Digital Twin Development for Cultural Heritage Buildings: A Multimodal Approach to Simulating Energy Performance

Elissavet Batziou*
Information Technologies Institute,
Centre for Research and Technology
Hellas
Thessaloniki, Greece
batziou.el@iti.gr

Nikolaos I. Dourvas*
ndourvas@iti.gr
Information Technologies Institute,
Centre for Research and Technology
Hellas
Thessaloniki, Greece

Konstantinos Ioannidis*
kioannid@iti.gr
Information Technologies Institute,
Centre for Research and Technology
Hellas
Thessaloniki, Greece

Sotiris Diplaris*
diplaris@iti.gr
Information Technologies Institute,
Centre for Research and Technology
Hellas
Thessaloniki, Greece

Stefanos Vrochidis*
stefanos@iti.gr
Information Technologies Institute,
Centre for Research and Technology
Hellas
Thessaloniki, Greece

Ioannis Kompatsiaris*
ikom@iti.gr
Information Technologies Institute,
Centre for Research and Technology
Hellas
Thessaloniki, Greece

Abstract

Cultural heritage buildings represent invaluable historical and architectural assets, but their preservation often conflicts with the need for modern energy efficiency. This paper presents a novel framework for digital twin development that adopts a multimodal approach to provide an open-source environment of a CH building with the goal to simulate and optimize energy performance in heritage structures. By integrating diverse data modalities, such as structural analysis, environmental monitoring, and multimedia documentation, the proposed digital twin provides a comprehensive, dynamic representation of the building's energy behavior. This approach enables more accurate simulations of energy performance, facilitating informed decision-making for sustainable retrofitting while respecting the unique constraints of cultural heritage conservation. The application of this framework in a real case study demonstrates the potential of multimodal digital twins to bridge the gap between preservation and energy efficiency, to increase immersiveness and to highlight their role in advancing sustainable management practices for heritage sites. The findings underscore the transformative potential of digital twin technology in fostering sustainable, data-driven solutions for cultural heritage conservation.

Keywords

Digital Twins, Cultural Heritage, Multimodal, Simulation, Energy Performance, Immersive technologies

How to cite this paper:
Elissavet Batziou, Nikolaos I. Dourvas, Konstantinos Ioannidis, Sotiris Diplaris, Stefanos Vrochidis, and Ioannis Kompatsiaris. 2025. Digital Twin Development for Cultural Heritage Buildings: A Multimodal Approach to Simulating Energy Performance. In *Proceedings of ACM IMX Workshops, June3 - 6, 2025.* SBC, Porto Alegre/RS, Brazil, 11 pages. https://doi.org/10.5753/imxw.2025.9461

1 Introduction

Cultural heritage buildings are invaluable architectural and historical treasures that capture the rich heritage of early societies. They are integral to Europe's identity, representing architectural and historical significance. However, many of these structures lack proper energy monitoring systems, leading to inefficiencies. Notably, approximately 35% of the EU's buildings are over 50 years old, with nearly 75% deemed energy inefficient [1]. This inefficiency often stems from outdated insulation and heating methods compounded by conservation laws that limit modifications and of course lack of efficient monitoring tools providing the capability to test different types of solutions and select the best approach that needs to be finally applied in the specific building. Addressing these challenges, our research aims to develop a digital twin framework that integrates transient thermal modeling with real-time data processing. However, their preservation presents a critical challenge in the context of energy efficiency and sustainability. In contrast to modern constructions, which are designed with advanced insulation materials and optimal HVAC systems, heritage buildings often suffer from significant thermal inefficiencies due to outdated construction methods, high thermal mass, and a lack of climate-adaptive design. Energy optimization is therefore a critical issue because these buildings have high energy consumption, inefficient heating and cooling systems, and significant thermal losses. Energy retrofitting of historic structures is a complex and diverse challenge that requires a balance between preserving historical authenticity and enhancing thermal performance. Traditional retrofitting strategies, including adding insulation layers or modifying ventilation systems,

---

[*] All authors contributed equally to this research.

[1] Source: https://build-up.ec.europa.eu/en/resources-and-tools/articles/overview-energy-efficiency-historic-buildings-state-art

ACM IMX Workshops, June 3 - 6, 2025.

https://doi.org/10.5753/imxw.2025.9461

may alter the original architectural features, potentially violating conservation regulations. To ensure sustainable and non-intrusive retrofitting, a data-driven, simulation-based decision-making approach is essential for evaluating energy performance without changing the fundamental characteristics of the building.

The energy modeling of cultural heritage buildings presents unique challenges that distinguish it from conventional energy efficiency assessments. One of the primary difficulties is the heterogeneous material composition of historic buildings, where multi-layered walls often consist of stone, wood, brick, and mortar, each with different thermal properties. This variability complicates heat transfer calculations, as traditional energy models often assume uniform material behavior. Another challenge is the lack of historical energy consumption data. Many cultural heritage buildings do not have smart meters or sensor-based monitoring, making it difficult to collect real world energy data for validation. Additionally, conservation regulations often restrict modifications to heritage buildings, preventing the installation of modern insulation materials or energy monitoring systems. These factors necessitate the development of alternative modeling approaches that estimate energy demand based on physics-based heat transfer simulations rather than relying on empirical energy data. Furthermore, many heritage buildings are subjected to complex environmental conditions, including varying external climates, urban microclimates, and fluctuating occupancy patterns. These factors introduce dynamic thermal loads that cannot be accurately captured using static energy modeling techniques. To address these challenges, a high-fidelity transient heat transfer approach is required to model real-time temperature evolution and thermal exchanges in heritage structures.

Traditional energy modeling of buildings often relies on persistent hypotheses that do not take into account the time-dependent thermal behavior of materials. In heritage buildings, where walls are thick and highly thermally massive, heat is stored and released gradually, causing delayed thermal responses. This phenomenon, often referred to as thermal lag, significantly affects heating and cooling loads in historic structures. A transient heat transfer model provides a more accurate estimation of energy over time, ensuring a more realistic energy estimation. By integrating a time-dependent numerical formulation, this study models temperature variations dynamically, providing a more accurate prediction of HVAC energy demand.

Digital twin technology has emerged as a powerful tool for simulating, analyzing, and optimizing building energy performance. By integrating multimodal data sources, including Building Information Modeling (BIM)/Industry Foundation Classes (IFC), real-time environmental monitoring, and computational heat transfer simulations, digital twins can provide a dynamic, virtual representation of a building's energy behavior. This approach enables a more accurate, physics-based assessment of heat transfer, energy consumption, and HVAC system performance, aiding in sustainable retrofitting strategies for cultural heritage buildings.

