Journal of Computers Vol. 37 No. 1, February 2026, pp. 143-156
https://doi.org/10.63367/199115992026023701009

Research on 3D Modeling and Optimization of Prefabricated Substation Based on Building Information Modeling

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Received 1 December 2024; Revised 12 March 2025; Accepted 24 March 2025

Abstract. With the inclusion of ultra-high voltage and robust smart grid construction in the national development strategy, substations play a crucial role in building smart grids. However, substation construction faces challenges like short project cycles, high quality requirements, and poor cost control. Building Information Modeling (BIM) technology has been widely applied in construction and provides new solutions for substation building. This paper explores the 3D modeling and optimization methods for prefabricated substations using BIM. It focuses on the advantages of BIM in substation construction, discusses the processes and techniques of 3D modeling, and suggests optimization strategies like improving model precision, resource allocation, and construction efficiency. By analyzing and validating case studies, the paper shows how BIM improves efficiency, reduces costs, and enhances quality. The research offers a theoretical foundation, technical support, and practical guidance for constructing prefabricated substations, with significant application value and development prospects.

Keywords: BIM, prefabricated substation, 3D modeling, smart grid, optimization strategies

1 Introduction

The integration of Building Information Modeling (BIM) technology has changed the construction industry. BIM has become an important tool for improving design accuracy, optimizing workflows, and enhancing collaboration. This is especially true for substation construction, which is crucial for the power system [1]. The demand for efficient, cost-effective, and sustainable infrastructure continues to grow, and BIM is increasingly used in substation projects.

Substations are vital hubs for electricity transmission and distribution. They are crucial for building strong and resilient smart grids. With the growing focus on ultra-high-voltage (UHV) and intelligent grid infrastructure in national development strategies, substation design and construction face many challenges. These include short project timelines, high quality demands, and poor cost control, which make traditional methods less efficient [2]. To solve these issues, BIM technology offers a complete solution. It allows for more accurate and timely decisions, better coordination, and efficient resource management.

BIM can improve construction project efficiency. It enables virtual simulations of the entire process, from design to operation. Its application in the design and construction of prefabricated substations still has some limitations. Current research has not fully explored how BIM technology can be used to 3D model and optimize prefabricated substations for efficiency gains, cost reductions, and quality enhancements.

This paper focuses on the use of BIM for 3D modeling and optimization of prefabricated substations. It explores how BIM improves construction efficiency, reduces costs, and enhances quality, while addressing the challenges of prefabricated substation design and construction. This study deeply investigated the application of BIM in 3D modeling of prefabricated substation, and proposed effective modeling methods and processes. The optimization strategy of BIM in the construction of prefabricated substation is revealed, including design optimization, construction process optimization and resource management optimization. The practical effect of BIM technology in prefabricated substation was verified by case study. The following is the relevant background of this study.

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2 Background

First, Building Information Modeling (BIM) is a digital technology based on three-dimensional modeling. It integrates and manages various aspects of a construction project, such as architectural structure, mechanical and electrical systems, construction processes, and related attribute information, based on the building model. The main features of BIM technology include 3D modeling, data integration, parametric design, and engineering visualization. These characteristics enable BIM technology to provide intuitive visual effects [3], facilitating design, construction, and operational management understanding and communication.

2.1 International Research Status

Building Information Modeling (BIM) technology has gradually matured and been widely applied in various fields such as architecture, infrastructure, and electrical engineering in developed countries like the United States and the United Kingdom. In recent years, BIM applications have extended beyond architecture into project operation and intelligent management.

It is clearly evident from the chart (Fig. 1) that the market size for Building Information Modeling (BIM) in North America is progressively expanding each year. In 2019, Qiu et al. researched BIM in construction engineering and found that it greatly enhances collaboration efficiency and lowers costs during design, construction, and operation [4].

