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RESEARCH ARTICLE

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# Knowledge-guided digital twin modeling method of generating hierarchical scenes for a high-speed railway

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## Abstract

China's railway construction is rapidly transitioning toward integrated management of “stakeholders, management elements, and management processes”. Therefore, comprehensive and whole-process digital twin scene modeling is urgently needed for intelligent railway construction. However, the requirements of three-dimensional scenes in different stages vary hierarchically, resulting in a lack of construction semantics and limited universality in modeling. This article proposes a knowledge-guided digital twin modeling method of hierarchical scenes for a high-speed railway. We first build a knowledge graph of “knowledge-model-data” to achieve an accurate and hierarchical description of railway scenes. We then establish a parameter-driven modeling method that integrates knowledge guidance and primitive combination to generate a display scene and a virtual design scene automatically. Third, we propose joint linkage and model growth methods for construction action modeling, which are used to generate a virtual construction scene. Finally, in response to the hierarchical scene-generating requirements in different stages, we conduct intelligent modeling experiments for the entire design and construction process. The knowledge graph of the hierarchical semantic description mode significantly

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improves the flexibility and universality of the modeling method. The proposed modeling method for the entire process contributes to the rapid representation of design data, in-depth design, visual exploration, and dynamic optimization of the construction process. This article provides a reliable digital twin modeling solution for the entire process to improve design and construction quality.

## 1 | INTRODUCTION

Intelligent railways are at the core of China's transportation strategy and a vital driver of the country's digital economy. With national initiatives such as the Belt and Road Initiative and the construction of the Sichuan-Tibet Railway, railways are extending to complex and challenging mountainous areas, presenting new construction conditions such as high altitude, cold climate, and plateaus. Railway engineering construction is a vast, complex, and highly dynamic system engineering process that spans multiple stages and involves various disciplines. It is characterized by the complexity of influencing factors, the dynamic nature of the construction process, and the uncertainty of interaction among different professional objects. Given the complexity of the geographical and geological environment and the challenges posed by the engineering process (Li, Zhu, Fu et al., 2020), implementing high-quality and high-standard railway engineering projects has become an urgent issue that needs to be addressed (Lu & Cai, 2019).

Intelligent construction creates a twin model and a two-way mapping mechanism between the real and virtual worlds, which has become an essential means for the high-quality development of intelligent railways through sensing, analyzing, and controlling the construction process (Jiang et al., 2021; Li et al., 2023; Lu et al., 2019; Shirowzhan et al., 2020). By pre-simulating the construction activities of physical entities in real-time in a digital twin scene, potential problems that may arise in the actual project can be identified using the "trial before build" approach. Therefore, by generating a digital twin scene of a railway engineering project (Chen et al., 2015; Chen & Lin, 2018; Ham & Kim, 2020; Lü et al., 2018, 2019; Tao et al., 2022; Zhang et al., 2023), the design and construction process of railway engineering projects can be visualized and analyzed, allowing for better decision-making and optimized construction processes.

The objects within the railway scene have fixed types and standard sizes, and the arrangement of these objects follows linear laws and similar features. Therefore, the railway twin scene is typically generated using primitive model assembly. The railway twin scene generation involves creating surface or BIM solid models (Beck et al., 2020; Kurwi et al., 2021), assembling them in the geographic coordinate system, and fusing them with GIS data (Li et al., 2016). However, this modeling method only focuses on the descriptive and visual representation of the railway scene at the geometric level. It fails to consider essential construction elements such as construction processes, methods, and materials. Some studies use ontology to establish hierarchical semantic constraint rules, including spatial layout semantic constraints, composition modeling semantic constraints, and spatial position semantic constraints. This approach effectively guides and constrains the complex modeling process, enabling the automatic modeling of railway scenes (Zhang et al., 2016; Zhu et al., 2015) and the reuse of modeling knowledge (Zhang et al., 2018, 2019). However, this method only focuses on the semantic description of the modeling process and fails to establish a clear relationship between data, models, and business requirements. It also fails to clearly understand and quickly respond to differentiated business requirements (Qiu et al., 2017; Xue et al., 2019). Other studies simulate the construction progress by inputting the construction progress data (Ning et al., 2020; Wang, Pan, & Luo, 2019) or by simulating the construction process through collision detection and virtual assembly (Boton, 2018; Dashti et al., 2021; Kim et al., 2021). However, these methods are mainly based on site-level applications and local systems, and they need careful consideration and systematic integration of factors such as environment and materials.

Railway construction is a dynamic and complex system that involves “man, machine, material, method and environment” (4M1E). The interactions and mutual influences of various construction elements include spatial position relationships, sequence relationships, and causal relationships, making it necessary to deal with complex objects at different stages. Furthermore, a railway engineering project involves different levels of scene generation requirements and multimodal thematic data. Existing scene modeling methods are designed for single-stage and scattered construction sites, which separate the internal connection between railway construction stages. The separation of information flow between the design and construction phases results in inaccurate expression and understanding of design intent. As a result, dynamic changes in construction need to be updated in real-time, leading to safety, quality, investment, and construction period control issues. These issues increase the risk of project implementation. China's railway construction is currently transitioning rapidly from a mode of separation of design and construction to an integrated management mode of “stakeholders, management elements, and management processes”. Therefore, a semantic description mode of scene modeling throughout the entire process and establishing a comprehensive, cross-stage, and whole-process digital twin modeling mechanism have become an urgent need to achieve intelligent railways.

Given the varying digital twin scene requirements across different stages and levels of hierarchy, this article addresses two fundamental research questions. First, what are the interrelations among “business requirements—modeling expression—spatio-temporal data” at different stages? Second, how do the numerous railway features interact within the dynamic and intricate DC (Design and Construction) environment? We focus on knowledge graph development, digital twin scene generation and dynamic updating, and construction action modeling to address these two fundamental research questions. This article proposes a reliable digital twin modeling method for the entire construction process to enhance design and construction quality. The structure of this article is as follows: Section 2 provides an overview of the pertinent literature concerning knowledge graphs and the generation of railway scenes. Section 3 outlines our proposed method. Section 4 describes our experiments involving intelligent modeling from planning and design to implementation, construction, and installation. The final section summarizes our findings and outlines future research directions.

## 2 | LITERATURE REVIEW

### 2.1 | Knowledge graph

The concept of the knowledge graph was introduced by Google in 2012 to enhance the capabilities of search engines, and since 2013, it has gained significant traction in both academia and industry (Wang, Huang, et al., 2019). Notably, artificial intelligence (AI) has garnered escalating interest in recent years (Gil et al., 2018), and the knowledge graph, as a novel generation of knowledge engineering technology, has progressively emerged as a vital subject in AI (Ma, 2022; Tiddi & Schlobach, 2022). The knowledge graph serves as a visual representation of structured real-world knowledge, wherein nodes symbolize entities of interest and edges denote relationships between these entities, offering enhanced capacity for organizing, managing, and comprehending vast information about the world (Li, Zhu, Zhang et al., 2020; Ma, 2022; Shen et al., 2022).

The current methods for constructing knowledge graphs can be broadly classified into top-down and bottom-up approaches. The top-down approach initially identifies the subject domain and specific requirements, then collects pertinent concepts and relationships to design a conceptual model (Li et al., 2022). For instance, this could entail creating an ontology as a schema layer and subsequently instantiating the identified concepts and relationships to construct a knowledge graph (Zhang et al., 2020). On the other hand, the bottom-up development of knowledge graphs is often driven by crowd-sourced data. This approach commonly employs natural language processing and text mining techniques to automatically extract hidden entities and relationships from extensive data sources, thereby constructing a comprehensive knowledge graph (Cudré-Mauroux, 2020).

Due to its unique capacity for representing and managing extensive knowledge, the knowledge graph has found application in diverse domains, including information retrieval (Reinanda et al., 2020), intelligent question-answering (Xiong et al., 2021), data integration (Kalaycı et al., 2021), and financial analysis (Wen et al., 2022). However, there appears to be a limited exploration of the amalgamation of the knowledge graph with three-dimensional (3D) scene modeling, especially concerning the creation of high-speed railway scenes. This integration presents substantial advantages for the streamlined management of geographic entities and the intricate relationships intrinsic to high-speed railway construction.

## 2.2 | Railway scene generation

Generating a railway scene involves two distinct stages: 3D model crafting and the fusion of multimodal spatial data. Based on variations in model outcomes and modeling tools, the production of 3D models can be categorized into two primary types: surface models and solid models. Similarly, considering diverse modeling techniques, it can be further classified into two approaches: manual modeling and automatic modeling (Beck et al., 2020).

