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Research Article

Digital-Twin-Based Evaluation of Nearly Zero-Energy Building for Existing Buildings Based on Scan-to-BIM

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In recent years, the global energy environment has become increasingly severe, and the problems such as global warming, soaring carbon emissions, and excessive use of petrochemical energy have attracted increasing attention from all walks of life. The construction industry, which accounts for about 30% of the total energy consumption, needs to effectively manage and use renewable energy. The application of building information model (BIM) in the evaluation of retrofitting schemes of existing buildings is one of the main research issues in the field of building digital twins at present. The method of this research is to use 3D laser scanning technology to efficiently create the building energy model (BEM) of existing buildings and to identify and evaluate the feasibility of existing building retrofitting schemes. The purpose of this research is to evaluate the retrofitting scheme of existing buildings based on the concept of nearly zero-energy buildings (nZEBs), aiming to improve the energy efficiency of existing buildings and use clean energy to satisfy building energy demand. According to the case study in this paper, an nZEBs solution suitable for the building can reduce building energy costs by 14.1%, increase solar photovoltaic power generation by 24.13%, and reduce carbon dioxide emissions by 4306.0 kg CO_2eq/a.

1. Introduction

As the idea of sustainable development gains popularity, the problem of energy shortage cannot be ignored, and energy conservation has received widespread attention. At present, about 30% of the world's energy is consumed in buildings, which will seriously affect the sustainable development of the construction industry [1]. From the perspective of architects, a sustainable development strategy must be developed to minimize the consumption of nonrenewable energy and provide a healthy working and living space for the users. At present, building energy conservation is regarded as the most direct and effective way to alleviate the contradiction between economic development and energy shortage [2]. In 2018, the total energy consumption of residential buildings in China is 899 million tons of standard coal, accounting for 20.6% of the total national energy consumption. The total floor area of constructions is 63.5 billion m^2, and the urban per capita residential floor area is 34.9 m^2. With such a large amount of constructions, the carbon emission from constructions is 1.96 billion tons of carbon dioxide equivalent (CO_2eq), accounting for 19.4% of the total energy carbon emissions in China [3]. Therefore, this paper takes residential buildings as the research object and aims to improve the energy utilization efficiency of residential buildings through energy-saving retrofitting of existing buildings.

The nearly zero-energy buildings (nZEBs) refer to adapting to climatic characteristics and site conditions, through passive architectural design (adjusting building orientation, maximizing building lighting, shading measures, etc.) to minimize heating, air conditioning, and lighting energy consumption requirements and through active technical measures (the thermal performance and air-tightness of building, fresh air heat recovery system, etc.) to maximize the efficiency of energy equipment and systems and make full use of renewable energy (solar energy, geographical energy, and wind energy) such that the indoor environmental parameters and energy efficiency indicators of these buildings meet the requirements of the Technical Standard for Nearly Zero-Energy Building [4–6]. In the architectural design process, the energy consumption of building heating, lighting, air conditioning, and ventilation can be reduced by adjusting building orientation, maximizing building lighting, and shading measures [5]. Improving the thermal performance and air-tightness of building envelopes can reduce building operation energy consumption [7, 8]. The fresh air heat recovery system can effectively reduce the energy demand of the building air conditioning system [9]. The application of renewable energy in the built environment is mainly used in power generation, domestic hot water, and building heating systems [10–12]. Due to the limitation of urban space and the seasonal variation of wind, the application of wind power in the built environment is relatively rare [13]. Building integrated photovoltaic (BIPV) refers to the solar photovoltaic power generation system attached to the building. While the main function of the BIPV system is to generate electricity, it is also important to make sure that the BIPV system attached to the building does not conflict with the main function of the building. Ideal spaces to place the BIPV system include roofs and exterior walls of buildings [14]. The electric energy generated by the BIPV system can not only meet the electricity consumption of buildings, but also make up for the lack of electricity [15]. However, the current research on nZEBs mainly focuses on the design of new buildings, instead of retrofitting existing buildings into nZEBs with BIPV systems [16].

Therefore, it is necessary to evaluate the nZEBs retrofitting schemes of existing buildings. The purpose of this study is to visualize the energy efficiency and carbon emissions of existing buildings and to evaluate the nZEBs retrofitting schemes of existing buildings. In recent years, many scholars have conducted research on the applications of digital twin (DT) technology in building energy consumption simulation [17]. DT is able to simulate the behavior of physical entities in the real environment with digital virtual models through virtual and real interactive feedback, data fusion analysis, and decision-making iteration optimization, thereby playing a role as a bridge connecting the physical model and the information model [18–20]. Sakdirat et al. [18] established a BIM6D digital twin system to evaluate the time plan, cost, and sustainability of the whole life cycle of the project, and the calculation results showed that the carbon footprint of materials was the main influencing factor. With the development of BIM technology, 3D building feature modeling provides a perspective centered on individual buildings [21]. This just solves the problem of completeness and accuracy of information the model carried. Therefore, energy consumption analysis based on the BIM model has profound significance for the development of building energy-saving technology.

The BIM model can express the functional and physical characteristics of the building, and the point cloud model provides good support for the existing building modeling [22]. Therefore, creating a BIM model based on 3D point cloud data and performing energy consumption simulation is one of the most important challenges in the nZEBs retrofitting of existing buildings. In order to accurately evaluate the retrofitting scheme of existing buildings, BIM energy model needs to be established [23]. The accuracy of the model will directly affect the feasibility of the existing building retrofitting scheme. However, existing buildings have no BIM model when they were being constructed or the BIM model could be outdated. The common method to solve this problem is to manually fit the point cloud model within the allowable error range and build an ideal energy BIM model in reverse.

