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Improving energy efficiency while preserving historic buildings with digital twins and artificial intelligence

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Abstract. This study proposes a digitalization framework for historic buildings. In this framework, advanced techniques, like Internet of Things (IoT), cloud computing, and artificial intelligence (AI), are utilized to create digital twins for historic buildings. A digital twin is a software representation of a physical object. This study uses digital twins to protect, predict, and optimize through analytics of real-time and historical data of selected features. Heterogeneous data of historic buildings, such as indoor environment, energy consumption metering, and outdoor climate, are collected with proper sensors or retrieved from other data sources. Then, these data are periodically uploaded and stored in the database of the cloud platform. Based on these data, AI models are trained through appropriate machine learning algorithms to monitor historic buildings, predict energy consumption, and control energy-consuming equipment autonomously to reach the balance of energy efficiency, building conservation, and human comfort. The cloud-based characteristic of our digitalization framework makes the digital twins developed in this study easy to be transplanted to many other historic buildings in Sweden and other countries.

Keywords – Historic Buildings Preservation; Energy Efficiency Optimization; Digital Twins; Artificial Intelligence; Internet of Things

1. Introduction

In the European Union, 35 % of buildings are over 50 years old, and almost 75 % of buildings are energy inefficient [1]. Therefore, improving energy efficiency of historic buildings contributes to reducing energy consumption and lowering greenhouse gas emissions.

Many factors can affect the energy consumption of a building. Typical factors include weather conditions outside the building, characteristics of the building itself, and occupancy inside the building [2]. Figuring out how a building currently consumes energy is a critical step in reducing energy consumption. On the one hand, it helps optimize the scheduling of heating, ventilation, and air conditioning (HVAC) systems. On the other hand, it provides a benchmark for the renovation, which can quantify energy efficiency improvements after the renovation [3].

Researchers have proposed two main approaches to predict the energy consumption of a building: the physical modelling approach and the data-driven approach. The physical modelling approach uses physical principles to calculate thermal dynamics and energy behaviour on the whole building level or sub-level components [2]. Establishing a comprehensive physical model of a building requires detailed design information of the building and scheduling of HVAC systems [4]. The data-driven approach does not perform such energy analysis or require such detailed data about the target building but learns from

available historical data for prediction. Artificial neural network (ANN) is one of the most popular algorithms used for energy consumption prediction [5], [6].

Historic buildings require continuous monitoring and maintenance to sustain functionality. Many previous studies have been conducted on deploying various types of sensors to monitor indoor environment [7], surface conditions [8], and structural health [9] of a building in real-time. Assisted by the evolvement of cloud computing, universal frameworks [10], [11] have been proposed for indoor environmental quality monitoring and management. Public cloud platforms enhance the reliability and scalability of frameworks while lowering the deployment cost.

This study aims to develop a cloud-based digitalization framework for energy efficiency optimization and smart maintenance of historic buildings. Advanced techniques, such as Internet of Things (IoT), artificial intelligence (AI), and cloud computing, are utilized in the framework to create digital twins of buildings. Three historic buildings located in Norrköping, Sweden, as shown in figure 1, are selected for case studies. All these three buildings have a history of more than a hundred years and are still used to host various social and cultural activities. These three buildings are different in their construction age, internal structure, and actual use, which can help verify the adaptability and portability of our framework. Environmental sensors are installed in these three buildings, and corresponding digital twins are created and stored in the cloud. Based on continuously collected sensing data, the digital twins can genuinely reflect real-time operating conditions and predict future states of historic buildings. The framework also facilitates maintenance to realize energy efficiency optimization and sustainable preservation with trained AI models.



Figure 1. Three historic buildings in Norrköping are selected for case studies. (a) The City Theatre (Östgötateatern), (b) the Auditorium (Hörsalen), and (c) the City Museum (Stadsmuseum).

2. Methodology

In this study, the research objects are historic public buildings used for different social and cultural activities, and the purpose is to realize energy efficiency optimization and smart maintenance with advanced digitalization means.

