

Article

Automatic Planning Method of Construction Schedule under Multi-Dimensional Spatial Resource Constraints

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Abstract: To enhance the application of building information modeling (BIM) in schedule management for engineering projects, improve spatial planning capabilities, and minimize subjective factors in schedule preparation, this paper presents a framework and method for automatic construction schedule planning based on BIM and data-driven approaches under multi-dimensional spatial resource constraints. The method includes data acquisition, construction process reasoning, time parameter calculation, and schedule generation and scheduling. Initially, the construction data from the BIM model and manual input are imported into the reasoning system to establish the logical relationships of the construction process. Construction time parameters and spatial resource requirements are then automatically calculated using MySQL. Subsequently, the spatial layout and resource allocation data exported from the BIM model are compared to assess whether the space meets the project requirements. Finally, a construction schedule that satisfies the space constraints is generated. The method was validated through a case study, demonstrating its effectiveness in automatic schedule planning under human-computer interaction. This study introduces an innovative approach that considers spatial conflicts in the automatic scheduling process, improving planning efficiency and reducing the risk of spatial conflicts on construction sites.

Keywords: building information modelling (BIM); data-driven; spatial-constrained; schedule planning; building construction management



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1. Introduction

The schedule is one of the most critical control objectives in project management, and timely completion is an essential factor for managing and evaluating the performance of construction projects [1]. Traditionally, preparing a construction schedule involves arranging construction procedures and coordinating resource input based on experience, which is a time-consuming process. Schedule planning is knowledge-intensive work. Due to the different experiences and abilities of various staff, there may be issues such as unreasonable construction process divisions, disorganized logical relationships, low schedule accuracy, and difficulties in effectively guiding construction [2]. Additionally, most projects face resource-constrained scheduling challenges [3]. Space is a crucial and limited resource on construction sites, and each construction process requires adequate space [4]. When the working spaces required for two processes overlap, space conflicts arise, negatively affecting the project schedule and potentially creating safety hazards [5]. Traditional project scheduling methods typically account for three resources: human resources, material resources, and machinery, but they often overlook spatial constraints.

Building information modeling (BIM) plays a vital role in promoting the transformation and modernization of the construction industry, serving as the core of building information technology. Many schedule management software, such as MS Project and Primavera P6 (P6), have implemented functions like work time calculation, schedule optimization, and resource balancing [6]. The prerequisite for these functions is understanding

the logical relationships of the construction process, which allows for computer-aided planning [7]. Construction space management primarily focuses on construction sites. Artificial Intelligence (AI) can simulate human cognition to store and identify knowledge [8,9]. Using AI to assist in schedule formulation can enhance the rationality and efficiency of planning. However, this method lacks a knowledge reasoning platform, and the algorithm is separated from the building information. In addition, with the development of BIM and the Internet of Things (IoT), the construction industry has become a data-intensive field, collecting large volumes of data at every project stage [8]. Therefore, the construction industry has the conditions to use data-driven intelligent management.

Despite the revolutionary changes that information technology has brought to engineering management, existing scheduling methods often fail to fully utilize these technological advantages, particularly in considering spatial resource constraints. To develop systematic solutions that assist engineers in scientifically and objectively automating schedule planning, this paper proposes a schedule planning method that considers multi-dimensional spatial resource constraints and uses BIM technology to manage space–schedule integration. This method reduces errors related to workload and subjective judgment, improves the efficiency and reliability of planning, avoids the risks of low construction efficiency and safety incidents, and provides guidance for subsequent work. Firstly, the BIM model constructed in Revit and construction process data are extracted using Dynamo, supplemented by manual inputs. The reasoning system is developed using the Pandas toolbox to derive the logical relationships of the construction process. MySQL is then employed to store and process data and automatically calculate construction time parameters and spatial resource requirements, ensuring the construction schedule meets the spatial constraints. Finally, an optimized construction schedule that satisfies spatial constraints is generated in MS Project. This study applies data-driven principles to develop a systematic solution that enables building information to facilitate the automatic planning of construction schedules. It represents a novel approach to applying BIM in schedule management. Meanwhile, this method innovatively considers the impact of potential spatial resource constraints on schedule planning and solves the issue of data interaction.

This paper is organized as follows: Section 2 reviews the current status and limitations of automatic planning methods and spatial scheduling. Section 3 describes the framework and method of BIM-based data-driven schedule planning. Section 4 introduces the technical support for the implementation of the BIM-based data-driven schedule planning method. Section 5 validates the feasibility of the proposed method through a case study, followed by the discussion and conclusion.

2. Literature Review

2.1. Automatic Planning Method of Construction Schedule

The research on schedule planning primarily focuses on three aspects: reasoning mechanisms, information interaction, and framework development. However, a comprehensive solution for automatic schedule planning remains lacking.

Faghihi et al. [10] have summarized various methods for the automatic planning of construction schedules, including case-based reasoning (CBR), knowledge-based reasoning, model-based reasoning, genetic algorithms, expert systems, and neural networks. Most studies developed for the construction industry are based on CBR systems. Dzung and Lee [11] established a common knowledge framework to detect scheduling errors through Schedule Coach and proposed corrections using CBR. However, this method is limited to low-rise construction projects. Ryu et al. [12] developed a general CBR-based planning tool, CONPLA-CBR, applicable to different project types by integrating dynamic case methods and construction schedule data. Mikulakova et al. [13] employed AHP and TOPSIS to construct a decision support system based on the CBR system. They evaluated alternative construction methods derived from the CBR system and selected the best construction scheme by considering all relevant factors. While CBR can help reduce some tedious and repetitive scheduling steps, the unique conditions of construction projects may hinder

the accurate scheduling capabilities of CBR deployment [14]. This approach necessitates cumbersome manual data input and lacks a method for automatic acquisition, creation, and maintenance [15]. Knowledge-based reasoning approaches can utilize an object-oriented representation method to construct rules and configure the construction process for specific structured subtasks [1]. This rule applies to a single component, rendering the deployment of such methods cumbersome [13]. Consequently, Amer and Golparyar-Fard [16] proposed a dynamic process template using embedded vectors of Action and Object activity components to represent construction activities. Based on this representation method, the generative Long Short-Term Memory Recurrent Neural Network (LSTMRNN) is used to decode the logical relationships of logical activities. Knowledge pertaining to construction schedules is extracted from historical project plans and schedule records. Model-based reasoning employs digital models to automatically generate schedules [17]. de Vries and Harink [18] utilized the topological relationships between components in the CAD model to generate and organize the construction process. The building components are linked to construction activities by predefining model components to generate the construction process and its precedence [19]. The BIM-based schedule planning method mainly uses geometric and spatial information from the model [17,20]. While the aforementioned methods are capable of reasoning about sequencing dependencies and logic, few studies have succeeded in performing complete planning tasks [15]. Additionally, some studies have explored the potential of AI in generating construction schedule plans [21,22].

The IFC standard provides numerous required object definitions. Therefore, Sigalov and König [7] utilized the IFC standard to extract information from the BIM model, enabling the algorithm to automatically generate schedules. Kim et al. [23] extended the object definitions of the IFC and extracted the space, geometry, quantity, material, and other information of building components to assist in schedule planning. Wang and Azar [17] used Revit in conjunction with Dynamo to extract data, including family types, spatial data, quantities, geometry, and material types of components.