The scan-to-BIM is a practice of acquiring existing building data with BIM as the main technology and the assistance of point cloud technology so that BIM model is associated with existing building data [24]. Wang et al. [25] proposed a technical framework for applying scan-to-BIM and described the main steps of reverse modeling for buildings. Kwon et al. [26] proposed a modeling method for point cloud local space fitting and creating basic constructions such as planes, cuboids, and cylinders. Valero et al. [27] developed an algorithm for indoor planes that scans key locations of buildings and uses point cloud data to automatically generate boundary models. However, these methods are suitable for idealized buildings, regardless of specific building construction practices. Therefore, this paper uses the traditional modeling method of manually fitting point cloud models to create BIM energy models of existing buildings.

In the Chinese context, although the design and evaluation of new nZEBs has witnessed some progresses in the past few years, nZEBs retrofitting of existing buildings still lacks essential and adequate evaluation strategy. In order to solve the above problems, this paper proposes a scan-to-BIM-based digital twin evaluation method for nZEBs retrofitting of existing buildings, which evaluates the retrofitting scheme through comprehensive analyses of building energy consumption and building carbon emission indicators. A BIM energy model is created based on 3D laser scanning data of existing buildings. On the one hand, the BIM model carries detailed geometric information of the existing buildings, and on the other hand, the BIM model can be used for energy consumption simulation in the DesignBuilder software for evaluation of the feasibility of different retrofitting schemes.

2. Methodology

BIM technology has been widely used in many projects, and its use in the energy-saving retrofitting of existing buildings has been neglected because it is difficult to obtain relevant data. However, the scan-to-BIM method just solves this pain point [26]. The extensive applications of BIM technology in China have only just begun in recent years, and there is basically no complete BIM model in existing buildings. Reverse digital modeling technology based on point cloud data effectively solves this problem [28]. Therefore, the focus of this paper is to create a BIM model of existing buildings through the scan-to-BIM technology and to simulate the nZEBs retrofitting schemes of existing buildings through DesignBuilder. Based on the simulations, the effectiveness and feasibility of the retrofitting scheme are evaluated based on building energy consumption, building carbon emission, and other technical indicators. Figure 1 shows the proposed technical process of nZEBs retrofitting of existing buildings.

2.1. Scan-to-BIM. The method of converting 3D scanning point cloud data of existing buildings into BIM model is known as scan-to-BIM [29]. From the perspective of academic value, the application of point cloud technology in the construction industry is still at the initial stage, and there is still no unified standard or application mode. However, in order to ensure the reliability of our research results, this study chose the scan-to-BIM scanning parameters proposed by Wang et al. [25]. The accuracy (≤20 mm), spatial resolution (≤20 mm), and coverage (≥80%) are used to evaluate the quality of data collection. The coverage is calculated only when the scanned building has the required scanning accuracy and spatial resolution [25].

The processing of point cloud data required to scan a target building with a 3D laser scanner has been discussed in detail in previous studies [26, 29, 30]. The application process of 3D laser scanning technology is shown in Figure 1. This paper uses Autodesk Revit software, which is a commonly used BIM modeling tool, to create the BIM model through approximate matching and boundary matching with the point cloud data.

2.2. Building Energy Simulation. At present, one of the methods to improve the energy efficiency of buildings and reduce the carbon emissions of building operations for the retrofitting of nZEBs is BIM modeling and energy consumption simulation [31, 32]. Based on the establishment of the BIM model of the existing building, it is necessary to create a building energy model (BEM) of the building and to reasonably divide the thermal zone [33]. The thermal zone is the basic unit of energy consumption simulation calculation. The temperature and humidity parameters of the air in a thermal zone are the same [34]. In the simulation, each room of the building can be divided into a thermal zone, or multiple rooms can be divided into the same thermal zone.

Thermal zone division is to partition the building from the perspective of building thermal engineering, rather than partitioning in the spatial sense [35, 36]. The following principles should be followed in the thermal zone division. First, while ensuring that the physical and geometric characteristics of the building model are not affected, the zone division should reduce the number of divided thermal zones as much as possible. Second, in terms of the function of the internal rooms of the building, the space with the same function should be incorporated into the same thermal zone. Third, as far as the set temperature is concerned, the spaces with the same indoor temperature control scheme are combined into the same thermal zone.

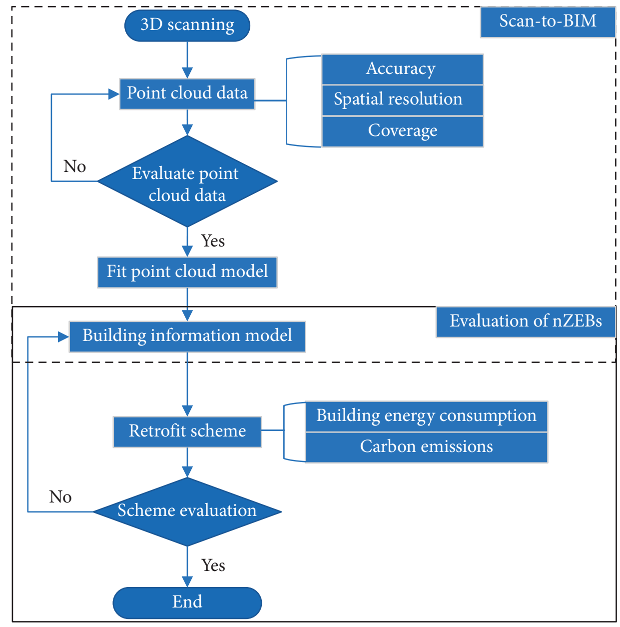


Figure 1: The proposed technical process of nZEBs retrofitting of existing buildings.

