. For example, in the design stage, it includes calculational models for catenary components and project budget assessment models. In the manufacture stage, it contains pre-assembly models for cantilevers and droppers and automated recognition models. In the construction stage, it includes intelligent equipment models for autonomous operation and control. In the operation stage, the library stores numerous intelligent inspection and monitoring models, data mining models based on extensive maintenance data, predictive analysis models and pre-alert models.

Above is the model-data processing layer. This layer consists of functions such as model-data management, model-data computation and model-data aggregation. Model-data management includes representation model management, mechanism model management, dynamic and static data management, and model-data integration management. It ensures quality governance and storage management of massive data, representation and mechanism models. Model-data computation offers capabilities of autonomous parametric modeling, model-data correlation analysis, model-data driven collaborative computation and intelligent analysis with domain-specific large models. Model-data aggregation provides support for domain-specific knowledge modeling, model-data service orchestration, model-data collaborative scheduling and model-data service sharing.

The top layer is the analysis application layer. This layer provides support for intelligent applications throughout the four stages of the catenary system's lifecycle management. Examples include generative design in the design stage, all-element automated production in the manufacture stage, fully automated assembly and installation during the construction stage, and AI-based inspection and monitoring applications in the operation stage.

4. Key technologies for lifecycle management of the catenary system

4.1 BIM model-data integration transmission method

This method focuses on the integration of both static and dynamic data throughout the entire lifecycle of the catenary system. By employing clustering techniques, it consolidates data into geometric and non-geometric information of catenary models, thereby establishing an efficient model-data integration system. The use of universal data standardization methods, such as industry foundation classes (IFC) and eXtensible Markup Language (XML) Schema, ensures that the models and data associated with the catenary system adhere to a consistent structure and representation across all stages of the lifecycle (Wang, Huang, Liang, Zhang, Zhao, Zhang, & Ma, 2024a).

BIM model transmission carrier. High-speed rail BIM model-data integration transmission method follows a "model-data separation-model-data aggregation" technical approach. It uses BIM models' inherent Globally Unique Identifier (GUID) or assigned unique identification codes to separate data attributes and generate data formats such as IFC, XML Schema, RailML and JavaScript Object Notation (JSON) for easy access. This ensures data completeness during transmission. Based on the management requirements at different stages, the model is processed into lightweight data formats such as Unified Database (UDB), and finite element analysis formats such as Standard ACIS Text (SAT) and Comma-Separated Values (CSV). Through coding management techniques, the model and data are aggregated, enabling multi-dimensional data association (Meng, Shi, & Xie, 2019).

BIM model transmission method. Base on standardized data methods such as IFC, XML Schema and RailML, the model, data storage structure and representation methods for the catenary system at various stages are established. Additionally, a model data directory that supports the lifecycle management of the catenary system is established, along with a cross-platform access solution.

Model and data review method. Based on the standards issued by China Railway BIM Alliance, and in accordance with the requirements of various stages, standards for model accuracy and data attribute levels are formulated. Furthermore, data and models generated during the design and construction stages are reviewed, covering attribute information checking, location information checking, geometric shape checking and progress model checking.

4.2 BIM model format conversion and lightweighting technologies

Model format conversion technology. Due to the linear structure, numerous components and large volume of catenary engineering, issues such as long loading time, inconvenient operations and browser crashes are prevalent. This research examines model conversion technologies using SuperMap 10 and Unreal Engine 5 (UE5). The primary approach involves using conversion plugins to convert Revit (RVT) or Bentley Design (DGN) model files into Unified Database (UDB) and GL Transmission Format Binary File (GLB) formats, as well as converting data information into JSON files. Additionally, an oblique photography model is integrated into the software, enabling the deployment of clients or web applications based on specific requirements.

Model lightweighting technology. The lightweighting of models is approached from two aspects: geometric transformation and model rendering (Yuan, Yang, & Shao, 2022). Geometric transformation reduces file size through the strategies of separating data and models, and utilizing instantiation storage for identical models (Xue, Li, & Hu, 2024). Model rendering ensures display quality while decreasing the triangle count of the models through techniques such as hierarchical loading and multiple levels of detail (LOD) (Xu, Han, & Wang, 2024; Wang, Huang, Xu, An, Li, Chen, & Guo, 2024c). The research aims to conduct lightweighting validation on segments of equal length using SuperMap 10 and UE5, comparing smoothness and scene quality (Jian, Fan, Xu, & Li, 2023).