Although previous studies have leveraged EnergyPlus, COMSOL, or OpenFOAM for building energy simulations, these tools often rely on steady-state assumptions or require historical energy consumption data. However, in the case of cultural heritage buildings, historical energy consumption records are often unavailable and conventional energy modeling tools may not be applicable. To address these challenges, this work proposes a multimodal Digital Twin framework specifically designed for the simulation and optimization of energy performance in heritage buildings. The key contributions of this framework are:

- BIM/IFC-Based 3D Spatial Modeling: By extracting geometric and material properties directly from the IFC models, from real test case buildings, the framework ensures a high-fidelity 3D spatial representation of heat transfer. This approach enables an element-wise and room-level thermal analysis, enhancing the accuracy of energy assessments. Additionally, this rich spatial information can support immersive explorations—such as virtual representations by providing robust descriptive metadata that can be used to present building elements and different layers of walls in more engaging experience.
- Visual based validation: Validates spatial classification and element grouping using Unreal Engine visualization, ensuring accuracy in IFC-based room and material categorization. Beyond model verification, these visualization methods also create a foundation for immersive or interactive user experiences—allowing stakeholders to virtually explore the building's thermal and architectural details in a more metadata-rich environment.
- Multi-Layered Material Representation and Dynamic Property Testing: Integrates a multi-layered material modeling approach. By incorporating detailed material layers and enabling the dynamic exchange of material properties, this system allows for in-depth conservation analysis and optimization of restoration strategies. This feature is particularly crucial for heritage buildings, as it enables non-invasive virtual testing of different material combinations, helping to select the most efficient energy-retrofitting solutions while adhering to preservation constraints. This distinguishes our work from existing heritage Digital Twins that rely solely on static material properties and do not provide interactive material simulations within a digital twin environment.
- Computational Heat Transfer Analysis: The framework computes transient heat transfer using a time-dependent numerical approach. This technique enables a realistic simulation of temperature evolution over time, accounting for thermal storage and dissipation effects in historical materials. By providing this thermal analysis, we showcase the capabilities of the digital twin in capturing and modeling the dynamic heat behavior of heritage buildings.
- Dynamic Energy Consumption Estimation: Energy demand is estimated based on heat transfer simulations, eliminating the need for historical energy records. The model dynamically links computed heat losses and gains to HVAC energy requirements, providing an accurate representation of heating and cooling loads. This estimation further demonstrates the digital twin's potential by offering actionable insights on energy performance, supporting more informed and data-driven retrofitting decisions

By integrating these components, the Digital Twin provides a comprehensive, immersive, multimodal simulation based on HVAC operation, linking heat transfer computations with energy demand estimation, and ensuring an accurate, data-driven analysis of cultural heritage building energy performance. Unlike traditional energy modeling tools, which often rely on generalized assumptions, the proposed framework captures dynamic heat flow across multilayered materials in three-dimensional space, ensuring a physics-based and spatially accurate representation of thermal behavior. Additionally, by eliminating the dependency on historical energy data, the methodology provides a scalable approach that can be applied to various historic structures where energy consumption records are non-existent.

This work introduces a system that automates the entire process of energy performance analysis by integrating multiple data sources, including Industry Foundation Classes (IFC) models, real-world weather conditions, and sensor measurements. The system is capable of autonomously extracting relevant building parameters, applying existing computational models, and generating detailed energy consumption insights, enabling a more streamlined and automated solution for energy performance analysis in cultural heritage buildings, overcoming the limitations of existing modeling approaches.

The remainder of the paper is structured as follows. Section 2 provides an overview of the state-of-the-art approaches related to digital twin technology, heat transfer modeling, and building energy performance estimation. Section 3 presents the proposed framework, detailing the integration of multimodal data, transient heat transfer computations, and energy consumption estimation. Section 4 describes the experimental setup, including dataset details, and simulation configurations. Finally, Section 5 summarizes the key findings, highlights the major contributions of this study, and discusses potential future research directions.

2 Related Work

The application of Digital Twin (DT) technology in building energy management has earned significant attention in recent years, leading to advancements in energy efficiency and sustainability. Ni et al., [20] propose a solution that integrates deep learning with DTs to better understand building energy use and identify opportunities for improving energy efficiency. The research involves creating parametric digital twins to ensure data consistency across different building systems and employing deep learning methods for data analytics. A case study conducted in a historic building in Norrkoping, Sweden, demonstrates the effectiveness of this approach in forecasting energy consumption and optimizing energy performance. However, the work does not focus on immersive Digital Twins using Unity or Unreal Engine for visualization or interactive exploration. It also does not incorporate multi-layered material modeling to simulate conservation scenarios or assess the impact of different material properties. While the study integrates environmental monitoring and computational analysis, it does not explore interactive material-switching capabilities in VR environments, limiting its scope in immersive heritage applications. A comprehensive review by Bortolini et al., [7] examines various DT applications aimed at improving building energy efficiency. The study discusses the integration of DTs with building management systems to enable real-time monitoring and control, predictive maintenance, and optimization of energy consumption patterns. The authors highlight the potential of DTs to provide detailed insights into building performance, facilitating informed decision-making for energy optimization Yeom et al., [24] explore the multifaceted impact of DT and Extended Reality (XR) technologies on building energy management. Their study investigates how the integration of DTs with XR can enhance visualization and interaction with building data, leading to improved energy management practices. The authors discuss the potential benefits of this integration, including enhanced user engagement, better understanding of energy consumption patterns and more effective implementation of energy saving strategies. Bekele et al., [6] provide a survey on the use of Augmented, Virtual, and Mixed Reality in cultural heritage, analyzing various projects that employ Unity and Unreal Engine for digital reconstructions and interactive museum experiences. While these works enhance user immersion through real-time rendering and interactive storytelling, they do not integrate multi-layered material modeling or conservation-driven simulations. Similarly, Carrozzino & Bergamasco, [8] explore the role of VR in cultural heritage, presenting case studies of immersive museum installations that utilize real-time graphics for engagement but do not implement parametric material switching or structural analysis. The comprehensive study of Arsecularatne et al., [3] investigates the use of DTs to enhance building energy management and analyze occupant behavior. The research highlights the role of DTs as virtual replicas of physical assets, facilitating real-time monitoring, predictive maintenance, and data-driven decision-making, thereby improving energy performance and occupant comfort. The study also identifies challenges such as interoperability issues, data privacy concerns, and the need for standardized frameworks to guide DT implementations. Kong, [16] presents a photogrammetry-driven Digital Twin for heritage monitoring, leveraging UAV-based scanning and high-resolution 3D reconstructions to track structural changes. However, this work remains focused on damage assessment rather than immersive visualization or real-time material adaptability. Similarly, Lucchi, [17] discusses the application of Digital Twins for heritage construction automation, emphasizing data synchronization and predictive modeling but lacking an interactive visualization component or multi-material experimentation. Additionally, the study of Caspedes et al., [9] focuses on the application of DTs in building operations and maintenance, emphasizing energy efficiency throughout the building lifecycle. The research underscores the potential of DTs to optimize energy usage by providing detailed insights into building performance and facilitating informed decision making. While Digital Twins have been widely explored in energy management and cultural heritage visualization, few studies integrate immersive technologies (Unity/Unreal) with conservation-focused material modeling. Barzaghi et al., [5] propose a FAIR-based approach for managing 3D heritage data but focus primarily on metadata structuring rather than interactive experimentation. Niccolucci & Felicetti, [21] extend Digital Twin ontologies for sensor-based monitoring and decision-making, yet their framework does not account for VR-based material simulations or structural testing. These studies highlight a key research gap: the lack of immersive Digital Twins that allow real-time material property adjustments for heritage conservation.