Figure 2 shows the process of building energy consumption simulation. Autodesk Revit supports the conversion between data formats and provides the required gbXML format for DesignBuilder. The user will use the BIM model established by Revit to divide the thermal zones according to the basic thermal zone partitioning principles and set appropriate parameters. Then, the Revit model is export to gbXML data format to simulate whether the nZEBs retrofitting scheme of existing buildings meets the specifications. This paper uses DesignBuilder to simulate different retrofitting schemes to determine a better retrofitting solution for nZEBs.

2.3. Evaluation of Nearly Zero-Energy Buildings. The nZEBs are defined as a new type of building, which can meet its energy needs by using clean energy [37].

2.3.1. Building Energy Consumption. The value of building energy consumption (≤55 kWh/m^2·a) is an indicator to represent the overall energy efficiency of residential buildings, including the contribution of renewable energy [4]. The value of building energy consumption is the only binding index to determine whether a building meets the nZEBs standard or not [4]. Under the set calculation conditions, the difference between the terminal energy consumption of heating, ventilation, air conditioning, lighting, domestic hot water, elevator and the power generation of renewable energy system is converted into equivalent power consumption uniformly by using the energy conversion

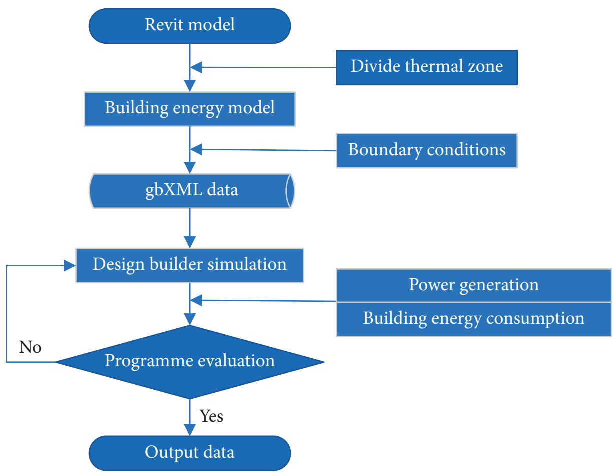


FIGURE 2: Process of building energy consumption simulation.

coefficient. The building energy consumption index calculation is as follows:

$$E = E_E - \frac{\sum E_{r,i} \times f_i + \sum E_{r\,d,i} \times f_i}{A}, \tag{1}$$

where E represents the value of building energy consumption (unit: kWh/(m^2·a)), E_E represents the value of building energy consumption without renewable energy generation (unit: kWh/(m^2·a)), A represents the building area (unit: m^2), f_i represents the energy conversion coefficient of type i energy, and the conversion coefficient f_i of electric power equals 2.6 [4], $E_{r,i}$ represents the type i renewable energy generation generated by the building itself (unit: kWh), and $E_{rd,i}$ represents the type i renewable energy generation generated around the building (unit: kWh).

The value of building energy consumption without renewable energy generation should be calculated as follows:

$$E_E = \frac{E_h \times f_i + E_c \times f_i + E_l \times f_i \times E_w \times f_i + E_e \times f_i}{A}, \tag{2}$$

where E_E represents the value of building energy consumption without renewable energy generation (unit: kWh/(m^2·a)), E_h represents the energy consumption of the heating system (unit: kWh/a), E_l represents the energy consumption of the lighting system (unit: kWh/a), E_w represents energy consumption of domestic hot water system (unit: kWh/a), E_e represents the energy consumption of the elevator system (unit: kWh/a), and A represents the usable area of residential buildings (unit: m^2).

2.3.2. Building Carbon Emissions. This study uses the carbon emission coefficient method, which is popularly adopted in China, to evaluate the retrofitting scheme [38]. Building carbon emissions include annual heating, ventilation, air conditioning, lighting, domestic hot water, elevator terminal energy consumption, and renewable energy system power generation, which are converted to equivalent carbon dioxide using the carbon emission coefficient.

$$E_n = E_b - E_z, \tag{3}$$

where E_n represents the total carbon emissions of buildings for a complete crediting calculation (one year) (unit: kg CO_2eq), E_b represents the carbon emissions generated by the building operation (unit: kg CO_2eq), and E_z represents the carbon emissions reduced by renewable energy (unit: kg CO_2eq). Here, E_b is calculated as follows:

$$E_b = \sum_{i=1}^{n} (E_i \times \mathrm{EF}_i), \tag{4}$$

where E_i represents the carbon emission of the hot zone considering the personnel in the room rate (unit: kg CO_2eq), EFi represents the carbon emission coefficient of the energy consumed in the thermal zone, and i represents the building thermal zone. On the other hand, E_z is calculated as follows:

$$E_z = \sum_{i=1}^{n} (C_i \times \mathrm{CF}_i), \tag{5}$$

where C_i represents clean energy consumed by the building during the calculation period, CF_i represents the carbon emission factor of type i clean energy, and i represents the type of clean energy.

3. Case Study

As shown in Figure 3, this case study is conducted in Dezhou City, Shandong Province, in eastern China. According to the design code for heating ventilation and air conditioning of civil buildings, this zone is a cold zone [39]. The design temperature of the air-conditioning room in winter is 20°C, and the design temperature of the air-conditioning room in summer is 26°C.