5. Application verification of catenary system lifecycle management

The Shanghai–Kunming High-Speed Railway, Sichuan–Chongqing section is selected as a demonstration application site to establish a comprehensive lifecycle model-data integration application platform for high-speed catenary. This platform facilitates the collaborative transmission validation of BIM models and data throughout the entire lifecycle of HSR catenary system in typical scenarios.

During the design stage, the project implementation is conducted in accordance with the provisional standards established by the China Railway BIM Alliance, with the catenary design delivery model accuracy conforming to Level of Detail 3.0 (LOD 3.0) requirements as specified in *The Railway Engineering Information Model Delivery Accuracy Standard (Version 1.0)*. After standardizing the catenary BIM model and data, parameterized rapid modeling plugins and a 3D component family library management plugin are developed for lifecycle application of the catenary BIM system. This approach not only enhances modeling efficiency across various stages, but also ensures the standardization of modeling parameters, as shown in Figures 3 and 4.

After finishing modeling parameterizing, BIM models of catenary components are further structured based on *Classification and Coding Standard for Railway Engineering Information*

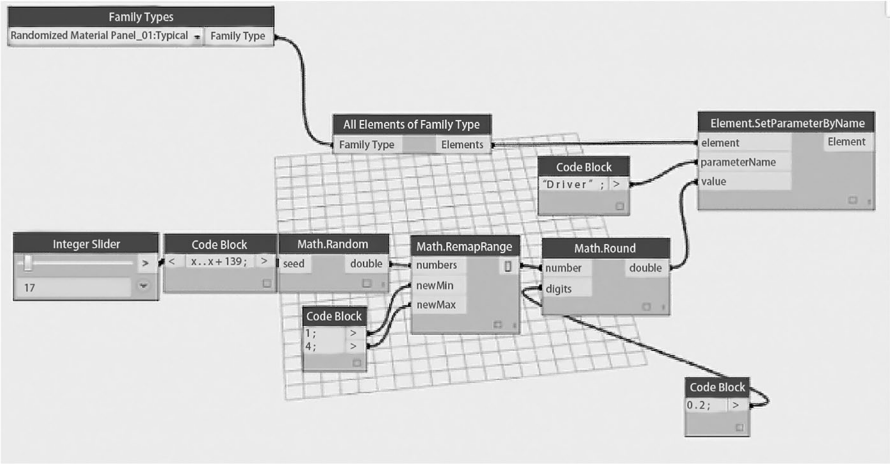
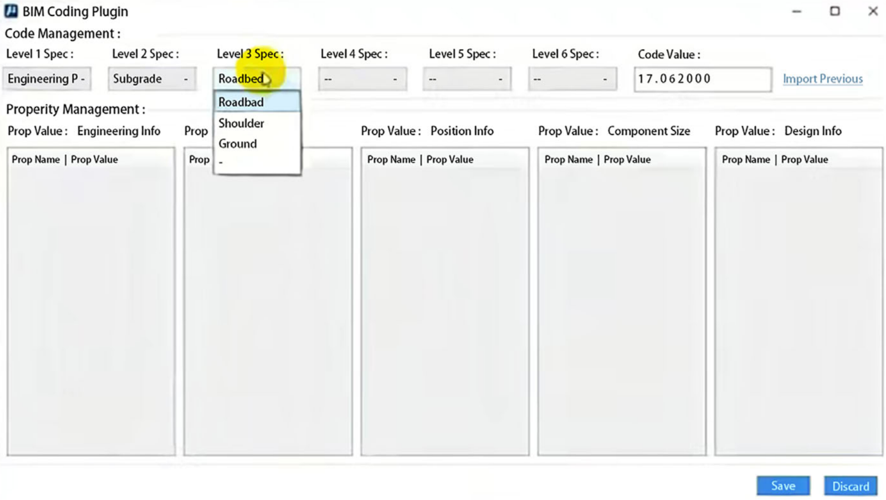


Figure 3. Component 3D family library management plugin. Source: Authors' own work



Code Management:

Level 1 Spec: Engineering P -

Level 2 Spec: Subgrade

Level 3 Spec: Roadbed

Level 4 Spec: --

Level 5 Spec: --

Level 6 Spec: --

Code Value: 17.062000

Properity Management:

Prop Value: Engineering Info

Prop

Prop Value: Position Info

Prop Value: Component Size

Prop Value: Design Info

Figure 4. Parametric rapid modeling plugin. Source: Authors' own work

Models Version 1.0 by China Railway BIM Alliance, which is then stored in the public BIM database. Through the automatic coding software, a unique Information Framework Dictionary (IFD) code is assigned to each catenary component. It not only acts as a unique identification code for each component within the project and across different projects, but the key to bind the BIM representation model and corresponding properties and parameters during BIM collaborative design. Relying on BIM standard framework from China Railway BIM Alliance, new BIM coding categories are added to the BIM design platform during the design stage and further adopted as catenary engineering BIM design deliverables, as important supplements to IFD standards.

Besides, through BIM technology, the catenary design models are integrated with design models from other disciplines based on a unified coordinate system. Through this unified coordinate system, collision detection between catenary engineering and other disciplines, including spatial interference check and boundary overlap check, is achieved. By modifying collision-related BIM design, the collision problems during the construction stage are significantly reduced, which saves reconstruction costs and improves construction efficiency. This demonstrates an application of plane-level collaboration across catenary engineering and other disciplines at the design surface, established by BIM technology.

In the manufacture stage, by utilizing BIM model data delivered from the design stage, remote intelligent production lines can automatically perform batch production control. This process has already enabled intelligent pre-assembly and production of cantilevers and droppers as shown in Figures 5 and 6.

To achieve in-depth integration with construction stage, the intelligent cantilevers pre-assembly production line adopts technologies such as intelligent and information-based management, intelligent mechanical pre-assembly, production management platform and on-site video surveillance. By leveraging intelligent equipment interconnection, the industrialized, mechanized and intelligent cantilevers production is promoted, thereby enhancing construction efficiency and process quality, while laying the foundation for subsequent intelligent operation.

The production of cantilevers adopts industrialized, automated and pipeline procedure. It utilizes pre-assembly data to drive robotic arms for cantilevers pre-assembly. The intelligent equipment achieves functions such as automatic pre-assembly data recognition, automatic pipe feeding, automatic length cutting and drilling, automatic coding and marking, automatic part positioning, automatic part fastening and automatic product stacking, reducing massive labor cost while improving production efficiency.

The intelligent dropper pre-assembly production line adopts mechanized pre-assembly technology, including remote pre-assembly data transmission, automatic pre-assembly data recognition, automatic dropper length measuring and conveying, tension-controlled automatic cutting, automatic part feeding, automatic threading, automatic tightening, constant pressure and tension-controlled automatic pressing and automatic marking. Mechanized pre-assembly reduces human error, improves pre-assembly accuracy and thus increases pre-assembly efficiency.

In the construction stage, a model-data integration platform supports construction management across various operational dimensions, including technical management, safety

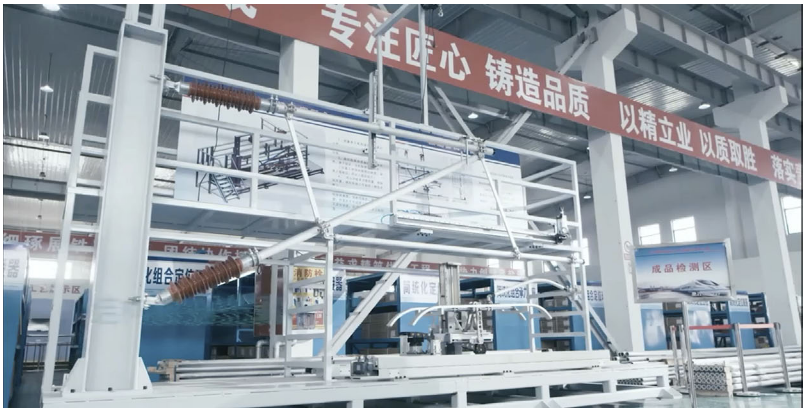


Figure 5. High-speed railway intelligent cantilevers pre-assembly production line. Source: Authors' own work