Researchers aim to establish a framework for achieving automatic schedule planning. Wang and Yang et al. [17,24] proposed a BIM-based schedule planning framework for reinforced concrete frame structures and prefabricated buildings, respectively. They enhanced the BIM-based hybrid construction of precast and cast-in-place components within the new construction schedule planning framework. Other researchers use IFC to combine BIM models with genetic algorithms to generate schedules and construction scheduling plans [25,26]. In a recent study, researchers employed BIM and genetic algorithms to propose a framework encompassing schedule generation, optimization, and simulation. They successfully integrated BIM into the automatic generation and optimization of construction schedules [27].

2.2. Project Space Resource Scheduling

The spatial scheduling problem involves linking the construction schedule with the availability and constraints of the workspace [28]. Such problems necessitate determining both the start and end times of each activity, as well as ascertaining the position and direction that each activity should occupy within the specified space, which complicates their resolution [29]. Shang et al. [30] conceptualized the space-constrained scheduling problem as a time-constrained three-dimensional packing mathematical model. They constructed a two-dimensional planar space to represent the physical dimensions of the total work face and the work face required for each activity, introducing the z-axis to represent time. The starting point of the work activity is limited between the earliest and latest start times, with the duration of the activity represented by height. Isaac et al. [31] represented workers' movements using three-dimensional curves in the coordinate system to avoid conflicts in the workspace caused by multi-disciplinary interspersed construction, while also constructing a mathematical model for scheduling time and space. He et al. [32] proposed technology for determining the optimal total amount of resources using construction time annotations as the connection constraint and constraining the three workspaces mutually. Schedule

resources in the assembly workspace to ensure optimal resource utilization, the shortest construction time, and minimal cost. The existing research on space management mainly focuses on employing visualization and simulation technologies to identify space conflicts and respond to feedback during the construction phase. However, there is a notable lack of research concerning the overall design of scheduling schemes for spatial resources.

3. Framework and Methodology

3.1. The Framework of the BIM-Based Data-Driven Schedule Planning Method

This paper proposes a methodology for construction schedule planning under multi-dimensional spatial resource constraints based on BIM and data-driven principles. This approach is a reasoning method grounded in knowledge and models. The data are systematically organized from its original state for processing to achieve specific functions. In accordance with the flow direction of data, Figure 1 illustrates the framework, which includes the presentation layer, application layer, data layer, and data source. Furthermore, the operational process of the proposed planning method is defined through a demand analysis of the application layer. The task content of this methodology is divided into four modules, which are elaborated upon in Section 3.1.5.

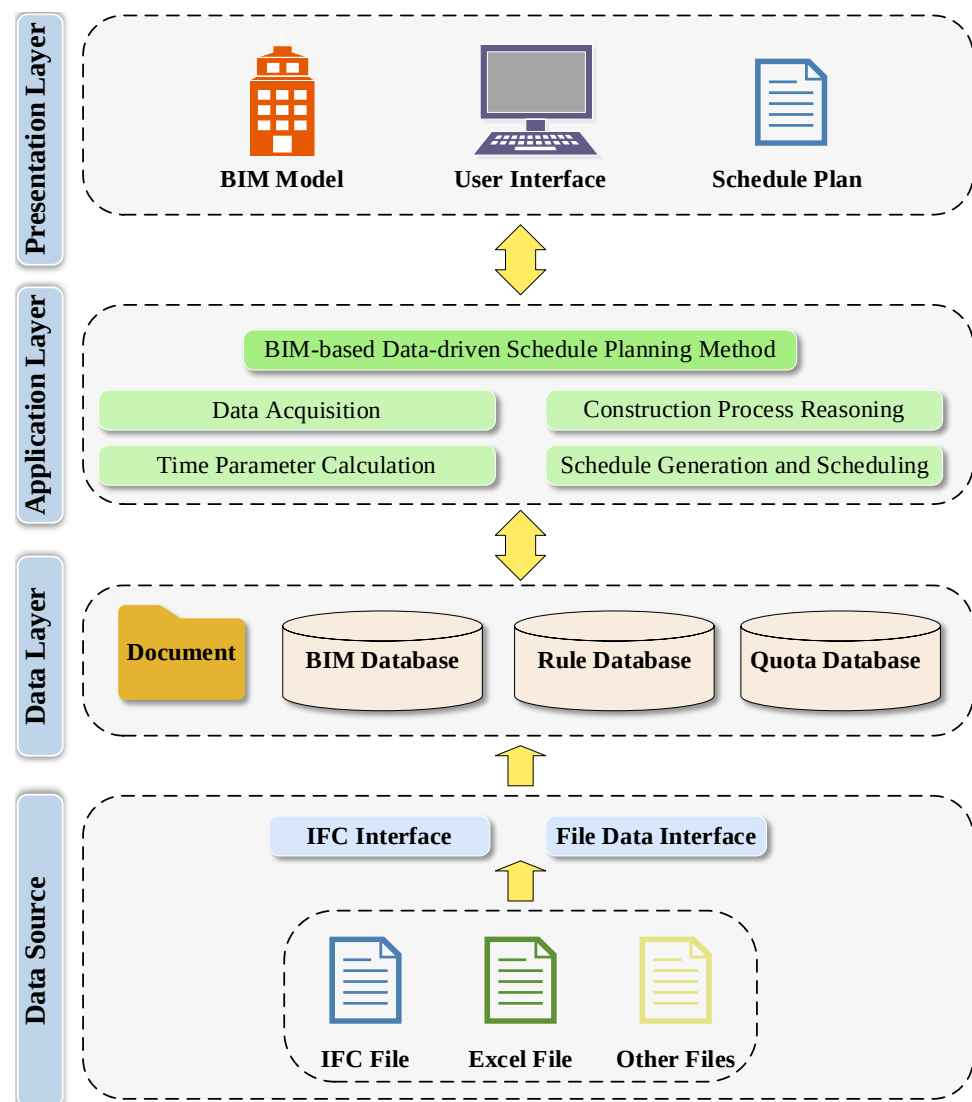


Figure 1. BIM-based data-driven schedule planning framework.

3.1.1. Presentation Layer

The presentation layer serves as the operation interface for users to access the system, encompassing information interaction, models, and the schedule display interface. Users can view information such as the building model, component information, and the construction schedule. Additionally, this method requires not only the data from the BIM model but also necessitates that the user input supplementary data through this interface.

3.1.2. Application Layer

The application layer is responsible for obtaining and analyzing data to compile and display the construction schedule. This layer comprises four functional modules: data acquisition, construction process reasoning, time parameter calculation, and schedule generation and scheduling.

3.1.3. Data Layer

The data layer is tasked with storing and managing data, which includes the BIM database, rule database, quota database, and document database. The BIM database stores geometric and attribute data extracted from the BIM model. The rule database contains rules for construction process matching, integration, and reasoning. The quota database maintains national norms and enterprise quotas. The document database stores and manages interactive documents.