Creating a 3D surface model involves software like 3D Max and Maya. Its key strengths lie in its robust 3D rendering capabilities, resulting in lifelike model effects. While commonly used in film animation for special effects, this model type lacks functionalities such as structural calculation and analysis. The emergence of Building Information Modeling (BIM) software such as Revit, Bentley, and CATIA has significantly propelled BIM entity modeling forward. These tools offer collaborative design, structural calculation, and analysis advantages. The China Railway Corporation established the China Railway BIM Alliance (CRBIM) and orchestrated 17 BIM pilot projects in 2014. The "Railway BIM Data Standard (Version 1.0)" (CRBIM1002-2015) gained buildingSMART approval for publication as a public specification (Kupriyanovsky et al., 2020; Pu et al., 2022), which marked international recognition of the China Railway BIM standard. Research into integrating BIM and GIS revolves around the CityGML and IFC standards, leveraging two common methods: data standard extension and data format conversion (Colucci et al., 2020; Floros et al., 2018). The former extends the CityGML and IFC standards, creating a new data exchange standard. The latter approach focuses on the conversion between IFC and CityGML, becoming the prevalent method. However, geometric representation and information storage differences between GIS and BIM give rise to notable integration challenges. These challenges include the loss of geometric and attribute information and semantic information ambiguity when merging BIM and GIS. As a result, the seamless transmission of design information to the construction stage remains a significant obstacle, and the merging and application of data and BIM models continue to be subjects of exploration.

A surface or solid model can be automatically created using the parametric modeling method. Parametric modeling refers to the approach of describing the design and characteristics of the model using a set of parameters or variables. These parameters define specific attributes such as dimensions, shapes, angles, materials, and other relevant properties of the bridge. With parameterized modeling, the process becomes automated and driven by algorithms or software programs. Instead of manually creating every model detail, users define the parameters and let the program generate the model accordingly. Parametric modeling utilizes adjustable parameters for designing structures that harmonize with the surrounding terrain. This approach involves determining variables such as slope angle, curvature, and alignment through landscape analysis, mainly when dealing with road and embankment structures. Algorithms then generate designs that follow the natural contours of the land. Designers can experiment with different scenarios by tweaking these parameters in real-time, ensuring optimal functionality and visual harmony with the environment (Li et al., 2016). This approach enhances decision-making, and the models can be integrated with BIM and GIS for a comprehensive understanding of how the structures interact with the terrain. However, the parametric modeling method demands a greater depth of domain knowledge, and the simplistic abstraction of structures limits its efficacy in representing detailed models through a reduced set of feature parameters. While parametric modeling is adept at swiftly showcasing schemes during the preliminary design phase, it needs to catch up regarding finely detailed management during the engineering construction phase.

Whether a surface or solid model, the 3D model must be reconstructed within the geographic coordinate system to generate the railway scene. Railway scene objects often share similar shapes and follow regular arrangements in linear space, making the method of primitive combination highly suitable for crafting a railway scene. Certain studies have introduced ontology semantics, establishing rules that guide and restrict the automatic and precise assembly of railway scenes—a current research focus (Zhang et al., 2016, 2018, 2019).

However, most of these studies primarily calculate model positions and orientations. They often overlook establishing the connection between data, models, and business requirements, resulting in the limited capability to comprehend and address diverse modeling requirements effectively. In addition, the dynamics of the railway construction process are complex, and a wide variety of construction elements interact and influence each other in terms of spatial position, time sequence, and causality. The method of model assembly from the geometric and topological levels can only generate static scenes, which can only meet the descriptive and visual expression requirements along the railway. This method cannot accurately simulate the spatio-temporal dynamic interaction between facilities, equipment, and geographical environment elements. It cannot satisfy the collaborative decision-making and exploratory visual analysis of complex problems.

In summary, using knowledge graphs, parametric modeling, and model assembly techniques to generate railway 3D scenes effectively meets the diverse demands at various stages of railway construction. However, the existing methods exhibit several shortcomings in effectively capturing hierarchical requirements and catering to a wide range of services. Therefore, this article focuses on establishing a depiction of the semantic connections between hierarchical scene construction needs and construction elements within railway development processes. We will integrate parametric and assembly-based automatic modeling to facilitate a knowledge-guided approach to generate and dynamically update railway digital twin scenes. Additionally, we will establish a sequential process-oriented digital twin modeling strategy for procedures and techniques by incorporating joint linkage and model growth methods. By analyzing distinctive scene modeling requisites during different construction phases, we aim to conduct comprehensive railway digital twin modeling experiments spanning the entire construction process. Ultimately, we aim to offer a cohesive, cross-stage railway digital twin scene modeling solution.

# 3 | METHODOLOGY

## 3.1 | Overall modeling framework

### 3.1.1 | Research questions and objectives

In the context of advancing railway design and construction, this article addresses two fundamental research questions. The first question involves uncovering the interrelationships among "business requirements—modeling expression—spatio-temporal data." Railway engineering constitutes a multifaceted, dynamic, and adaptive systematic endeavor, encompassing distinct stages with varying business requirements and feature types. Thus, the primary scientific objective of this article is to devise a hierarchical semantic description approach that caters to the entirety of this process. For instance, how does the modeling expression accurately capture the specific demands of visualizing a high-speed railway during the initial planning stage?

Railway engineering encompasses an extended lifecycle, involves multiple stages, and entails intricate process dynamics. A diverse array of features interact and influence each other, posing challenges in accurately simulating the spatio-temporal dynamics resulting from these intricate interactions. Consequently, unveiling the interaction mechanisms of space, timing, and causality among various objects during dynamic evolution is another fundamental research question requiring resolution.

Addressing the first research question facilitates the dynamic generation of digital twin scenes tailored to varying requirements. Solving the second issue can enhance the modeling quality of hierarchical scenes. Addressing these pivotal inquiries advances our comprehension and steers the creation of intelligent and efficient solutions for railway engineering. Table 1 illustrates the correlation between these research questions and the subsequent sections.

We aim to establish a systematic framework that effectively captures the relationships between business requirements, modeling expressions, and spatio-temporal data, generating accurate and dynamic digital twin scenes. Additionally, we strive to reveal the intricate interaction mechanisms among various construction elements and objects, facilitating a deeper understanding of their spatial, temporal, and causal connections. Ultimately, this article endeavors to provide innovative solutions for enhancing the efficiency and quality of railway engineering through intelligent digital twin modeling.

### 3.1.2 | Overview of the proposed method

The overall modeling method of this article is shown in Figure 1, and the specific steps are as follows.

1. We comprehensively consider the business requirements, modeling methods, and scene data throughout the process and propose a knowledge graph construction mode. This mode can describe the generation of hierarchical scenes from multiple aspects, including "data-model-knowledge". We extract entity element types, inter-entity relationships, and entity attributes during hierarchical scene generation to build knowledge graphs. Then, we store and dynamically update these knowledge graphs.
2. Through the study of the transformation of model geometry and the encapsulation of semantic attributes, we propose a multi-granularity modeling method based on component assembly. We analyze the transformation relationship between multiple coordinate systems, design a model reassembly method that considers geometry, semantics, and attributes under the geographic coordinate system, and achieve automatic generation and dynamic update of railway scenes.
3. We perform a parametric decomposition of the construction process and study the mapping relationship between construction control and joint linkage parameters. We propose a construction modeling method for the joint linkage of construction machinery. We clarify the content and relationship of construction process elements, guide the dynamic growth of infrastructure models, and achieve construction action modeling.
4. We developed a digital twin modeling prototype system, analyzed the hierarchical scene modeling requirements, and generated three levels of railway construction scenes: a display scene, a virtual design scene, and a virtual construction scene. During the planning stage, we rapidly generated a display scene, addressing problems such as unintuitive planning solutions and difficulties in updating models caused by repeated modifications of planning parameters. During the design stage, we produced a detailed 3D design that considered terrain constraints, addressing problems such as a need for detailed design plans in complex and hazardous mountainous

**TABLE 1** Correlation between research questions and subsequent sections.

| Research questions | Section | | | | | |
|---|---|---|---|---|---|---|
| Q1 | → | 3.2 | → | 3.5 | → | 4 |
| Q2 | → | 3.3 | | | | |
| | | 3.4 | | | | |