2.1 Digital Twins for Heat Transfer and Energy Modeling in Buildings

Recent research has explored the use of Digital Twin technology in heat transfer modeling and energy consumption estimation, particularly in buildings with complex material compositions such as cultural heritage structures. The study by Morkunaite et al. [19] proposes an architecture for grey-box modeling of building thermal dynamics by integrating real-time IoT data with 3D representations of buildings. This approach facilitates the creation of predictive and proactive digital twins, enabling informed decision making for optimizing heating energy strategies. The architecture was validated through a case study that developed a digital twin platform, allowing stakeholders to analyze and evaluate building thermal dynamics without extensive expertise or time resources. In the context of heritage buildings, a study by Marra et al. [18] presents a workflow that integrates Heritage Building Information Modeling (HBIM) and Building Performance Simulation (BPS) tools for data-driven analysis. This integration aims to enhance the management and preservation of cultural heritage sites by providing detailed insights into the buildings' thermal behavior and energy performance. The proposed workflow facilitates the creation of digital twins that support informed decision-making for conservation and energy efficiency improvements. While HBIM-based approaches provide valuable structural insights, other works have focused on automating the transition from IFC-based models to energy performance simulations. Andriamamonjy et al. [2] developed an automated IFC-based workflow using Modelica to generate energy performance simulations directly from BIM data, improving simulation accuracy and efficiency. Similarly, Elagiry et al. [13] conducted a systematic review of the most widely adopted tools and approaches for converting IFC models into Building Energy Performance Simulation (BEPS), highlighting key interoperability challenges. These studies emphasize the need for standardized workflows that seamlessly extract geometric and material properties from IFC files, reducing manual preprocessing efforts. However, many existing approaches rely on steady-state modeling techniques or lack transient heat transfer integration, limiting their applicability to heritage buildings with complex thermal behaviors. In contrast to these physics-based methods, El-Gohary et al., [12] introduced an artificial neural network (ANN)-based digital twin, which estimates energy consumption using machine learning techniques. The study utilized data simulations carried out with the Quick Energy Simulation Tool (eQuest) software, considering various factors such as insulation material thickness, conductivity values, and window types. While AI-based approaches can rapidly approximate energy demand, they often require large datasets for model training and do not inherently account for transient thermal behaviors. Our work builds on these findings by proposing a fully automated open-source pipeline from IFC model processing to transient energy performance predictions, ensuring a seamless and physics-based approach tailored to cultural heritage applications.

2.2 Extending Digital Twins for Heritage Building Management

Beyond thermal modeling and energy prediction, Karatzas et al. [15] present a multi-level framework of Digital Twins (DTs) that interact hierarchically to comprehensively understand, assimilate, and seamlessly integrate intricate social dynamics into heritage building management. The framework emphasizes the importance of incorporating social factors to enhance the effectiveness of DT applications in preserving and managing heritage structures. The work of [10] proposes a novel and systematic approach based on Digital Twin technology to improve thermal performance effectively in unregenerated residential heritage buildings. The methodology involves creating a DT that integrates various data sources to simulate and analyze the building's thermal behavior, leading to informed decision-making for preservation efforts. Furthermore, the work of [1] focuses on improving the energy consumption of buildings by creating a Digital Twin that accurately reflects the behavior and characteristics of future or existing structures. The study utilizes Autodesk REVIT to model various disciplines influencing the building's energy performance, aiming to develop a comprehensive DT model tailored for building energy management in the Moroccan context.

2.3 Heat Transfer Modeling and Energy Performance in Heritage Buildings

Accurate heat transfer modeling is essential for understanding the thermal behavior of historic buildings, where multilayered wall structures and heterogeneous material compositions introduce complex conduction and convection mechanisms. Several studies have investigated heat transfer mechanisms in building materials to improve energy modeling accuracy. Egamova and Matyokubov [11] analyze the heat transfer coefficient and thermal resistance of different building materials, highlighting how variations in material properties influence energy efficiency. Their findings support the need for accurate material property integration in Digital Twins, as variations in thermal conductivity, specific heat capacity, and density directly impact heat flow and energy loss predictions. Jankovic and Goia [14] investigate heat transfer mechanisms in double-skin facades (DSFs) using Computational Fluid Dynamics (CFD), providing insights into convective and radiative heat transfer modeling. The study emphasizes how advanced numerical simulations can enhance the precision of energy assessments, reinforcing the importance of transient heat transfer modeling in Digital Twin applications. Babiarz and Szymański [4] propose a finite difference method (FDM) to simulate heat flow across building envelopes under real world climatic conditions. This approach is particularly relevant for heritage buildings, where temperature variations across thick walls require time dependent modeling approaches rather than steady state assumptions. Wu et al. [23] explore the impact of surface heat transfer coefficients on energy load predictions in buildings. Their study demonstrates how hourly variations in heat transfer coefficients influence HVAC energy demand, highlighting the need for dynamic weather data integration in Digital Twins to ensure accurate boundary conditions in simulations. Furthermore, R.G. et al. [22] examine the role of multi-layered meta-material walls, including Phase Change Materials (PCMs), in reducing heat losses. Their study employs Fourier's Law and latent heat storage models to predict thermal inertia effects, providing further justification for integrating transient heat transfer formulations in Digital Twin models.

2.4 Research Gap and Motivation

These studies highlight the significant impact of Digital Twin technology on improving energy efficiency and sustainability in both modern and heritage buildings. They emphasize the necessity of integrating diverse data sources, addressing interoperability and data privacy challenges and developing standardized frameworks to guide effective DT implementations in building energy management. Despite these advancements, a significant research gap remains in the application of Digital Twins for transient heat transfer modeling in heritage buildings. Existing Digital Twin frameworks often rely on steady-state assumptions or empirical energy models that necessitate historical energy consumption data. However, for cultural heritage buildings, such records are frequently incomplete or entirely unavailable. Furthermore, while previous studies have explored heat transfer equations and building performance simulations, few have integrated a comprehensive framework that combines BIM/IFC-based spatial data extraction, transient numerical heat transfer modeling, and real-time sensor integration into a single Digital Twin environment.