3.1.4. Data Source

The data source comprises raw data without processing, including IFC, Excel, and other files. The IFC is a file format for data interaction among different modeling software. The Excel files contain both geometric and non-geometric data extracted from the BIM model, as well as data facilitating interaction between software. Other files include construction drawings and schedules. These data sources enable data interaction and integration through the IFC interface or file data interface.

3.1.5. Operation Process

The operation process of the schedule planning method consists of three stages, as illustrated in Figure 2:

- (1) Data acquisition: There are two primary data-acquisition paths. The first path entails extracting building information data from the BIM model, while the second involves manually inputting information or adjusting results during the reasoning process.
- (2) Data processing: Data processing encompasses construction process reasoning and time-parameter calculation. First, the component data from the BIM model is imported into the reasoning system to match the construction process and determine the logical relationships. The preparation personnel first audit the accuracy of these logical relationship and make manual adjustments as necessary. The engineering quantity calculation plug-in TH SWARE 2022 for Revit in BIM modeling software can export the engineering quantity list and workspace parameter data related to the construction process from the BIM model.
- (3) Data output: The resource allocation plan integrates the transportation space index and the material storage space index to calculate the space required for transportation and material storage. The BIM model is then utilized to verify whether the construction site layout meets the space requirements. If the layout is unsatisfactory, the preparation personnel must manually adjust the time parameters of the construction process for the non-critical path.

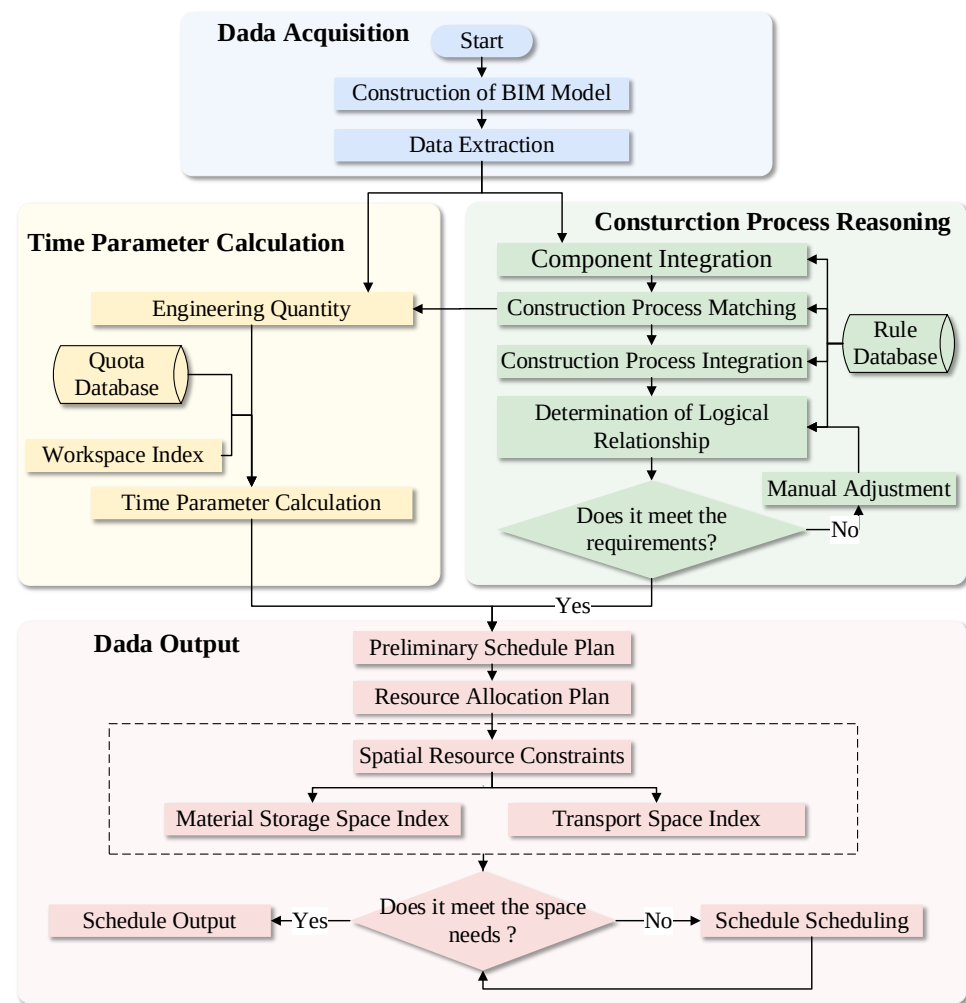


Figure 2. Operation process of BIM-based data-driven schedule planning method.

3.1.6. Assumption

This study establishes the following assumptions regarding the applicability of the planning method:

- (1) There are engineering quantity calculation plug-ins based on modeling software development to extract the engineering quantity data from the BIM model. Therefore, this study assumes that the bill of quantities can be imported externally.
- (2) This study assumes that the division results for the construction layer and construction segment are predetermined at the time of BIM model creation, as these factors must be considered when planning the schedule.
- (3) This study assumes that the project resource consumption is calculated using BIM application software.

3.2. Reasoning Mechanism of the Construction Process

The BIM-based data-driven schedule planning method employs AI to learn, reason, and self-correct by simulating human expert knowledge [9]. To effectively design the construction process reasoning mechanism, it is essential to decompose, integrate, and match the construction process and components. Subsequently, the logical relationship between these process must be clarified and an expression scheme constructed. These logical relationships are derived from previous projects, forming the basis for the logical reasoning system.

3.2.1. Matching of the Construction Process

The BIM model is constructed from component primitives and the extracted information corresponding to component details. The basic unit of the schedule is the construction process. Therefore, it is necessary to match the construction process with the building components. The construction decomposition rule serves as the basis for this matching process. An existing coding system is organized according to the requirements of schedule planning and adheres to the principle of work breakdown structure (WBS). The construction project is hierarchically broken down into the professional categories, construction layers, construction segments, component categories, construction methods, and construction processes [33,34].

3.2.2. Integration of the Construction Process and Components

Flexible WBS minimizes the number of tasks while still accommodating the varying levels of detail required by the project [33,34]. This paper proposes the concepts of “component group” and “construction process group” based on the flexible WBS to integrate different types of components and construction processes. The component group and the construction process group will inherit the original information.

Definition of component group: (1) It is a combination of several simple construction methods and similar components, characterized by short construction duration; (2) it is composed of different types of components—their corresponding construction processes and construction process logical constraint relationships are similar—and (3) all components within the component group have the same start time and end time, and the construction personnel and mechanical equipment required for component construction are the same.

Definition of construction process group: (1) It is a combination of several construction processes with similar content, and their working spaces are adjacent. (2) All construction processes in the group have the same start and end times, and the construction personnel and equipment required to perform the construction process are the same.

3.2.3. Logical Relationships of the Construction Process

The logical relationship rules for the construction processes proposed in this paper are derived from an analysis of completed construction projects:

- (1) Construction rules between professional types: The main structural engineering can only commence after foundation engineering is complete. The other professional types can be interspersed in the main structural engineering.
- (2) Construction rules between different components: The components from different construction layers are constructed from bottom to top. The components within the same layer are also constructed from bottom to top, except for decoration projects, which proceed from top to bottom. For load-bearing components, vertical elements are prioritized over horizontal ones.
- (3) Construction process constraint relation rules: The relationship between building components is determined by the construction method employed.
- (4) Organizational constraint relation rules: According to the flow construction organization methods, the construction layers are divided into building floors, and the construction segments are manually defined.