2.1. A cloud-based digitalization framework

To achieve the research goals, we propose a cloud-based digitalization framework for historic buildings. This unified digitalization framework for historic buildings can be developed with state-of-the-art communication and computing technologies. The preservation of historic buildings is a long-term process, and a large amount of data will be accumulated over time. The cloud-based framework can provide enough storage space and computing resources for these data. We also apply machine learning algorithms to learn from these data to develop AI applications to perform specific tasks, such as energy consumption prediction, visitor flow, facade or artwork decay detection, and anomaly detection, considering different cultural and historic buildings in differential indoor and outdoor climate conditions.

Figure 2 depicts the architecture of the proposed digitalization framework. The framework has two main parts: the local part and the cloud part. The transmission layer is a bridge between the local part and the cloud part for exchanging data. In the local part, sensors and actuators are deployed in the perception layer to collect indoor environment, occupants' behaviour, and facility operation status about

a building. Edge devices are used for packaging these sensor readings and uploading them to the cloud. Besides, edge devices can receive control commands issued from the cloud. In the cloud part, the storage layer is responsible for storing data from heterogeneous sources in relational or non-relational databases. Digital twins are also created and stored in this layer. Once data are ready, evaluation methods and AI models deployed in the analysis layer can utilize them to achieve different goals. The application layer provides interactive functions to users, such as data visualization, smart maintenance, and energy consumption prediction.

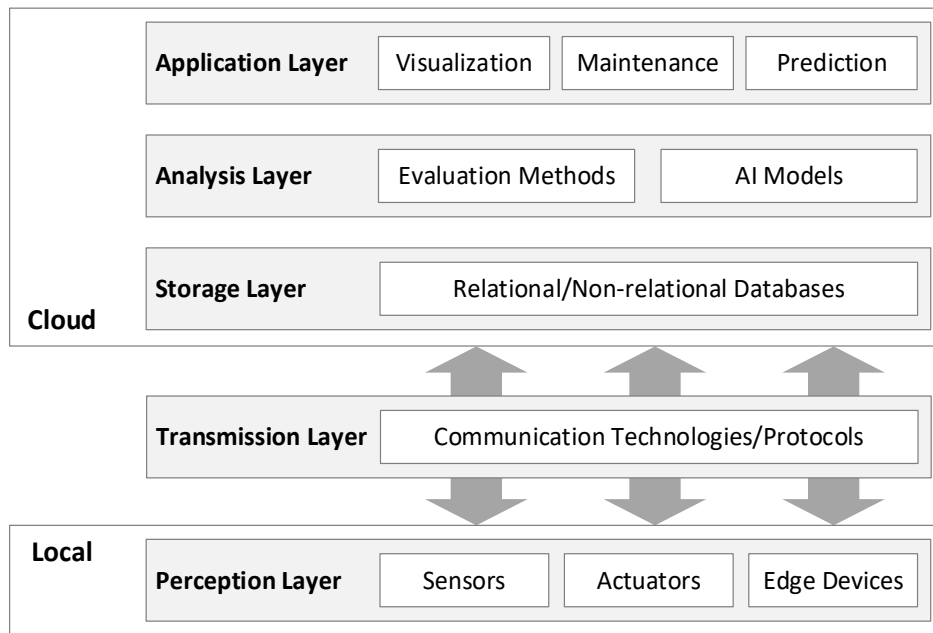


Figure 2. Layered architecture of the cloud-based digitalization framework for historic buildings.

A brief introduction of the techniques integrated into this framework is illustrated in the following subsections.

2.1.1. IoT and cloud computing. Historic buildings require continuous monitoring and maintenance to keep sustainable functionality. IoT techniques enable a long-term goal to collect data. Cloud computing is a method for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services). Cloud computing has advantages in computing, storage resources, and scalability. Nowadays, the maturity of cloud computing has allowed data storage, processing, and visualization to be done remotely in the cloud. In this study, Microsoft Azure is used as the cloud computing platform. Microsoft Azure provides plenty of components and services, which facilitates the implementation of our framework.

2.1.2. Digital twins. The term Digital Twins was proposed by Grieves [12] and has been widely used in manufacturing [13]-[15]. A digital twin can be interpreted as a software representation of a physical object. Based on the real-time information obtained from the physical object, a digital twin allows for rapid analysis and real-time decision-making through accurate analytics [16]. Digital twins can be created and stored in the cloud with specific domain knowledge concerning cultural heritage care and preservation.