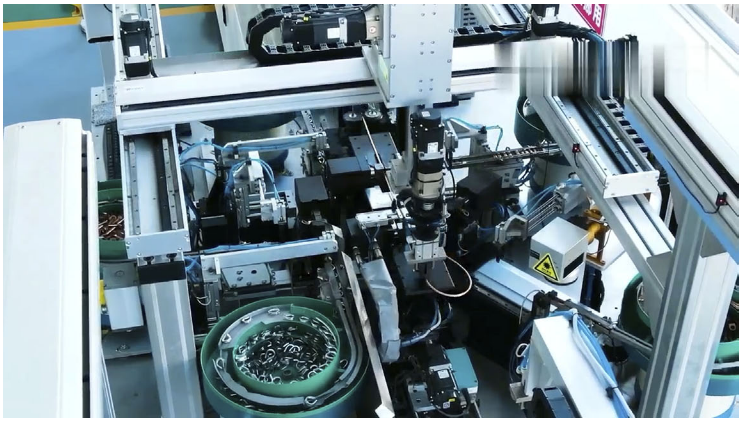
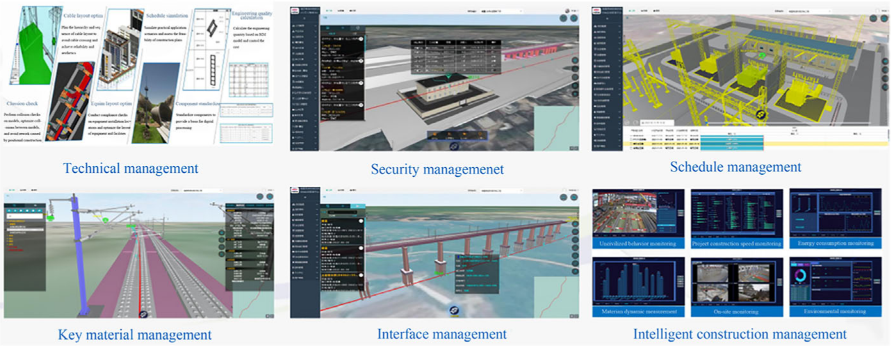


Figure 6. High-speed railway intelligent dropper pre-assembly production line. Source: Authors' own work

management, schedule management, key material management, interface management and intelligent construction management, as illustrated in Figure 7.

The technical management consists of collision checking, cable layout optimization, construction plan deepening and engineering quantity calculation. The collision checking function fixes collision problem in real time relying on the BIM and digital twin technology, and reduces re-arrangement and re-construction issues during the construction stage. The cable layout optimization function automatically plans cable layouts, solving problems of cable crossing, insufficient cable turning radius and insufficient cable reservation. The construction plan deepening function solves unspecific or undetermined construction location and procedures by construction plan simulation with BIM technology, and reduces the waste of time, cost, labor and materials caused by re-arrangement. The engineering quantity calculation function establishes automatic engineering quantity calculation of catenary components based on imported BIM construction in-depth models. Construction engineering quantities are automatic calculated and exported as a detailed engineering quantity calculation table. In accordance, refined management of material procurement and allocation are achieved, which avoid material waste.

Security management is a critical part of engineering project management. In response to the difficulties in data collection, data sharing, and coordinated rectification of safety and



Technical management

Security managemenet

Schedule management

Key material management

Interface management

Intelligent construction management

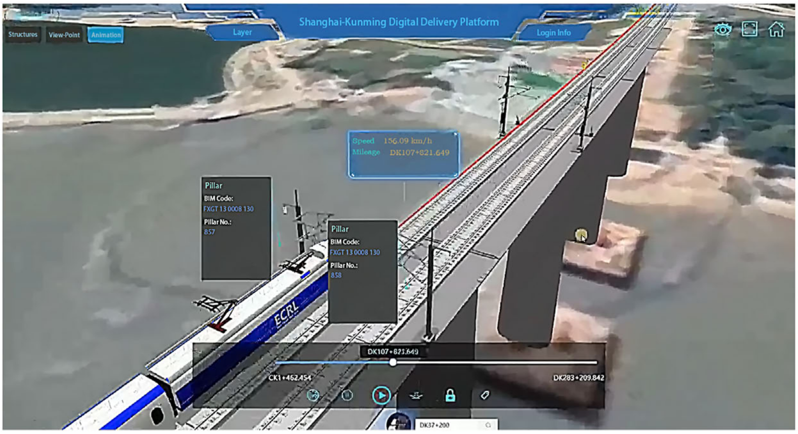
Figure 7. Construction management interface of the catenary system. Source: Authors' own work

quality issues during the construction process, the BIM + GIS model-data integration management platform is utilized to develop a safety and quality management module that covers safety and quality issue inspections, external inspection management, internal safety permit management, safety risk management and flood prevention and control management. Safety and quality issues are collected through mobile apps and web platforms. Then data is shared with relevant responsible persons to achieve online closed-loop management and on-site safety and quality visualization.

