Research Paper

A Digital-twin Based Conservation of Campus Historic Buildings under Sustainable Development Framework

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Abstract

The construction of Chinese campuses has entered a phase focused on existing assets, and a number of campus buildings recognized as built heritage have emerged. However, there is a lack of a comprehensive sustainable development framework for the conservation and renovation of these buildings. This paper first identifies the sustainable development goals for historic buildings in campuses through literature review and theoretical analysis. Subsequently, a sustainable development framework for campus historic buildings integrated with Digital Twins technology is proposed, with applications of certain aspects of the framework illustrated through case studies. This research contributes to the theoretical understanding of digital twin applications in campus historic buildings, incorporating sustainable development principles. Additionally, it provides a reference for applying the digital twin sustainable development framework in other practical projects.

Keywords

Sustainable Development, Digital Twins, Campus, Historic Buildings, Framework

1. Introduction

The construction of Chinese campuses has gradually reached a saturation point, with campus buildings entering a phase of stock development. Many historic campuses have buildings recognized as cultural heritage that urgently need conservation and renovation. As an emerging computer technology, Digital Twins creates virtual simulation models of buildings, enabling real-time monitoring, fault diagnosis, and trend prediction for systems. This technology provides a new perspective and tool for building operation, maintenance, and renovation management. Although numerous studies have applied Digital Twins for the conservation and renovation of built heritage, a comprehensive Digital-Twin based sustainable development framework for campus historic buildings is lacking.

To address this gap, a literature review was conducted on related topics. By reviewing theories related to historic buildings, built heritage preservation, and relevant national laws and regulations, combined with existing research on campus historic buildings, sustainable development goals for campus historic buildings were identified. Furthermore, an extensive review of Digital Twins applications in campuses and built heritage was conducted to outline existing frameworks. By integrating the existing frameworks with the sustainable development goals, a new framework is proposed. Based on this, the application of part of the theoretical framework was initially realized through the introduction of case-study building and the construction of a Digital Twins platform.

1.1. Sustainable development goals for campus historic buildings

The principles of authenticity and integrity mentioned in the Venice Charter remain central to the conservation of built heritage toady. These principles emphasize the authentic and complete preservation of a building's original appearance, materials, and surrounding environment, and have driven theoretical and regulatory developments in built heritage preservation worldwide. In 2015, China's Cultural Relics Protection Law specified that the protection of cultural relics should follow a process of investigation, assessment, planning, and implementation, with an evaluation of historical, artistic, and scientific value being key to determining graded protection levels (The Information Office of the State Council, 2016). Protection measures should focus on the structure, materials, techniques, functions, and environment of the heritage, maintaining its authenticity (Lin, 2012). Integrity, on the other hand, requires that the scope of heritage protection be defined based on its protection level and legal boundaries, emphasizing the coordinated protection of external and internal spaces (Chen *et al.*, 2022).

As modern built heritage, campus historic buildings in China should prioritize preventive conservation. For example, a Historic Building Information Model based multi-indicator preventive conservation platform can effectively reduce maintenance costs (Mora, 2021). Since the interior and exterior spaces of these buildings will continue to serve faculty and students for the long term, space performance and functionality should be optimized within permissible limits, promoting user well-being. A research in China used the Nanjing University clock tower as an example, explored reuse strategies under Chinese regulations that focus on authentically preserving architectural style, structure, materials, surrounding environment, and functional upgrades, following a process from value assessment to planned restoration (Wang *et al.*, 2022). Another research in China developed a conservation assessment framework for campus historic buildings, using quantitative methods such as AHP (Analytic Hierarchy Process), which includes value protection, use protection, safety measures, maintenance, and user perception dimensions(Huang *et al.*, 2024). With the development of emerging technologies like Digital Twins and artificial intelligence, the goals of sustainable building conservation are expanding to include human-centered values. Public participation in decision-making and social media promotion play increasingly important roles in heritage conservation and cultural value continuity (Rios, 2024). Resilience, as the capacity of heritage to withstand rapid disasters and long-term climate change, is also gaining importance in conservation and maintenance decision-making (Esposito *et al.*, 2021). Lastly, sustainability encompasses areas such as sustainable tourism management, green performance improvements, and the use of eco-friendly materials (Galiano-Garrigós *et al.*, 2024).

In summary, the theoretical framework for the conservation of campus historic buildings proposed in this paper is based on three main sustainable goals:

1. Conservation of Historical and Cultural Value - Maintaining the building’s appearance, storing digital data, and promoting online dissemination of building history to integrate both physical and digital environments.