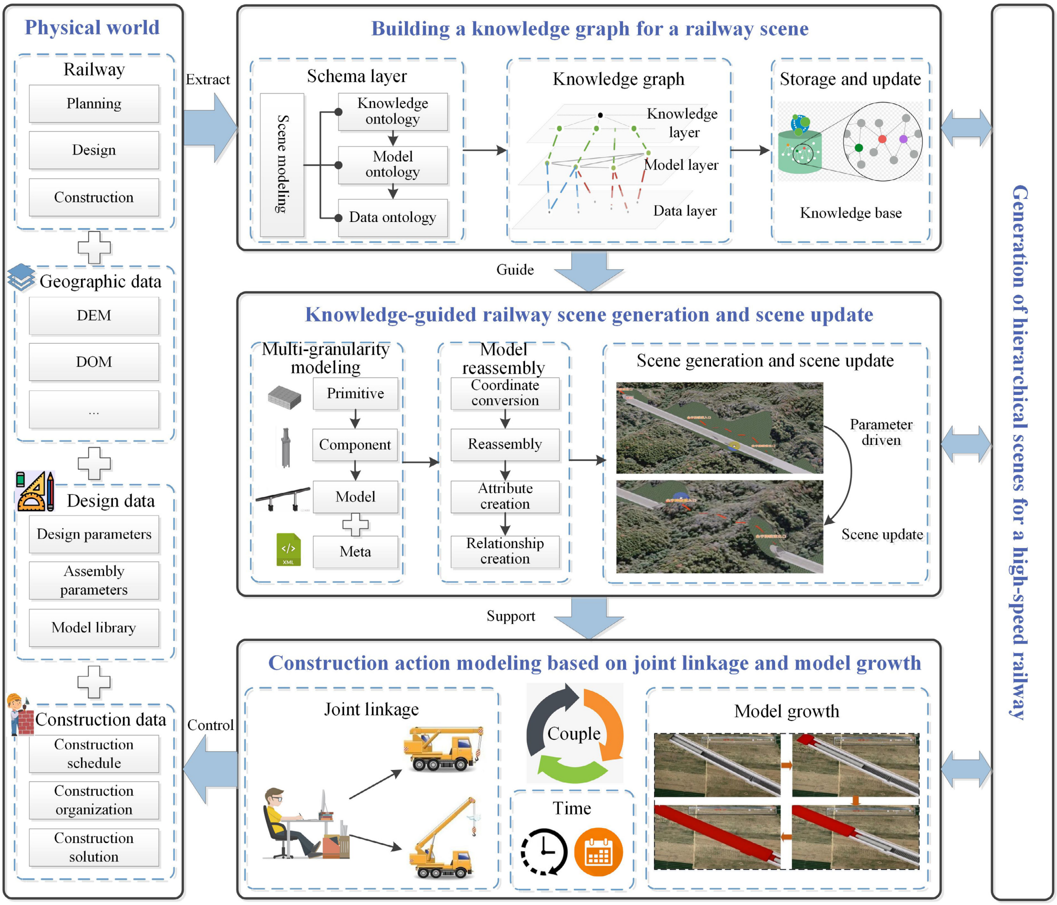

FIGURE 1 Overall modeling framework.

areas. During the construction stage, we achieved an integrated display of construction progress and schedules and a visual simulation of construction methods, addressing problems of frequently hidden dangers in the dynamic and changeable construction process.

## 3.2 | Building a knowledge graph for a railway scene

As a formal semantic association description knowledge system, a knowledge graph provides structured knowledge and enables the transformation of "data-information-knowledge-wisdom" (Jiang et al., 2019; Kang, 2018; Wang, Zhang, et al., 2019). It is the foundation of digital twin-driven intelligent railways. This article uses knowledge graphs to propose a multi-level correlation semantic description model of hierarchical scenes. Figure 2 illustrates the process of building the knowledge graph, which involves the following steps.

### 3.2.1 | Create the schema layer

We created the schema layer of a knowledge graph in a top-down manner. Firstly, we analyzed the knowledge in the railway field and divided the hierarchical scenes into three levels: a display scene, a virtual design scene, and a virtual

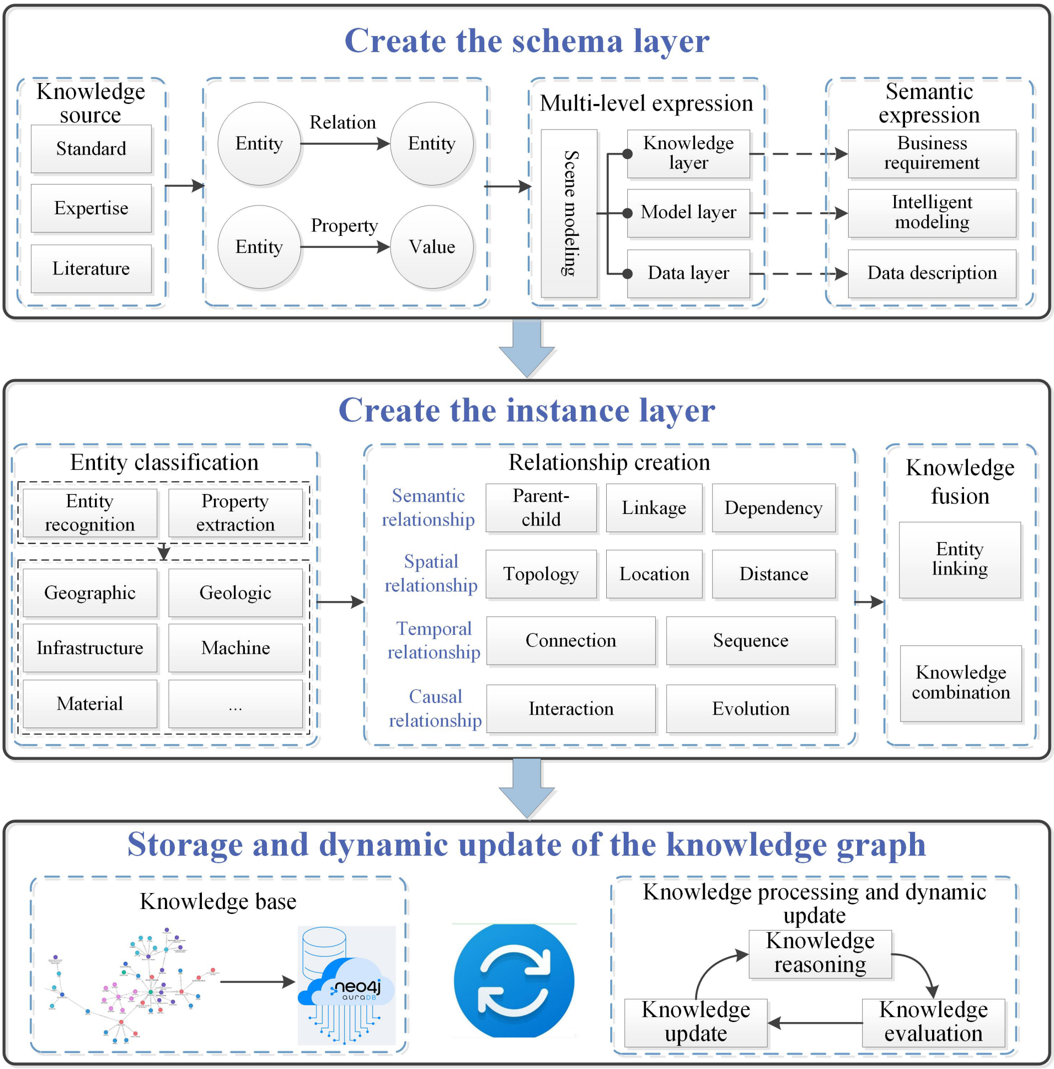

FIGURE 2 Building a knowledge graph for a railway scene.

construction scene. We then described the semantics of each scene modeling method using multiple layers, including a knowledge layer, a model layer, and a data layer (as shown in Figure 3). The knowledge layer involves the extraction and understanding of the business requirements. The model layer describes the modeling method of the hierarchical scenes, while the data layer describes various parameters and the relationships between parameters during the modeling process.

### 3.2.2 | Create the instance layer

We utilized a bottom-up approach to create the instance layer of our knowledge graph. Creating a knowledge graph involves several steps, including entity classification, relationship creation, and knowledge fusion. To satisfy the requirements of the railway business and the characteristics of hierarchical scenes, we divided entities into geographic, geological, railway infrastructure, machine, and material entities. We also performed named entity recognition and attribute extraction on these entities. We then established relationships between them, including semantic, spatial, temporal, and

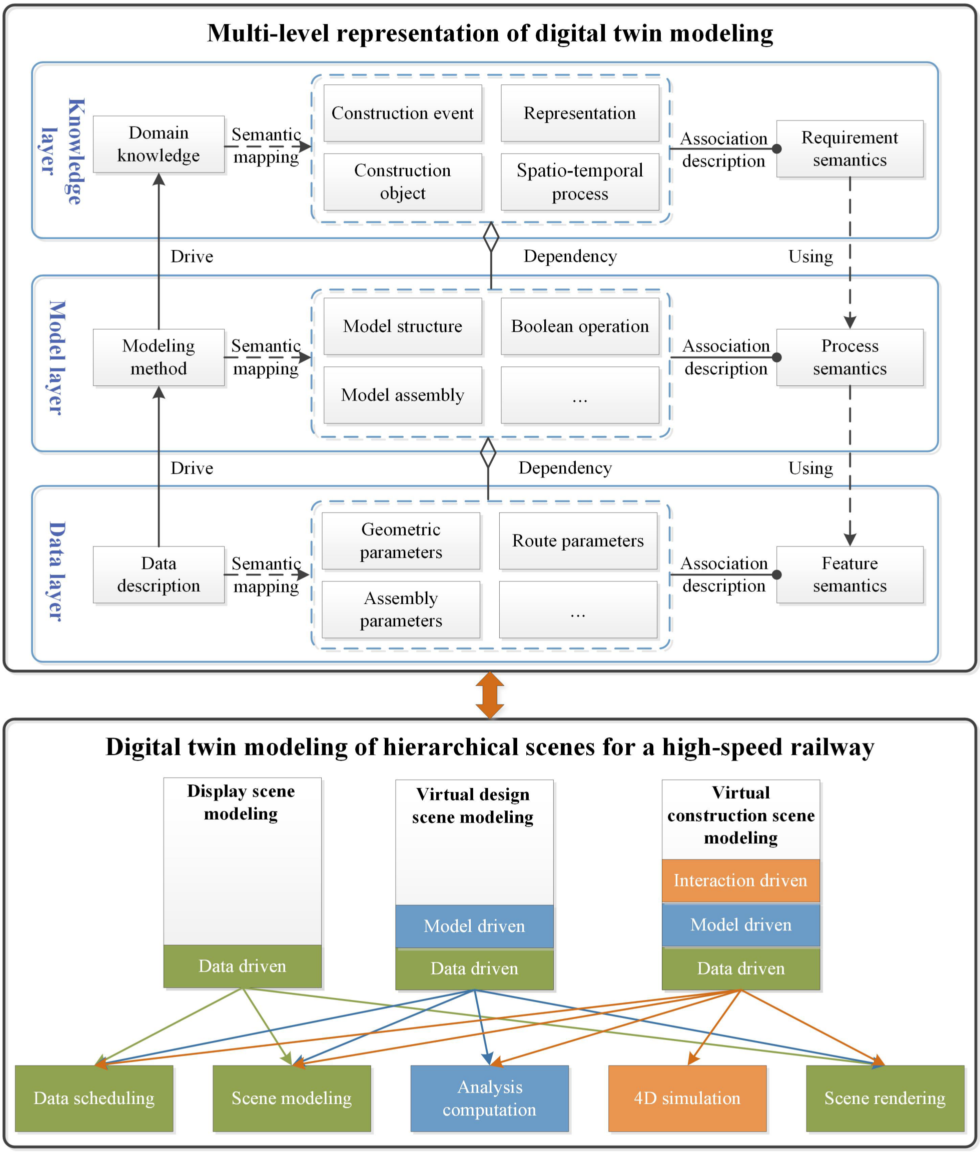

FIGURE 3 Multi-level representation of digital twin modeling.