A residential building is selected as the case building. The total floor area of the case building is 192 m^2, with the living room and open kitchen on the first floor and the bedroom on the second floor. The east and west facades of the building are made of prefabricated concrete wall panels, and the south and north facades are made of glass curtain walls. A total of 140 pieces of thin-film solar photovoltaic module are integrated on the east and west sides of the building envelope and installed on parallel walls. Each solar photovoltaic module area is 0.72 m^2, and the efficiency of solar photovoltaic is 15%. The roof of the building has 60 thin-film solar photovoltaic modules installed parallel to the roof. The area of each module is 1.67 m^2, and the solar photovoltaic efficiency is 17.4%.

Since the scan data should have an accuracy of 20 mm, the accuracy and spatial resolution of the scan data must be equal to or less than 20 mm. Therefore, this study uses a ground laser scanner (ScanStationP50) to scan the target building, and the ranging accuracy is within 120 meters, reaching the accuracy of the scan data of 1.2 mm. Since the BIM energy model of the existing building needs to be created based on the scanned data, horizontal components only consider the impact of thermal characteristics on the energy consumption of the existing building. As a result, the boundary of the floor and roof only needs to fit the boundary

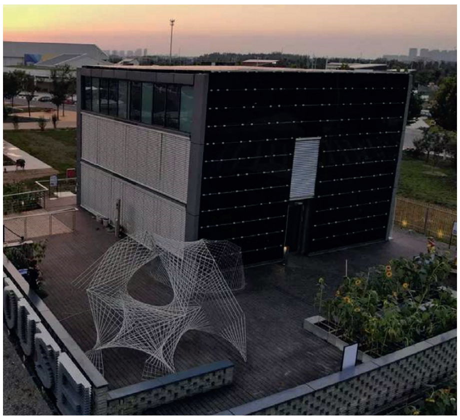


Figure 3: The photo of the case study.

of the facade and intersect with the facade components. The shape and size of doors, windows, glass curtain walls, and solar photovoltaic modules are known (Revit family), and they need to be positioned horizontally and vertically. Therefore, the scanning requirement for the facade data is complete coverage. As shown in Table 1, a total of four scans are conducted to cover the east, west, south, and north facades, respectively. The scanning accuracy is 1.2 mm, and the spatial resolution is always of 20 mm. In addition, the coverage for all facades is 100%.

The scanned data are shown in Figures 4–7. After scanning the existing building data, the point cloud data are imported to Revit to create the BIM model including walls, doors, windows, and solar photovoltaic modules based on fitting of the point cloud data. The BIM model is created as shown in Figure 8.

According to the functions of the rooms and the zoning principles proposed in this study, the highlighted sections in the figure are divided into two thermal zones. The thermal area on the first floor is the living room, and the occupancy rate is 19.5%; the thermal area on the second floor is the bedroom, and the occupancy rate is 35.4%. According to the design data, the comprehensive heat transfer coefficient of the building envelope is shown in Table 2. The south and north facades are integrated heat transfer coefficients containing windows and doors.

Figure 9 shows the monthly energy consumption simulation results of existing buildings. According to the simulation of energy consumption and photovoltaic power generation in DesignBuilder, the total annual energy consumption is 24771.10 kWh/a, and the photovoltaic power generation is 17645.35 kWh/a. According to the existing building simulation data, the building energy consumption value of the existing building is 83.96 kWh/(m^2·a), and the carbon emission of the building is 5013 kg CO_2eq.

According to the simulation results of existing buildings, the following retrofitting scheme is proposed in this study to adjust the installation angle of solar photovoltaic module to increase power generation (as shown in Figure 10). After retrofitting the existing building envelope, the heat transfer coefficient can meet the requirements of the building technical standard of nZEBs.

4. Results and Discussion

DesignBuilder was used to simulate the power generation of solar photovoltaic module in existing buildings and the energy consumption of existing buildings. With an angle increment of 3°, the influence of different installation angles of photovoltaic modules on existing building power generation and comprehensive energy consumption on the east facade, west facade, and roof was simulated, respectively. Figure 11 shows the impact of different installation angles of photovoltaic modules on the east facade, west facade, and roof on the total power generation of existing buildings.

According to the simulation results of DesignBuilder, the influence of installation angle on building energy consumption is shown in Figure 11. Considering the impact of photovoltaic power generation and building energy consumption, the best installation angle of photovoltaic modules on the west side is 33°, the best installation angle of photovoltaic modules on the east side is 36°, and the best installation angle of photovoltaic modules on the roof is 37° (to maximum power generation and minimum building energy consumption).

According to the simulation of energy consumption and photovoltaic power generation in DesignBuilder, the monthly energy consumption simulation results of existing buildings are shown in Figure 12. The total annual energy consumption is 24771.10 kWh/a, and the photovoltaic power generation is 17645.35 kWh/a.

In order to further improve the energy efficiency of buildings, the building envelope is an important part that needs to be renovated. The energy-saving retrofitting of the building facade makes it meet the requirements of nZEBs for building envelope structure. By simulating the building envelope to meet the requirements in Table 2, the energy consumption of the building is simulated, and the simulation results are shown in Table 3. The value of building energy consumption after retrofitting is 13.6kWh/m^2· a, which meets the requirements of the Technical Standard for Nearly Zero-Energy Building. It can be seen from Table 3 that the thermal efficiency of the energy model of the renovated existing building is 14.1% less energy consumption and cost than the original energy model building. With the optimization of the photovoltaic panels according to the angle, the maximum power generation of the photovoltaic system can reach 21903.76 kWh, which is an increase of 24.13% compared to the original power generation, and carbon dioxide emissions are reduced by 4306.0 kg CO_2eq.