Furthermore, it is crucial to develop a logical expression scheme to articulate the logical relationships among construction processes. This paper presents three types of logical relationships based on existing expression schemes, as depicted in Figure 3.

- (1) Context: It refers to the constraint relationship between two construction processes. One process must be completed before the other can commence. Intermittent time may exist between the two processes.
- (2) Equal: It means that two construction processes can be constructed simultaneously without affecting one another, typically occurring in different working spaces.

- (3) **Overlap:** Refers to a situation where construction process 1 has not been completed, yet construction process 2 begins. While these processes generally lack causal relationships, they may be limited by shared resources, preventing simultaneous execution.

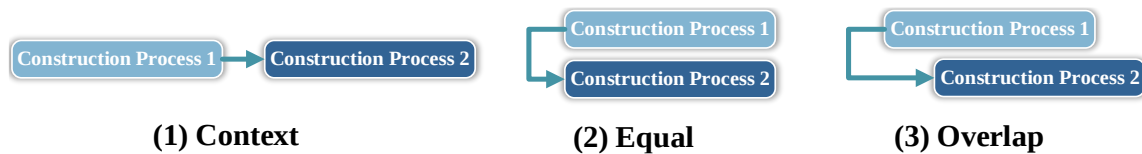


Figure 3. Construction process logical relation expression scheme.

3.3. Schedule Scheduling Mechanism under Multi-Dimensional Spatial Resource Constraints

BIM software can export the working spatial data of each construction process. The automatic calculation of time parameters is realized through MySQL. This paper constructs the process of schedule scheduling under multi-dimensional spatial resource constraints, as shown in Figure 4. The resource consumption is generated by the BIM software in accordance with the applicability assumption. The daily and monthly resource consumption is obtained from the resource allocation plan. This resource consumption data is then imported into the reasoning system to calculate the transportation space and material storage requirements. The schedule is subsequently adjusted based on a comparison with the data exported from the BIM software to meet the constraints of spatial resources.

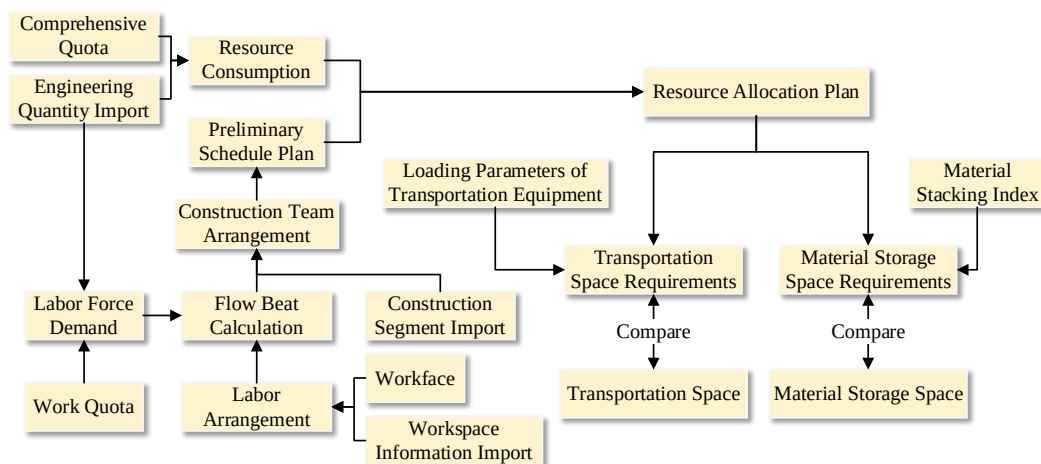


Figure 4. Scheduling process under the constraint of multi-dimensional spatial resources.

3.4. BIM-Based Data Extraction Mechanism

3.4.1. Construction of BIM Model

The modeling software used in this study must fulfill specific parameterization requirements. Revit was selected as the modeling software after comparing four mainstream modeling software from various development companies [35]. The naming convention for components follows the format: professional type-component type-parameter feature. Additionally, the model must be capable of identifying the types of building construction elements. Therefore, the refinement level of the BIM model needs to reach the LOD300 level.

The knowledge database within the reasoning system comprises various types of data. Certain data must be integrated and extracted by appending parameter attributes to the model, including the component type, construction method, construction process name, workface feature, workspace index, project feature, material storage space, and transportation space.

3.4.2. Data Extraction Mechanism Based on Dynamo

The data extraction method based on Dynamo is actually to realize the extraction of component attribute data through Dynamo's built-in scripts and Python. This process is divided into three steps:

- (1) Identify the object of data extraction: Three nodes are essential for identifying the family type: Select Model Elements, Element.Element Type, and List.Unique Items. All the family instances in the model are selected, converted into family types, and then duplicate family types are deleted. The identification of family instances involves two methods. The first method employs three nodes: Select Model Element, Element.Element Type, and All Elements of Family Type. This involves selecting a family instance within the target family type, converting it into the family type, and obtaining all family instances under that type. The second method simply selects all family instances in the model using the Select Model Elements node.
- (2) Extract the data of parameter attributes: Four nodes are needed for data extraction: Element.Get Parameter Value By Name, List.Add Item To Front, List Create, and List.Transpose. The extracted object is imported into the parameter extraction node, where corresponding parameter values are retrieved based on the parameter attribute names. These names are then added to the front of the parameter value list. All parameter attributes are consolidated into a single list, which is subsequently transformed to organize the data vertically.
- (3) Exporting data: Data exportation involves using the Data.Export Excel node. This step requires defining the file path, setting the worksheet position, specifying the starting row of data import, and determining the starting column of data import.

4. Development of a BIM-Based Data-Driven Construction Project Schedule Planning Method

4.1. Development of a Knowledge Database for the Reasoning System

The establishment of a knowledge database requires the classification, summarization, and integration of various types of original information into the database. The manager facilitates the functionality of the schedule planning method by calling the knowledge. Ultimately, the new knowledge generated during the application process is stored and processed. The reasoning system represents knowledge using a conditional result form and frame representation in the form of IF P-THEN Q.

The design content of the knowledge database structure mainly includes table structure design and table relationship design.

Structure design of data tables: The knowledge database of reasoning system consists of eight data tables: (1) component integration knowledge data table, (2) construction process matching knowledge data table, (3) construction process integration knowledge data table, (4) construction process logical relationship knowledge data table, (5) labor quota data table, (6) workface parameter data table, (7) material storage index data table, and (8) transportation space index data table. The first four tables are used for construction process reasoning, while the last four tables are employed for calculating time parameters and space requirements.

Structure design of the relationship between data tables: The construction process reasoning is based on the Pandas toolbox external to the knowledge database, thereby eliminating the necessity of constructing relationships between data tables. Conversely, the calculation of time parameters and space requirements is based on MySQL, which requires the establishment of relationships between data tables. The association among data tables can be achieved using MySQL.