causal relationships. Semantic relationships describe the hyponymy and logical relationship between component models. Spatial relationships describe the positional relationship of each entity. Temporal relationships describe the cohesive relationship between processes, while causal relationships describe the interaction between these entities. Finally, we linked different entities, merged the same or similar information, deleted wrong or redundant information, and fused the knowledge. Figure 4 depicts a schematic diagram of our multi-level correlation semantic description model.

### 3.2.3 | Storage and dynamic update of the knowledge graph

This article uses a directed graph structure to store the knowledge graph. Specifically, using the Resource Description Framework and the Web Ontology Language, we can represent the knowledge graph in a

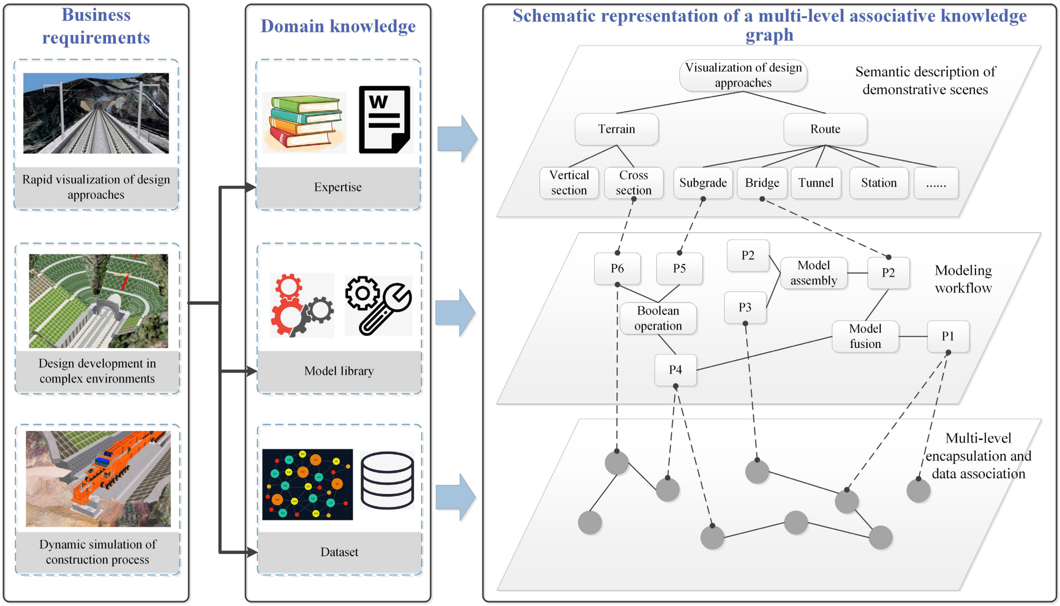

FIGURE 4 Schematic diagram of our multi-level correlation semantic description model.

machine-readable format, making it easier to process and analyze the data. We must dynamically update the knowledge graph when external requirements change to ensure accuracy and completeness. This process involves several steps. First, we need to identify the changes that have occurred, possibly due to new data sources, changes in business requirements, or other factors. Second, we must update the knowledge graph schema layer to reflect these changes, such as adding new classes, properties, or relationships. Third, we need to update the instance layer of the knowledge graph to incorporate the new data. Updating the instance layer may involve creating new entities, modifying existing entities, or deleting entities that are no longer relevant. Fourth, we need to ensure the consistency and coherence of the updated knowledge graph by checking for conflicts or inconsistencies between the old and new data and resolving them accordingly. Techniques such as ontology alignment and data fusion can be employed to achieve this. Finally, we must validate the updated knowledge graph to ensure it meets the expected quality standards and can be used effectively in the relevant application domains.

## 3.3 | Knowledge-guided railway scene generation and scene update

Figure 5 shows the knowledge-guided railway scene generation and update method, which includes the following steps.

### 3.3.1 | Parameter-driven modeling method

This article proposes a novel parameter-driven modeling method based on the model structure composition information in the knowledge graph. The method uses primitives as the primary modeling unit, which can be generated through automatic parsing of design parameters or extraction from an existing model library. By encapsulating geometric, functional, and spatial topology parameters, assembly parameters are achieved, allowing for the step-by-step transformation of coordinate systems and the assembly of “primitive-component-model”. Model metadata, including geometric size, assembly parameters, original positions, and structure tree,

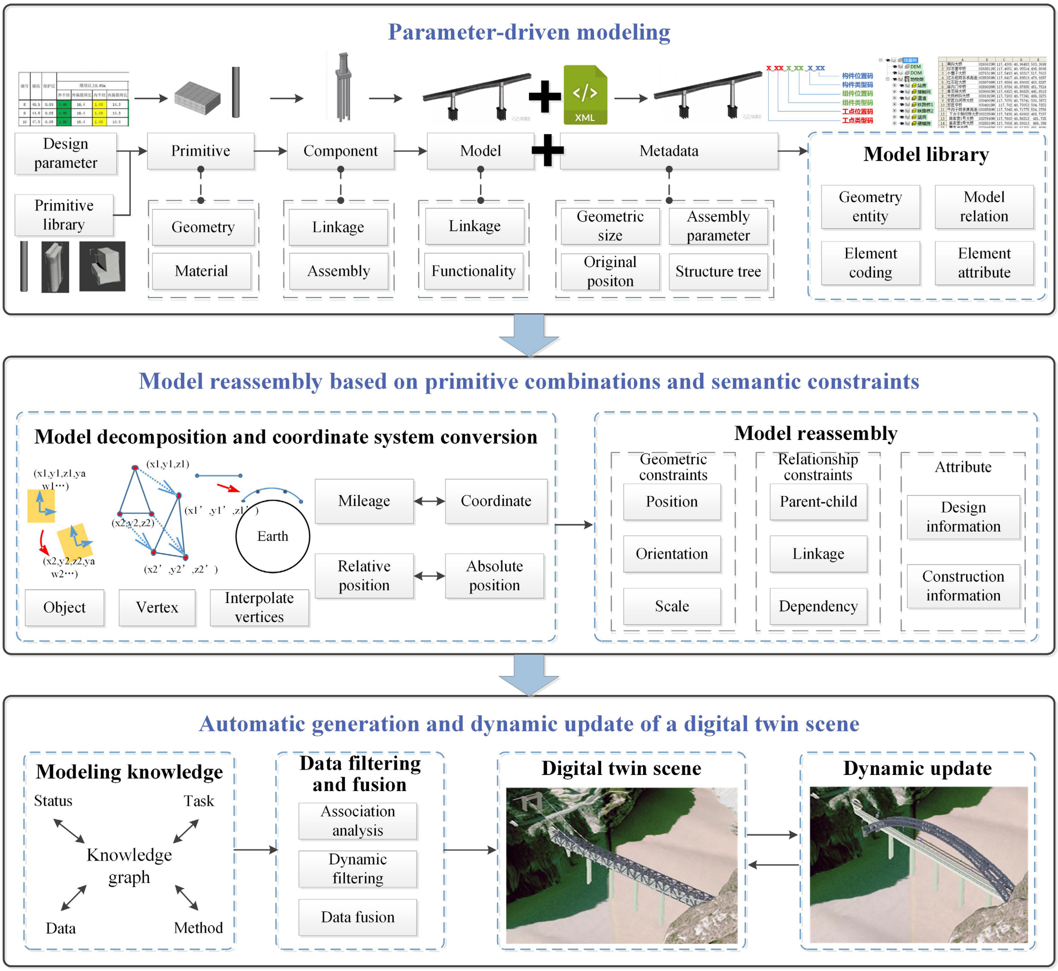

FIGURE 5 Knowledge-guided railway scene generation and update.

is generated based on parsed information. Through the integration of 3D models with geometry, coding, relationships, and attributes, a 3D model library is formed, enabling flexible parameter packaging and efficient model reuse.