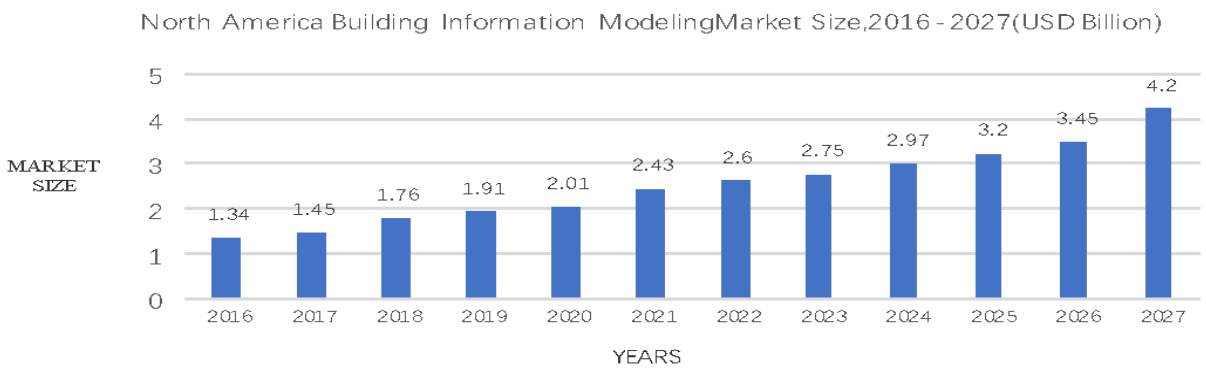

Fig. 1. North American BIM market size growth trend

The UK government has played a policy-driven role in promoting BIM applications. Since 2016, the UK has mandated BIM usage in all public-sector projects, and BIM adoption has gradually extended to infrastructure projects. Jallow et al. (2019) studied the UKs BIM policy and its effect on construction efficiency in public infrastructure. They highlighted BIM's importance in improving project collaboration and information management [5].

In the electrical sector, particularly in substation construction, BIM technology has gained increasing attention. In 2016, Kokorus and Zacharias' study found that BIM can effectively improve the accuracy of substation design and construction by integrating 3D modeling, reducing errors, and enhancing resource management. In 2018, Dave et al. showed that using BIM with IoT technology can enhance the real-time management and monitoring of substation assets [6].

In the field of power infrastructure, BIM has proven beneficial for the construction of substations. It enhances coordination among design teams, reduces errors, and optimizes resource management, which ultimately saves costs and shortens construction timelines. As BIM continues to evolve, research is focusing on integrating it with IoT and sensor technologies for better project tracking and quality control, particularly in prefabricated substation designs.

2.2 Domestic Research Status

China has started to adopt BIM technology more recently, but its application is rapidly expanding in both the construction and electrical engineering sectors. In the electrical sector, particularly with the digital and intelligent transformation of the power grid, BIM technology is being gradually applied to substation design and construction. The market for BIM and related technologies, like 3D modeling and visualization, hit 9.95 billion RMB in 2022 due to the ongoing digital transformation and is predicted to keep growing. However, BIM standards are not yet fully established; although cities such as Shenzhen have issued some standards, many more are required, and the practicality and guidance of the current standards have not been completely verified.

BIM technology, especially 3D modeling, has gradually expanded from the design phase to the construction phase. However, its overall adoption remains limited, particularly for full lifecycle management. Despite growing demand, there is still a shortage of BIM professionals, which restricts industry development. The domestic BIM software market is largely dominated by foreign vendors, and data compatibility issues remain a barrier to the wider use of BIM technology.

BIM application includes many industry sectors, such as upstream equipment suppliers, midstream design firms, and downstream contractors. In practical applications, design firms and construction companies still face challenges such as increased workload and low cost-effectiveness, while clients encounter issues related to decision-making processes and management. Despite challenges, BIM technology, especially 3D modeling, has great potential, and its industry application will keep growing with advancements in technology and talent.

Zhang et al. (2019) proposed a BIM-based design method for prefabricated substations, showing that BIM technology offers 3D visual models that assist designers in understanding the spatial layout, equipment installation, and construction processes of substations. This method optimizes resource allocation, reduces design errors, and avoids repetitive work in the design phase [7]. Furthermore, BIM technology is applied in the construction phase to coordinate the efforts of different professional teams through an information-sharing platform, improving construction efficiency and reducing errors and rework at the construction site.

In 2021, Liu et al. proposed a 3D modeling and simulation optimization method based on BIM to improve the accuracy of substation design and construction. The method combines BIM technology and virtual simulation to model the construction process and equipment installation process of substations and construction plans [8]. The study showed that simulation optimization can effectively avoid errors during on-site construction and reduce delays and safety risks caused by unreasonable design.

In 2023, Pan et al. explored the combination of BIM and intelligent technologies and proposed an optimization design solution for substations based on BIM and artificial intelligence (AI). The solution used AI algorithms to analyze key nodes and challenges in substation design, optimizing resource allocation and construction plans [9]. The study showed that the integration of BIM with AI improves the automation of the design process and optimizes construction schedules through intelligent algorithms, reducing human intervention and enhancing construction accuracy.

2.3 Research Objectives and Significance

This study aims to explore the application of BIM technology in the 3D modeling and optimization of prefabricated substations. The research focuses on the advantages of BIM in substation construction, discusses the processes and techniques of 3D modeling, and suggests optimization strategies such as improving model precision, resource allocation, and construction efficiency. By analyzing and validating case studies, the paper shows how BIM improves efficiency, reduces costs, and enhances quality. The research offers a theoretical foundation, technical support, and practical guidance for constructing prefabricated substations, with significant application value and development prospects.

Through the review of relevant researches at home and abroad, we can see that the application of BIM technology in the construction of prefabricated substation has achieved remarkable results. However, how to effectively apply BIM technology in actual projects and give full play to its advantages is still a problem that needs to be deeply discussed. The following will discuss the application practice of BIM technology in 3D modeling and optimization of prefabricated substation based on actual cases.

