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Digital twins-enabled heritage buildings management through social dynamics

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Abstract

Purpose – Heritage building management serves as a potent catalyst for sustainability, yet it poses a distinctive set of challenges. Achieving a harmonious balance between conserving the building's historical and cultural value and ensuring modern functionality and safety remains a primary concern. The present work proposes a socio-technical approach to the development and use of a digital twin (DT) that will integrate social data related to the use of heritage buildings with building and environmental data.

Design/methodology/approach – The paper presents a logical and systematic joined-up management framework to the targeted heritage buildings, according to a "Whole Building" approach. Our approach is informed by the underpinning assumption that a heritage building and even more a heritage neighborhood is a socio-technical, complex and dynamic system, the change of which depends on the dynamic interconnections of materials, competences, resources, values, space/environment, senses and time.

Findings – A heritage dynamics approach is adopted to unfold the dynamic nature of heritage and to better inform decisions that can be made in the present and future, achieving people-centered and place-based heritage management. This proposition underlines the heritage transformation as a complex systemic process that consists of nonlinear interconnections of multiple heterogeneous factors (values, senses, attitudes, spaces and resources).

Originality/value – This paper presents a multi-level framework of DTs that interact hierarchically to comprehensively understand, assimilate and seamlessly integrate intricate contexts, even when faced with conflicting conditions from diverse cultural heritage entities. This paper outlines the importance of the iterative system dynamics (SD) approach, which enables adaptive management and ensures the resilience of cultural heritage over time.

Keywords Heritage buildings, Digital twins, System dynamics, Whole building approach, Sustainability
Paper type Conceptual paper

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Introduction

Background

In recent years, European policies have increasingly pushed for strategies to reduce carbon emissions and energy consumption in the building sector (Energy Performance Certification (EPC)-1990s, Energy Policy Strategy (H2020)-2007, Paris Agreement-2015). Refurbishment and adaptive reuse of existing buildings are sustainable and can help in achieving such environmental goals, considering that 85–90% of today's buildings are expected to still be in use in 2050 (Fufa *et al.*, 2021). Given the fact that about 35% of the European Union (EU) building stock is over 50 years old (OVERVIEW | Energy Efficiency in Historic Buildings: A State of the Art | BUILD UP, 2019), such strategies must take into account buildings considered "traditional" or "historical." Although this is a term that usually refers to traditional buildings built before 1945, it is important to emphasize that heritage in the context of this work is understood in a broader sense, encompassing both protected heritage buildings of a later construction date as well as unlisted buildings, part of the historical urban fabric of city centers, which – although not protected by law – are places of cultural significance and therefore worthy of preservation.

These buildings are recognized as valuable assets due to their association with the past and their contribution to the collective memory of a community or society. The standard acknowledges that historic buildings have specific conservation requirements and challenges, particularly when it comes to enhancing their energy performance to meet modern energy efficiency standards. Therefore, the definition emphasizes the need for guidelines that consider both the preservation of the building's cultural significance and the implementation of energy efficiency measures in a manner that respects and maintains its historical integrity. The goal is to ensure that energy performance improvements are carried out in a way that safeguards the heritage value of the building while also promoting sustainability and reducing environmental impact.

New approaches that consider existing heritage in a holistic manner are thus required, fully acknowledging "the role of culture as a system of values and a resource and framework to build truly sustainable development". In fact, when working on the conservation, restoration and reuse of historic buildings, all four sustainability aspects (environmental, social, economic and cultural) should be taken into account and an appropriate balance sought between them, "understanding that they are complementary and mutually dependent, rather than isolated aspects" (Standards, 2017).

Despite the general awareness of the benefits of such approaches and their extensive theoretical study (Historic England (Historic England - Championing England's heritage | Historic England, 2023), Historic Environment Scotland (Historic Environment Scotland, 2023) etc.), little research has dealt regarding the cross section of energy efficiency, living comfort and heritage conservation (Fouseki *et al.*, 2020). As a result, there is a scarcity of data on energy use and thermal comfort improvement before and after their application, either individually or in combination (to identify their co-benefits from a "whole building" perspective). Furthermore, related initiatives often fail to grasp the ever-changing nature of heritage (Heritage Dynamics, 2022), which influences and shapes the proposed interventions and ultimately affects their successful implementation.

This paper delves into the pivotal intersection of digital twins (DTs), heritage building management and social dynamics, aiming to address the pressing need for innovative solutions that transcend the traditional boundaries of conservation and energy concerns. The significance of this research lies in the recognition that while listed heritage buildings may not be subject to the same energy performance regulations, their long-term survival depends on effective maintenance as inhabited spaces. The paper's main contribution lies in proposing a DT-enabled approach that integrates social dynamics into heritage building management, fostering sustainable practices that cater to both conservation imperatives and energy efficiency in a holistic manner.