The application of BIM-based scheduling management enables proactive control over project progress, enhancing overall project control and efficiency. Work items are divided based on component rules, with Work Breakdown Structure (WBS) codes established and linked to component codes. Mobile data entry of construction logs and equipment installation records allows real-time data aggregation, forming scheduling data tables. These data drive color changes in 3D BIM models on the BIM + GIS platform, enabling intuitive progress tracking and visual comparison with planned tasks. Through scheduling data collection and analysis, combined with visual presentation, refined construction organization is supported, ensuring steady project advancement.

Besides, based on BIM and other intelligent and information technologies, key material management, interface management and intelligent construction management modules are developed. Based on BIM + GIS management platform, key material management module addresses the issues of material management in the construction stage of HSRs, achieving information synchronization between construction scene and the platform. The interface management module connects data with mileage, customizes the key points of interface inspection, builds an interface problem library, thereby standardizes interface management. The intelligent construction management module establishes a refined closed-loop management system that integrates the design and construction stage, and guarantees accuracy and authenticity. By leveraging the platform to dispatch construction tasks, ensuring orderly construction on-site.

In the operation stage, the primary focus is on implementing visualization features based on the catenary BIM model and GIS model. This enables real-time display of operational data for the catenary system in a visual format and enhances operational efficiency, as shown in Figure 8. The system functions mainly include 3D scene data integrated management, operational data access and 3D scene operational data fusion display.



Speed 156.09 km/h
Mileage DK107+821.649

Pillar
BIM Code:
FXGT 13 0008 130
Pillar No.:
857

Pillar
BIM Code:
FXGT 13 0008 130
Pillar No.:
858

Figure 8. The “one pole, one file” maintenance interface of the catenary system based on the BIM + GIS fusion technology. Source: Authors’ own work

3D scene data integrated management involves uploading completed line data to establish an accurate and clear 3D scene of the completed line, providing environmental support for integrating as-built models with GIS. It also includes managing GIS data to construct 3D terrain, handling and classifying completed models by operational structure for storage and updates, and integrating completed lines and models with GIS terrain in the 3D scene to accurately display the overall status of power supply projects. Operational data access establishes an integrated data interface for operations and maintenance, integrates data such as maintenance window plans, operational tasks, 6C system data for catenary systems, defect rectification records, equipment operation status, operational environment data, alarm data and maintenance data, to enable seamless data integration. 3D scene operational data fusion display develops interactive functions, allowing users to load and view models and retrieve “one pole, one file” data, which includes scene query and positioning, scene roaming and data retrieval.

6. Conclusions

This paper establishes a model-data integration platform for lifecycle management of catenary systems, using the catenary BIM model as the foundation and applying the intelligent HSR “model-data driven, axis-plane coordination” methodology. According to the “model-data driven, axis-plane coordination” methodology, the platform is divided into four layers, including the model-data aggregation layer, the model-data storage layer, the model-data processing layer and the analysis application layer. BIM models and data produced during different stages of the catenary system lifecycle management are settled at bottom model-data layers, upon which builds different platform applications, aiming at optimal lifecycle efficiency of the catenary system. This platform enables coordinated data transfer and feedback optimization of catenary models across different stages, significantly enhancing efficiency throughout the lifecycle management process. It provides robust support for the safe, reliable and efficient operation of HSRs catenary systems.

The study is applied in the Shanghai–Kunming High-Speed Railway, Sichuan–Chongqing section, guiding BIM intelligent applications across the design, manufacture, construction and operation stages, showing significant efficiency improvement and cost reduction during the whole lifecycle of catenary engineering project. The application of the catenary lifecycle management methodology in the Shanghai–Kunming High-Speed Railway validates the value of proposed model-data integration platform and lifecycle management methodology, advancing the intelligent promotion and high-quality development of catenary engineering.

Moving forward, based on this model-data integration and collaborative data transfer approach across stages, further research may explore collaborative intelligence across different stages by leveraging the data integration capabilities of the platform, advancing the level of intelligence in lifecycle management for the catenary system.

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