### 3.3.2 | Model reassembled in the geographic coordinate system

The process of reassembling a model in the geographic coordinate system involves two steps: first, the model's coordinates must be converted from its original coordinate system to the geographic coordinate system; and second, the model's components must be reassembled in their correct positions within the new coordinate system.

Converting route mileages into geographical coordinates is known as coordinate system transformation. In this article, we propose a multi-level approach to ensure the accuracy and quality of data. Specifically, we use three levels: object level, discrete vertex level, and vertex interpolation level. The 3D model is treated as a 3D point for overall transformation at the object level. This level is suitable for coordinating the conversion of small models, such as bored pile models. The discrete vertex level involves the coordinate transformation of each vertex of a 3D model individually. This level is used for coordinate conversion of intermediate models, such as pile cap models. Finally, the vertex interpolation level performs vertex interpolation between the vertices of a 3D model and then performs coordinate transformation. This level can reduce the influence of the Earth's curvature on long-sized models and is thus used for coordinate transformation of large-scale models, such as 30 m-long box girder models. By using this multi-level approach, we can ensure that the coordinate system transformation is accurate and of high quality, which is crucial for the success of any railway construction project.

After the coordinate transformation, the 3D model must be reassembled in the geographic coordinate system. Model reassembly includes three aspects: geometric constraints, relationship constraints, and attribute linking. Geometric constraints refer to constraints on spatial position, orientation, and size scaling in the geographic coordinate system. Relationship constraints refer to constraints on the parent–child relationship, linkage relationship, and dependency relationship between the primitives. Attribute linking refers to attaching attributes to each model. By assigning a unique coding field to each primitive, design and construction information can be attached and tracked.

### 3.3.3 | Automatic generation and dynamic update of a digital twin scene

The assembled 3D model described in Section 2.3.2 integrates multiple sources of heterogeneous spatial data to generate a digital twin scene automatically. The dynamic update of the digital twin scene comprises two aspects: the dynamic update of the geometric dimensions of a primitive model and the dynamic update of the assembly relationships between primitive models. Real-time changes to the geometric dimensions of a primitive model can be made by dynamically modifying the design parameters discussed in Section 3.3.1. Similarly, by dynamically modifying the assembly parameters between the primitive models discussed in Section 3.3.2, different primitive models can be automatically assembled into another 3D model. In this way, users can view the 3D model status in real-time and even adjust model parameters to modify the plan or make predictions.

## 3.4 | Construction action modeling based on joint linkage and model growth

Figure 6 illustrates the construction action modeling method based on joint linkage and model growth. This method involves the following three steps.

### 3.4.1 | Joint linkage method of construction machinery

In order to achieve the visual simulation of construction actions, a construction machine model is broken down into multiple primitive models, and the linkage relationships between these models are established. This process involves complex control of mechanical joints, links between joints, and transmission relationships between machinery and materials. These relationships are described as parameters forming joint linkage parameters. The construction process is also parameterized, forming construction control parameters. A mapping between construction control and joint linkage parameters is established to determine the relative positioning method and attachment linkage relationship between a primitive model and its parent. Through multi-level coordinate system transformations, the absolute position and attitude parameters of each primitive model in a 3D scene can be obtained, allowing each component model to move simultaneously in different planes.

The parameters describing the joint linkage modeling results of each type of construction machinery can be standardized and stored in a construction method knowledge file. Each knowledge file describes the construction

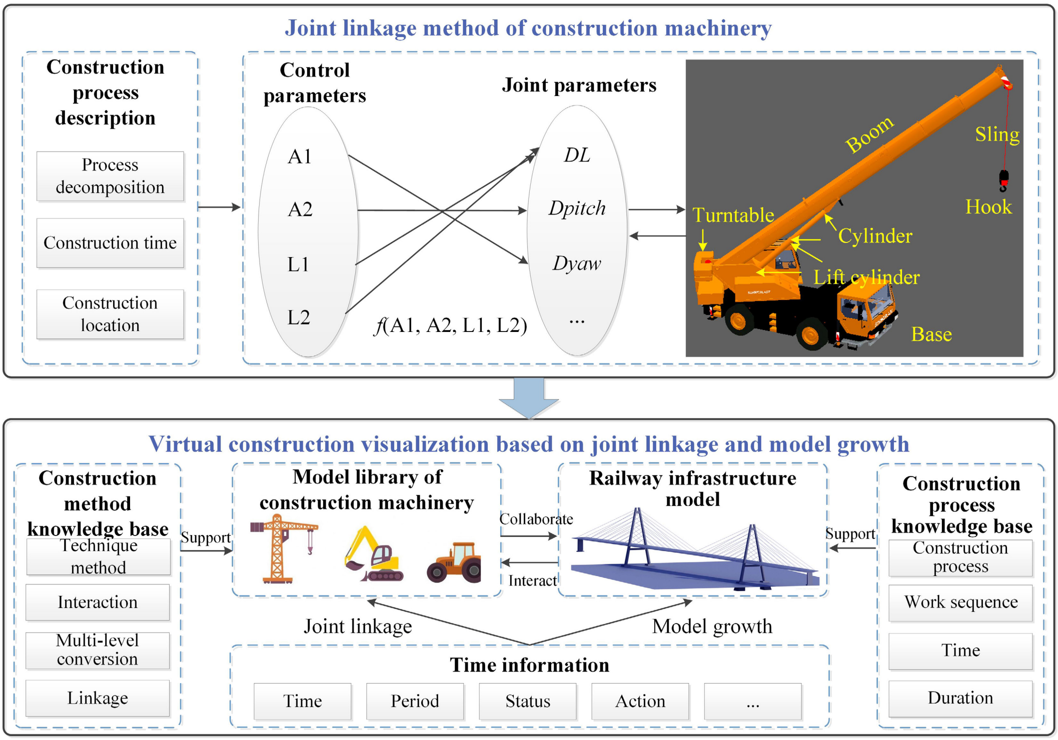

**FIGURE 6** Construction action modeling based on joint linkage and model growth.

activities of a specific construction machine, and together they form a construction method knowledge base. The construction method can be visualized in the digital twin scene by parsing the knowledge base.

### 3.4.2 | Virtual construction visualization based on joint linkage and model growth

The previous section discussed joint linkage models for visualizing construction methods. To complete virtual construction, it is also essential to visualize the construction process. Construction process visualization consists of four steps: process decomposition, information extraction, keyframe production, and model growth. The construction process is broken down into multiple steps in the first step. In the second step, the construction steps are defined along with their corresponding parameters, such as start and end points, duration, and equipment used. Typically, this information is obtained from project schedules or construction plans and is stored in the construction process knowledge file. Different construction process knowledge files form the construction process knowledge base. The third step is to map each construction process knowledge file into a keyframe. The fourth step involves parsing the keyframe and visualizing the construction process based on model growth using coloring or showing/hiding control. The coloring method involves assigning colors to 3D models representing different progress conditions. The showing/hiding control can gradually add or remove components based on the construction sequence to demonstrate the construction process.

The construction methods and processes are linked together to form a construction sequence, representing the order and dependencies of the actions. We have set up a timeline to correspond with the construction actions with time. This timeline allows the model to reflect the actual construction progress and generate a digital twin of the built environment. The construction processes and methods can be visualized in real-time to provide feedback and support decision-making during construction.

## 3.5 | Generation of hierarchical scenes for a high-speed railway

### 3.5.1 | Content of the hierarchical scenes

Hierarchical scenes are a way of organizing the digital twin scene into different levels based on their intended purpose. The three levels of scenes are a display scene, a virtual design scene, and a virtual construction scene. Table 2 shows the application stages and functions of the hierarchical scenes. Each scene level has its own set of functions and applications, as described in Table 2. The use of hierarchical scenes allows for greater flexibility and customization in the digital twin scene. It ensures that the scene is tailored to the needs of different stakeholders and users.

The display scene is the lowest level, used for demonstration and visualization. It is designed to present the railway project to stakeholders, such as clients, investors, and the public. This scene level typically includes the entire project site and all primary structures, focusing on aesthetics and visual appeal. During the planning and design stages, users often need help with problems such as low efficiency of visual modeling of design result data and difficulty in model updates caused by repeated changes in design schemes. Therefore, quickly generating a display scene based on design parameters can help users to realize the intuitive expression of design results. Moreover, the linked update of design parameters and 3D scenes can be utilized for comparing and selecting different design schemes.

The virtual design scene is the intermediate level for 3D design and design development purposes. It is primarily utilized by architects, engineers, and other design professionals to refine and develop individual structures and components. The virtual design scene includes detailed models of individual structures and their associated components, emphasizing accuracy and precision. 2D design proposals in areas with complex terrain may need to be more detailed to be used directly for construction, as they cannot accurately consider earthworks. However, a virtual design scene that supports 3D design and design development within a virtual geographic environment can help overcome this limitation.

The virtual construction scene is the highest scene level used for construction and management purposes. Construction managers and workers primarily use it to plan and execute the construction process. This scene level includes detailed models of individual components and their associated construction processes, focusing on efficiency and productivity. The construction process of railway engineering is dynamic and changeable, which makes the spatio-temporal relationship between construction machinery and the surrounding environment complex and poses significant risks to the construction process. However, the virtual construction scene supports the spatio-temporal rehearsal of the construction process in a virtual geographical environment, allowing for the “trial before build” method to be implemented. This approach enables construction teams to try different scenarios and identify potential risks and issues before construction occurs. It can also help to optimize the construction process and increase efficiency.