2. Enhancement of Built Environment Resilience - Aiming to respond long-term environmental changes, it’s necessary to ensure structural safety, improve energy performance to maintain indoor environmental stability, and reduce carbon emissions.

3. Promotion of Users’ Well-being - Enhancing users’ involvement in decision-making of heritage operation, maintenance, and renovation to increase their satisfaction with functional experiences and the heritage environment.

1.2. The application of Digital Twins technology in built heritage and campuses

Digital Twins can create a digital model by integrating static information and real-time data that reflect the state of physical entities. This enables a two-way interaction between the virtual and real systems, allowing for management, analysis, and prediction of the system (Dang, 2023). The establishment of a Digital Twins platform generally includes the setup of the Internet of Things (IoT), collection of static and real-time data, creation of a visual virtual model integrating multi-source data, and development of a decision support system based on computational technologies such as cloud computing or artificial intelligence.

Digital Twins technology has been widely applied in the conservation of built heritage, especially in older buildings. First, assessing and predicting the structural performance of heritage is crucial for preserving their integrity. A research proposed a risk assessment framework based on Digital Twins using low-cost IoT sensors and a Structural Health Monitoring system (Machete *et al.*, 2023). Another research developed a Digital Twins framework for assessing structural risk by comparing the geometric differences in 3D reconstruction models of heritage at different time points (Kong, 2023). Second, parameters of the physical environment within buildings, such as temperature and humidity, have been shown to impact heritage preservation. Thus, enhancing building energy performance not only promotes energy efficiency but also improves the physical environment surrounding the internal structure of the buildings. A research proposed a connected framework that integrates performance data detected by sensors within

Historic Building Information Model, enabling bidirectional data transfer (Moyano *et al.*, 2023). There is another study integrating Building Information Model and Building Energy Model to develop a comprehensive framework used to conduct real-time monitoring and assessment of building performance, as well as providing multi-criteria prediction for various intervention combination (Massafra, Predari and Gulli, 2022). Finally, many studies aim to apply Digital Twins in heritage management. For example, a project used system dynamics to incorporate stakeholder perspectives related to heritage usage into a conservation framework, which includes multi-source data collection, integration, and analysis to encourage public participation in decision-making (Lazari *et al.*, 2024).

Campuses have significant energy-saving potential, with lighting accounting for approximately 23-42% of the total energy consumption in educational buildings (Lizana, 2018). Therefore, current applications of Digital Twins in campuses mainly focus on enhancing energy performance and real-time safety management. A research in China introduced a smart campus system developed based on Unity3D, improving the teaching and management levels of the campus (Han *et al.*, 2022). Another researcher used a digital twin platform combined with a BP neural network model to predict campus building electricity consumption by considering various main factors to aid operational decisions (Han *et al.*, 2024). However, there are few Digital-Twin based frameworks applied for campus historic buildings, highlighting the need to adapt existing frameworks to meet the actual requirements of campuses.

According to what mentioned above, in first section, this study has reviewed related literature especially existing digital-twin based frameworks in these studies and proposed several main sustainable development goals for campus historic buildings. The second section explains the research methods and proposes the Digital-Twin based theoretical framework of this paper. In the third section, the study provides basic information of the case study building, including its history, cultural value, site situation, current condition and renovation needs. In addition, the fourth section presents the research results: the construction process of the Digital Twins platform for the campus and its applications in the conservation and renovation of the case study building have been demonstrated in this part. Finally, the last section covers the conclusion of the paper.

2. Methodology and framework

This is a preliminary study employing a series of qualitative research methods, including literature review, theoretical analysis, and case study. Therefore, the main contribution of this paper is the proposal of a digital-twin based sustainable development framework for campus historic buildings. On the basis of the framework proposed through reviewing of multiple related topics, historical and current information of the case study building are collected and analyzed to identify its renovation needs. In addition, the construction of a Digital Twins platform further demonstrates the practical application of parts of the theoretical framework, partially validating its feasibility, and a future research plan focused on quantitative methods has been developed.

The proposed Digital-Twin based sustainable theoretical framework for campus historic buildings is as follows (see Fig.1): First, a Digital Twins platform is built following a sequence of IoT setup, data collection, visualization modeling, integrated simulation and prediction systems establishment. And the real-time data from the visualization platform will be imported into multi-criteria evaluation system to assess the current state of the building. In addition, by use of simulation and prediction system, relation mapping of multi-source data, including environmental parameters, structural vibration, energy consumption, and user behavior, are analyzed and established, which can be used for supporting decision-making. Finally, different Intervention plans can be simulated and evaluated to identify suitable decision, so that the mangers of the building can assess and manage in a closed loop process.

