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Research on Skeleton-Based Parametric Modeling for the BIM Design of Underground Power Cable Project

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Abstract. With the continuous progress of building informatization, BIM (Building Information Modeling) is more and more widely used in construction projects, but its application in infrastructure projects still needs to be studied. This study aims at the current problems of building information modeling in municipal engineering and proposes a new method of BIM modeling for infrastructure projects called parametric skeleton modeling (PSM). PSM is based on skeleton system, using parametric diven mechanism and modular assembling mechanism, on API (application programming interface) of Autodesk Revit, which greatly improves efficiency and the precision of modeling. At the same time, the reusability and adaptability of the model are improved .The study developed a set of high-efficient modeling tools and applied it on the BIM design for underground power cable project, providing the reference for the application of the BIM on the design for infrastructure projects. In the future, this method can also be extended to the modeling process of various infrastructure construction projects such as underground pipelines and bridges, which can improve the modeling efficiency, have a wide range of application and promotion value, and can bring positive social and economic benefits.

Keywords. BIM, Infrastructure, Skeleton System, Parametric Skeleton Modeling, Underground Power Cable Project

1. Introduction

1.1. Background

Building Information Modeling (BIM) refers to the digital representation of physical and functional characteristics of facilities or equipment.

A comprehensive information model serves as a repository, providing reliable information for various decisions throughout the entire lifecycle of a building, from initial design concepts to eventual demolition.

A review of BIM research both domestically and internationally reveals that while the theoretical framework of BIM is taking shape, current BIM standards primarily focus on structural engineering in construction. Despite some expansion into other fields, BIM technology lacks a comprehensive system for certain foundational municipal

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engineering projects. Municipal engineering projects, characterized by long durations, large geographical spans, and close ties to the surrounding environment, pose challenges that the existing BIM systems cannot effectively address.

In the field of municipal engineering, the application of BIM design is constrained by various factors and is still in its early stages.

Today, municipal engineering projects are evolving towards larger and more complex undertakings with increased information exchange. Throughout the entire construction lifecycle, BIM technology holds great significance, aiding in communication, coordinating vast amounts of information, enhancing construction efficiency, and reducing errors and confusion. However, the current application of BIM technology in municipal engineering is limited by the complexity of its modeling and inefficiencies, lacking a well-established system to address issues in the design and modeling of municipal engineering projects. There are many scholars who have carried out research work in this area. Wang Guoxing proposed three methods to model the box-section structure of municipal engineering by using three methods: volume family, loadable family, and Dynamo plug-in[1]. Lin Guodeng proposed a municipal road modeling and integration method based on Roadeasy+ Infraworks, which solves the problems of slow overall progress of multi-discipline modeling of municipal roads and the difficulty of integrating various professional models[2]. Chen Bang discussed the application of BIM technology in the whole life cycle of underground municipal pipe network engineering[3]. Wang Yong studied the application of BIM technology in large-scale municipal projects in mountainous cities[4]. These scholars have promoted the application of BIM technology in municipal engineering, but most of their research directions focus on BIM modeling, integration, and application of subdivided project types, and the proposed methods are less versatile and scalable. Therefore, this study proposes a modeling method with wider applicability and stronger scalability for the application of BIM in municipal engineering, which makes the modeling process simpler and the model modification simpler, which is conducive to the application and promotion of BIM technology.

To enhance the efficiency of BIM design and modeling in municipal engineering, this paper proposes a new method—Parametric Skeleton Modeling (PSM)—suitable for rapid design. This method utilizes the secondary development technology of Autodesk Revit software, employing the concept of skeleton modeling through parameter-driven and modular assembly to achieve rapid design and efficient modeling in municipal engineering projects.