Some researchers have applied digital twins to buildings. In paper [17], a digital twin was created for an office building façade to lower maintenance costs while increasing human comfort. Y. Peng et al. [18] proposed a digital twin for a hospital to cope with sophisticated facility systems, special medical equipment, strict security requirements, and business systems. In paper [19], the authors presented a system architecture of digital twins that is specifically designed at both building and city levels, which integrates heterogeneous data sources and supports effective data querying and analysis, and decision-making processes.

2.1.3. AI and AI for historic buildings. AI is to make the behaviour of machines look like intelligent behaviours shown by humans. Early AI applications relied on rules summarized by humans [20]. Researchers used human experience to sum up rules based on logic or facts, and then wrote programs to let the computer complete a task. However, for many human intelligent behaviours, such as language understanding and image identification, it is difficult for humans to know the principles and summarize the rules behind these intelligent behaviours. Therefore, researchers began to shift the focus of research to let the computer learn from the data to solve such problems. This kind of process is known as machine learning. The main purpose of machine learning is to design some learning algorithms, so that the computer can automatically analyse and obtain rules from data. The learned rules, also called models, can be used to make predictions on unknown data and solve specific problems.

AI techniques have been used for preserving historic buildings, such as monitoring structural health [21], identifying superficial damage [22], and moisture analysis of walls [23].

2.2. Data collection

The amount and quality of collected data have a massive impact on model performance. In this part, we define what data to collect and how to collect the data.

The data to be collected mainly include the following categories:

- 1) Indoor environment: temperature, relative humidity, CO₂ concentration, dust concentration, air quality, vibration, noise, and volatile organic compound (VOC).
- 2) Operation status of HVAC systems and lighting.
- 3) Energy consumption metering: such as electricity, hot water, chilled water, and steam.
- 4) Characteristics of a building: total area size, floor count, and floor plan.
- 5) Outdoor weather conditions: temperature, cloud coverage, dew temperature, and precipitation.
- 6) Others: energy prices, activity schedule in the buildings.

The way to collect data includes: 1) Indoor environment: sensors; 2) Operation status of HVAC systems and lighting: query from building management system (BMS); 3) Energy consumption metering: query from BMS; 4) Characteristics of a building: from facility manager; 5) Outdoor weather conditions: from nearest weather station; 6) Others: query from corresponding official website.

Collect frequency needs to be determined for each data collection.

2.3. Data analysis

In this study, we mainly use machine learning algorithms to analyse the data to extract valuable models to achieve various predictions. The main four steps of data analysis are shown in figure 3.

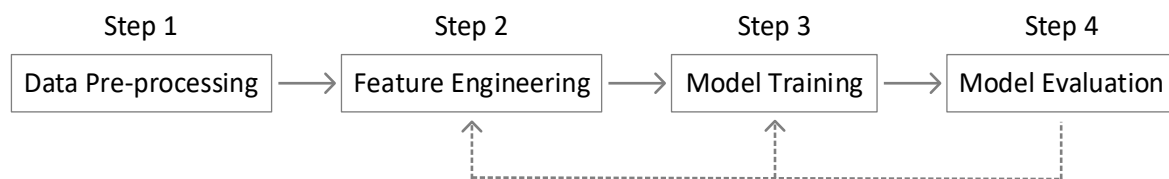


Figure 3. The main four steps in data analysis.

The main tasks in each step are as follows.

- 1) Data pre-processing: After data are collected, we must process data before use. Usually, we need to detect and correct erroneous data, fill for incomplete data, and randomize data to avoid the order of the data to affect the training. We also need to divide the data into two parts: the training set and the validation set. The training set contains most of the data and is used to train the model. The validation set contains the remaining data and is used to evaluate model performance.
- 2) Feature engineering: This step aims to extract useful features from the original data to improve the performance of machine learning algorithms. The extraction of features highly relies on specific domain knowledge. For example, temporal information is an important feature source for predicting the energy consumption of a historic public building because the energy consumption is different on opening hours and non-opening hours.