3 Methodology

This section describes the proposed multimodal digital twin system framework (Fig. 1) for simulating heat transfer and estimating energy consumption in cultural heritage buildings. The methodology consists of five key stages:

- IFC Data Extraction and Preprocessing
- Element Classification and Spatial Clustering
- Heat Transfer Computation
- Energy Consumption Estimation
- Multimodal Data Integration and Validation

Each stage is designed to ensure a robust and physics-based modeling approach, leveraging 3D spatial representation, thermal physics, and computational methods for accurate energy performance estimation. The proposed framework is designed as an end-to-end system that automates the processing of IFC-based building data, environmental conditions, and sensor inputs to estimate energy demand. Unlike traditional modeling approaches that require extensive manual parameterization, this system extracts geometric, material, and operational data directly from structured data sources. By integrating heat transfer computations within a digital twin environment, the framework enables real-time energy performance assessments without requiring user intervention in the data processing pipeline.

3.1 IFC Data Extraction and Preprocessing

A fundamental aspect of the proposed framework is the accurate representation of the building's geometric and material properties, which is essential for reliable heat transfer and energy consumption simulations. To achieve this, the Building Information Modeling (BIM) data stored in Industry Foundation Classes (IFC) format is extracted and processed using a custom Python pipeline. Unlike conventional approaches that directly utilize predefined IFC attributes, which may be incomplete or generalized, this study implements a more detailed methodology by computing essential thermal and geometric parameters directly from the 3D building model.

One motivation for this refined and custom approach is that many existing visualization or game engines cannot fully provide the distinct layers of wall assemblies from IFC data. For instance, many commercial tools merge layered walls into a single geometry, obscuring the unique material definitions and thicknesses that are vital for accurate thermal analysis. By contrast, the proposed pipeline extracts each layer's properties to maintain a high-fidelity representation of the as-designed building envelope.

The geometric attributes of each building element, such as walls, floors, and roofs, are computed to ensure a precise digital representation. Specifically, the surface area (A) of each element is derived based on its IFC geometry while the element thickness (d) is retrieved from layer definitions within the IFC material properties. Using these extracted parameters, the volume (V) of each structural component is computed allowing for a detailed volumetric characterization of all thermal zones within the building.

Beyond the geometric aspects, the thermal properties of materials play a crucial role in determining heat transfer behavior. To this end, key material characteristics, including density (ρ), specific heat capacity (c_p), and thermal conductivity (k), are retrieved from the IFC metadata. These values are essential for modeling the thermal interactions between structural elements and their surrounding environment, enabling a physics-based simulation of heat transfer processes.

To facilitate structured data organization and seamless integration with the subsequent heat transfer and energy consumption models, all extracted parameters are stored in a hierarchical JSON format. This structured representation maintains the relationships between individual building components, their respective spatial groups, and associated thermal properties, ensuring consistency and interoperability throughout the simulation pipeline. By adopting this approach, the digital twin framework can effectively model the thermophysical characteristics of the building, laying the groundwork for accurate energy performance estimation. The simulation results depend on the quality of the available IFC data. While this tool can work with basic geometric and material properties, more detailed IFC files, especially those that specify multiple wall layers and thermal properties, lead to more accurate energy performance estimations.

3.2 Element Classification and Spatial Clustering

Accurately categorizing building components into distinct rooms is a critical step in the development of the digital twin framework, as it ensures a meaningful spatial organization for heat transfer and energy consumption simulations. Instead of relying solely on the predefined spatial hierarchy provided by the IFC schema, which may be incomplete or inconsistent, a clustering-based approach is employed to group building elements according to their geometric and spatial relationships. This method enhances classification accuracy by utilizing spatial proximity and adjacency rules, allowing for a more flexible and data-driven segmentation of building elements.

The classification process begins with the extraction of element centroids, where the geometric center points of all structural components including walls and floors are computed directly from their IFC representations. These centroid positions serve as spatial

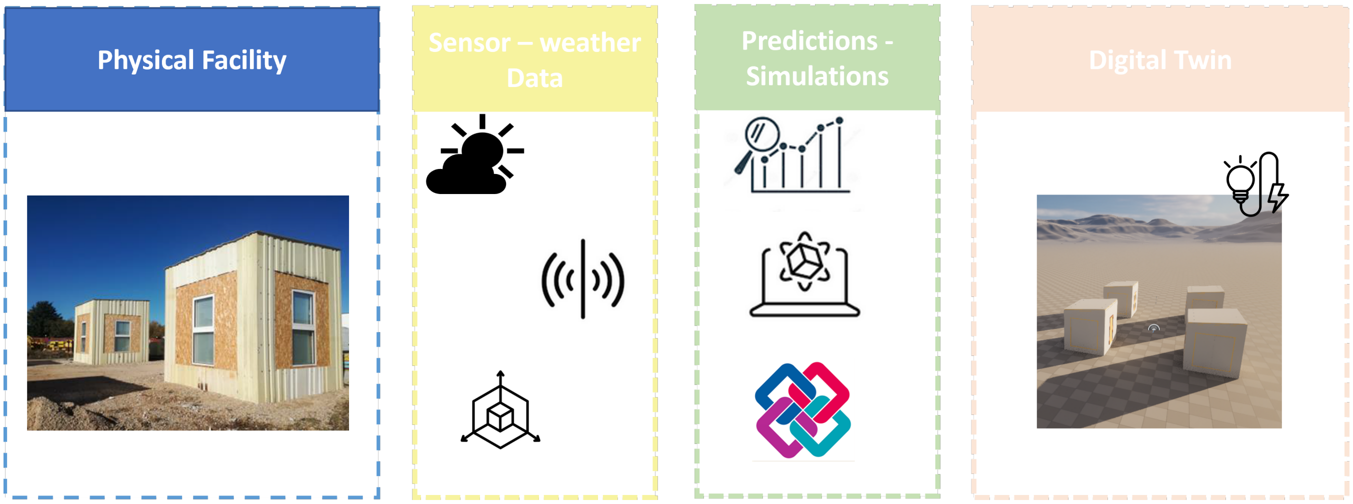

Figure 1: System framework

anchors for the subsequent clustering process. A distance-based clustering algorithm is then applied to group elements that fall within a predefined proximity threshold, ensuring that components belonging to the same room are correctly classified together. This method allows for adaptive room segmentation, particularly in cases where IFC-defined spatial boundaries are missing or ambiguous.