Literature review

In recent years, there has been a growing amount of social research, albeit limited, looking at the attitudes of inhabitants and users of heritage buildings towards energy efficiency. In-depth studies still remain rare, which may be explained by the fact that recruiting and interviewing residents in their premises is a time-consuming and resource-intensive process. For cross-cultural and cross-geographical studies, in particular, the involvement of local researchers is vital. Another possible reason is that the focus in studies related to energy efficiency in historic buildings has mainly been placed on the development of technical solutions (e.g. Cornaro *et al.*, 2016; Rohdin *et al.*, 2018; Webb and Castele, 2019), since heritage values are often perceived by heritage professionals as a nonnegotiable pre-condition upon which the guidance is shaped. Therefore, peoples' attitudes inhabiting historic buildings toward energy efficiency have been understudied. And yet, unless users' attitudes toward energy efficiency in relation to heritage values are understood, "there are no guarantees for achieving the planned level of energy efficiency". Fouseki and Cassar (2014) were among the first to identify the need for research that would enable understanding the dilemmas that residents of old buildings face between thermal comfort improvement, energy efficiency and conservation of heritage features. Six years later, a growing, but still limited, number of in-depth, qualitative studies in this area have emerged (Adams *et al.*, 2014; Yarrow, 2016; Bobrova and Fouseki, 2018; Koukou and Fouseki, 2018; Newton and Fouseki, 2018), providing a few first insights into the dynamic change of heritage values and the ways they drive or prohibit residents' choices on energy efficiency and thermal comfort. The limited existing studies inevitably focus on single case studies located in a confined geographical area. System dynamics (SD) have been used in this context in order to explore how heritage values change over time and the impact of that change on decisions related to energy efficiency and thermal comfort. Xu and Dai (2012) create a holistic SD model for Xidi World Heritage Village, examining the interplay of social, economic and heritage sectors. It reveals the importance of policies that integrate local community needs, providing economic opportunities alongside conservation efforts. Wu and Xu (2013) provide a SD and fuzzy multi-objective programming integrated approach for the prediction of energy consumption and CO_2 emissions at a regional level. The developed decision support model was applied to predict the energy consumption of a world heritage area in China during 2010–2020. The results reveal that energy consumption and CO_2 emissions increase dramatically with rapid economic growth. Soufivand (2012) developed a SD model in order to realize the potential problems and clearly understand the relations of causal factors within the cultural heritage sector through engaging tourists and the private sector.

Piselli *et al.* (2020) study an innovative integrated modeling and simulation framework consisting of the implementation of historical building information modeling (HBIM) for the energy retrofit of historical buildings with renewable geothermal heating, ventilation and air conditioning (HVAC) systems with a case study in Italy. Results show that the innovative renewable energy system provides relevant benefits while preserving minor visual and architectural impact within the historical complex and also in terms of energy savings, CO_2 emissions offset and operation costs compared to the traditional existing system. Thravalou *et al.* (2023a, b) aim to provide an agile and effective workflow that can be implemented in the renovation processes of heritage buildings, which, given their complexity (geometric, material and policy-induced), typically call for a case-by-case approach. The results of this study point to the need for a methodological compromise between multiple complex procedures, some of which involve uncertainties. Nieto-Julián *et al.* (2023) describe the technical processes applied to a 16th-century historic building to support an open and interoperable workflow between the participating agents. The process is transparent and controllable by operators and disciplines, ensuring direct and continuous access to project data. Khan *et al.* (2022) focus on implementing effective procedures for the identification and classification of heritage architecture. This study develops a novel HBIM framework to manage heritage buildings in an integrated and interoperable environment to conserve a heritage building and facilitate restoration planning and facility management (FM) activities. In Thravalou *et al.* (2023a, b), an integrated HBIM approach was developed by the authors in order to propose cost-effective energy efficiency upgrade measures, where the energy improvement measures concern the upgrade of the thermal transmission of the building envelope, the incorporation of efficient heating, cooling and mechanical ventilation systems, as well as the incorporation of renewable energy systems.

So far, research looking at energy efficiency and thermal comfort in historic buildings, is either technical or social (the latter is still limited).