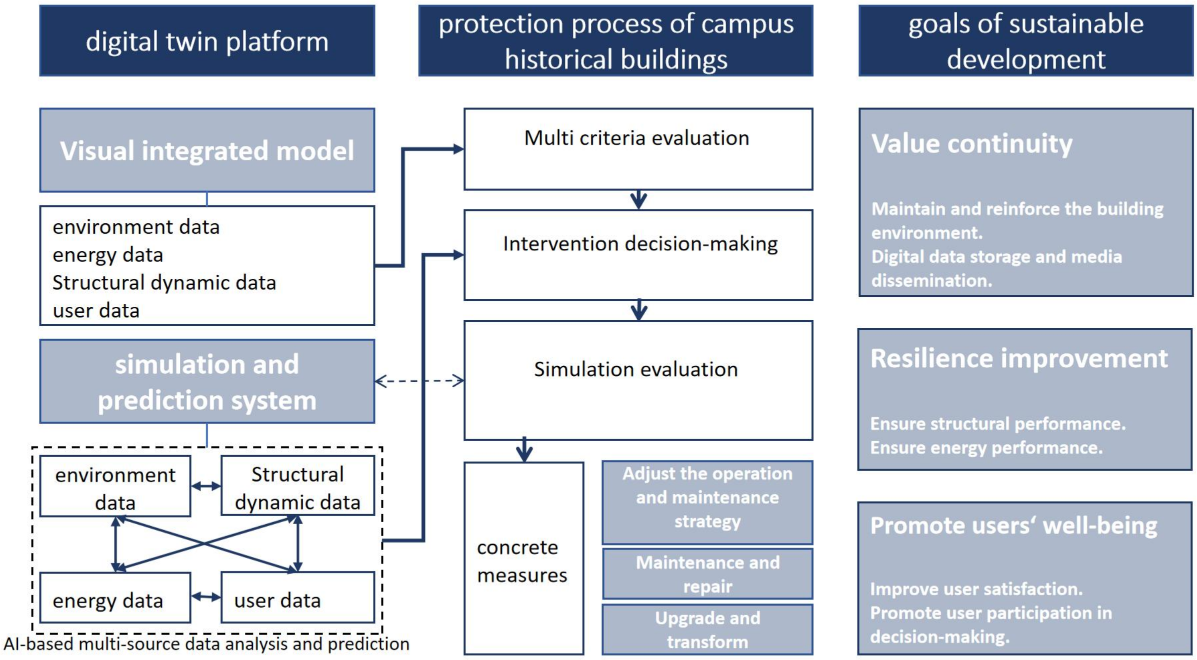

Figure 1. digital-twin based sustainable development framework . Source: Made by Author.

3. Case study

This paper takes the Zhu-Lou building in Harbin Institute of Technology (HIT) as an example, illustrating the construction process of Digital Twins platform and exploring its application on preservation and renewal of the case building.

3.1. Historical background

Harbin, the capital city of Heilongjiang Province is located in the northeast of China, with sever cold climate. At the end of the 19th century, Russia began building the China Eastern Railway in Harbin, turning the city into an international commercial hub in the early 20th century, attracting many foreign settlers. The development during this period made the urban planning of Harbin obtain certain characteristics similar to European city, such as a radial road network and multiple city center nodes. It also left behind numerous buildings in European or Russian architectural styles (Harbin Municipal People's Government, 2024).

HIT was founded in 1920 with the mission of training engineering and technical personnel for the China Eastern Railway. In 1945, the school was jointly managed by China and the Soviet Union until it was taken over by China in 1950. Today, HIT has developed into a comprehensive university focusing on science and engineering. The Zhu-Lou building of HIT was initially constructed in 1959, located between the Electrical Engineering Building and the Mechanical Engineering Building, and was completed in 1965, marking a history of 59 years (see Fig.2). The overall floor plan of the building forms a T shape, with a central tower comprising 13 floors and two wings with 6 floors. It is connected to the Electrical Engineering Building and the Mechanical Engineering Building through a passage, forming a unified structure and enclosing a courtyard that faces the campus. The building includes spaces of different functions such as classrooms, laboratories, offices, and an auditorium, and is constructed with a reinforced concrete frame structure.