To further refine the classification, an adjacency validation step is implemented, ensuring that no structural element is incorrectly assigned to multiple rooms. This step is crucial for maintaining consistency in thermal zone definitions, as heat transfer calculations rely on accurately segmented spaces. Any inconsistencies in the classification are flagged for correction, enhancing the overall reliability of the spatial model.

As a final verification step, the classified spatial groupings are rendered and visually examined within Unreal Engine, providing an interactive 3D validation of the room segmentation. This visualization allows for manual inspection of the computed clusters, ensuring that elements are logically grouped and properly assigned to their respective rooms. The integration of computational clustering with visual verification strengthens the robustness of the digital twin framework by combining automated classification with human oversight.

The entire process is implemented using Python, leveraging SciPy's clustering algorithms for automated room segmentation, and Unreal Engine for spatial validation. This approach ensures a precise, hierarchical organization of building elements, forming a solid foundation for subsequent heat transfer analysis.

3.3 Heat Transfer Computation

Once the building elements are classified into rooms, a time-dependent heat transfer model is applied. The framework initially used steady-state Fourier's Law but was later enhanced to a transient heat conduction model to capture thermal inertia effects. Initially, heat transfer was computed independently per timestamp using Fourier's Law:

$$Q = -kA\frac{dT}{dx} \tag{1}$$

Where Q is the Heat transfer rate, k is thermal conductivity, A is the Surface Area and $\frac{dT}{dx}$ is the Temperature gradient across the material thickness.

3.4 Transient Heat Transfer Model

In order to enhance the accuracy of the thermal simulation and better capture the dynamic thermal behavior of multilayered building materials, the heat transfer model was extended from a steady-state formulation to a time-dependent transient heat conduction model. The transient model captures the gradual accumulation and dissipation of heat, allowing for the simulation of temperature changes over time as heat transfers through the building's structural elements.

The governing equation for the transient heat transfer process is formulated as:

$$T_{new} = T_{old} + \frac{Q}{\rho c_p V} \times \Delta t - \lambda(T_{old} - T_{ambient}) \times \Delta t \tag{2}$$

where T_{new} and T_{old} represent the updated and previous temperatures of the material element, respectively. The heat transfer rate Q is derived from Fourier's equation (Equation 1), characterizing the conductive heat exchange across the element. The term λ represents the heat loss coefficient due to convective heat exchange with the surrounding environment and is computed as:

$$\lambda = \frac{hA}{\rho c_p V} \tag{3}$$

Here, h denotes the convective heat transfer coefficient, which varies depending on material properties, airflow conditions, and element type, and is assigned based on standard reference values. The parameter A represents the surface area exposed to convective heat exchange, while ρ, c_p, V correspond to the density, specific heat capacity, and volume of the material, respectively. The term

Δt represents the discrete time step used for numerical integration of the thermal response over time.

This time-dependent formulation allows for the simulation of gradual heat storage and release, ensuring that the delayed thermal response is accurately represented. By incorporating transient heat conduction principles, the proposed model allows for a more realistic estimation of energy consumption, as it reflects temperature variations over time instead of assuming an instantaneous response to external conditions. This improvement enhances the fidelity of the digital twin framework, making it more suitable for analyzing real-world thermal behavior in historic structures.

3.5 Energy Consumption Estimation

The estimation of energy consumption is a fundamental aspect of the digital twin framework, providing insights into the thermal efficiency and energy demand of the building. Rather than relying on historical energy consumption records, which may be unavailable or inconsistent in cultural heritage buildings, this approach directly computes energy demand based on simulated heat transfer dynamics. By leveraging the computed heat exchange within the building's multilayered materials and its interaction with environmental conditions, the framework ensures a data-driven, physics-based estimation of energy usage.

To quantify energy consumption, the heat transfer results obtained from the transient thermal simulations are used to compute the energy demand at multiple hierarchical levels, from individual elements to room-level aggregations. The energy required for heating or cooling is calculated using the following formulation:

$$E = \frac{Q \times \Delta t}{1000} \tag{4}$$

where E represents the energy consumption in kilowatt-hours (kWh), Q denotes the computed heat transfer rate, and Δt corresponds to the time interval over which the energy is accumulated. This formulation enables a dynamic estimation of energy consumption, adapting to variations in external climatic conditions and internal building thermal properties.

To provide a structured representation of energy usage, the estimated energy values are systematically aggregated from individual elements to spatial groups and ultimately to room-level consumption. This hierarchical organization is stored within a structured JSON output, ensuring that the energy distribution across different building components can be effectively analyzed and visualized. Such an approach allows for comparative analysis between different room types, material compositions, and heating/cooling demands, facilitating targeted retrofitting strategies.

A crucial aspect of energy consumption analysis in buildings is the evaluation of heating and cooling requirements, which are directly influenced by internal comfort conditions and thermal losses to the environment. To integrate these aspects, a simplified HVAC operational model is employed, where energy demand is adjusted based on deviations between actual room temperatures and predefined setpoints. The energy required to maintain a comfortable indoor environment is computed using the following conditional formulation:

$$E_{\text{HVAC}} = \begin{cases} \frac{Q}{\text{COP}}, & \text{if } T_{\text{room}} > T_{\text{setpoint}} \\ \frac{Q}{\text{COP}}, & \text{if } T_{\text{room}} < T_{\text{setpoint}} \\ 0, & \text{otherwise} \end{cases}$$

where *COP* (Coefficient of Performance) is assumed based on standard HVAC efficiency values, reflecting the real-world performance of heating and cooling systems. This formulation ensures that energy demand is estimated in a way that is both physics-based and applicable to real-world HVAC operations, allowing for more realistic energy performance assessments.

By integrating heat transfer modeling, room-level energy aggregation, and HVAC demand estimation, the proposed methodology provides a robust and scalable framework for energy consumption analysis in heritage buildings. This approach is particularly beneficial for assessing potential energy savings through material retrofitting, HVAC optimization, and climate-adaptive strategies, thus supporting informed decision-making in sustainable building management.

3.6 Experimental Test Site: Demopark Facility

To validate the proposed Digital Twin framework under real-world environmental conditions, the Demopark test site, located in Algete (Madrid, Spain) (Fig.2), serves as a controlled experimental facility. Managed by ACCIONA, the Demopark site has been used in previous EU-funded research projects to evaluate innovative and sustainable construction materials.

The facility consists of four experimental test cells, specifically designed to assess the thermal performance and energy efficiency of different refurbishment solutions under real climate conditions. To ensure controlled experiments, the north façade of each test cell is fully isolated, preventing thermal interference from external structures. Each test cell integrates advanced energy-efficient technologies, including thermal mortars for enhanced insulation, radiative cooling coatings for passive temperature regulation, Building-Integrated Photovoltaics (BIPVs) for renewable energy generation, and Digital Twin (DT) monitoring systems for real-time performance evaluation.