Cultural heritage is a perplexing system with entities that interact stochastically and in a nonlinear manner (Karatzas and Chassiakos, 2020). Most used frameworks and strategies regarding the improvement of energy performance do not consider the issues of cultural heritage in a holistic manner but rather focus on specific and limited subsets of issues, which lead to ineffective solutions from both a cultural and environmental perspective. DT technology has shown promise in transforming complex engineered systems. However, its adoption in the architecture, engineering, construction and operation (AECO) field, particularly for built cultural heritage (BCH) conservation, is still in its early stages (Vuoto *et al.*, 2023). Although many researchers attempted to develop DT models for part of a heritage building at the component or system level and test the models using real-life cases, their works were constrained by the availability of empirical data. Furthermore, data capture approaches, data acquisition methods and modeling with multi-source data are found to be the existing challenges of DT application in heritage facilities management (Hou *et al.*, 2023). The research framework presented in Jouan and Hallot (2020) consists of integrating HBIM models in the DT environment with a focus on supporting the preservation of cultural heritage. The encompassing method recognizes the importance of HBIM model integration beyond the project stage, automatization of data analytics and simulation processes in the DT and consequently increasing understanding of the effects preservation would have on cultural heritage sites and their patrons. In Marra *et al.* (2021), the authors utilize an integrated informational system in conjunction with DT technology for the maintenance and preservation of cultural heritage assets, specifically focusing on the impact of natural and human-induced disasters on tangible cultural heritage. The authors emphasize that a fully operational DT is essential for the protection and preservation of cultural heritage. The authors in Ni *et al.* (2021) suggest employing a DT to preserve historical buildings. They acknowledge that enhancing energy efficiency, combined with the application of machine learning models for predicting energy consumption based on historical data, can contribute to sustainable building maintenance. DT technology emerges as the inevitable progress of the virtual and physical worlds, coupling and providing integrated solutions to monitoring, diagnostic, predictive and optimizing tasks. Even though DT technology is used successfully in many different fields, the cultural heritage domain has yet to experience its full impact.

The current work proposes a multi-level framework of DTs that interacts in a hierarchical but integrated manner to comprehend, assimilate and interoperable integrate complex contexts adhering to contradictory conditions imposed by the various entities of the cultural heritage. Achieving interoperability among the DTs requires transforming information in a peer-to-peer manner or to a common (standardized) DT format. The proposed multi-layer DT will ensure improvement of the building's energy efficiency as well as the well-being of its users by examining the results of each intervention through simulations and deciding on the best possible scenario. The paper presents a logical and systematic joined-up management framework for the targeted heritage buildings, according to a “Whole Building” approach perspective. This introduces, as opposed to a one-size-fits-all, a site-specific approach that uses an understanding of a building in its context (structure and use, environmental, sociocultural and community) to find balanced solutions on fabric measures, services and people's behavior.

This paper is organized as follows: Section 1 presents the socio-technical approach in heritage management considering the heritage DTs and heritage system dynamics. Section 2 discusses the conceptual framework where "*Whole Heritage Building Approach*" is suggested. Section 3 introduces the architecture of the proposed framework, whereas in Section 4 the conclusions of this research are being outlined.

Socio-technical approach in heritage management

Socio-technical approach. The socio-technical approach to heritage management is a multidisciplinary framework that recognizes the inherent connection between cultural heritage and the communities that surround and interact with it. In this approach, heritage management goes beyond merely safeguarding historical artifacts and monuments; it extends to the dynamic relationship between people and their heritage. It considers the needs, beliefs and aspirations of local communities, as well as their cultural practices and identities tied to heritage sites.

The adoption of a socio-technical and dynamic approach is groundbreaking, as DTs tend to incorporate vast amounts of technical data on building components, system specifications and building performance. Although useful for decision-making and long-term management, these data reflect only part of a building's use. To more fully understand this, it is imperative to incorporate data on owner/occupant perspectives, cultural values and information about space use. Through the combination of technical performance and sociocultural aspects, a more holistic understanding of decision-making in heritage building management is achieved. The integration of sociocultural information, i.e. data about space use, non-technical aspects of energy retrofit and decision-making and cultural values and norms, into DTs is of an imperative value. These data are in disparate formats and include a range of data types (numerical, textual and visual, among others), which introduces additional challenges. The systemic and dynamic interconnections between heritage values, thermal comfort, heritage conservation and energy efficiency will be explored through the participation of the key stakeholders in all stages of research – i.e. design of the methods employed to gather the data, analysis of the data; visual representation of the data and model creation and model validation. Figure 1 represents the steps of the methodological sequence of the research procedures; the heritage building conceptualization defines and develops a holistic assessment of the footprint of existing buildings and environments by including historic, architectural and esthetic considerations when establishing the values. The system dynamic analysis of "heritage assemblies" refers to the modeling of the dynamic complexities of the heritage environments and the heritage DT design develops the system architecture and the models and back-end digital solutions. Each of these steps fall under the umbrella of the overall socio-technical approach, heritage system dynamics and heritage DTs, respectively.