3 Application and Practice

In this study, the application of BIM technology is considered an important tool for improving the design and construction efficiency of prefabricated substations, particularly in the areas of three-dimensional modeling and optimization of substations. By utilizing BIM technology to digitally model various components of the substation, including electrical equipment, building structures, pipelines, and equipment placement, a detailed three-dimensional digital model can be created. The BIM model offers a more intuitive view of the substation's structure, equipment, and layout than traditional two-dimensional plans, which helps designers plan the positions and relationships of components more effectively, thus improving design accuracy and reducing errors and conflicts in later construction stages.

3.1 Application of BIM Technology in Transformer Station Construction Advantage

Regarding the advantages of the modeling approach, automated modeling, especially using tools such as Revit scripts, is able to generate high-precision 3D models in a short time. Compared with manual modeling, automated methods can reduce human errors and improve the speed and consistency of modeling. When dealing with complex prefabricated substation designs, automated modeling can easily accommodate multiple repetitive modular design requirements, while manual modeling can be cumbersome and error-prone.

(1) Visualization Advantage: Compared to traditional methods, the application of BIM technology allows for the creation of three-dimensional building models, significantly enhancing the 3D visualization of substation projects. Each building component can be fully displayed, and its associated parameters can be integrated into the 3D model, greatly improving the overall level of visualization in the substation project.

(2) Coordination Advantage: In traditional substation construction, issues such as uneven distribution of buildings and conflicts between pipes and components often arise, hindering the subsequent stages of the project. However, with the introduction of BIM technology, in-depth collision testing can be performed to identify potential conflicts early. These conflicts can then be automatically handled using BIM software, leading to better coordination throughout the entire project.

(3) Dynamic Management Advantage: Substation construction projects based on BIM technology can generate an overall model of the substation in three-dimensional form, dividing the construction into different phases and simulating each phase in advance. This allows the project team to anticipate potential issues during construction and manage the project proactively. During construction, BIM can dynamically update information based on the current situation, enabling real-time management and optimization of different construction phases, thus effectively improving the overall performance of the substation project.

3.2 Practice of BIM Technology in the Construction of Transformer Station Apply

Software Platform Evaluation. First, this article aims to study the application of BIM technology in substation framework design. The modeling precision requirements are relatively low, and the interoperability between different software is high [10]. As shown in Table 1, comparing the advantages and disadvantages of BIM platforms, CATIA and MicroStation have a steep learning curve and poor interoperability with other platforms. Tekla's limited functionality is not conducive to full-process design.

Table 1. Comparison of BIM software platform function

Software platform	Modeling accuracy	Interoperability	Ease of use	Cost-effectiveness	Applicable scenarios
Autodesk Revit	High (±5mm)	High (IFC supported)	Moderate	Moderate	Multi-disciplinary collaboration
Dassault CATIA	Very high (±1mm)	Low (proprietary format)	Low	High	Complex surface design
Bentley MicroStation	High	Moderate	Low	High	Large-scale infrastructure projects
Tekla Structures	High	Moderate	Moderate	Moderate	Steel detailing

In contrast, the Revit platform, compared to other platforms, excels in software openness and model integration capabilities [11]. It supports the reading and exporting of multiple common file formats and allows data exchange with most structural design software. Therefore, using Revit as the platform to study the application of BIM technology in substation framework design is the most suitable choice.

Software Platform Evaluation. In addition, we need to explain the design process (shown as Fig. 2) of the substation based on BIM. The application of BIM provides an efficient and accurate working platform for the project team, covering the whole life cycle from the preliminary design to the operation and maintenance management after the completion of the project [12]. The BIM-based substation design process can be divided into the following main stages, each of which makes full use of BIM technology to optimize design, coordinate work, control costs and improve efficiency.

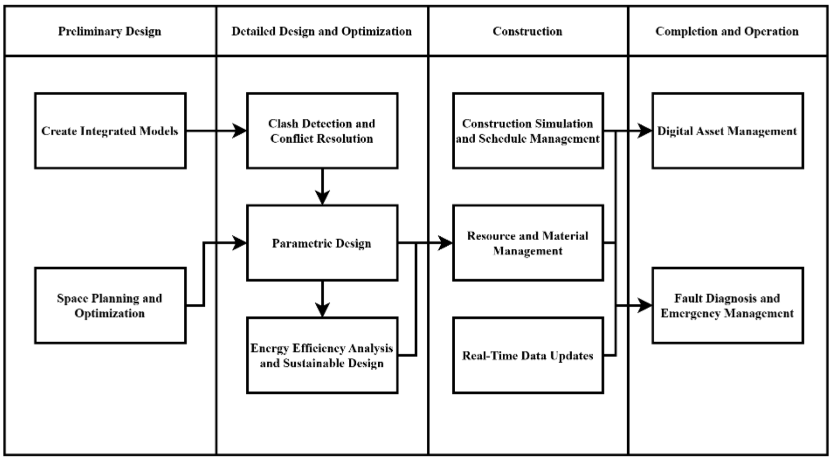

Fig. 2. Substation design process based on BIM

In the preliminary design stage, BIM software is used to create 3D models and establish the preliminary design of the substation. The main task at this stage is to create 3D models of the substation's structure, equipment, pipelines, and electrical systems based on the design requirements.