According to the code for quality acceptance of concrete structures' construction, construction errors are allowed, and the maximum allowable construction error is ±30 mm. DesignBuilder is used to simulate building energy consumption based on CAD-to-BIM (computer-aided design, CAD, represents 2D CAD drawings), scan-to-BIM, and the maximum allowable error of construction. Figure 12 shows the building simulation results. After calculation, the building energy consumption of scan-to-BIM is 0.76‰ higher than that of CAD-to-BIM, the building energy consumption with the maximum allowable construction error is 5.76‰ higher than that of CAD-to-BIM, and the

Table 1: Scanning parameters.

Number	Element	Accuracy (mm)	Spatial resolution (mm)	Coverage (%)
1	East facade	1.2	0.5–13	100
2	West facade	1.2	0.5–5	100
3	South facade	1.2	0.4–7	100
4	North facade	1.2	0.5–4	100

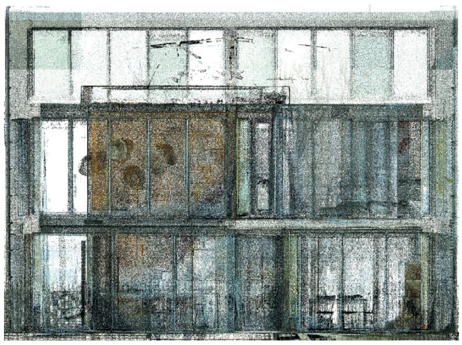


Figure 4: Scan of the south facade.

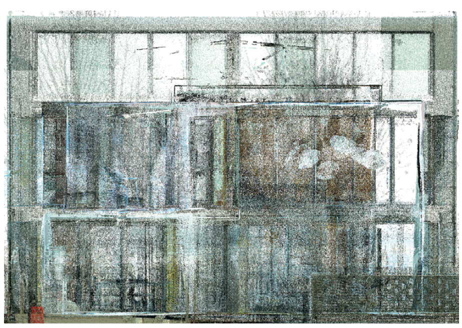


Figure 5: Scan of the north facade.

Figure 6: Scan of the east facade.

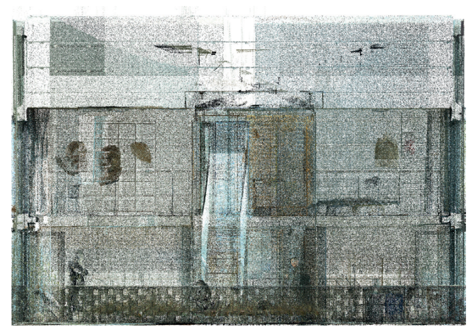


Figure 7: Scan of the west facade.

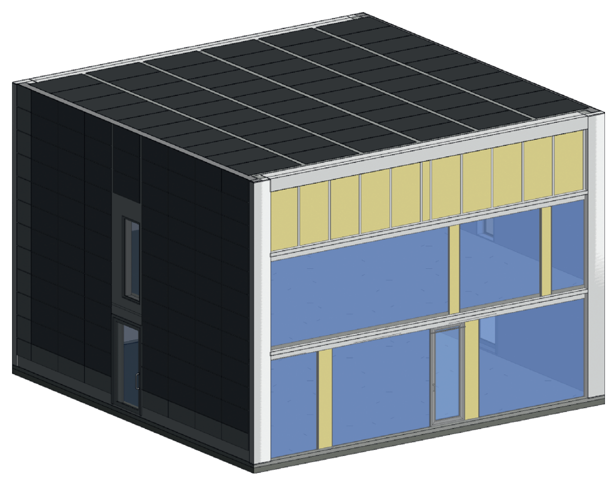


Figure 8: Reconstructed BIM model in Revit based on laser scan data.

building energy consumption with the maximum construction error is 4.99‰ higher than that of scan-to-BIM. Therefore, it is necessary to simulate the nZEBs retrofitting of existing buildings by acquiring detailed information after construction.

In the traditional computer-aided architecture design mode, it requires to manually measure the existing building. During the measurement process, it is necessary to compare the building components in CAD drawings to determine the influence of construction allowable error on the architectural design. This method needs to consume a lot of manpower and material resources. However, due to the subjective error in the measurement process, it is a must to calculate the average value for several times of measurements to reduce the error. The scan-to-BIM can effectively solve the problem of subjective error and measurement error and can accurately measure and effectively save time. Since the construction error of ±30 mm is acceptable, it can be seen from Figure 13 that the construction error has the greatest impact on building energy consumption. Therefore, simulating the energy consumption of existing buildings through scan-to-BIM can more accurately calculate the

Table 2: Heat transfer coefficient of building envelope.