TABLE 2 Content of the hierarchical scenes.

| | Display scene | Virtual design scene | Virtual construction scene |
|---|---|---|---|
| Stage | Planning and preliminary design | Detailed design | Construction |
| Advantage | Rapid 3D visualization | Interactive visualization | Visual simulation |
| Function | 3D visualization | 3D visualization and data analysis | 3D visualization, data analysis, and visual simulation of a spatio-temporal process |
| Application | Visualization of design results; comparison of design schemes | Refinement of design results | 4D preview of the construction process |

### 3.5.2 | Generation of the hierarchical scenes

Figure 7 shows the generation of the hierarchical scenes, including the following three steps.

1. We carefully analyzed the specific business requirements for each stage. We developed three types of knowledge graphs: a display scene knowledge graph, a virtual design scene knowledge graph, and a virtual construction scene knowledge graph. Each knowledge graph was designed to effectively represent and organize the relevant information for its respective stage, providing valuable insights and facilitating decision-making processes.
2. To facilitate functional reuse, we have developed a digital twin modeling prototype system componentized by splitting and reorganizing multiple functional modules into various components. These components include a data service component, a dynamic modeling component, a spatial analysis component, a 4D simulation component, and a 3D visualization component. The data service component provides multimodal data services such as publishing, access, and updates. The dynamic modeling component generates a 3D scene of the railway project, with parametric modeling, assembly modeling, and coordinate conversion functions. The spatial analysis component is used for data analysis, including functions like cut/fill analysis, statistical analysis, and spatio-temporal correlation analysis. The 4D simulation component simulates the spatio-temporal process, including time sequence control of the construction process, joint linkage, and spatial reconstruction of model relationships. Lastly, the 3D visualization component can visualize multimodal spatio-temporal data, including 3D graphics API, high-performance GPU, and matrix transformation.
3. We use different components to generate hierarchical scenes. For the generation of the display scene, we require three components: the data service component, the dynamic modeling component, and the 3D visualization component. We parse design parameters and use the dynamic modeling component to create 3D models automatically. We use the data service component to publish modeling results as data services and the 3D visualization component to achieve visualization of the display scene. To generate the virtual design scene, we need four components: the data service component, the dynamic modeling component, the 3D visualization component, and the spatial analysis component. We add the spatial analysis function based on generating the display scene. We perform real-world Boolean operations on the 3D model and the surrounding terrain to achieve an interactive design in the 3D scene. For the generation of the virtual construction scene, we require five components: the data service component, the dynamic modeling component, the 3D visualization component, the spatial analysis component, and the 4D simulation component. We use the joint linkage method to achieve the 4D simulation of a construction method and the model growth method to achieve the 4D simulation of a construction process.

## 4 | EXPERIMENT OF GENERATING THE HIERARCHICAL SCENES

### 4.1 | Case description

In order to demonstrate the universality of the method proposed in this article, we conducted an experimental analysis on a high-speed railway. The experimental data were divided into three categories:

1. Basic geographic information data, which were used to generate a geographic scene, including digital line graph (DLG), digital orthophoto map (DOM), digital elevation model (DEM), oblique photography data, vector data, and annotation data.
2. Design parameters include the position parameters of the railway center line, the design parameters of critical structural components such as subgrades, bridges, and tunnels, and the assembly parameters between components.

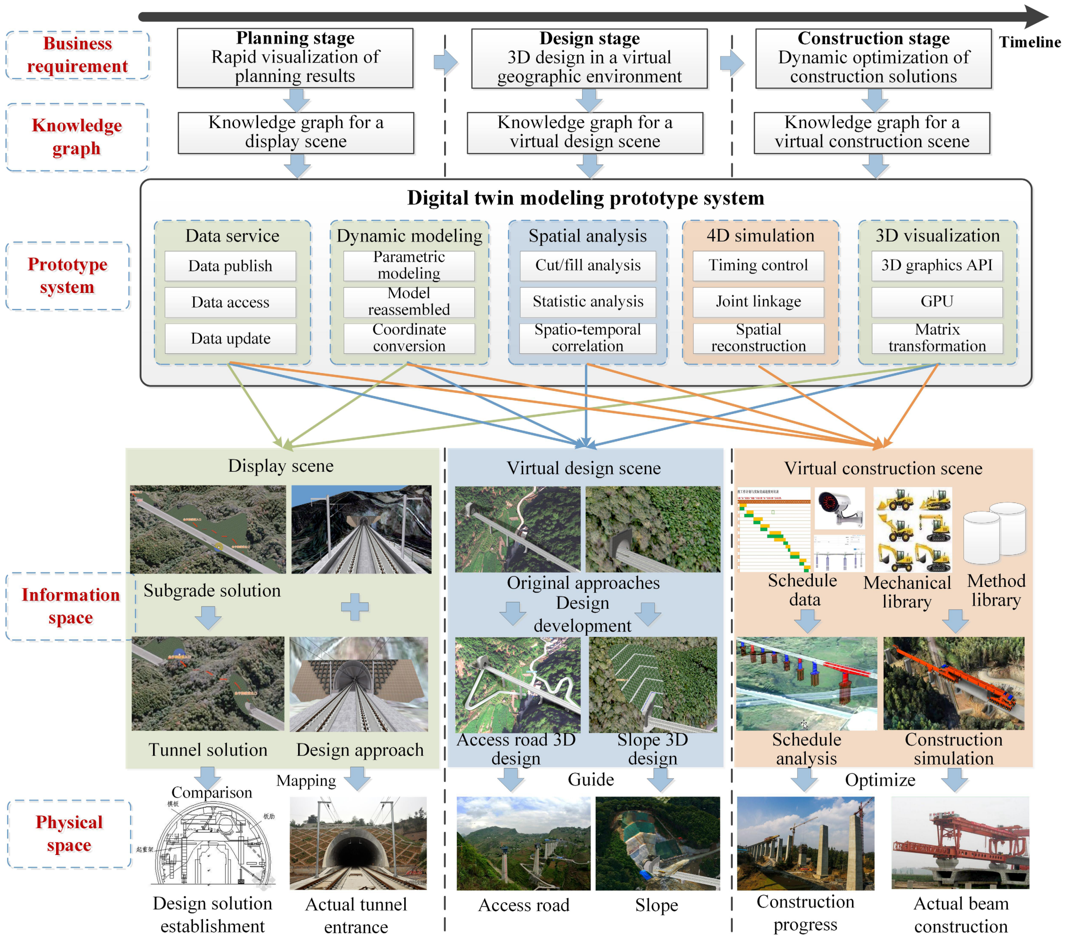

FIGURE 7 Generation of the hierarchical scenes.

3. Construction process data, including construction progress data, construction progress schedule, and construction organization plan for major and complex projects. These data were used to simulate and evaluate the spatio-temporal performance of the virtual construction scene.

The different modeling requirements and data types led us to create various knowledge graphs stored in the neo4j graph database. As depicted in Figure 8, the knowledge graph parametrically describes the construction sites of the entire railway project. It includes construction site type, mileage range, geometric size, and engineering quantity. Moreover, we have created several knowledge graphs, including a railway line knowledge graph, a model assembly knowledge graph, a construction progress reporting knowledge graph, and a joint linkage knowledge graph. These knowledge graphs serve as the foundation for generating hierarchical scenes.

## 4.2 | Experimental analysis

Compared to existing approaches, the proposed methodology in this article exhibits notable advantages. By integrating knowledge graphs, parametric modeling, and model assembly techniques, our method enables the dynamic