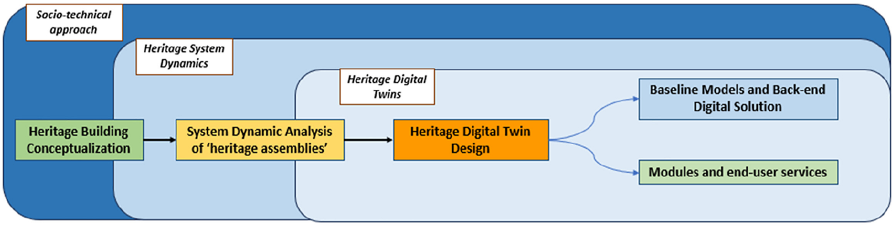

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Figure 1. Methodological framework

Heritage digital twins. DTs are virtual representations of physical assets or processes that can be updated in real time and give a strong true presence scene to support the decision-making of various activities in the life cycle of the physical product. Artificial intelligence, machine learning and sensor technology are involved when that "real" digital image model is built. The combination of real data and virtual model analyses can prevent the occurrence of real problems before they occur, reduce production interruption and cost and even make plans for future activities through simulation (ISO/IEC 21823-4:2022, ISO, 2022). As DTs become cost-effective and more widely available, building owners and public authorities (municipalities, ministries) drive the uptake of DTs to represent their buildings by accessing real-time data, simulation the results and solutions and efficiently performing many operational tasks.

The proposed framework employs DTs to produce virtual models of heritage sites that provide access to all relevant information in an intuitive and straightforward manner. These technologies can inform and support initiatives regarding conservation, maintenance and restoration. Furthermore, they can provide the framework for a wide variety of interventions covering preventive and social aspects, integrating a variety of scales from community to citizen (Laing, 2020). DTs can provide added value to the aforementioned framework and are currently underutilized in the context of cultural heritage. More specifically, the DT paradigm can strengthen the link and improve interconnections between the physical and digital aspects of heritage assets (Jouan and Hallot, 2020). A DT can be understood as a probabilistic, multi-scale, multi-physics-integrated simulation of a system that uses state-of-the art physical models, sensors for real-time data and history to mirror the life cycle of its corresponding twin (Alam and El Saddik, 2017; Tao *et al.*, 2019). This paper proposes a novel socio-technical approach to the development and use of a DT that integrates social data related to the use of heritage buildings and the meanings they are associated with, combined with building and environmental data. Our approach is informed by the underpinning assumption that a heritage building and even more a heritage neighborhood is a socio-technical, complex and dynamic system the change of which depends on the dynamic interconnections of materials (e.g. original features), competences (e.g. restoration skills), resources (e.g. costs), values, space/environment (e.g. natural light), senses (e.g. thermal comfort) and time (e.g. years living in the building) (Fouseki *et al.*, 2020).

Heritage system dynamics. Heritage management and system dynamics form a powerful combination for addressing the complex challenges of preserving and promoting cultural heritage in a rapidly changing world. System dynamics is an interdisciplinary methodology that allows heritage managers to analyze the intricate and interconnected relationships between various factors influencing heritage sites (Chondrogianni and Karatzas, 2023). By employing dynamic models, such as feedback loops, stock and flow diagrams and causal loop diagrams, heritage managers can gain a deeper understanding of the long-term consequences of different management decisions. This approach facilitates the identification of potential risks and impacts on heritage assets and surrounding communities, enabling proactive strategies to mitigate adverse effects (Al-Masri *et al.*, 2021). Moreover, system dynamics allows heritage managers to explore various scenarios and policy interventions to optimize conservation efforts, visitor experiences and sustainable development (Mylonakou *et al.*, 2023). It aids in recognizing both direct and indirect impacts of interventions and how they might affect the sociocultural fabric of the area. The iterative nature of system dynamics encourages adaptive and flexible approaches to heritage management, acknowledging that heritage is a dynamic entity and requires continuous monitoring and adaptation to ensure its resilience. By incorporating the insights from SD into heritage management plans, stakeholders can make informed decisions, anticipate and respond to challenges and work toward the sustainable preservation and appreciation of our diverse cultural heritage for generations to come. In response to the need to approach heritage building conservation as a dynamic process intertwined with social, cultural, environmental and economic aspects, this paper introduces technologically, architecturally and socially innovative and inclusive solutions to ameliorate the use of energy and demonstrate that it is possible to have better performance of heritage buildings without compromising their values with social acceptance, considering and boosting low-cost interventions.