Number	Envelope element	U coefficient (W/m^2·K)	U coefficient (requirements for nZEBs [4, 40] (W/m^2·K)
1	East/west facade	0.5	0.2
2	South/north facade	1.9	1.2
3	Roof	0.42	0.2
4	Floor	1.39	0.4

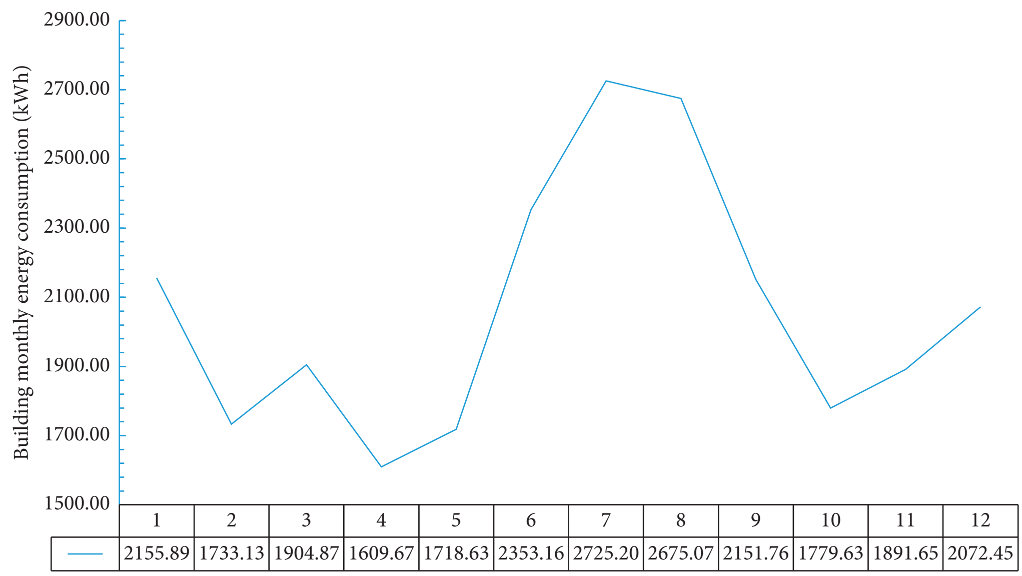


Figure 9: Simulation results of monthly energy consumption of existing buildings.

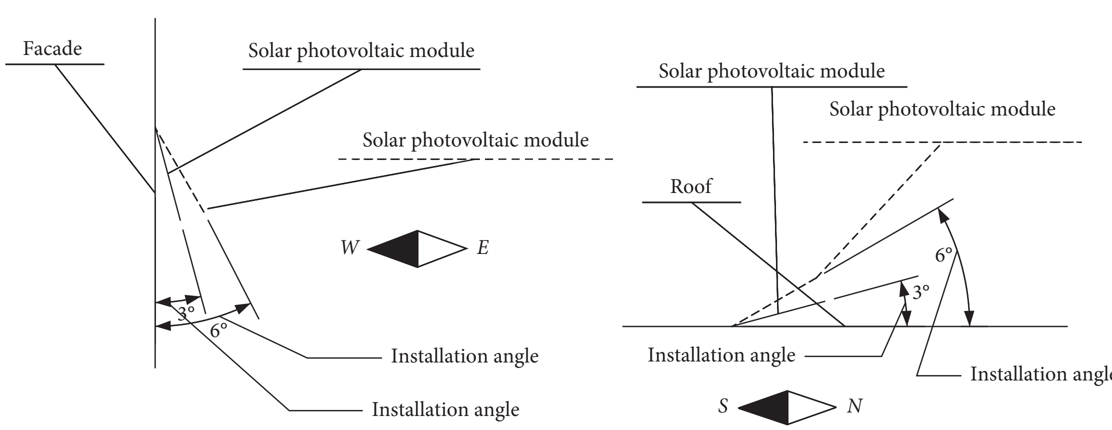
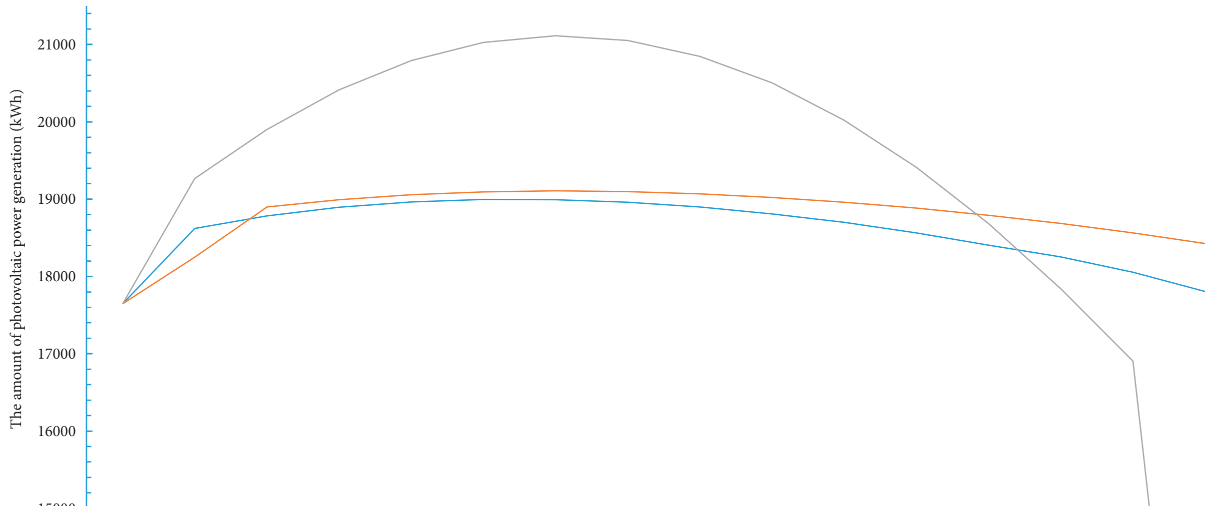


Figure 10: The facade and roof adjust the installation angle of solar photovoltaic module.

energy consumption of existing buildings, which is also helpful for the nZEBs retrofitting of existing buildings.