Parametric modeling is a new modeling method, which can effectively improve the design efficiency and modification simplicity. Alexis et al. proposed a parametric modeling approach to bridge project design, providing a practical and innovative solution for bridge design that is suitable for many types of projects[5]. Valentina Boretti proposes a generative approach to enhance the bridge design process, creating different bridge families through the model's parameter settings, reducing computational costs and modeling efforts to increase efficiency[6]. S. A. Biancardo used parametric modeling methods to study the creation of parametric objects for railway components[7].

1.2. Purpose and Significance

Parametric modeling methods are gradually applied in many fields, but they are rarely used in municipal engineering projects[8]. Parametric modeling methods are gradually applied in many fields, but they are rarely used in municipal engineering projects. The main difference between this study and other studies is that we introduce the idea of parametric modeling into the field of municipal engineering. Building upon this method, the study has developed a set of fast and efficient modeling tools, which were applied in underground power cable line projects with positive outcomes. The research outcomes can be utilized to address existing issues in BIM design for municipal engineering, particularly in modeling, to enhance work efficiency and increase modeling accuracy. In the future, the method of parametric modeling can be extended to other fields of municipal engineering to improve the modeling efficiency. On the basis of parametric modeling, problems such as automatic modeling of municipal engineering can also be studied to achieve rapid modeling[9]. Parametric modeling can save labor costs and time costs, has good economic benefits, and has broad market application prospects.

2. Parametric Skeleton Modeling Method

The Parametric Skeleton Modeling method utilizes Autodesk Revit software as the modeling and development platform. In comparison to other BIM software, Revit not only allows for the creation of various system families such as buildings, structures, and equipment but also facilitates the modeling of custom families. In essence, Revit provides greater flexibility in modeling, enabling the creation of models required in various fields beyond buildings, structures, and equipment.

Key features of the parametric skeleton system modeling method include:

(1) Organic Whole Model: The model is considered as a hierarchical whole, divided into the skeleton and components, with components attached to the skeleton.

(2) Model Mobility: Due to the presence of the skeleton and the effect of constraint relationships, the model can be adjusted along with the skeleton, facilitating modifications to design schemes.

(3) Automated Modeling: Using Revit's secondary development, simple repetitive steps are automated by the program. A large number of components in municipal engineering can be generated at once. Additionally, due to the existence of the skeleton, component positioning and size adjustments can be automated, significantly improving efficiency.

When using traditional methods for municipal engineering modeling, each component is individually designed and modeled, followed by inefficient placement and assembly, resulting in low efficiency and accuracy. The Parametric Skeleton Modeling (PSM) method, based on a skeleton system, considers the engineering project as a whole.

Just as the human body is determined by its skeleton, with organs directly or indirectly attached to it, municipal engineering also has its "skeleton." The form of municipal engineering is primarily linear, exhibiting regularity, such as pipelines, tunnels, power transmission lines, etc., which can be abstracted as networks composed of lines. During modeling, the form of municipal engineering can be abstracted into a series of reference points, reference lines, and reference planes, forming its skeleton.

When using the PSM method, the modeling process begins by using reference points, reference lines, and reference planes to construct a framework that determines the overall form of the project and provides the assembly positions for various components. Subsequently, project components are placed as modules at their respective positions and connected to the skeleton and surrounding components to complete the assembly. This creates a model that forms an internally cohesive whole with various interconnections and constraints.

The PSM method can theoretically be divided into three key theoretical components: skeleton, parameter-driven, and constraint relationships. Each component serves a specific purpose and complements the others. The following sections will elaborate on the specific meanings of these three components.

2.1. Skeleton

The skeleton of municipal engineering refers to a series of reference points, reference lines, reference planes, and key components that determine the overall shape and dimensions of the project. A complete skeleton should include the essential information required to determine the overall shape and dimensions of the project.

The information embodied in the skeleton primarily includes three aspects: (a) the spatial position and orientation of nodes within the skeleton, forming the shape of the project and allowing component placement and posture determination; (b) internal topological relationships within the skeleton, representing the interconnections between nodes, enabling the skeleton to function as a whole that can be manipulated and adjusted; (c) constraint limitations formed by the skeleton, allowing components to move and adjust only within specific geometric ranges. When constructing the skeleton, the spatial arrangement characteristics of the project should be analyzed to identify key nodes that determine the overall shape and positioning of various components.