4.2. Development of the Reasoning Engine

4.2.1. Development of Construction Process Reasoning

The reasoning engine for the construction process must facilitate the functions of matching construction process, integrating components and the construction process, and determining the logical relationships among construction processes. The foundation for these functionalities is the exportation of relevant knowledge in Excel file format through MySQL, which is then structured into a new database that serves as the basis for reasoning within the Pandas toolbox.

The specific implementation steps for the construction process reasoning function are as follows:

- (1) Integration of components: The component name and construction method serve as search criteria. By reading data from the worksheet and the component integration database, components are integrated according to predefined rules, with the synthesized name values filled into the component name using the filling method.
- (2) Matching of construction process: The component name and construction method are used as search criteria. By reading data from the worksheet and the construction process matching database, components are matched according to the construction process rules, thereby facilitating the division of the construction process.
- (3) Integration of the construction process: The database data is integrated by reading from the worksheet and the construction process, using the construction process name as the search criterion to integrate the construction process according to the established rules.
- (4) Determination of logical relationship in the construction process: The results from the construction process integration are merged into the construction process logical relational database, with the construction processes sorted according to specified rules. The construction processes exhibiting parallel logical relationships are marked. Finally, the reasoning results are generated and exported to an Excel file.

4.2.2. Development of Time Parameter and Spatial Requirement Reasoning

The calculation of time parameters, material storage space requirements, and transportation space requirements for the schedule can be executed using MySQL according to the analysis in Section 3.3.

5. Case Study

5.1. Case Background

A large-scale residential project was examined as an illustrative example to validate the practical effectiveness of the proposed BIM-based data-driven schedule planning method. This project is a mixed-use development, including nine residential buildings, five retail shops, and two levels of underground parking, situated in Zhongshan City, Guangdong Province, China. The total land area is 51,966 m² with a total construction area of 210,090.89 m². The base area measures 12,433.63 m², and the building density is 28.09%. This study focuses on the second phase of the project to evaluate the actual impact of the BIM-based data-driven schedule planning method. The phase includes five residential buildings and two shops, with the BIM model illustrated in Figure 5.



Figure 5. BIM model of engineering project.

The ground-level structures of the second phase are divided into three construction areas to enhance construction efficiency, while the foundation engineering is not segmented into construction areas. Figure 6 depicts the division of the specific construction areas. The three construction areas are developed in parallel, with Area A designated for practical application in the second-phase project.

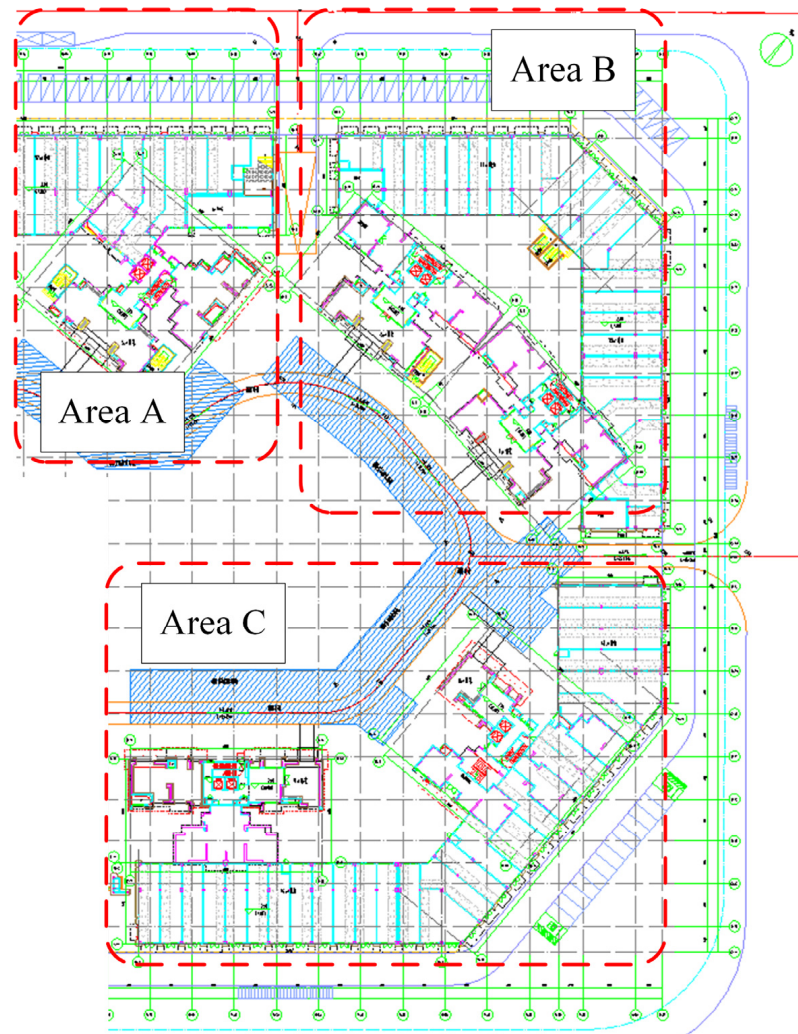


Figure 6. Division of construction areas of the second-phase project.

5.2. The Application Process

The construction process for basic engineering and main structural engineering represents the critical path for housing construction projects, with associated subentry engineering identified as the key route, while the remaining subentry engineering tasks will be interspersed.

5.2.1. Data Collection

The first method for data collection mainly involves using Dynamo to extract parameter attributes from Revit and export data in Excel files. The second method entails manually importing information into the reasoning system as an Excel file. Users can interact with the system by adding information to the Excel table and subsequently importing it into the reasoning system, as shown in Figures 7 and 8.

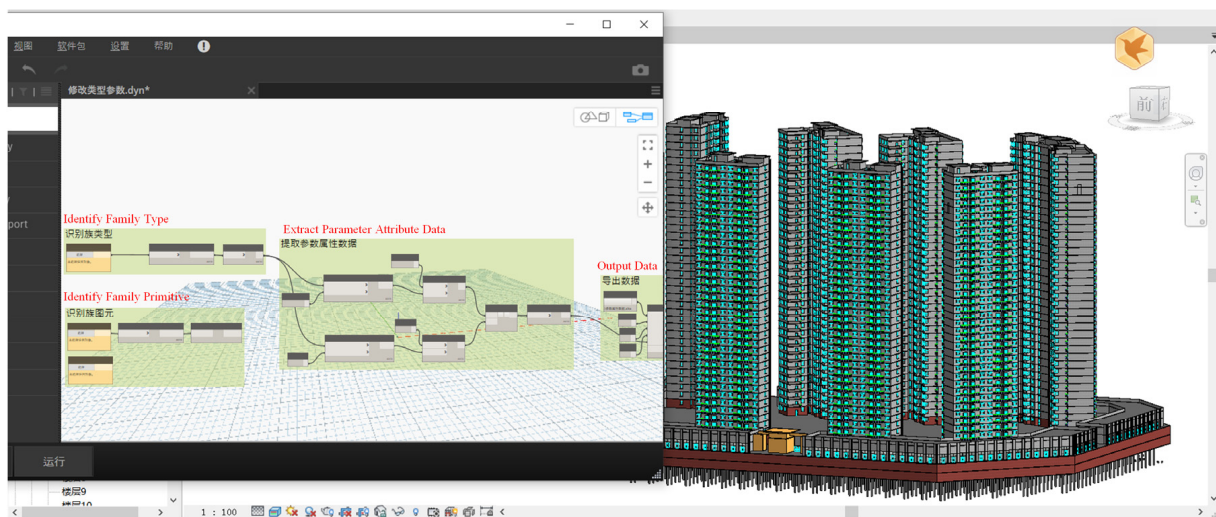


Figure 7. Parameter attribute data extraction based on dynamo.