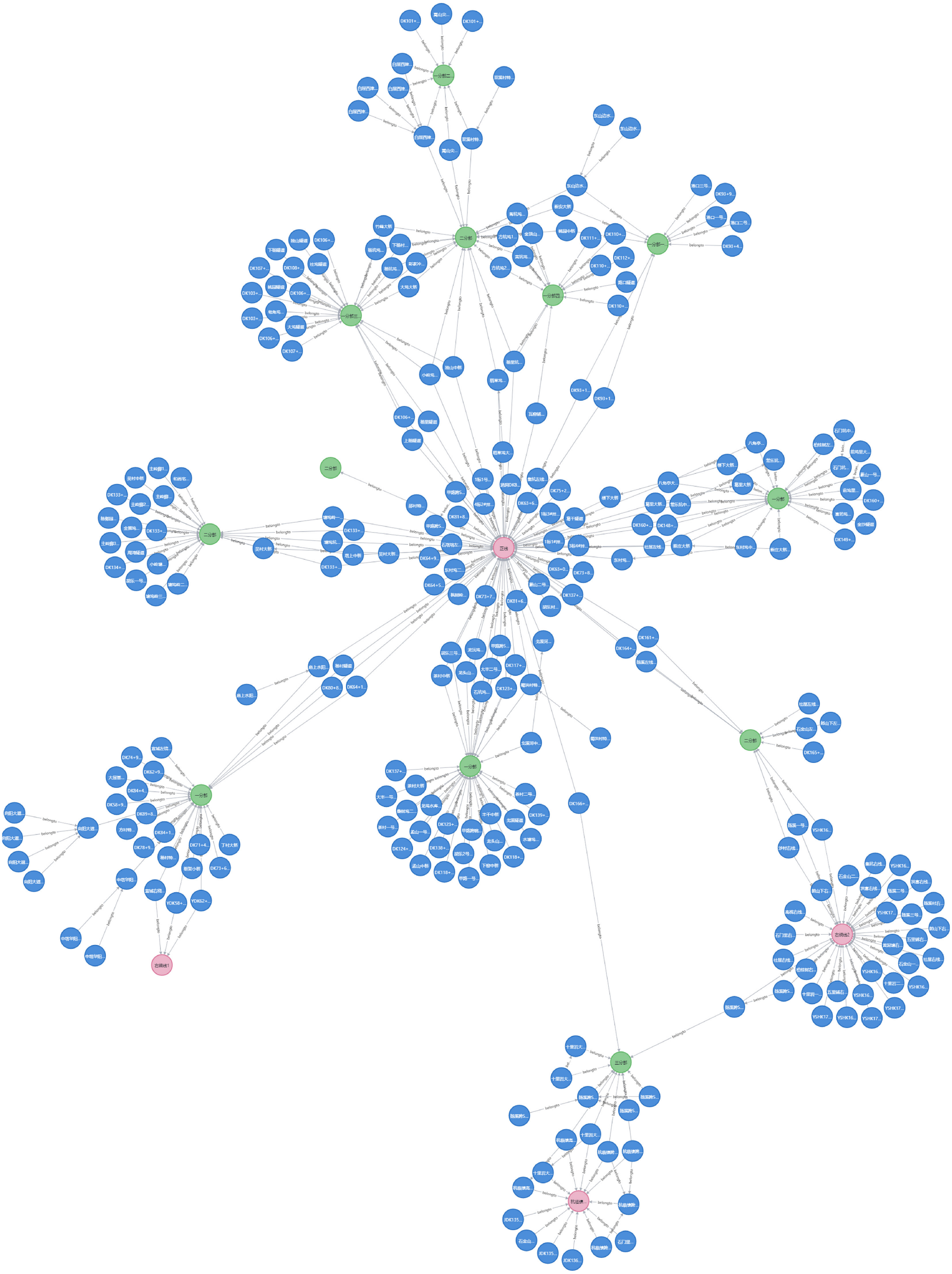

FIGURE 8 Construction site knowledge graph.

generation and updating of railway digital twin scenes across various stages. This comprehensive approach overcomes limitations in accurately representing diverse business requirements and intricate interactions among railway features. Moreover, our method contributes significantly to the field of GIS by addressing fundamental

TABLE 3 Summary of methodological advancements and contributions.

| Aspect | Knowledge graph | GIScience |
|---|---|---|
| Conventional approaches | • Conventional approaches could potentially miss out on grasping the interconnectedness of "knowledge-model-data," thus constraining a holistic understanding<br>• Conventional approaches exclusively utilize knowledge graphs for semantic depiction, lacking their application in guiding 3D scene generation | • Limited scene modeling variety: Conventional methods are restricted to generating a specific type of 3D scene<br>• Static 3D scenes: Conventional methods are confined to producing static 3D scenes, incapable of dynamic updates in response to changes in external parameters |
| Advances | • Hierarchical semantic description: The approach in this article considers the interconnectedness of "knowledge-model-data" and formulates a model for hierarchical semantic description<br>• Extending application in the GIS domain: Innovating the fusion of GIS and railway data into knowledge graphs, expanding its relevance within the GIS domain | • Hierarchical scene modeling: Offers an innovative method for generating hierarchical 3D scenes, incorporating modeling requirements and geographic objects<br>• Real-time 4D visual simulation: Presents an approach facilitating real-time mapping, thereby enabling 3D design and virtual construction |
| Contributions | • Enhanced spatio-temporal understanding: Contributes to a hierarchical semantic description model encompassing the "knowledge-model-data" relationship, improving overall scene comprehension | • Knowledge-guided hierarchical scene generation: Using knowledge-based guidance to create hierarchical 3D scenes enhances understanding and representation of complex spatio-temporal relationships |

research questions related to hierarchical scene generation and spatio-temporal dynamics in railway engineering. Table 3 provides a concise overview of the advances and contributions brought forth by our approach.

#### 4.2.1 | Display scene

The display scene can be quickly generated based on the route data and the existing model library. Moreover, the display scene can be updated in real-time based on the changes in design parameters, enabling the comparison and analysis of different design solutions. This feature enhances the flexibility and efficiency of the design process, allowing for exploring various design options and identifying the optimal solution.

As illustrated in Figure 9, the proposed method can generate high-speed (Figure 9a) and normal-speed railway display scenes (Figure 9b). Additionally, it can dynamically update a construction site model in the display scene based on different design parameters. Figure 9c demonstrates the dynamic generation of a tunnel 3D model according to tunnel design parameters. In contrast, Figure 9d displays the effect of modifying the tunnel design parameters to subgrade parameters and dynamically generating a subgrade 3D model.

#### 4.2.2 | Virtual design scene

1. Design of slope protection engineering at the tunnel entrance

By inputting design parameters, the terrain can be quickly filled or cut by automatically performing Boolean operations on the generated 3D model and the terrain. Analyzing the filling and excavation volume can assist in decision-making and detailed design. At the tunnel entrance, the 3D design of slope protection engineering can be carried out dynamically by inputting parameters such as slope rate and slope level, effectively guiding actual slope protection construction, as shown in Figure 10.

2. 3D design of construction access road

To create a construction access road, we can select or edit a line in the virtual design scene as the centerline. By adjusting the design parameters of the access road, we can generate a model and automatically fill or cut the terrain to display the design results intuitively and efficiently. In this article, we developed three solutions using the virtual design scene. The first solution features a straight road with a high slope, the second uses a zigzag access road, and the third involves laying a trestle at the bottom of the opposite valley. The results of the three solutions are presented in Figure 11. These solutions can assist decision-making and help optimize the construction process.

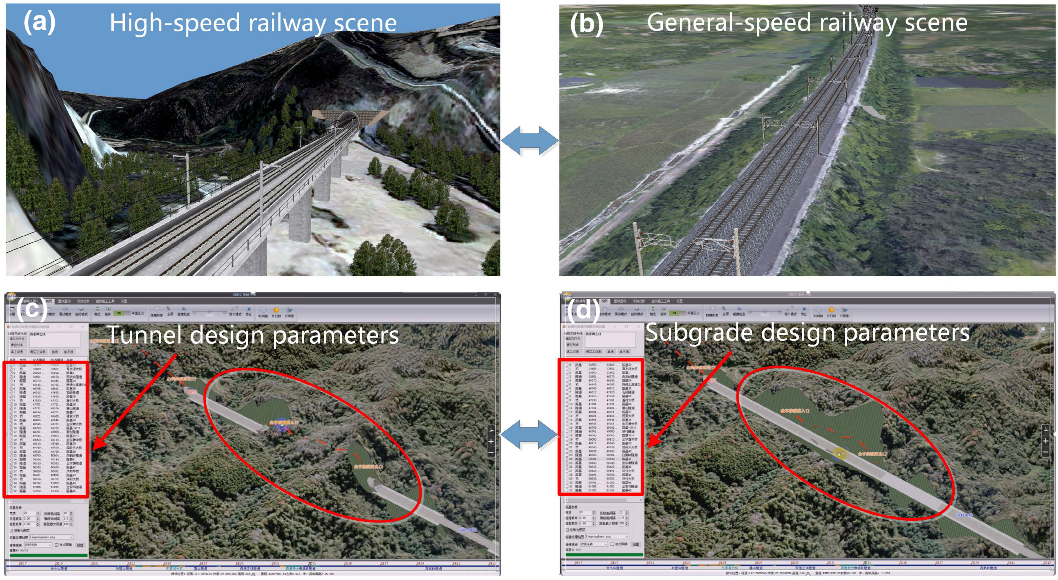

FIGURE 9 Display scenes: (a) High-speed railway scene; (b) General-speed railway scene; (c) Using tunnel design parameters to generate a tunnel 3D model in the scene; and (d) Using subgrade design parameters to generate a subgrade 3D model in the scene.

FIGURE 10 Design of slope protection engineering at the tunnel entrance.

The length, average slope ratio, maximum slope ratio, height difference, cutting volume, and excavation volume of the three construction access road solutions were calculated and presented in Table 4.

After comparing and analyzing the data in Table 4, it was found that Solution 1 had a significant slope, which posed a relatively high risk to construction safety. Solution 2 adopted a zigzag shape to reduce the slope. However, the corners would be challenging to construct and susceptible to landslides. In contrast, Solution 3 had a smaller slope, and the volume of filling and excavation was relatively small, which can reduce the risk of landslides and ensure the safety of construction. Therefore, Solution 3 was selected as the final choice.

### 4.2.3 | Virtual construction scene

1. Virtual construction progress

The digital twin modeling prototype system allows construction personnel to input construction progress information in a two-dimensional graphical format, ensuring precise progress tracking down to the component level. The progress data is then parsed and visualized in three dimensions using two methods: coloring 3D models and controlling the showing or hiding states of 3D models. These methods enable the real-time display of construction progress for various types of construction sites, such as bridges, tunnels, stations, subgrades, and foundation pits, as illustrated in Figure 12.