Conceptual framework

The proposed method synthesizes parameters related to values and meanings, the sense of comfort as well as emotions, environmental, economic and attitudes/behaviors toward energy efficiency in order to develop a SD model to enable decision-making that takes into consideration the full spectrum of needs and values of stakeholders. Also, involving and gaining support from local communities and stakeholders is essential, as they often hold strong emotional connections to heritage buildings, and their input can influence the success of renovation projects. Culturally, heritage buildings provide local character and a very tangible connection between esthetics and community into the past and have greater links to locality and history, something that cannot be easily replaced. All energy efficiency measures should consider the destination of the building and avoid hindering it. In order to address the aforementioned challenges, this work proposes a framework for heritage management and renovation that is conceptualized as a dynamic interconnection of three main components, meaning the “Whole Building” approach, system dynamics practices and DTs technology (Figure 2), which are described in the next sections.

Whole heritage building approach

Achieving sustainable, energy and resource-efficient performance in heritage buildings requires a whole heritage building approach whereby there is integration and balance of fabric measures in the envelope (walls, windows, floors and roof such as insulation, draught proofing, glazing and rainwater protection) and services such as HVAC, lighting, thermostatic controls and renewables along with people’s behavior (improving habits and management practices) and proper consideration of how people understand and use (maintain, DIY management and building management system (BMS)) their buildings. These three areas interact with each other and offer opportunities for saving energy and reducing greenhouse gas emissions. All measures, but particularly fabric measures, affect the rest of the building and the people who live or work in the building (Santamouris and Vasilakopoulou, 2021). These three areas interact with each other, offer opportunities for saving energy and reducing greenhouse gas emissions and should be adapted to the context of the building, which means:

The environmental context. The location and orientation of a building make a considerable difference to how a building performs and what can be done in retrofit, which is considered in the renovation decisions.

The heritage and community context. A building’s shared history, beauty, place in the community and social life all contribute to its heritage and community value, which must be considered alongside its condition, occupant use and location in any retrofit strategy.

The building structure and use. The types of material (i.e. brick, stone, timber, lime mortar and cob), the type of construction, the thickness of walls, the sizes and types of windows, the types of fireplaces and chimneys, all affect the energy use and health of the building and influence what can be done. Different building users also have different energy use. The energy use and cost-effectiveness of varying retrofit measures will, therefore, be highly influenced by the type of occupant as well as the use of the building.

All of these determine the way in which a Whole Heritage Building Approach is emulated as well as the options and constraints for renovation.