The existence of the skeleton plays a crucial role in assembling project components. The skeleton enables each component to have a clear orientation and size, achieving precise positioning. It also integrates the entire project into a cohesive whole, providing the potential for the implementation of the other two components of the skeleton system —parameter-driven and constraint relationships.

2.2. Parameter-Driven

Parameter-driven refers to controlling the attributes of various components in the model through parameters. Municipal engineering components vary in shape and size, requiring the categorization of various component types during modeling. This categorization is then parameterized, creating parameterized families. Parameterized families can control the dimensions, materials, and other attributes of components through changes in parameters. To enhance modeling efficiency, components with different shapes and sizes but similar geometric patterns only need to be created as a single family, with different-sized components obtained by modifying parameters.

In the skeleton system, when modeling, the parameters of parameterized components can be manually set or assigned by the skeleton or other components. Parameterized families are not only necessary for components of different sizes in the model; during design, parameter-driven methods can also be used for easy adjustment or modification of design schemes. The implementation of parameter-driven methods significantly improves the efficiency of design and modeling.

2.3. Constraint Relationships

During the engineering design phase, changes to design schemes are frequent, with the adjustment of routes being crucial. Route adjustments imply changes in the spatial position of the engineering skeleton. To ensure that components can still be effectively positioned and connected to each other after the skeleton changes, design needs to maintain the topological relationships between components and the skeleton before and after the skeleton's alteration.

The constraint relationships in the skeleton system refer to restrictive relationships in the spatial positions between components and the skeleton, as well as among various components. These relationships ensure the preservation of topological relationships. After changes to municipal engineering route schemes, moving the skeleton ensures that each component moves accordingly, automatically positioning itself in the respective locations. The dimensions also adapt to the skeleton, maintaining unchanged topological relationships between components, ensuring that components can still connect properly. This significantly enhances the efficiency of design and modeling.

When using the Parametric Skeleton Modeling method for design and modeling, the basic process is as follows:

(1) Analyze the characteristics of the engineering project to be modeled, including overall layout, pattern of form, types of components, etc.

(2) Generalize the basic types of components in the project and create parameterized families for the components[10].

(3) Identify key nodes that determine the form of the project and build the skeleton needed for modeling.

(4) Assemble various components on the skeleton and establish constraint relationships within the model.

(5) Make final adjustments and modifications to the model.

These five steps are the fundamental steps for modeling using the Parametric Skeleton Modeling method. In practical operation, depending on the characteristics of the project, the order of these steps may vary, and some steps may be repeated multiple times or even iterated.

In summary, the Parametric Skeleton Modeling method is constructed from a series of points, lines, planes, and nodes, determining the overall shape of the project and the orientation of various components[11]. Components can be adjusted in shape through parameter-driven methods, and constraint relationships maintain connections with the skeleton and other components, forming the entire project into a cohesive whole. The characteristics of this method include precise positioning, automatic assembly, and flexible adjustments, significantly improving the efficiency of design and modeling.

3. Underground Power Cable Line Project BIM Design Tool

3.1. Overview

In this study, a BIM rapid design tool for underground power cable line structures has been developed using the Autodesk Revit secondary development platform.

The constructed model primarily consists of two major components: duct pipes and manholes (referred to as "manholes"). The duct pipes, characterized by their positioning at both ends and arbitrary spatial orientation, are created using Revit's metric structural framework support family. On the other hand, the manholes are constructed using Revit's metric standard model. The model effects for the 2x5 duct family and the straight-through manhole family are illustrated in Figure 1 and Figure 2, respectively.