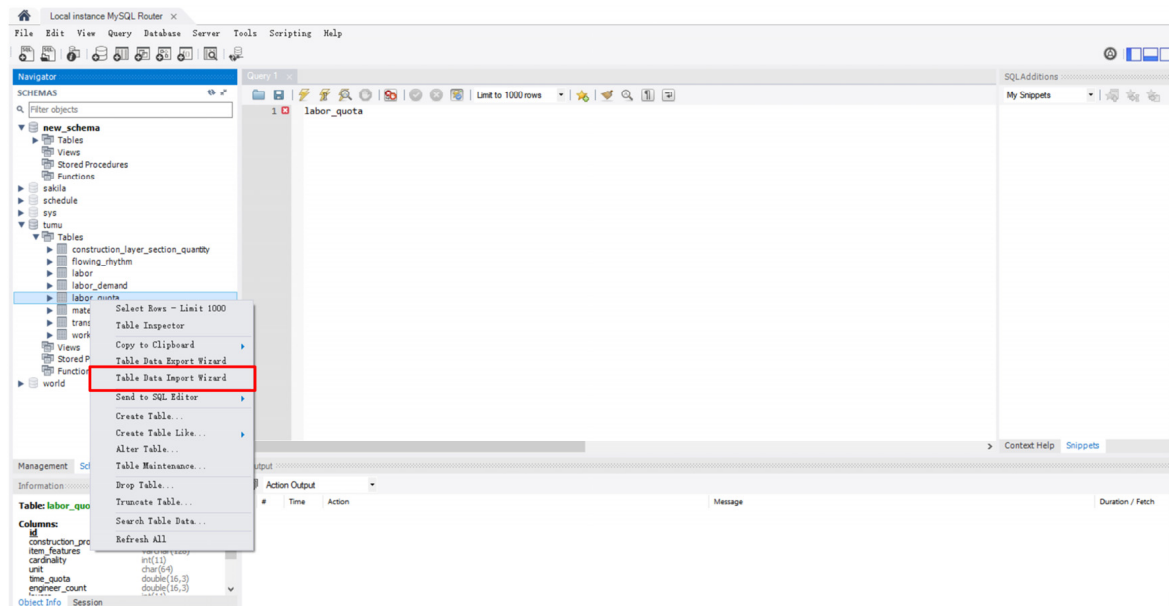


Figure 8. Data interaction interface of the reasoning system.

The bill of quantities and resource consumption are predetermined according to the applicability assumptions. The bill of quantities for the model components is generated by TH SWARE 2022 for Revit and exported from the BIM model. The material consumption calculations are conducted by setting the quota, and a daily resource consumption plan is formulated in combination with the schedule plan to facilitate subsequent analysis of the limited construction space.

5.2.2. Construction Process Reasoning

The data file is stored in a specified path after exporting the data of the component name and construction method from Revit. The integration of components, the matching and integration of the construction process, and the determination of logical relations are realized through the reasoning system. The final reasoning results are output as an Excel file, as shown in Figure 9. The accuracy of the logical relationships of the construction process is verified, and any discrepancies can be manually adjusted.

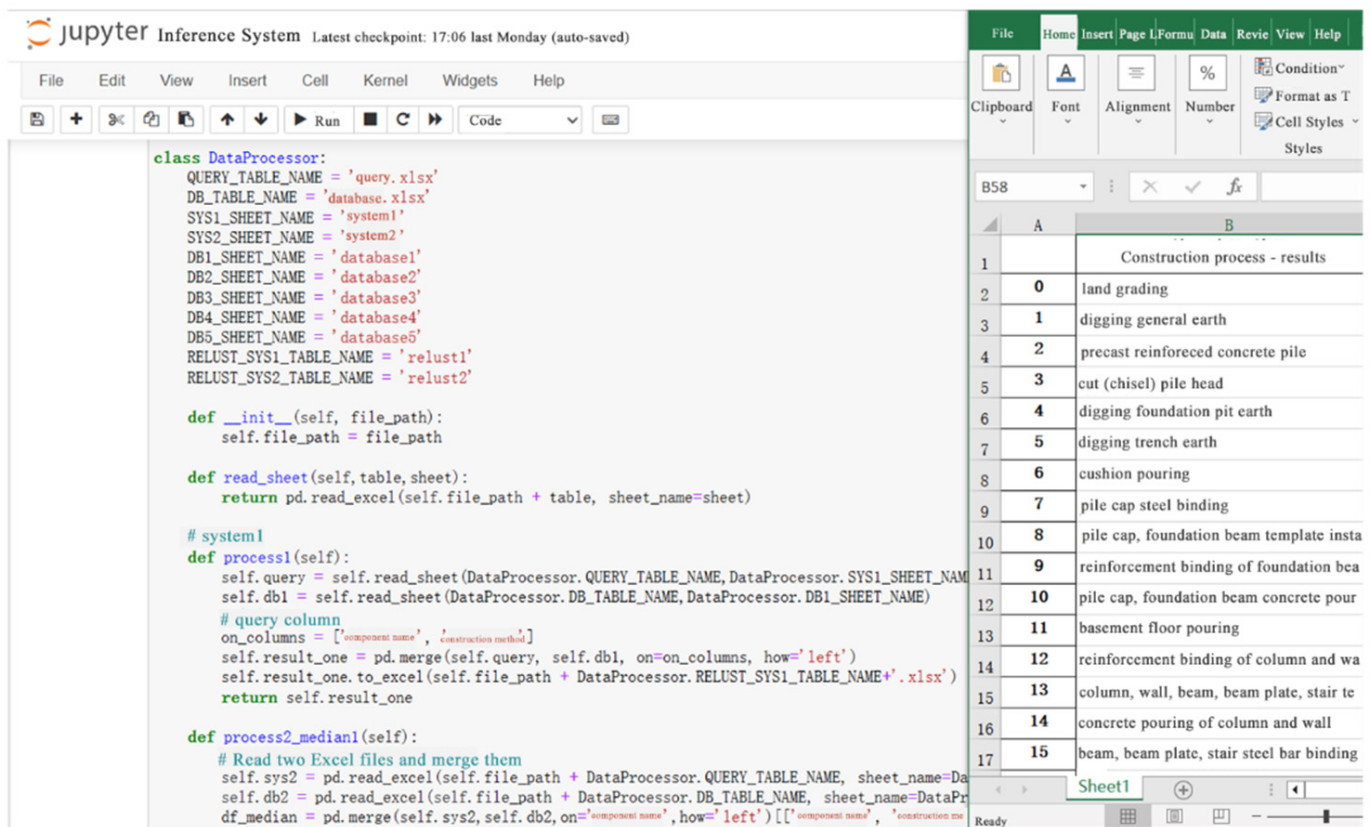


Figure 9. Construction reasoning schema.