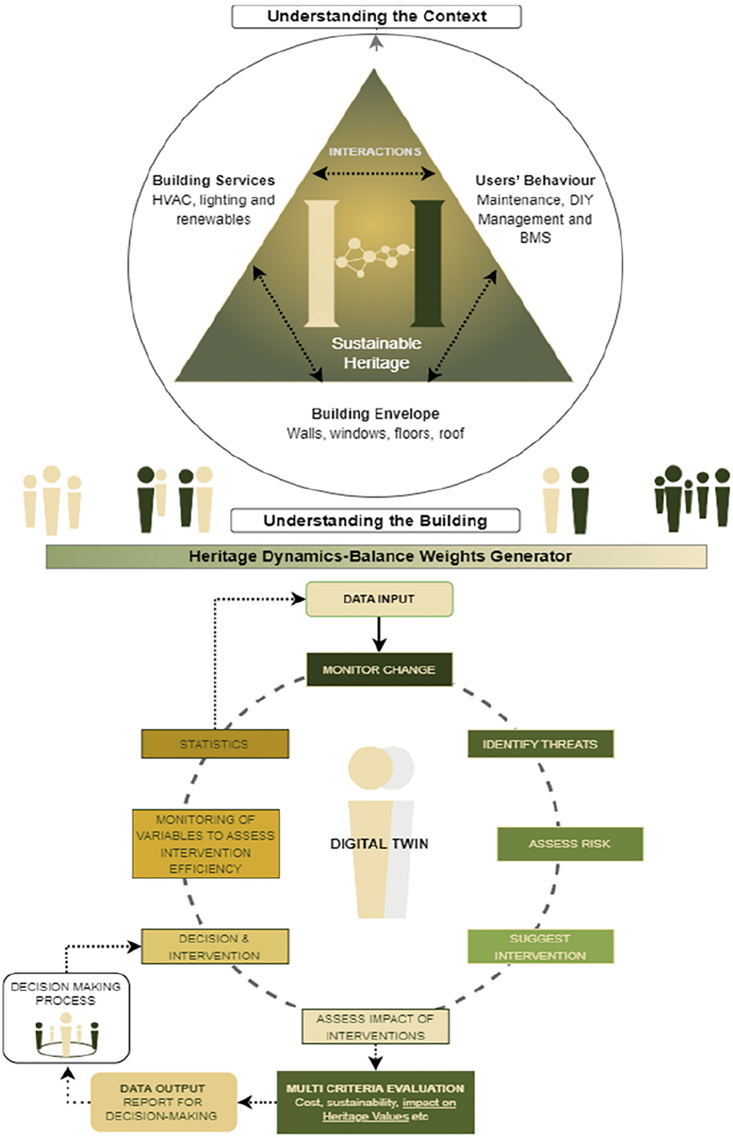

Figure 2.
"Whole Building" approach

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Interventions catalog

The main idea of this paper is to present an approach to the renovation tasks according to a minimum intervention methodology, as laid out in the Burra Charter ("as much as necessary but as little as possible") (Burra Charter & Practice Notes | Australia ICOMOS, 2013), while focusing on conservation options that are potentially applicable to a wide variety of historic buildings (listed or not). The paper aims at presenting a structured catalog with possible interventions as part of the "Whole Building" approach. Given that historic buildings' preservation may impose constraints on certain interventions, retrofit measures can be grouped into three levels of increasing impact from the perspective of a step-by-step approach to energy efficiency improvements.

The first level concerns low-impact interventions, i.e. noninvasive conservative options potentially applicable to any building. At the second level, the sustainability of the intervention depends on the characteristics of the building and the climatic zone in which it is located. They can be invasive to some extent but are generally compatible with historical material consistency. The third level has the greatest impact and therefore requires careful reflection because it is aimed at achieving high performances and a significant reduction in energy demand while taking little account of the values of the historic buildings. Before considering the building, interventions on services like simple improvements to controls (better-located switches, timers and programmers, thermostats, etc.) or a new HVAC system can be a source of energy efficiency. At the same time, an active approach is pursued aimed at motivating occupants to change their behavior by improving the way the building and its systems are used and managed. The list of potential interventions can only then be taken into consideration, which usually refers to building fabric with the aim of improving its insulation.

Traditionally, historic buildings used passive strategies (thermal inertia, natural ventilation and buffer zone) and proto-technical systems with simple heating or cooling systems and the use of the water and vegetation (carpets, tapestries and curtains). According to the lessons learned from the past, it is always better to start the list of interventions by considering simple but effective benign measures using traditional materials because they are compatible from the chemical, physical and social point of view. Compatibility is not the only concept to have in mind, reversibility and minimum interventions are also at the base of any conservation projects, so using or improving natural ventilation is a typical win-win action.

The intervention portfolio is built upon the "*Whole Building*" approach including different types of measures concerning the building envelope (walls, windows, floors, roof), building services (HVAC, lighting and renewables) and users' behavior (maintenance, control and DIY management). This work adopts a categorization of the considered measures based on a three levels impact approach (Table 1).

System dynamics for aims deconfliction

While energy efficiency is often the primary aim of most retrofit strategies, there may be different reasons for this, such as the desire for cost savings, reductions in CO_2 emissions or improved comfort. Those involved in the retrofit at different stages may have varied and conflicting aims or priorities, for e.g. occupant health issues or historic character of the property (Galassi and Madlener, 2017). This paper proposes a "Heritage Dynamics" approach acting as a balance weights generator for evaluating and prioritizing several factors considering the needs of the community with the goal of finding a balance between social, cultural, environmental and economic development. These weights will be developed from methods that are capable of combining qualitative and quantitative information to assist complex decision-making, such as multi-criteria decision-making and analytic hierarchy process (AHP).

Participatory SD modeling is a process that encourages stakeholder engagement, synthesizes research and knowledge, increases trust and consensus and improves transdisciplinary collaboration to solve these complex types of problems (Rieder *et al.*, 2021). A step-by-step process of a participatory SD modeling is suggested to address these conflicting aims, building trust and consensus among diverse partners to reduce conflict and improve the efficacy of interventions. At each step, new information is learned and the identified problem may change, along with system components In this way, the proposed methodology proposes, in the first instance, the construction of a model of participatory SD