- 3) Model training: This step is to select and use appropriate machine learning algorithms for training models. We need to select machine learning algorithms to learn from data.
- 4) Model evaluation: Once the training is complete, we need to evaluate the model to determine if it works on data that it has never seen before. If model performance does not meet expectations, we need to go back to the training step to improve it. Sometimes it is necessary to go back to the feature engineering step to redesign the features.

Using the above data analysis process, we can train the corresponding prediction model for the following application scenarios.

- 1) Advanced monitoring and alarm functions to avoid disasters.
- 2) Energy optimization based on the number of shows and audience, indoor environment, and outdoor climate will be developed.

2.4. Framework performance metric

The evaluation for the digitalization framework mainly needs to be carried out from two aspects. One is to evaluate the stability and portability of the framework. The other is to measure the actual effect of each AI model obtained by training, including the prediction performance, whether it is the optimal energy consumption, the amount of labour time saved, and an abnormal alarm calling for emergency action.

3. Modelling and evaluation

To preliminarily test and verify the functionalities of the framework, we created a digital twin of an office room TP6137 at Linköping University based on Azure Digital Twins [24]. Azure Digital Twins is a platform as a service (PaaS) that enables creating knowledge graphs based on digital models. Digital models are defined according to the actual composition of a physical object. For example, to create a digital twin of a building, a series of digital models, such as Building, Floor, and Room, need to be defined. Each digital model can have several fields to reflect objects in the real world. These fields can be grouped into three categories, namely property, telemetry, and component. Properties are data fields that represent the metadata of an entity. Telemetry fields represent measurements or events. Components are used to represent a group of instances of other models.

Figure 4 shows the composition of the created digital twin. The room TP6137 is located on the sixth floor of a building called Tappan, and the relationship “Contains” between models reflects this. Properties of room TP6137 include area and height. Telemetries consist of measurements of environmental conditions, such as temperature and CO₂ concentration. Room TP6137 contains instances of other models, e.g., actuators such as lighting devices and heating equipment.

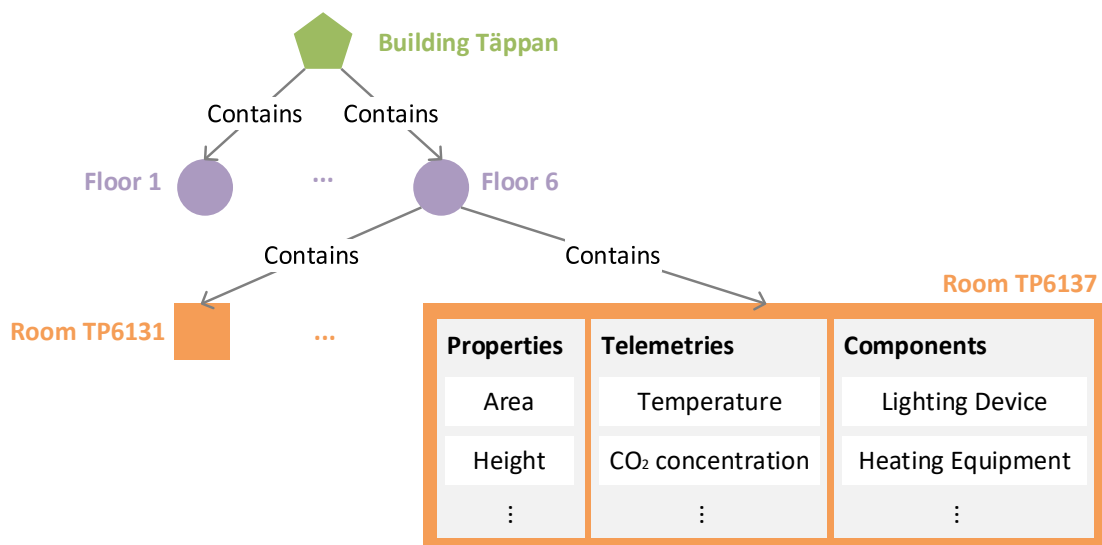


Figure 4. A digital twin of room TP6137 in building Tappan.