5.2.3. Time Parameter Calculation

It is necessary to derive the name of each construction process, the project features relevant to the construction process, the workspace parameter index, and the workface features from Revit after generating the logical relationships. The bill of quantities generated by TH SWARE 2022 for Revit is then organized, and the corresponding project characteristics are appended to each construction process. The bill of quantities and workspace parameters are imported into the reasoning system. The engineering quantity is matched based on the construction process name and project features, while the workspace index is matched based on the construction process name and workface features. This facilitates the alignment of the engineering quantity and labor quota of each construction process, as well as the workspace index and workface parameters. Finally, the labor demand and labor force for each construction process are calculated using the Select command of MySQL, and the running rhythm of each construction process is determined by combining the division of the construction layers and segments as shown in Figure 10.

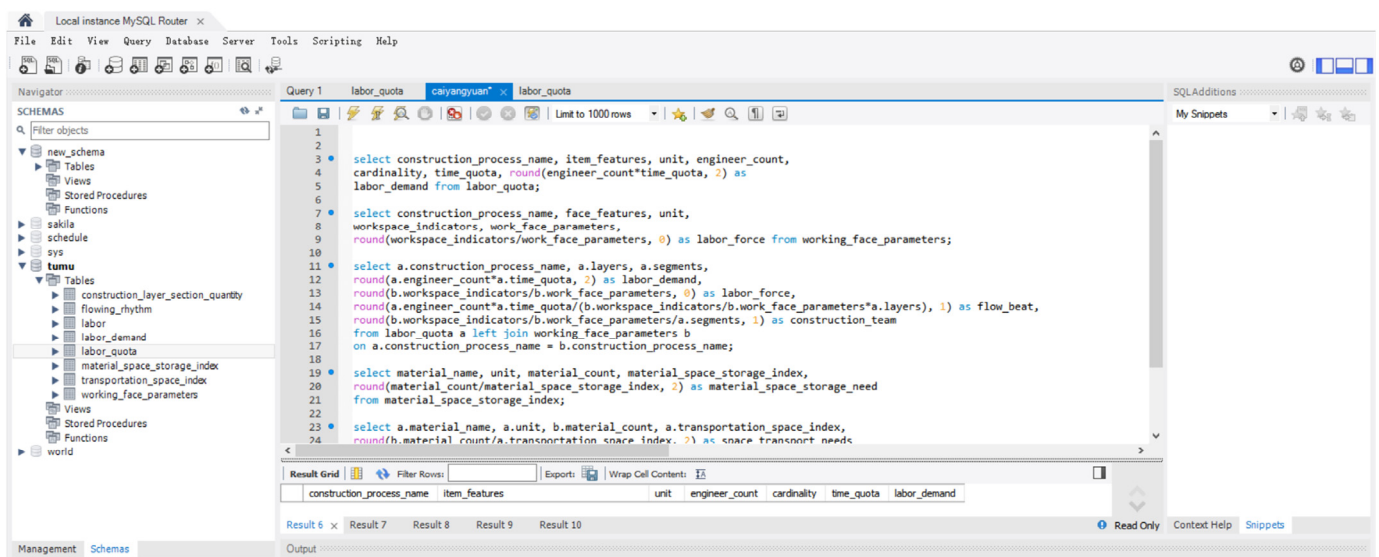


Figure 10. Schematic calculation of time parameters.

5.2.4. Construction Schedule Generation and Scheduling

The preparation personnel can manually adjust the order of the construction processes according to the actual requirements and engineering experience after the initial construction process relationships are established. Additionally, the time parameters corresponding to each construction process must be integrated based on component and construction process integration. Finally, the construction process and time parameter data are imported into MS Project 2021 to generate the corresponding Gantt chart to guide the on-site construction, as illustrated in Figure 11.

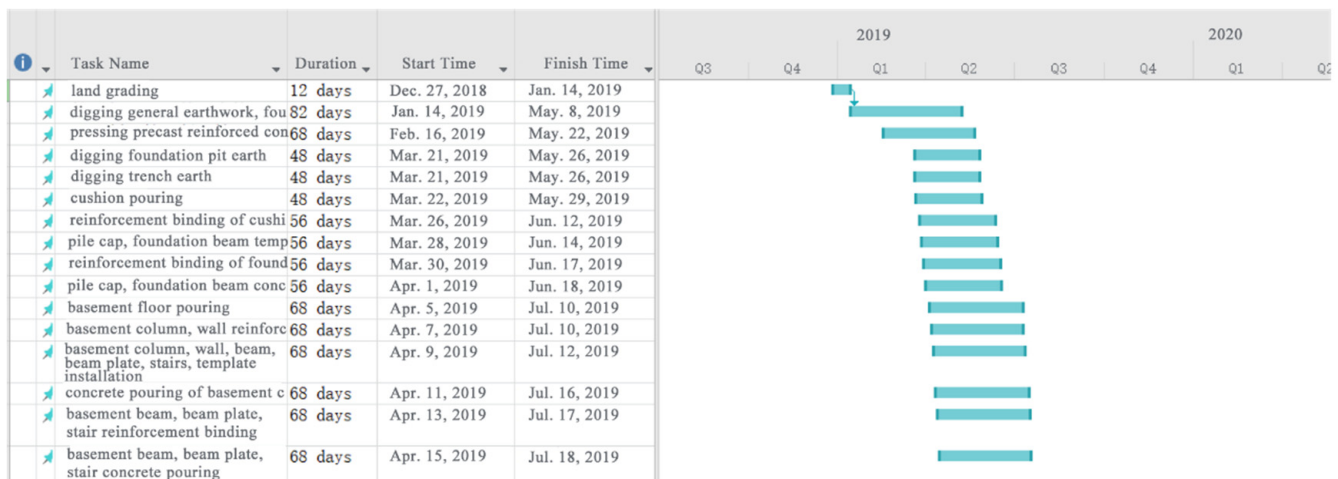


Figure 11. Schedule of Phase II Project.

The area parameter is attached to the floor as an example parameter because the floor family in Revit is automatically counted. Therefore, the data extraction of the material storage space index and transportation space demand index can be completed by modifying the floor group type name, designating it as the material storage space index and transportation space demand index. The floor types named after the material storage space index and transportation space demand index are identified when extracting the parameter attributes, allowing for the actual example parameters to be extracted, as shown in Figure 12.

Finally, the space is evaluated to determine its adequacy in meeting construction requirements by comparing the material and space requirements and indicators. The

time parameters for the non-critical path construction processes are scheduled to avoid congestion if the space is insufficient.