Table 1.
Measures per impact level

Impact level	Services	People	Measures Building fabric Walls	Roofs	Floors	Windows
1	Simple improvements to controls (better-located switches, timers and programmers, thermostats, etc.)	Better monitoring and control of energy use. Make building users more aware of energy and carbon performance (education) and adopt simple DIY measures	Repairing action and lining interior walls with hangings	Repairing action and insulating roofs at ceiling level	Repairing action, adding rugs or carpets to ground floors	Repairing action, draught-proofing action, recovering or adding curtains and recovering or adding shutters
2	Implementation of existing services by more efficient models, trying to reuse existing distribution ducts etc. Modify HVAC systems to provide better local or zone control; more comprehensive control upgrades	Technology to assist management or user interaction (building management system – BMS)	Thermal insulating plaster, reflective coating, lining interior walls with tapestries and boiserie	Insulating pitched roofs, insulating flat roofs and application of paint on roof tiles	Adding wall-to-wall carpeting and insulating existing ground floors	Adding window films, adding interior or exterior storm windows, replacing glass units and installing secondary glazing
3	Insertion of new building services, Add renewable energy systems	*N/A*	Insulating walls internally or externally	Replacing roofs and tiles	Replacing an existing floor with a new insulated floor	Replacing windows

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that allows to integrate citizen factors (determined through the participatory rural diagnosis and generate information in the short, medium and long term that can facilitate decision-making and, in the second instance, the translation to a complex network of multiple criteria that allows the evaluation and prioritization of alternatives.

Following the principles of grounded theory, the collected data will be coded through open and axial coding. The aim of the coding process is to identify the individual factors and variables that affect decisions and interventions. Hence, “cause” and “effect” relationships will be mapped that are reinforcing each other or balancing with each other. Using the method of “system dynamics,” the “cause” and “effect” relationships will be mapped into a causal loop diagram created on software like Vensim. These diagrams can visualize the nonlinear dynamic interrelationships of all the factors above and should be co-created in partnership with the key stakeholders from each case study who can feed back their ideas and perceptions as to how the variables interconnect based on the data collected through interviews and questionnaires. The “heritage system dynamics” model will investigate the interrelationships between the several parameters (values, energy efficiency, comfort, etc.), how these interrelationships shape preferences toward heritage conservation solutions and assess change in attitudes and behavior of users' before and after their participation in the development and implementation of such solutions. The weighting method will be carried out at different instants of time and consider the information obtained by means of the SD model for each moment of time. In this way, it is possible to observe the various interpretations that citizens and a panel of experts can make when there are many data and it is possible to group different decisions about the same issue and establish a valid proposition. The heritage dynamics model will act as an inner dimension enabler that will feed the DT system, by generating weights for a predefined set of key performance indicators to enable decision-making based on the stakeholders' preferences.

Digital twins for complex interaction management

Heritage buildings and communities are approached as a dynamic and complex system – the transformation and sustainability of which depend on the dynamic interactions of elements that correspond to and transcend over the fundamental pillars of sustainability (social, cultural, environmental and economic). There are complex interrelationships between the different "thermal elements" of a building (walls, floors, roof, windows and doors), the space heating and ventilation systems, the use of the building and its context. If alterations are made to one element, then there may be knock-on effects with other elements (Historic England - Championing England's heritage | Historic England, 2023). This research proposes the DT technology to manage these complex interrelations and act as a *balancing scenario generator*.

A DT improves the relationship between the digital model and the physical domain of heritage assets by merging digital replicas with near-real time operational data from on-site sensors using Internet of Things (IoT) infrastructure. Virtual replicas maintain constant remote control over their physical counterparts, collecting data from a variety of sources via sensors (Ćosović and Maksimović, 2022). By examining the obtained data, potential problems can be predicted and addressed in a timely manner. Hence, the benefit of a DT is that it may be accessed from anywhere, allowing users to remotely monitor and adjust system performance. It can be used as a tool for communicating and documenting the physical twin's behavior and mechanics. Near-real-time information combined with automated reporting contributes to keeping stakeholders informed, thus improving transparency (Ćosović and Maksimović, 2022). A multi-level DT will backtrack from detected real-world conditions, intake sensor data, simulate conditions quickly, design complex what-if scenarios and predict results more accurately. Through the combined use of semantically enriched HBIM models with real-time operational data provided by on-site sensors through IoT infrastructures, the DT will be the link between the digital model and the physical realm of heritage assets to provide tailored information to experts and non-experts stakeholders involved in the decision-making process for the management of the whole heritage-built environment's life cycle.