A sensor box integrating IoT techniques, as depicted in figure 5, is deployed in room TP6137 to collect indoor environmental conditions. Sensor readings are periodically uploaded to the cloud platform and ingested to telemetry fields of the digital twin. Based on these sensor readings, the digital twin can reflect the status of the room TP6137 in real-time.

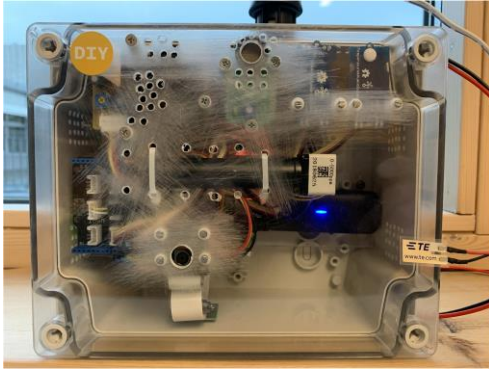


Figure 5. A sensor box is deployed in room TP6137 to collect environmental conditions, such as temperature, humidity, CO₂ concentration, dust concentration, air quality, and vibration.

As an illustrative example of indoor environmental status, figure 6 shows historical data from a dust sensor dated from December 14 to 18, 2020. The dust concentration was high from 9 am to 3 pm, because the scheduled indoor ventilation in the building during that period enhanced the fluidity of indoor air and drove the movement of small particles.

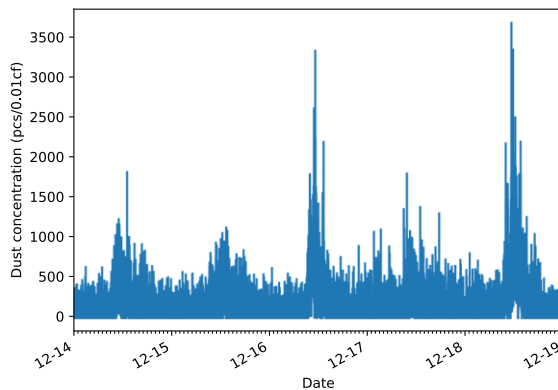


Figure 6. Historical data of a dust sensor from December 14 to 18, 2020. The dust concentration was high from 9 am to 3 pm. The scheduled indoor ventilation in the building during that period enhanced the fluidity of indoor air and drove the movement of small particles, which led to the increase of dust concentration in the room.

4. Future work

Our ultimate research goal is a cloud-based solution with both IoT and AI for maintaining unique characters that define values of historic buildings while saving energy. The project has been running for about one year and will totally last for four years. The methodology, together with the developed sensor box presented in this paper, will be utilized in the chosen historic buildings. Moreover, research questions concerning both energy-saving and historic building conservation, summarized as follows, will be studied.

- 1) Research questions concerning energy efficiency optimization:
 - a. What are the characteristics of the current energy consumption of a historic building?
 - b. What are the main factors that can affect the energy consumption of a historic building, and how to involve these factors in the digital twin of a building?
 - c. How to quantify the energy efficiency of a historic building?
 - d. What methods are currently available to optimize building energy efficiency, and what are their advantages and disadvantages?
- 2) Research questions concerning smart maintenance:
 - a. What are the specific scenarios and objects of smart maintenance?
 - b. What are the requirements for smart maintenance?

- c. What are the optimum conditions to preserve sensitive parts of the buildings?
- d. What technologies can be utilized for smart maintenance, and what are the advantages and disadvantages?
- e. What parameters of a building need to be included in the corresponding digital twin to realize smart maintenance?

5. Conclusion

This study proposes a cloud-based digitalization framework for creating digital twins and developing AI for historic buildings, which is to be deployed to three historic buildings that are chosen for case studies. The research result so far obtained shows that data can be reliably collected, transmitted, and stored in the cloud, while digital twins that reflect the latest status of a building can be created and fed with real-time sensor data.

In the future, after deploying sensor boxes to the selected historic buildings, we will focus more on extracting useful information from collected data. More specific AI models can be trained to provide plenty of applications, such as anomaly detection, occupancy prediction, and autonomous control for historic buildings to reach energy efficiency optimization and building preservation.

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