By leveraging environmental data from Demopark, the proposed Digital Twin framework is tested against real-world heat transfer dynamics and energy consumption patterns. This setting allows for comparative analysis between conventional, non-refurbished buildings and modern sustainable materials, evaluating their impact on thermal performance and energy efficiency. Furthermore, experimental data from Demopark provides valuable insights for calibrating and refining the Digital Twin simulation model, ensuring that numerical predictions align with observed thermal behavior. The integration of BIM/IFC data from the Demopark test site further strengthens the connection between geometry-based thermal modeling and energy performance assessment in heritage-inspired building prototypes. Ground-truth energy consumption data were not used because no such measurements were currently available for the Demopark test setup. Instead, simulated HVAC and PV datasets were used to ensure consistent and controlled evaluation of the different heat transfer models across all rooms.

3.7 Multimodal Data Integration and Validation

The final stage of the methodology involves the integration of multiple data modalities to construct a fully functional digital twin capable of accurately representing heat transfer and energy consumption dynamics within the building. This integration ensures that various sources of information are harmonized, allowing for a comprehensive analysis of thermal performance.

The geometric and material characteristics of the building are extracted from BIM/IFC data, providing essential information such as coordinates, materials, thermal properties for each structural element. These parameters serve as the foundation for the heat transfer computations, which are implemented using Python-based numerical simulations to model temperature evolution across the different building components.

Environmental conditions play a crucial role in thermal modeling, and real-world weather data is incorporated to define the boundary conditions influencing heat exchange processes. This dataset includes factors such as external temperature, solar radiation, and wind speed, all of which impact the thermal behavior of the building envelope. In addition, sensor and HVAC data, generated through a controlled pseudo-data approach, are used to simulate room-level thermal responses and operational HVAC dynamics. This enables the estimation of heating and cooling loads based on computed heat transfer values, bridging the gap between thermal modeling and energy consumption estimation.

To ensure the accuracy of spatial classifications within the digital twin, the extracted IFC-based room segmentation is validated through 3D visualization in Unreal Engine. This step provides a means of visually inspecting the classification of elements, ensuring that building components are correctly grouped within their respective rooms. By incorporating multimodal validation through geometric analysis, computational simulations, environmental data integration, and interactive visualization, the framework guarantees a robust and reliable digital twin capable of supporting accurate energy performance assessments.

This paper presents a comprehensive end-to-end system that transforms Industry Foundation Classes (IFC)-based building models into detailed energy consumption predictions. The proposed workflow automates the entire process, from extracting geometric and material properties from IFC data to performing transient heat transfer simulations and computing room-level energy consumption estimates. By integrating physics-based modeling with multimodal data processing, the system eliminates the need for manual parameterization, ensuring a seamless pipeline from raw spatial data to actionable energy insights. This approach enables scalable and automated energy analysis for heritage buildings, bridging the gap between digital twin modeling and real-world implementation.

4 Experiments

The experimental analysis focuses on evaluating the capability of the system to process IFC, weather, and sensor data automatically. The objective is to demonstrate the ability of the system to autonomously extract data, apply established models, and generate energy performance outputs with minimal manual configuration.

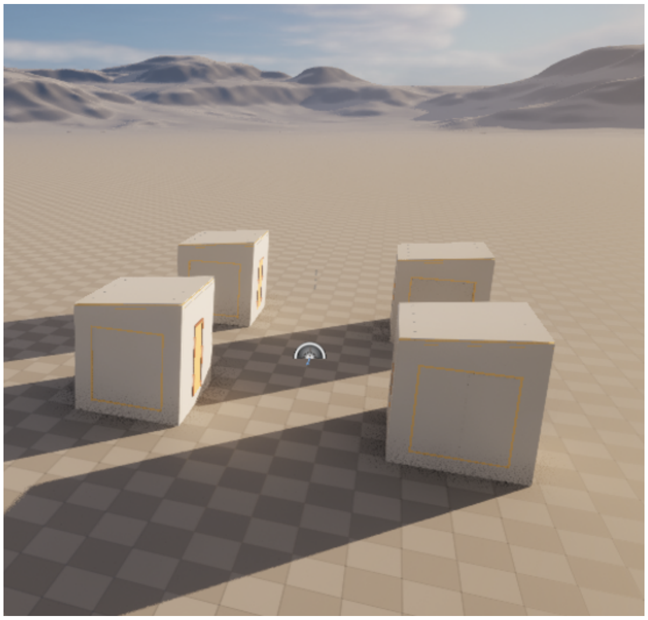

Figure 2: 3D Visualization of the Experimental Test Rooms

4.1 Datasets

The IFC-based building information dataset serves as the structural foundation for energy modeling. The IFC model provides detailed geometric and material properties of each building component, including wall thickness, thermal conductivity, density, and heat capacity. These properties are automatically extracted from the IFC schema, allowing the system to create a spatially resolved energy consumption model without manual parameterization. The IFC dataset also enables room classification and zoning, ensuring that heat transfer calculations are performed with accurate spatial resolution.

To simulate real-world climatic conditions, historical weather data from 1980 to 2020 is utilized as a primary source. This dataset, obtained from real weather station records, provides long-term trends and seasonal variations. For future predictions covering the period 2024 to 2025, a machine learning approach is employed, specifically using Random Forest regression. This model leverages past meteorological trends to generate high-resolution, location-specific climate forecasts, ensuring that the simulation accounts for expected temperature fluctuations, solar radiation levels, and humidity variations that influence building thermal performance.

Sensor data is collected from physical environmental monitoring systems deployed within the study's test environment. These sensors record real-time indoor parameters including temperature and humidity.