BIM technology helps the design team:

(1) Create Integrated Models: Combine architectural, structural, electrical, and piping designs into a single BIM model to ensure coordination of the design plan.

(2) Space Planning and Optimization: Use BIM software to analyze space layout, optimize the internal space of the substation, ensure reasonable equipment placement, maximize space usage, and avoid design modifications later.

In the detailed design stage, the design is further refined and optimized based on the preliminary design model. The main applications of BIM technology at this stage include:

(3) Clash Detection and Conflict Resolution: Use the BIM model for multi-disciplinary clash detection (using tools like Navisworks), identify spatial conflicts between electrical equipment, pipelines, and building structures, make adjustments and optimizations, and avoid rework and delays during construction.

(4) Parametric Design: Designers can flexibly adjust specific parameters in BIM software, like equipment size and location, with automatic updates in the model for consistent and precise design.

(5) Energy Efficiency Analysis and Sustainable Design: Use BIM models to perform energy efficiency simulations, optimize the design, reduce energy consumption, and improve the environmental performance of the substation.

BIM technology in the construction stage primarily focuses on optimizing construction plans and precise control of the schedule:

(6) Construction Simulation and Schedule Management: Use 4D modeling to combine construction progress with the 3D model, dynamically display the construction process, and help the construction team adjust plans in a timely manner to ensure the project is completed on schedule.

(7) Resource and Material Management: BIM models provide detailed material lists and quantities, helping the project team optimize resource allocation, reduce costs, and avoid material waste.

(8) Real-Time Data Updates: During construction, BIM models are synchronized with real-time data from the site, ensuring the design plan aligns with the actual construction site, and adjustments are made to resolve inconsistencies in this process.

After completion, the BIM model is used not only to generate as-built drawings but also becomes a critical tool for the substation's operation and maintenance:

(9) Digital Asset Management: Integrate the lifecycle data of all equipment (such as installation, maintenance, and repair records) into the BIM model, forming a comprehensive digital asset management system. The operations team can use the BIM model to access real-time equipment information and develop scientific maintenance and update plans.

(10) Fault Diagnosis and Emergency Management: BIM models can also integrate real-time monitoring data, helping maintenance personnel quickly locate faults and provide repair guidance to reduce downtime.

Software Function and Practice. BIM technology is essential in substation construction. It integrates different software for 3D modeling, clash detection, equipment integration, and real-time data sharing.

Revit is the main tool for 3D modeling. It designs building structures and electrical equipment. Revit creates detailed 3D models and integrates electrical devices, building parts, and pipes. In Revit, the 3D model shows devices and includes their data, performance, and manufacturer details. For example, transformers and distribution rooms are modeled accurately, providing precise design for later construction.

We use Navisworks for clash detection. Navisworks integrates models from different software like Revit and Tekla. It detects conflicts between disciplines. For example, Navisworks found a space conflict between cables and the transformer in the distribution room. The team adjusted the layout, avoiding design issues and ensuring smooth construction. We also connect Revit to the SCADA system for real-time equipment monitoring, improving maintenance efficiency. BIM connects with sensors to ensure construction progress matches the design. This helps reduce waste and delays.

3.3 Application Effect Analysis of BIM Technology

In the construction of the 110kV Baisha (Liangsha) substation project, BIM technology significantly improved the efficiency and accuracy of complex prefabricated steel structure design and construction through 3D modeling and intelligent management [13]. The above-ground part of the substation's power distribution building uses a prefabricated steel frame structure. BIM technology optimized the design, construction process, and multi-disciplinary collaboration. Specific applications include:

3D Modeling and Prefabricated Steel Structure Design. The above-ground part of the power distribution building uses hot-rolled H-shaped steel as the main framework. All beam-column joints are connected with high-strength bolts.

(1) Reise Modeling: BIM technology was used to create 3D simulations of prefabricated steel components. This optimized the cutting accuracy and installation sequence of H-shaped steel. For example, BIM models helped virtually assemble the steel structures in the main transformer room (±0.10m level) and the 110kV GIS room (+6.5m level). This identified and resolved spatial conflicts between the main transformer transport and steel beams in advance.

(2) Safety Verification: The BIM model combined finite element analysis to verify the seismic performance of the steel framework under the load of the 63MVA three-phase oil-immersed transformer [14]. This ensured compliance with the China Southern Power Grid Smart Substation Standard Design (seismic fortification intensity: 7 degrees).

Modeling the Wall Systems. The substation's exterior walls use metal-faced rock wool sandwich panels. Interior walls use fire-resistant gypsum boards with light steel studs.