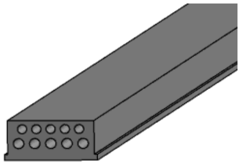

Figure 1. 2x5-type cable ducts

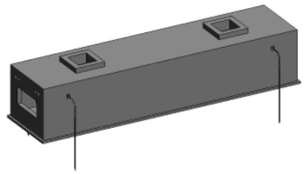

Figure 2. Two-connector manholes

The modeling program developed in this study utilizes an external application within Revit, employing five external commands to achieve the required functionalities. A new tab named "laying cable ducts" is added to the Revit workspace, containing five buttons for invoking their respective external commands. The interface of the "laying cable ducts" tab is depicted in Figure 3.

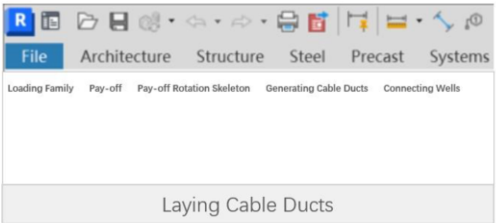

Figure 3. Ribbon panel of "laying cable ducts"

The five major functionalities of this program are as follows:

(1) Automatically load the required component families into the Revit project.

(2) Manually draw model lines in the Revit project as the initial path for engineering modeling.

(3) Set the desired types of manholes and default spacing between manholes. Automatically arrange manholes along the path in the Revit project. Turning points and intersections in the initial path will be accommodated with the corresponding types of manholes, with orientations adjusted automatically.

(4) After adjusting the elevation, position, and angle of the generated manholes and determining the final layout scheme for the project, set the duct type. Automatically arrange ducts between manholes in the Revit project.

(5) Select any two manholes in the Revit project, set the duct type, and automatically connect the ducts between them.

3.2. Framework Construction

The form of underground power cable line projects can be abstracted into a series of nodes and line segments, as shown in Figure 4.

Given its physical characteristics, a two-stage skeleton generation approach is designed. The first skeleton is constructed by drawing the preliminary path of the cable route on the horizontal plane using model lines[12]. The second skeleton forms the exact path based on the connection information between manholes and ducts.

The first skeleton is created from model lines on the horizontal plane. CAD drawings required for project construction can be imported, and model lines can be manually drawn along the designed route. Alternatively, model lines can be created by setting coordinate values. The former is more intuitive and convenient, while the latter offers higher precision. The constructed first skeleton is depicted in Figure 5.

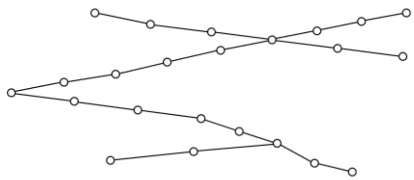

Figure 4. Skeleton of an underground power cable project

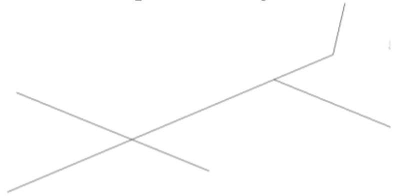

Figure 5. First skeleton

Using the program and setting the default manhole spacing (typically 120m) and manhole types, it becomes possible to automatically arrange manholes along the initially drawn path.

On straight line segments of the preliminary path, straight-through manholes are evenly placed, aligning their orientation with the model line. At turning points, if the angle is small, a straight-through manhole is automatically placed with a deflection angle equal to half of the turn angle. If the angle is around 90 degrees, a three-way manhole is automatically placed, with one duct connecting to the end opening of the manhole and the other connecting to the mid-opening of the manhole. At T-shaped intersections in the preliminary path, a three-way manhole is automatically placed, while at cross-shaped intersections, a four-way manhole is automatically placed. All manholes are generated at once, and the previously drawn model lines are automatically deleted.

In actual projects, there may be rich variations in the plan layout and elevation of the cable route[13]. Based on the manholes automatically arranged according to the first skeleton, adjustments to the plan positions, rotation angles, and elevations of each manhole are made manually according to the specific geographical environment of the project to obtain the final layout scheme. Subsequently, all ducts are automatically generated at once, connecting each manhole. Examples of the effects of the second skeleton and duct generation are shown in Figure 6 and Figure 7, respectively.