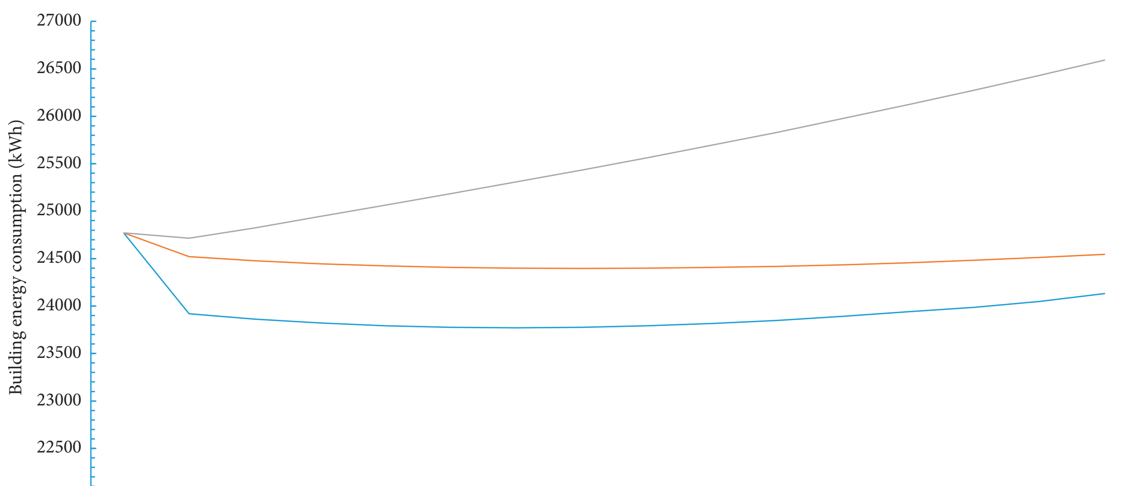
In traditional building operation management, building data are represented in different data formats such as CAD drawings, engineering records, and on-site photos. Among different types of data, the information is not linked to each other, and there are even many problems such as information expression errors, omissions, and contradictions, which cannot guarantee the smooth application of “information flow” in the life cycle management of buildings. Therefore, it is necessary to establish a virtual digital model through digital twin to establish a connection with the existing buildings and overcome the limitations of traditional database management.

Figure 14 shows the digital twin BIM model after the simulation of the nZEBs retrofitting of existing buildings. The photovoltaic modules are adjusted according to the installation angle of the simulated maximum generating capacity: 36° for the east facade, 33° for the west facade, and 37° for the roof. Digital twin can map and store the component information of existing buildings into the BIM model, which maintains a high degree of correlation and



	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90
West PV	17645.35	18621.34	18781.51	18894.36	18964.7	18995.37	18992.61	18958.44	18897.74	18809.94	18698.46	18563.53	18404.05	18254.45	18055.03	17804.08
East PV	17645.35	18248.94	18898.63	18993.34	19058.44	19093.84	19106.56	19096.71	19068.58	19022.22	18959.94	18883.54	18790.82	18685.69	18562.06	18425.53
Roof PV	17645.35	19264.85	19901	20412.65	20791.13	21025.42	21113.76	21053.38	20846.55	20502.93	20021.53	19410.27	18680.63	17840.5	16903.43	8590.98

Figure 11: Influence of installation angle on BIPV power generation.



	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90
West PV	24771.1	23920.2	23863.7	23821.8	23792.5	23776.4	23771.8	23777.4	23792.5	23817	23849.7	23890.8	23939.9	23987	24049.8	24131.6
East PV	24771.1	24520	24477.9	24446.2	24422.8	24408.1	24399.7	24397	24399.9	24407.2	24419.2	24435.6	24456.9	24482	24512.1	24546.4
Roof PV	24771.1	24715.8	24824.3	24943.4	25064.2	25184.7	25308.3	25433.4	25562.4	25697.5	25833.3	25976.8	26124	26273.6	26431.6	26591.9

Figure 12: The impact of photovoltaic module installation angle on building energy consumption.

consistency with the building components in the BIM model. Particularly when editing and modifying the BIM model, the editing and modification performed in any display mode can be faithfully reflected in other display modes in real time.

This study attempts to evaluate the nZEBs retrofitting scheme of existing buildings by means of digital twin to improve energy use efficiency and reduce greenhouse gas emissions of buildings. This paper discusses in detail the impact of the installation angle of solar photovoltaic modules on building energy consumption and photovoltaic modules power generation. In the simulated case, by adjusting the installation angle of photovoltaic modules, the energy consumption of the existing buildings is at a minimum of 22908.67 kWh and the power generation of photovoltaic modules is at a maximum of 21903.76 kWh, and the utilization rate of renewable energy is increased by 24.13%.

The scan-to-BIM-based digital twin evaluation method proposed in this paper further analyses and simulates the impact of existing building retrofitting schemes on building energy consumption and photovoltaic power generation, as well as the subsequent changes in related building carbon emissions. Therefore,

Table 3: Building energy consumption and photovoltaic module power generation.