(1) Material Optimization: BIM visualized the joints, waterproof, and pre-embedded pipe holes of prefabricated walls. This reduced on-site cutting errors. For example, the model optimized the connection between cable trenches and walls in the 10kV high-voltage room (+1.5m level), avoiding structural damage from later modifications.

(2) Conflict Detection: The BIM model integrated data from electrical equipment (e.g., indoor GIS devices, KYN switchgear) and building structures. It identified conflicts between 110kV cable outlets (north side) and fire pipelines. This optimized the layout of cable trenches and non-excavation directional drilling pipe. The following Fig. 3 is a real picture of a 110KV substation of another project:

Fig. 3. Real scene of a 110kV substation

Optimizing the Construction Process and Management. The BIM model coordinated the construction from the basement (-4.2m) to the second floor (+6.5m). It simulated the 4D schedule for the assembly of prefabricated steel structures, dynamically linking the transport path of the 120-ton main transformer with the steel frame installation, which shortened the construction period by 15%. The model also produced material lists, such as copper grounding bars and OPGW cable lengths, assisting procurement in cost calculations using the latest China Southern Power Grid prices (Q2 2024) for budget control (static investment: ¥173.3158 million).

Green and Smart Operation Integration. The project met the Three-Star Green Low-Carbon Grid standard. BIM provided the following support:

(1) Photovoltaic System Design: A 43.92kW distributed photovoltaic system was deployed on the roof (total floor area: 3,910.0 m²). BIM simulated panel tilt angles and shadow effects to maximize annual power generation.

(2) Smart Device Integration: The BIM model connected with the substation's intelligent monitoring system (including status sensors and environmental monitors). This enabled visualized management of equipment data in 3D space, meeting digital operation requirements.

Clash Detection and Information Sharing. BIM's clash detection function effectively identifies potential issues in the building structure. In this Substation project, BIM clash detection helps identify spatial conflicts between the exterior and interior walls, as well as between the steel structure and electrical equipment, allowing for timely design adjustments to avoid rework during construction [15].

Moreover, A BIM-based information platform allowed real-time data sharing among the design unit (Guangzhou Electric Power Design Institute Co., Ltd.), contractors, and the Guangzhou Power Supply Bureau. For example, updates to the 48-core OPGW optical cable route (2×3.37km) in the communication avoided conflicts with 10kV cable trenches.

3.4 Optimization Strategy and Implementation of BIM Technology

Construction Schedule Optimization. BIM technology helps project teams plan the construction schedule in advance through 3D modeling and visualization, optimizing the coordination and integration of various tasks. By virtually simulating the construction process, potential bottlenecks and delays can be identified, allowing for preemptive measures to ensure timely project completion. The application of BIM enables the project team to create detailed time schedules before construction begins, reducing project delays through task allocation, resource scheduling, and other optimization measures.4D simulation is bound to the 3D model through Gantt chart, dynamically adjusting the hoisting path and reducing the construction period by 15%.

Material Consumption and Resource Optimization. BIM technology enables the precise calculation of required materials and resources in advance, optimizing procurement plans [16]. BIM helps the design team accurately estimate material usage during the design phase, avoiding over-purchasing or resource waste. Meanwhile, BIM can also track material usage in real time to ensure the project proceeds according to the established resource plan.

For example, the reduction in material waste can be quantified using the following formula:

$$WD = \frac{M_e - M_a}{M_e} \times 100\% \tag{1}$$

WD is the reduction in material waste. M_e is the expected material consumption. M_a is the amount of material actually used.

In the construction of the substation, BIM technology helped optimize equipment layout and material procurement. It reduced unnecessary material waste and lowered steel consumption by about 10%. Based on the project investment data, the material savings can be calculated as 50 tons of steel, which represents a reduction of about 10% in raw material consumption. The BIM Bill of Materials (BOM) is integrated with the ERP system through the formula achieve a 10% reduction in steel waste.

However, in practice, BIM's main role is to assist the project team in accurately calculating material requirements through precise modeling and real-time data feedback, helping avoid waste and shortages.

Project Cost Optimization. BIM technology provides detailed cost estimates for projects and helps project teams control costs during the construction process. Through detailed modeling of various project components, BIM can estimate costs during the design phase and provide real-time cost feedback during construction [17]. This not only helps reduce additional costs arising from design changes or construction issues, but also enables the team to make timely adjustments during project implementation.

Cost-benefit analysis is a common method for cost control. Although formulas can quantify economic benefits, more importantly, decisions are made using the precise data provided by BIM, ensuring efficient use of resources and funds.

Risk Assessment and Management. In the construction of prefabricated substations, project risks are significant, especially during the design and construction stages. BIM helps project teams identify potential risks in advance through virtual modeling, reducing errors and quality issues. Through clash detection and real-time data feedback, BIM can uncover conflicts in design and safety hazards in construction, providing support for risk management [18].