Figure 6. Second skeleton

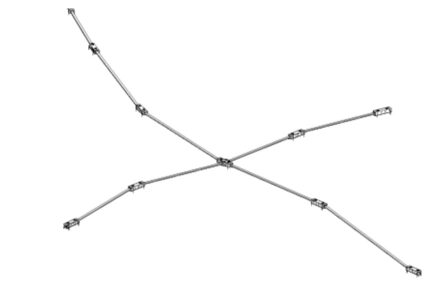

Figure 7. Model of a power cable project

3.3. Parameter-Driven

Both manholes and ducts are created as parametric families, allowing the generation of different shapes and sizes through parameter-driven approaches.

3.3.1. Parameter-driven for manholes

The length of the manhole and the dimensions of each opening can be parameter-driven. In the family file, numerous reference planes are set up. The surfaces of various components within the manhole are aligned with the corresponding reference planes using the "Align" function. Dimension annotations are added between reference planes, and parameters are set. This allows the control of the position of reference planes through parameter settings, thereby controlling the shape of the manhole and achieving parameter-driven functionality. Additionally, as the length of the manhole changes, the number of supports inside the manhole should also change accordingly. This functionality is achieved by using an array and setting the array quantity as a formula to ensure that the number of supports changes with the length of the manhole. Modeling using the program developed in this study, the effects of changes in manhole length and opening size are illustrated in Figure 8 and Figure 9, respectively.

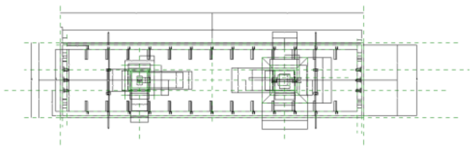

Figure 8. Use the program to adjust the manhole length

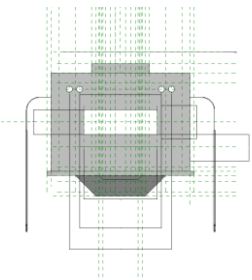

Figure 9. Use the program to adjust the manhole size

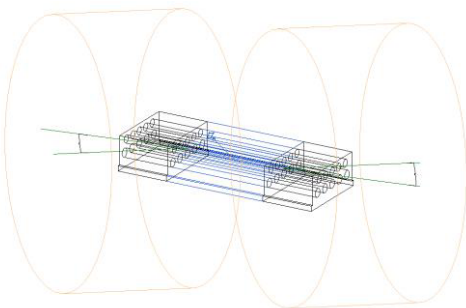

Figure 10. Modelization of cable duct family

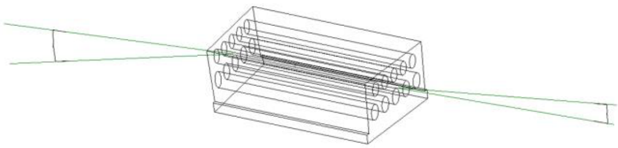

Figure 11. Change of the degrees of end-faces of a cable duct

3.3.2. Parameter-driven for ducts

The angles of the end faces of ducts can be parameter-driven. When there is a certain angle between the duct and the opening of the manhole, the angle of the duct end faces needs to vary to facilitate smooth connection. By using the angle parameter of reference lines and the shear function of hollow geometries, it is possible to set parameters for horizontal and vertical directions, creating ducts with various cross-sectional angles in Revit. The modeling principles for duct families and the effects of changes in the angle of duct end faces are shown in Figure 10 and Figure 11, respectively.

3.4. Constraint Relationships

In the model of underground power cable line projects, two crucial constraint relationships exist[14]. The first is the constraint relationship between ducts and the skeleton, meaning that ducts must always be positioned between two manholes. The second is the constraint relationship between the ends of ducts and the openings of manholes, implying that the end faces of ducts must be parallel to the openings of manholes.