In this study, a synthetic dataset was generated to simulate energy consumption and photovoltaic production within the digital twin framework. The synthetic data generation process was designed to replicate realistic variations in system behavior while maintaining full control over parameter distributions. The methodology integrates randomized variability, Gaussian probability distributions, and rule-based logic to approximate real-world HVAC operation and PV energy production trends. The HVAC dataset was generated by assigning a system state to each timestamp, categorized as "OFF," "ACTIVE," "STANDBY," or "INACTIVE." It is important to note that the energy values in Table 1 are based on simulated HVAC consumption, while the input conditions (such as weather and sensor data) are derived from real-world sources. This setup allows for a controlled comparison between the Fourier and transient models under realistic yet consistent environmental conditions. No real HVAC energy metering was used in this specific analysis, as the test site could not provide at the moment such measurements. When the HVAC system was in an active state, its energy consumption was drawn from a uniform distribution within the range of 2.0–10.0 kWh, representing variations in heating and cooling loads under real-world operating conditions. In standby or off modes, energy usage was significantly lower, fluctuating between 0.5–3.0 kWh, reflecting background power consumption in idle states. The system type was randomly assigned as either HVAC or photovoltaics, ensuring a balanced distribution within the dataset. The stochastic assignment of HVAC status ensured that the dataset captured realistic fluctuations in system operation, resembling real-world heating and cooling cycles. The PV energy production dataset was generated using a Gaussian probability distribution to model natural solar radiation cycles. The peak energy generation was centered at midday (12:00 PM), following a normal distribution with a standard deviation of three hours. This approach ensured that solar power output was highest around midday while gradually decreasing in the morning and afternoon, reaching zero production at night. The daylight factor, computed using a probability density function (PDF), was used to scale PV energy production between 0 and 15 kWh, with additional randomized variations introduced to account for natural fluctuations in solar energy availability. The PV status was determined based on the daylight factor, where the system was classified as "ACTIVE" when daylight exceeded a threshold of 0.1 and "INACTIVE" otherwise. The heating and cooling coefficients of performance (COP), representing HVAC efficiency, were randomly assigned values within the range of 2 to 5 to account for real-world variations in system performance across different operational scenarios. The thermostat-controlled setpoint temperature was also modeled synthetically, with values randomly distributed between 20°C and 24°C to reflect common indoor climate control settings. This ensures that the dataset maintains a realistic representation of temperature regulation and energy consumption in response to dynamic environmental conditions.

4.2 Thermal Performance Analysis of Building Materials

The four rooms analyzed in this study feature different material compositions, affecting their thermal performance. Below is a breakdown of the construction materials used in each room:

- **Room 1:** Galvanized Steel, XPS Insulation, YTONG Block, Interior Wood, PCM, SelfHealing, Natural Fibers
- **Room 2:** Galvanized Steel, XPS Insulation, YTONG Block, Interior Wood, PCM, SelfHealing, Natural Fibers
- **Room 3:** Galvanized Steel, XPS Insulation, YTONG Block, Interior Wood
- **Room 4:** Galvanized Steel, XPS Insulation, YTONG Block, Interior Wood, PCM, SelfHealing, Natural Fibers

Table 1: Comparison of Average and Total Energy Consumption Between Fourier-Based and Transient Heat Transfer Models

Room	Fourier Avg. Energy (kWh)	Transient Avg. Energy (kWh)	Fourier Total Energy (kWh)	Transient Total Energy (kWh)
1	2.94	2.81	3389.36	229.65
2	3.53	2.82	4058.83	3250.29
3	2.47	2.84	2846.70	3267.52
4	2.94	2.77	3380.26	3188.63

Room 3 has the simplest construction, consisting only of Galvanized Steel, XPS Insulation, YTONG Block, and Interior Wood. This suggests a lower thermal mass and reduced heat storage capacity compared to the other rooms. Rooms 1, 2, and 4 include additional materials that enhance thermal regulation and insulation properties. The presence of PCM (Phase Change Material) in these rooms is expected to improve thermal buffering by absorbing and releasing heat during phase transitions, reducing temperature fluctuations. SelfHealing Material found in Rooms 1, 2, and 4, this material could enhance structural durability and thermal stability over time, potentially reducing heat losses due to material degradation. Natural Fibers which is included in Rooms 1, 2, and 4, offer additional insulation, reducing conductive heat transfer and improving energy efficiency. These material variations are expected to influence the thermal performance and energy consumption of each room.

As it is presented in Table 1 the Fourier based model consistently predicts higher energy consumption compared to the transient model, except for Room 3. The differences between the models range from +4.76% to +24.47% for most rooms, suggesting that steady state assumptions overestimate heat loss in materials with high thermal mass and phase change effects. The total energy consumption follows the same trend, with Fourier's model predicting up to 24.47% higher total consumption, except in Room 3, where it predicts lower energy usage (13.91%) compared to the transient model.

Rooms 1,2 and 4 contain Phase Change Material (PCM), SelfHealing materials, and Natural Fibers, which enhance thermal storage and insulation. The Fourier model does not account for transient thermal storage effects, leading to an overestimation of energy demand. Room 2 exhibits the highest discrepancy (+24.23% in average consumption and +24.47% in total energy use in Fourier's model). This is likely due to higher thermal mass or increased PCM effectiveness, which is better captured by the transient model. The transient model considers the delayed heat release from PCM, leading to reduced immediate energy demand. Room 3 is the only case where the transient model predicts higher energy consumption than the Fourier model (14.17% Avg, 13.91% Total). Since Room 3 lacks PCM, SelfHealing materials, and Natural Fibers, it has lower thermal mass and less heat retention. In the transient model, rapid temperature changes increase energy load, leading to higher predicted energy use. The Fourier model, assuming steady state conditions, underestimates total energy losses, which explains why it predicts lower energy consumption for Room 3.

These observations lead to the conclusion that PCM and other thermal storage materials significantly impact energy demand, leading to lower energy consumption in transient models. Moreover, steady state Fourier models tend to overestimate heat loss in well insulated rooms, as they ignore the thermal delay effects of high mass and PCM materials. Finally, poorly insulated rooms (such as Room 3) experience larger energy fluctuations in transient simulations, resulting in higher predicted energy consumption compared to steady state estimations. These findings highlight the importance of selecting appropriate heat transfer models when estimating energy consumption. Transient models offer a more accurate representation of real world thermal dynamics, especially in buildings that incorporate high mass materials and phase change technologies.

5 Conclusion and Future Work

This study presented a Digital Twin framework for simulating heat transfer and estimating energy consumption in cultural heritage buildings. The proposed methodology integrates Building Information Modeling (BIM)/Industry Foundation Classes (IFC) data, real-world weather conditions, and computational heat transfer models to provide a physics-based representation of thermal interactions within a building. By utilizing a transient heat transfer approach, the framework captures the gradual storage and release of heat within multilayered structures, leading to a more precise estimation of energy demand. The simulation results highlight the potential of Digital Twins to provide detailed insights into the thermal behavior of historic buildings, offering a valuable tool for optimizing energy efficiency while preserving structural integrity.

A key contribution of this study is the ability to estimate energy consumption without relying on historical energy records, instead deriving energy demand directly from simulated thermal behavior. This approach is particularly relevant for heritage buildings, where energy data may be scarce or unavailable due to the absence of modern monitoring systems. Additionally, the multimodal integration of spatial data, heat transfer modeling, and environmental conditions ensures a holistic understanding of building energy performance, bridging the gap between computational simulations and real world building operations. Future work should focus on integrating real time sensor data to enhance model accuracy and ensure greater alignment with actual building conditions.