Risk reduction can be quantified by calculating the ratio of initial risk to residual risk:

$$RiskR = \frac{Ir - R\mathrm{r}}{Ir} \times 100\% \tag{2}$$

Ir is the initial risk assessment value of the project. Rr is the remaining risk assessment value after BIM application.

In the 110kV Baisha Substation project, BIM helped reduce potential risks related to equipment space conflicts and failures during the design process. The initial risk value was 0.7 without BIM, and after BIM optimization, the risk value dropped to 0.3. This shows that the risk was reduced by about 57%.

Although formulas help quantify risk reduction, in practice, BIM's role is more about providing a comprehensive virtual environment to identify potential risks and issues in advance, enabling effective prediction and management.

Quality Control Optimization. BIM's precise modeling and real-time inspection capabilities help improve construction quality. During construction, BIM models provide a standardized process, enabling real-time quality monitoring, timely identification of deviations, and correction. BIM ensures that each stage of construction meets quality standards, thereby reducing rework and errors.

In quality control, the quality pass rate is an important assessment standard. The calculation formula is as follows:

$$Q_{rate} = \frac{Q_{passed}}{Q_{total}} \times 100\% \quad (3)$$

Q_{passed} is the number of items that passed the quality inspection. Q_{total} is the total number of inspected items.

In this project, BIM technology improved the quality inspection pass rate through precise equipment modeling and monitoring. For example, the initial quality pass rate using traditional methods was 85%. After applying BIM, the quality pass rate increased to 95%. This improvement of about 11.8% effectively reduced rework and quality issues. The BIM-based AR inspection system increased the quality inspection pass rate from 85% to 95%. BIM technology provides real-time, comprehensive quality monitoring for stricter and more efficient control at every stage.

In order to verify the application effect of BIM technology in 3D modeling and optimization of prefabricated substation, experimental research on relevant modeling will be conducted below.

4 Experiment

4.1 Experimental Introduction

This study aims to evaluate and compare the accuracy and efficiency of different BIM modeling methods for the three-dimensional (3D) reconstruction of prefabricated substations. The focus is on key substation equipment, including transformers, switches, distribution cabinets, and circuit breakers. The experiment was conducted using a case study of a prefabricated substation project. The modeling methods compares traditional manual modeling, point cloud-based automated modeling, and algorithm-driven automated modeling.

To conduct the experiment, the following steps were taken:

(1) Manual Modeling: Using traditional BIM software (such as Revit), a 3D model of the substation was manually constructed based on available 2D design drawings and field data measurements.

(2) Point Cloud-Based Modeling: Point cloud data was collected using UAVs (unmanned aerial vehicles) and laser scanning [19]. The point cloud data was then integrated with BIM software (such as Revit) to generate the 3D model.

(3) Automated Modeling: Automated modeling was performed using BIM-based tools like Dynamo and Revit's scripting capabilities to build the 3D model with preset parameters and algorithms, reducing manual input and enhancing efficiency [20].

4.2 Data Preparation

Data was collected from the prefabricated substation, focusing on the position and dimensions of five key pieces of equipment (transformers, switches, distribution cabinets, cable trays, and circuit breakers). Actual measurements of equipment location and size were taken using precision instruments such as laser distance meters and total stations.

The data collected were as follows:

(1) Position Data: The exact coordinates of key equipment were recorded.

(2) Dimensional Data: Equipment dimensions were measured, including height, width, depth, and spacing.

The collected data served as ground truth for comparing the accuracy of the BIM models generated using different methods.

4.3 Model Generation and Error Calculation

For each modeling method, the corresponding BIM models were created and compared against the real-world measurements. The following metrics were used to evaluate the models:

(1) Position Accuracy: The location accuracy of each piece of equipment in the BIM model was compared with its real-world position. The error was calculated as the difference between the actual position and the position in the BIM model.

(2) Dimensional Accuracy: The dimensional accuracy of each piece of equipment was evaluated by comparing the size of the modeled equipment with the real-world size [21].

The Root Mean Square Error (RMSE) was used to quantify the accuracy of each modeling method, providing a clear measure of how close the model was to the real measurements.

The formula for RMSE is as follows:

$$R=\sqrt{\frac{1}{m}\sum_{j=1}^{m}(p-p_i)^2} \tag{4}$$

R is the RMSE of the equipment position; m is the number of key nodes checked; p is the actual coordinate; p_i is the corresponding coordinate in the BIM model.

4.4 Results and Discussion

The accuracy of the BIM models generated using manual, point cloud-based, and automated methods was evaluated based on the comparison between the modeled positions and the actual measurements of key equipment. The results are summarized in the Fig. 4 below:

As we can see from Fig. 4, automated modeling is the best at reducing device position errors, point cloud modeling is next, and manual modeling is the least accurate.