When modeling using the parametric skeleton system, ducts can still connect between the corresponding manholes when the skeleton moves. To achieve this constraint relationship, the program automatically records the connection information for each duct, including the manholes and their openings at both ends of the duct. Therefore, in this program, the generation of ducts is based on the information of the skeleton itself rather than the spatial position provided by the skeleton. Consequently, regardless of how the manholes move after generation, ducts can be generated between the corresponding manholes and connected to the specified openings, forming the constraint relationship between ducts and the skeleton.

To ensure effective connection between ducts and manhole openings when there is an angle, it is necessary to maintain a parallel relationship between the duct end face and the opening plane. When creating the duct family, parameter-driven changes to the cross-sections at both ends of the duct have already been implemented. The program can automatically calculate the angle data between ducts and manholes and assign values to the angle parameters of the duct end face, ensuring that the end face of the duct is parallel to the connected manhole opening when the duct is generated. Thus, regardless of how the manholes move after generation and the angle between ducts and manhole openings, the end face of the duct can remain parallel to the corresponding opening, forming the constraint relationship between ducts and openings.

The connection effect between ducts and manhole openings is illustrated in Figure 12.

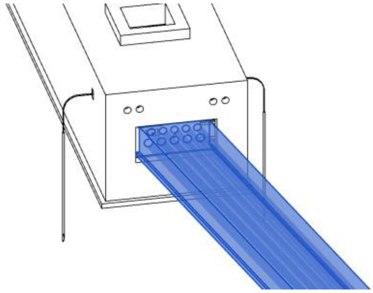

Figure 12. Connection between a cable duct and a hole

3.5. Summary

When modeling using traditional methods, each component of the cable route needs to be manually placed and oriented, and its type and size adjusted one by one[15]. Then, ducts are manually created, connected between manholes, and the angle of the duct end face is manually adjusted to be parallel to the opening. Later adjustments to the scheme also need to be done manually, resulting in a significant workload and high errors.

In contrast, using the parametric skeleton system modeling method, although an additional step of constructing the skeleton is introduced, the subsequent creation, adjustment, and assembly of components are automated. Thus, a considerable portion of the work can be completed automatically through the program, reducing workload and significantly increasing efficiency while ensuring model accuracy.

4. Conclusion

In this study, in order to solve the problem of modeling underground power cable lines in municipal engineering, a parametric skeleton system modeling method is proposed, which uses parameter-driven to improve the modeling efficiency and enhance the simplicity of model adjustment and model reusability. Through actual modeling cases, we found that parametric modeling is very efficient in steps such as sizing and wiring. The proposed parametric skeleton system modeling method, compared with existing BIM modeling methods, demonstrates innovation and high efficiency.

In traditional modeling methods, project components are independent of each other, with no connections, and are individually created and placed. The parametric skeleton system modeling method considers the entire project as a whole, abstracting a skeleton system from its shape patterns. The modeling process involves first creating the skeleton and then assembling components while ensuring constraints between them. This ensures that the entire model forms a tightly interconnected whole.

Parametric modeling has the characteristics of organic overall model, model mobility, and automatic modeling. The new characteristics of the parametric skeleton system modeling method result in a substantial improvement in both efficiency and accuracy compared to traditional BIM modeling methods in municipal engineering. In addition, this method effectively improves the reusability and modification simplicity of the model, enhances the adaptability of the model, and can better adapt to the needs of construction projects. The implementation of this method can provide a basis for automatic modeling, and the automatic generation and modification of models can be studied in combination with computer technology in the future. In the future, with the popularization and application of parametric modeling, model construction will become easier and data transmission will be more efficient. This method represents an innovation in the application of BIM technology in municipal engineering and is suitable for modeling in various municipal engineering projects, such as bridges and underground power cables, with broad application and promotion value, leading to positive social and economic benefits.

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