Overall, this study underscores the potential of Digital Twin technology in transforming the energy management of cultural heritage buildings. By integrating physics based heat transfer models with multimodal data sources, the framework provides a robust and scalable solution for sustainable energy optimization , facilitating informed decision-making in heritage conservation and building management. Although this work is framed within the context of cultural heritage buildings, the methodology is equally applicable to any building typology facing similar modeling constraints—such as undocumented material layering, time-varying usage, or preservation restrictions—as commonly seen in many public-sector or institutional structures. Future enhancements of this framework may include the integration of immersive XR-based interfaces that allow stakeholders to explore energy performance metrics directly within the 3D environment, for example by overlaying HVAC loads or material-level thermal maps in real-time. In addition, since this tool is being developed as part of a broader and more integrated system, future work will also consider how the extracted energy performance information can be presented and explored through XR interfaces in later stages of the project, further supporting informed decision-making and engagement.

6 Acknowledgments

This research was funded by the European Union under the Grant Agreement No 101123293 (The second life of modern period architecture: Resilient and adaptive renovation towards net-zero carbon heritage buildings-H2020 SINCERE). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

References

[1] Abdelali Agouzoul, Mohamed Tabaa, Badr Chegari, Emmanuel Simeu, Abbas Dandache, and Karim Alami. 2021. Towards a digital twin model for building energy management: case of Morocco. *Procedia Computer Science* 184 (2021), 404–410.

[2] Ando Andriamamonjy, Dirk Saelens, and Ralf Klein. 2018. An automated IFC-based workflow for building energy performance simulation with Modelica. *Automation in Construction* 91 (2018), 166–181.

[3] Buddhika Arsecularatne, Navodana Rodrigo, and Ruidong Chang. 2024. Digital Twins for Reducing Energy Consumption in Buildings: A Review. *Sustainability* 16, 21 (2024), 9275.

[4] Bożena Babiarz and Władysław Szymański. 2020. Introduction to the dynamics of heat transfer in buildings. *Energies* 13, 23 (2020), 6469.

[5] Sebastian Barzaghi, Alice Bordignon, Bianca Gualandi, Ivan Heibi, Arcangelo Massari, Arianna Moretti, Silvio Peroni, and Giulia Renda. 2024. A Proposal for a FAIR Management of 3D Data in Cultural Heritage: The Aldrovandi Digital Twin Case. *arXiv preprint arXiv:2407.02018* (2024).

[6] Mafkereseb Kassahun Bekele, Roberto Pierdicca, Emanuele Frontoni, Eva Savina Malinverni, and James Gain. 2018. A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH)* 11, 2 (2018), 1–36.

[7] Rafaela Bortolini, Raul Rodrigues, Hamidreza Alavi, Luisa Felix Dalla Vecchia, and Núria Forcada. 2022. Digital twins' applications for building energy efficiency: A review. *Energies* 15, 19 (2022), 7002.

[8] Marcello Carrozzino and Massimo Bergamasco. 2010. Beyond virtual museums: Experiencing immersive virtual reality in real museums. *Journal of cultural heritage* 11, 4 (2010), 452–458.

[9] Andres Sebastian Cespedes-Cubides and Muhyiddine Jradi. 2024. A review of building digital twins to improve energy efficiency in the building operational stage. *Energy Informatics* 7, 1 (2024), 11.

[10] Jack CP Cheng, Jiaying Zhang, Helen HL Kwok, and Jimmy CK Tong. 2024. Thermal performance improvement for residential heritage building preservation based on digital twins. *Journal of Building Engineering* 82 (2024), 108283.

[11] Marguba Egamova and Bobur Matyokubov. 2023. Improving the energy efficiency of the external walls of residential buildings being built on the basis of a new model project. 3, 3 (2023), 150–155.

[12] Mohamed El-Gohary, Riad El-Abed, and Osama Omar. 2023. Prediction of an Efficient Energy-Consumption Model for Existing Residential Buildings in Lebanon Using an Artificial Neural Network as a Digital Twin in the Era of Climate Change. *Buildings* 13, 12 (2023), 3074.

[13] M Elagiry, N Charbel, P Bourreau, E Di Angelis, and A Costa. 2020. IFC to Building Energy Performance Simulation: A systematic review of the main adopted tools and approaches. In *BauSim Conference 2020*, Vol. 8. IBPSA-Germany and Austria, 527–534.

[14] Aleksandar Jankovic and Francesco Goia. 2021. Impact of double skin facade constructional features on heat transfer and fluid dynamic behaviour. *Building and Environment* 196 (2021), 107796.

[15] Stylianos Karatzas, Vasiliki Lazari, Kalliopi Fouseki, Valeria Natalia Pracchi, and Evagelos Balaskas. 2024. Digital twins-enabled heritage buildings management through social dynamics. *Journal of Cultural Heritage Management and Sustainable Development* (2024).

[16] Xiangxiong Kong. 2024. Monitoring Time-Varying Changes of Historic Structures Through Photogrammetry-Driven Digital Twinning. *arXiv preprint arXiv:2407.18925* (2024).

[17] Elena Lucchi. 2023. Digital twins for the automation of the heritage construction sector. *Automation in Construction* 156 (2023), 105073.

[18] Angelo Massafra, Giorgia Predari, Riccardo Gulli, et al. 2022. Towards digital twin driven cultural heritage management: A Hbim-based workflow for energy improvement of Modern buildings. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 46 (2022), 149–157.

[19] Lina Morkunaite, Justas Kardoka, Darius Pupeikis, Paris Fokaides, and Vangelis Angelakis. 2023. Digital Twin for Grey Box modeling of Multistory residential building thermal dynamics. In *2023 IEEE 9th World Forum on Internet of Things (WF-IoT)*. IEEE, 1–6.

[20] Zhongjun Ni, Chi Zhang, Magnus Karlsson, and Shaofang Gong. 2023. Leveraging deep learning and digital twins to improve energy performance of buildings. In *2023 IEEE 3rd International Conference on Industrial Electronics for Sustainable Energy Systems (IESES)*. IEEE, 1–6.

[21] Franco Niccolucci and Achille Felicetti. 2024. Digital Twin sensors in cultural heritage applications. *arXiv preprint arXiv:2407.07750* (2024).

[22] Greesan R, Mekala C, and Rajesh B. 2024. Numerical study and experimental validation of heat transfer in a CenoPCM reinforced multi-layered meta-material wall for energy efficient buildings. *Building Services Engineering Research and Technology* 45 (08 2024). doi:10.1177/01436244241277163

[23] Yanwen Wu, Wenna Jian, Liu Yang, Tengyue Zhang, and Yan Liu. 2021. Effects of Different Surface Heat Transfer Coefficients on Predicted Heating and Cooling Loads towards Sustainable Building Design. *Buildings* 11, 12 (2021), 609.

[24] Seungkeun Yeom, Juui Kim, Hyuna Kang, Seunghoon Jung, and Taehoon Hong. 2024. Digital twin (DT) and extended reality (XR) for building energy management. *Energy and Buildings* (2024), 114746.