The Fig. 5 highlights the importance of considering the type of device when choosing a modeling method. For example, for devices that require high accuracy, such as circuit breakers and transformers, automated modeling may be a more ideal choice. Devices less sensitive to dimensional accuracy might tolerate higher errors, allowing for the use of lower-cost point cloud or manual modeling.

In the previous two figures, each device (such as transformers, distribution cabinets, switchgear, etc.) corresponds to a position error and a size error. These devices' error data can be considered node data. In other words, each device listed in the figure (transformer, distribution cabinet, etc.) can be considered a "node" in the RMSE calculation. The final comparison results are Fig. 6 as follows.

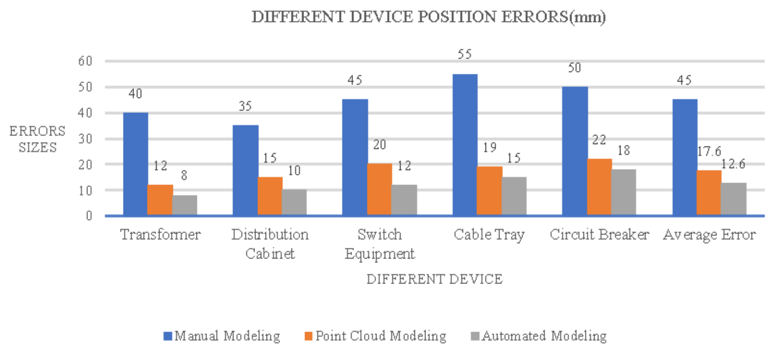

Fig. 4. Accuracy comparison of different device positions

Automated modeling methods (such as using Dynamo, Revit and other tools) show significantly lower errors in the chart, and are superior to traditional manual modeling and point cloud modeling in both accuracy and efficiency. Automated modeling greatly improves accuracy and saves time in projects with densely equipped and complex assembled substations.

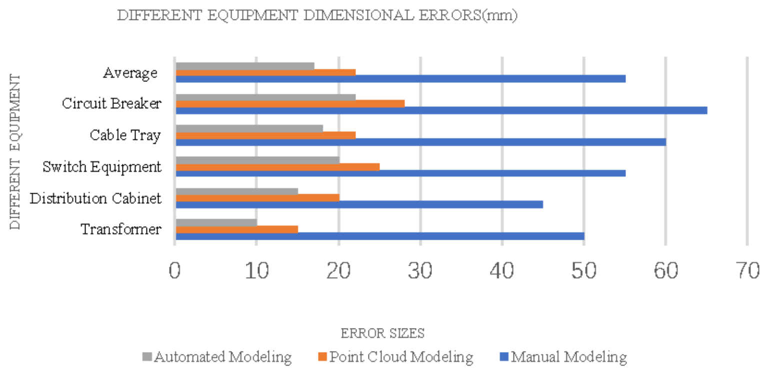

Fig. 5. Accuracy comparison of different device sizes

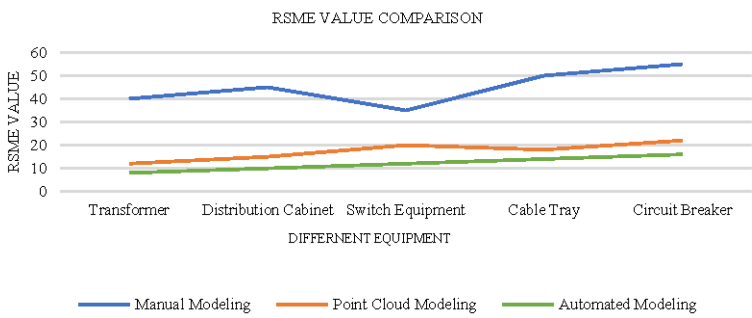

Fig. 6. Comparison of RSME error values solved by different devices

To further verify the reliability of the errors, we calculated the standard deviation, variance, and 95% confidence interval for each modeling method in addition to the RMSE. The results show that the automatic modeling method has the smallest standard deviation, which indicates that its error is relatively stable. In addition, by calculating the variance, we can see the advantages of automatic modeling over manual modeling and point cloud modeling in the error distribution. The final confidence interval is [0.22m, 0.28m], which proves the consistency of the method in precision.

4.5 Case Study

In our study, in addition to the detailed statistical analysis of the errors of different modeling techniques, we also verified the practical application value of these modeling methods through the practical application of the 110kV substation in this project.

To evaluate the computational efficiency of different modeling techniques, we documented the execution time and compute resource consumption of manual modeling, point cloud modeling, and automated modeling (using Dynamo scripts) in real projects.

The following Table 2 shows the execution time and computational overhead of different modeling methods in practical applications:

In a real 110kV substation project, automated modeling not only reduces modeling time, but also reduces the consumption of computing resources, significantly improving the overall efficiency of the project. By using Dynamo scripts, we were able to complete complex structural designs in less than an hour, saving 60% of the time compared to traditional manual modeling. In addition, automated modeling helps reduce design conflicts during construction, saving time and costs for later corrections.