Figure 2. The location of the main building in campus one of HIT.
Source: Made by Author.

Figure 3. The picture of main building
Source: Made by Author.

3.2. Heritage value

The building adopts a Russian architectural style (see Fig.3), symbolizing the deep connection between HIT and Russian educational models, and fully reflecting the unique history of the institution. The facade of the main building facing Xidazhi Street serves as an important urban interface, becoming a symbol of the campus and the city alike, thus holding significant historical and cultural value.

Connected to the Electrical Engineering Building and the Mechanical Engineering Building, the Zhu-Lou building presents a dignified appearance. European architectural elements, such as columns and cornices, are used in the decoration, with intricate moldings, adding to its aesthetic appeal. Faculty and students highly recognize the building's aesthetic image, making it essential to the campus's identity and lending it high artistic value.

3.3. Current state of the building

The building is currently designated as a Category II protected structure by Harbin Planning Bureau. According to Article 44 of the *Regulations on the Protection of Historical and Cultural Cities in Harbin*, 'the original facade design, surface materials, main layout, and distinctive interior decorations of Category II protected buildings must not be altered' (Harbin Government Website, 2020). Thus, the appearance and primary spaces of the building cannot be modified. As the structure remains in good condition, exterior repainting, detailed repairs, and partial interior renovations were completed by 2020 (see Fig.4). Additionally, the main hall on the second and third floors in the center of the building was refurbished as a campus history exhibition area (see Fig.5). Thus, building's heritage value is preliminarily protected through physical restoration and the addition of exhibition spaces.

Currently, the building is primarily used by the School of Electronics and Information Engineering and the School of Astronautics, with its auditorium and exhibition areas open to the entire campus. However, the installation of modern office and research equipment has led to higher energy consumption. The changing behaviors and needs of students also call for more flexible learning spaces and greater autonomy in choosing study environments. Therefore, future updates and maintenance of the main building should prioritize enhancing the experience of faculty and students, optimizing energy performance, and improving the resilience of this heritage asset.

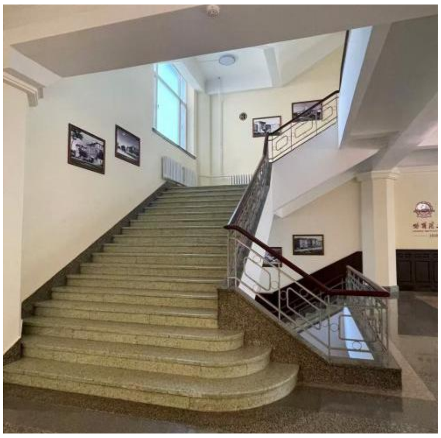

Figure 4. The renovated lobby staircase

Source: Made by Author.

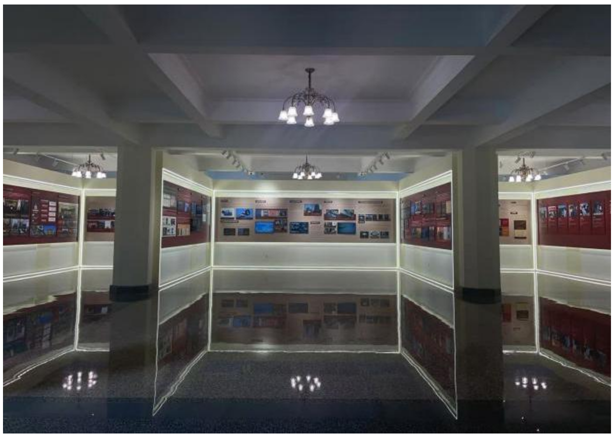

Figure 5. The renovated school history exhibition hall.

Source: Made by Author.

4. Results

4.1. Digital Twins platform construction

Currently, Digital Twins models have been established across three campuses of HIT (see Fig.6). The main functions of this platform include safety management, teaching evaluation, and energy monitoring. The system is based on a C/S architecture model using the Unity3D engine, allowing for real-time transmission and rendering of model data and sensor data after programming setup. The architectural and environmental models are generated from integrated CAD drawings and elevation information of campus buildings. All sensors use the same data security protocols and are connected to the campus network. In addition to devices like cameras and electricity meters, controllable devices such as parking lot barriers are also included. By integrating and rendering static models with dynamic real-time information, a basic visual interactive platform has been formed.

Figure 6. The currently built campus digital twin platform. Source: Made by Author.