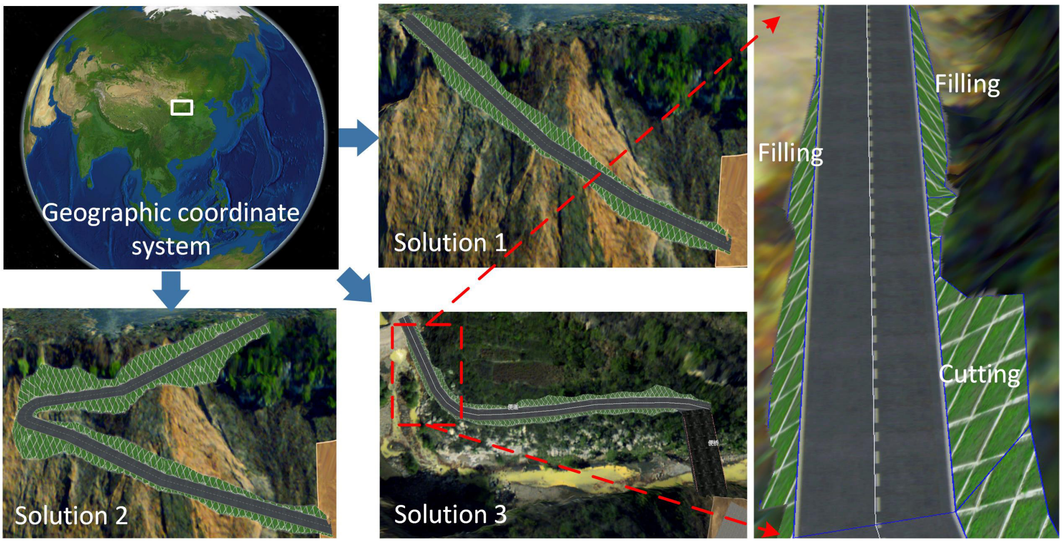

FIGURE 11 Three solutions for construction access roads.

TABLE 4 Data statistics of different construction access road schemes.

| Solution | Length (m) | Average slope (%) | Maximum slope (%) | Height difference (m) | Cutting ($m^3$) | Excavation ($m^3$) |
|---|---|---|---|---|---|---|
| Solution 1 | 125 | 29.82 | 33.10 | 37.28 | 255 | 607 |
| Solution 2 | 186 | 22.47 | 24.50 | 41.8 | 408 | 894 |
| Solution 3 | 161 | 3.11 | 10.00 | 5 | 417 | 460 |

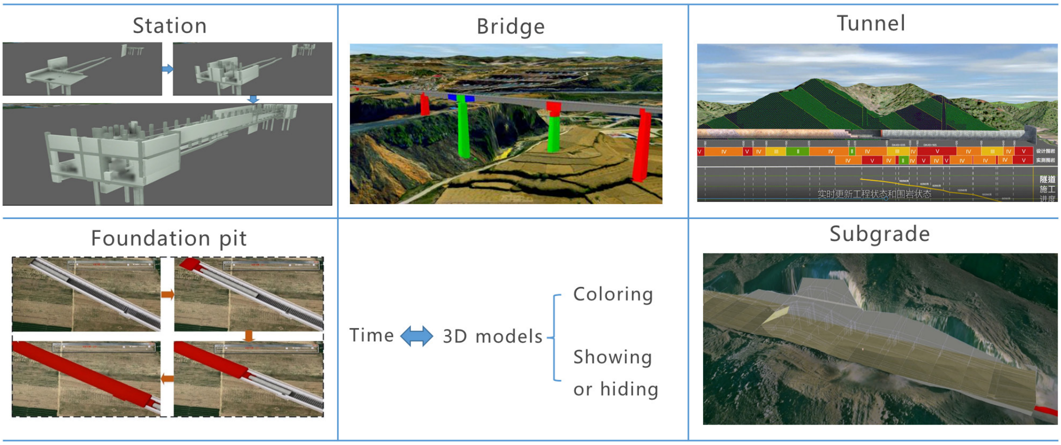

FIGURE 12 Virtual construction progress.

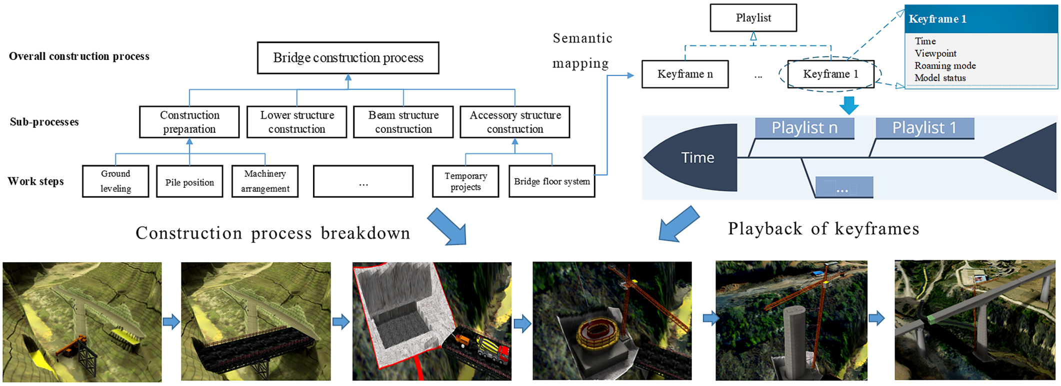

FIGURE 13 Virtual construction process and virtual construction method.

2. Virtual construction process and virtual construction method

To explore the potential of virtual construction techniques in construction site projects, we conducted an experiment where we simulated and analyzed the construction process using a 3D model. The construction site model was broken down into various primitive models, and their semantic relationships were established. By reassembling these models, we created a virtual construction environment where the construction process was simulated by controlling the visibility of the primitive models. Additionally, we established dynamic linkage constraint relationships among the primitive models of construction machines, such as tower cranes and concrete pump trucks, to carry out a virtual construction method. This approach proved valuable in planning the construction and identifying any potential risks, as illustrated in Figure 13.

## 5 | CONCLUSIONS

This article addresses the need for construction semantics and better universality in intelligent railway and digital twin modeling. One of the significant challenges is the hierarchical demand of scenes in different stages, along with the significant variability of modeling rules. To overcome these challenges, we explore the semantic description mode of hierarchical scenes, reveal the dynamic relationship between "business demand-modeling expression-construction elements" in different stages, and clarify the interaction mechanism of railway construction elements in a dynamic and complex environment. Through vital technological breakthroughs such as digital twin scene generation and construction action twin modeling, we have achieved a display scene, a virtual design scene, and a virtual construction scene. The proposed model is expected to significantly improve the quality and safety of railway construction by providing a comprehensive and cross-stage digital twin scene intelligent modeling solution.

The method introduces an advanced hierarchical semantic description model in the realm of knowledge graphs, emphasizing the intricate interplay between "knowledge-model-data," thus enhancing the holistic comprehension of scenes. Furthermore, in the GIS domain, the approach pioneers using knowledge-based guidance for generating hierarchical 3D scenes, thereby augmenting the portrayal and comprehension of intricate spatio-temporal relationships. Moreover, the method significantly contributes to supporting real-time 4D visual simulation. The main contributions are as follows:

1. This article proposes a multi-level correlation semantic description model of a railway scene that accurately describes the correlation relationship between "business requirements-modeling expression-construction elements" at different stages. We begin by analyzing the diverse needs of railway scenes in different stages and then divide the hierarchical scenes into three levels: display scenes, virtual design scenes, and virtual construction scenes. To finely describe the relationships between the digital twin modeling method and elements such as facilities, equipment, construction methods, and the environment in the entire process of railway construction, we construct "data-model-knowledge" knowledge graphs. These graphs are designed to guide the on-demand generation of hierarchical scenes at different stages and improve the intelligence and efficiency of digital twin modeling.
2. This article presents a parameter-driven modeling method for achieving dynamic updates of virtual design scenes. The method involves parsing design parameters to generate primitive models, followed by an automatic modeling method based on assembly parameters. By reassembling the primitive models in the geographic coordinate system and seamlessly integrating them with the terrain through Boolean operations, we can achieve the dynamic linkage between parameters and 3D models. This approach effectively addresses the problem of untimely scene updates caused by frequent changes in design schemes and enables quick comparisons of different design options.
3. This article proposes a novel construction action modeling approach based on joint linkage and model growth that enables spatio-temporal dynamic preview and hidden danger prediction. To achieve this, we first analyze the complex linkage relationships between primitive models and study the relative positioning and multi-level conversion method between a primitive model and its parent, which lays the foundation for our joint linkage method. Building on this foundation, we then utilize the model growth method to visualize the construction process. By combining joint linkage and model growth, our approach achieves comprehensive and accurate construction action modeling, which can improve the quality of railway projects.

In our future work, we plan to delve deeper into modeling the physical environment by incorporating elements such as wind field, gravity field, and temperature field. Our objective is to establish a correlation between the physical environment and the hierarchical scenes, allowing us to investigate how the physical environment affects a railway project at different stages.

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## CONFLICT OF INTEREST

No potential conflict of interest was reported by the author(s).

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author upon reasonable request. The data are not publicly available due to privacy or ethical restrictions.

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