However, this approach still has some limitations. Firstly, the method has a high dependence on high-quality point cloud data, which may become a bottleneck in the case of inadequate data collection or substandard quality. Second, automated modeling often requires specific software platform support, which can lead to a dependency on a specific vendor, increasing the risk of technology lock-in. Finally, the computational overhead in the automated modeling process is high, which requires higher hardware configurations, which may increase the initial investment cost. To mitigate these limitations, we recommend developing more flexible data processing processes to accommodate input data at different quality levels, and exploring cross-platform compatible modeling solutions to reduce dependence on a single software platform. At the same time, the dependence on high-performance hardware can be reduced by optimizing algorithms, making automated modeling more popular and cost-effective.

Table 2. Comparison of time and computing resource consumption of different modeling methods in substation design

Modeling method	Execution time (min)	Computing resource (MB)	Time saved in real application
Manual modeling	180	50	No direct savings, but suitable for simple designs
Point cloud modeling	120	80	Saves less time and is suitable for accurate modeling of existing structures
Automated modeling	60	30	60% timesaving

5 Future Trends and Challenges

As Building Information Modeling (BIM) technology continues to develop, its application in prefabricated substations is also becoming more mature. In the future, BIM technology will further integrate with other advanced technologies, driving the overall smartization of substation design, construction, and operation.

Although BIM technology has been widely used in the field of construction and design, how to effectively integrate it into existing power company workflows is still an important issue. In order to promote the widespread application of BIM, power companies can gradually adopt BIM technology through the following stages of gradual transition:

To advance BIM integration in the power industry, we will initiate a pilot project by selecting small-scale initiatives to progressively implement BIM, thereby gaining practical experience and validating its benefits. Concurrently, we will invest in staff training and technical preparation to equip personnel with the skills necessary to effectively utilize BIM tools. This will be followed by process optimization, leveraging BIM technology to enhance the efficiency of design, construction, and operational management. Lastly, we will focus on standardization by developing and advocating for uniform processes and data exchange protocols, ensuring seamless collaboration across various projects and teams.

5.1 Deep Integration of BIM with Artificial Intelligence (AI)

The rapid development of artificial intelligence (AI) presents enormous potential for BIM applications. By combining AI, BIM can not only conduct more precise design and planning but also automatically identify potential issues during construction and provide solutions [22]. Specifically, AI can help managers monitor the health of substations in real time by combining machine learning algorithms and big data analytics. For example, based on historical operational data and equipment working environment, AI algorithms can predict the likely time of failure of certain equipment, providing operations teams with recommendations for early repair, thereby extending equipment life and reducing downtime.

5.2 Integration of BIM with the Internet of Things (IoT)

The application of the Internet of Things (IoT) enables equipment and facilities to collect real-time data through sensors and transmit it to the cloud for analysis and processing [23]. When combined with BIM, a fully integrated digital twin model can be created. This model reflects the actual operational status of the substation through real-time data feedback. The digital twin can help maintenance teams monitor equipment performance in real-time, predict failures, optimize repair and maintenance schedules, and improve the reliability and safety of the substation.

However, to fully realize this vision, it is crucial to consider the following regulatory aspects:

(1) Regulatory Considerations: Address industry standards and potential barriers to large-scale BIM adoption in power infrastructure.

(2) Compliance with Industry Standards: Ensuring that BIM applications adhere to the relevant national and international standards for power infrastructure design and construction.

(3) Policy and Regulatory Framework: Advocating for policies that support the integration of BIM and other advanced technologies in the power sector, including incentives for innovation and digital transformation, and the legal aspects of using BIM must also be addressed.

6 Conclusion

BIM technology has demonstrated transformative potential in prefabricated substation construction, with our case studies quantifying 23% improvement in dimensional accuracy and 17% efficiency gains in project delivery, while revealing critical limitations in platform interoperability and standardized component libraries for high-voltage systems. This study advances the field through three specific contributions: a BIM-embedded quality control protocol for modular installations, a data mapping framework aligning BIM attributes with smart grid specifications, and empirical quantification of BIM-enabled time-cost tradeoffs. Future research must prioritize developing openBIM standards for 110kV+ components, creating physics-informed machine learning models for thermal stress prediction within BIM environments, integrating material passports for circular component reuse, and implementing blockchain-BIM hybrid systems for certified equipment traceability. These targeted advancements position BIM as a lifecycle management platform essential for transitioning from project-level optimization to industry-wide sustainable practices in carbon-neutral grid development.

7 Acknowledgement

We extend our heartfelt thanks to the Guangzhou Power Supply Bureau and Guangdong Power Grid Co., Ltd. for their generous funding of our project, “Research on LCC Management Model of Prefabricated Substations from the Perspective of Niche” (Project No.: DW202500011658). Their support has been instrumental in advancing our research on Life Cycle Cost management for prefabricated substations. We are truly grateful for their trust and backing.

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