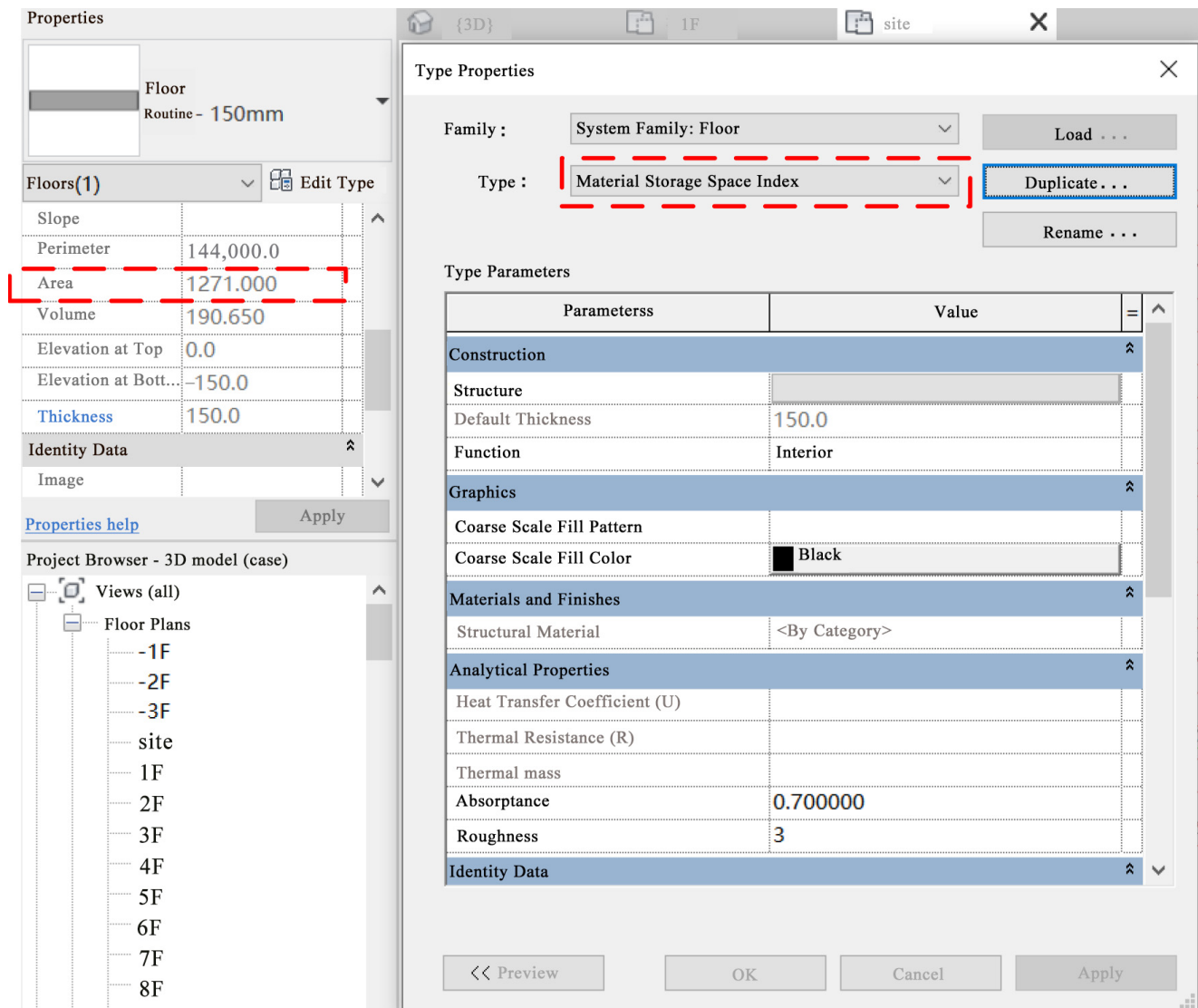


Figure 12. Extraction of parameter attributes of spatial indicators.

6. Discussion

Compared with other studies, this research more effectively integrates BIM into the planning process of construction schedules. It provides a comprehensive verification of the complete process, including the creation of the Revit model, data extraction, inference of the construction process, calculation of time parameters, and schedule generation through a case study. The schedule planning method proposed in this research efficiently facilitates reasoning regarding the construction process, calculation of time parameters, generation of the schedule, achieving effective automated planning based on practical applications. The reasoning results meet construction requirements and can effectively guide the construction process. This method improves the efficiency of the construction units in preparing the schedule. Secondly, it fully utilizes the characteristics of Revit component parameterization and establishes a mechanism for extracting component parameters from Dynamo, specifically addressing the problem of data incompatibility during data transmission. Furthermore, this method considers the schedule scheduling problem under limited construction space, which avoids a decrease in construction efficiency. However, the schedule planning method proposed in this research relies on the collaboration of multiple

software applications, necessitating manual intervention for data interaction among these applications. For instance, certain data must be correctly preprocessed manually to meet the requirements of different software. It is necessary to manually verify the correctness of each process before proceeding with the subsequent process. Engineers must adjust parameters manually when the final output fails to meet the requisite spatial requirements. Consequently, a limitation of this study is the lack of an overarching platform capable of achieving full automation in the truest sense. Future research should aim to develop a more intelligent system that completely delegates this task to the computer. Meanwhile, the reasoning system depends on a robust knowledge database, and insufficient knowledge can lead to scheduling errors. Therefore, it is essential to construct an updatable and extensible knowledge database.

AI excels at transforming massive amounts of data into valuable information and achieving a high level of automation and intelligence. This efficient knowledge representation and reasoning mechanism significantly enhance the automation, efficiency, and objectivity of project management. Additionally, AI has the capacity to mine knowledge from historical engineering data, thereby facilitating the development of reasoning methodologies. The integration of BIM and AI can be utilized not only to develop schedule plans but also to enhance their optimization [9,21,36]. In a recent study, researchers demonstrated the potential of ChatGPT for schedule generation, although the applicability of this approach remains limited to simple projects [22]. However, the deviation of training data may severely impact the quality of AI outputs. These efforts are still in their infancy, and their effectiveness and accuracy require validation and refinement through further practice and research.

7. Conclusions

This study proposes a BIM-based data-driven construction schedule planning method to help planners accurately and swiftly realize automated construction schedule planning while considering the limitations of multi-dimensional space. The modules of this method are designed to facilitate data acquisition, storage, and processing functions to generate the optimal construction schedule. Firstly, the data acquisition module is designed to obtain the necessary data for planning, including the acquisition of the BIM model and manual input. This module solves the issue of data incompatibility through the secondary development of Revit. Secondly, the construction process reasoning module serves as the core of the construction schedule planning, aiming to establish reasoning rules that conform to the logical constraint relationships, thereby constructing a logical reasoning system. Thirdly, the time parameter calculation module is responsible for processing the preliminary data into the information needed for schedule planning. While calculating time parameters, it also considers the constraints imposed by the workspace index. Fourth, the schedule generation module is responsible for rationally scheduling the results of the previous operations under the constraints of the workspace index and outputting the optimal construction schedule. Finally, the feasibility of the method is proven through practical case applications. Notably, this method represents a systematic solution for the automatic planning of schedules using BIM, innovatively addressing the challenges of spatial constraints and data interaction. Furthermore, this study enhances the application of BIM in the field of schedule and space management, effectively elevating the level of schedule space management.

Schedule management plays a crucial role in the project management process. The compilation of a reasonable and effective construction schedule is essential for ensuring the smooth progress of the project. The application of the BIM-based data-driven construction schedule planning method can save engineers time and effort, reduce the possibility of subjective consciousness errors, improve planning efficiency and reliability, and provide guidance for the implementation and monitoring of subsequent plans. Additionally, this method utilizes spatial resources as constraints to minimize the occurrence of spatial con-

fluctuates at the construction site, which helps prevent risks such as low construction efficiency, rework, and safety accidents.

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