	Energy consumption (kWh)	Power generation (kWh)	Carbon emission (kg CO_2eq)
Existing building	24771.10	17645.35	5013.0
Retrofitting scheme	22908.67	21903.76	707.0

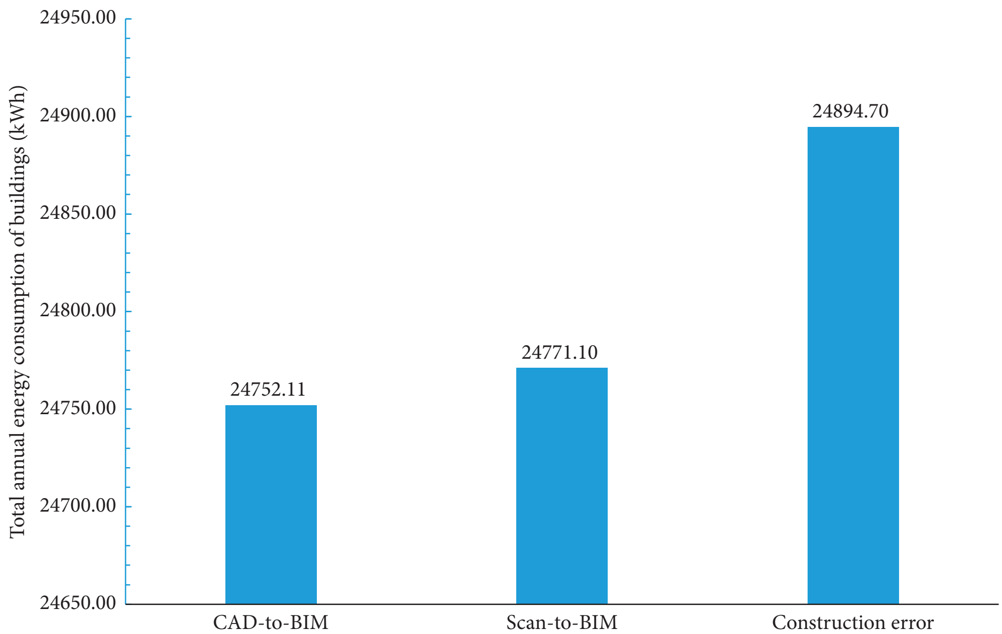


Figure 13: Comparison of building energy consumption in different scenarios.

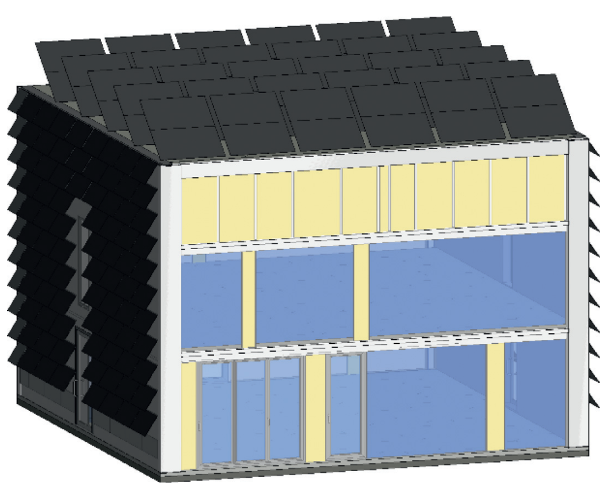


Figure 14: BIM model of retrofitting scheme with optimized angles of photovoltaic modules.

the method proposed in this paper is reproducible, which is helpful to study the evaluation of the nZEBs retrofitting of existing buildings. However, from the perspective of renewable energy utilization, there are certain spatial limitations in the nZEBs retrofitting of existing buildings. The limitation of existing building space may make it impossible to support the application of renewable energy technology.

5. Conclusion and Future Work

With the development of nZEBs technology and digital-twin-based evaluation of nZEBs retrofitting scheme of existing buildings, achieving high energy efficiency or nearly zero-energy consumption is a significant step to enhance built environment sustainability. This study presented a methodology based on scan-to-BIM to evaluate nZEBs retrofitting for existing building which allows researchers and designers to effectively transfer data between modeling software and energy consumption simulation software and move beyond energy evaluation towards improving energy efficiency and reducing carbon emissions. In the establishment of data mapping between the real world and the virtual world, this study uses the scan-to-BIM method, which can increase the modeling efficiency and reduce errors. It has been proved to be an effective BIM model reconstruction method for the digital-twin-based evaluation of nZEBs retrofitting scheme of existing buildings.

The calculation results of this case study show that the nZEBs retrofitting of existing buildings reduces building energy consumption by 7.52%. In addition, energy changes will also have an impact on the environment. According to the calculation results, carbon emissions can be reduced by 85.9%. The results of this study are universal, and the results support that the nZEBs retrofitting of existing buildings can reduce the energy demand of existing residential buildings and achieve the goal of nZEBs. In terms of applicability, the method proposed in this study can be easily reproduced and help designers to more effectively evaluate nZEBs retrofitting scheme of existing buildings. Accordingly, this method can serve as an adaptable design decision-making tool for nZEBs retrofitting scheme of existing buildings to achieve maximum energy efficiency and minimum carbon emissions.

The calculation results show that it is feasible to carry out energy-saving retrofitting of buildings and provide a basis for the nZEBs retrofitting of existing buildings. This study is conducted by manually fitting point cloud data modeling, which means that future study can generate a digital twin BIM model of an existing building through artificial intelligent algorithms. In addition, the areas of future research include (1) applying more retrofitting technologies to existing buildings and providing more financial data and (2) extension of the nZEBs retrofitting of existing buildings proposed on the basis of this study, including more data integration into the BIM model, to allow more technologies to be applied to the digital twin of existing buildings.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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