4.2. Application of the platform in campus historic building conservation

Given that the Zhu-Lou building's facade and structural body are well-preserved, and that some maintenance of the facade and interior was conducted before the platform's deployment, the current application of the platform focuses on enhancing energy performance and improving the user experience for faculty and students (see Fig.7).

The Digital Twins platform updates the detailed status of the building in real-time through IoT sensors, allowing for the collection of multi-source data including occupancy situation, energy consumption, and camera footage of different rooms. Specifically, the energy consumption and occupancy situation are uploaded to the managers, supporting to conduct better energy usage plans and reducing energy consumption. What's more, the occupancy information is also synchronized to student service applications and the screens outside the classrooms, allowing students to choose study spaces conveniently.

Additionally, the camera footage can reflect the teaching quality as the status of teachers and students can be evaluated accurately by image recognition technology based on Artificial Intelligence. Also, with these cameras installed in the whole building, unexpected incidents can be monitored automatically to ensure users' safety.

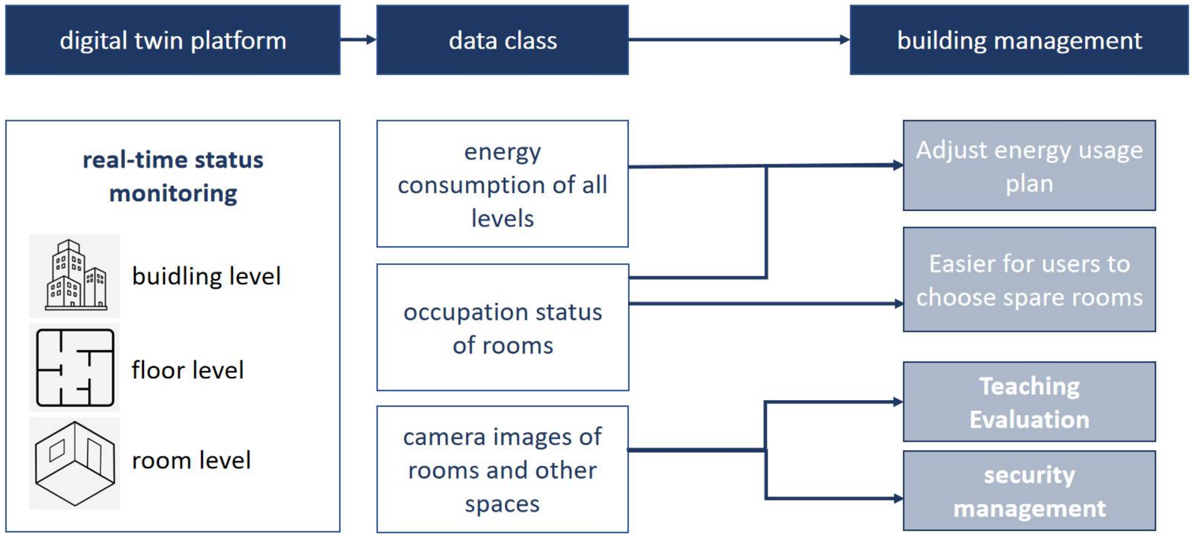

Figure 7. The current usage functions of the platform. Made by Author.

4.3. Future application plans of the platform

Currently, the platform's applications primarily focus on safety management and basic maintenance, but the potential value of the vast amounts of historical and real-time data stored on platform remains to be explored. Additionally, it is necessary to collect more types of building environmental data to develop an AI-based simulation and prediction system that can assist in decision-making from a quantitative perspective.

The theoretical framework proposed by the research institute is still relatively macro and foundational. To achieve the goal of protecting the historical architectural style and structural integrity through data-driven methods, it is critical to further refine the systems and pathways within the framework. For the multi-criteria assessment system, specific indicators and evaluation methods should be clarified, and the feasibility of further developments based on the platform should be assessed. For instance, periodic drone photography and 3D reconstruction can be utilized to identify physical changes in the facade. Moreover, a Structural Health Monitoring system can be employed for risk assessment and classification of structural components.

5. Conclusion

This paper focuses on the conservation and renovation of historical buildings in campuses, proposing a theoretical framework for the sustainable development of campus historic buildings based on Digital Twins technology and sustainable development concepts. Case studies illustrate the completed applications within the framework, providing preliminary references for the preservation and renovation of other campus historical buildings. Future research plans have also been formulated, with an emphasis on the collection of multidimensional data, the development of AI-based decision-making and assessment systems, and further quantitative and practical validation.

6. Funding

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