The DT operation cycle starts with a preliminary assessment based on advice on energy performance and sustainable scenarios for renovation based on the building typology, considering criteria such as climate zone, construction period and building size. Condition assessment will uncover the deficiencies of the building to support the decision-making process and the management of its maintenance. Each heritage building is a particular case with a unique combination of values (historical, symbolic, artistic, urban, architectural and social functional value) that together reflect its heritage cultural significance. The evaluation of values will be conducted by analyzing them in qualitative and complementary quantitative approaches through a combination of research techniques: desktop research, surveys and *in situ* investigation, in order to assess the impacts of interventions on these values and hereinafter utilize them in the decision of the type and degree of changes to the building's components. Then the DT will output balanced renovation scenarios enhance building operation, issue identification and energy management in order to ensure optimal living conditions for the users and benefit maintenance the process with early detection of threats, risk assessments, solution identification and impact assessment.

Different combinations of interventions will be tested through the DT platform and evaluated based on multi-criteria analysis to predict the optimal ones for each case study. The optimization tool will weigh the cost-effectiveness of the intervention(s) against its impact on the heritage value from an energy, environmental and economic point of view while considering the peculiarities of the specific building. The post-renovation performance of the building will be monitored, and maintenance activities will be proposed to enhance its energy performance.

Architecture of the proposed framework

Figure 3 provides a bird's-eye view in the high-level technical architecture of the integrated solution, including the core elements involved and how they interact together to deliver the desired functionality and services. The proposed architecture is conceptually divided in three main tiers:

Data governance layer

The data governance layer consists two core components, namely (1) the semantic interoperability management component, which delivers the mechanisms and tools for ensuring the semantically interoperable exchange of data across data assets, systems and actors; (2) the data governance component, which facilitates the effective handling and collection of upstream and downstream data, their curation and semantic harmonization to the common information model. It is responsible for effectively collecting, processing and exchanging static building data (International Foundation Class (IFC)-based BIM models) with the DT implementation involved in the *back-end digital solutions layer* in an independent and exclusive manner to facilitate the execution of advanced simulations across different levels of buildings and blocks of buildings.

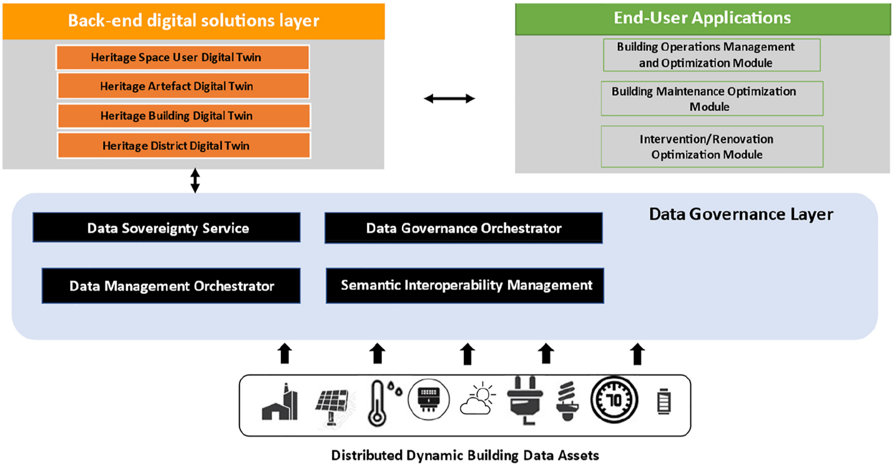

Figure 3.
Architecture of the proposed framework

Source(s): Created by authors

Baseline models and a back-end digital solution

This layer bundles baseline and intelligence components for extracting insights from building data and defining effective, data-driven strategies for renovation and improved energy performance. Standalone DTs can be integrated into a single platform, accessible via a graphical user interface, allowing easy access for analyses and data complementation. It includes:

Heritage spaces user digital twin (HSUDT). Modern spaces prioritize comfort and energy efficiency in design or renovation, while heritage spaces offer less flexibility due to limited intervention options. However, interventions aim to optimize energy use, maintain comfort and preserve esthetics. Heritage space experts require data on intervention impacts for optimal renovation. The HSUDT assesses user comfort and well-being, relying on IoT technology for data collection and prediction.

Heritage moveable artefact digital twin (HMADT). The goal is to evaluate how environmental factors and human activity affect artifacts in heritage spaces and devise effective strategies for preserving them. This comprehensive approach involves analyzing various parameters to develop tailored protection and maintenance plans based on acquired knowledge. Cultural heritage artifacts are vulnerable to anthropogenic emissions, behaviors, pollutants, dust and luminance intensity. The HMADT utilizes advanced techniques like data fusion and 3D CFD (Computational Fluid Dynamics) models to simulate the impact of ambient conditions on artifacts. AI techniques such as Two- Dimensional Convolutional Neural Networks) 2DCNN and clustering are employed to assess defects and forecast IAQ (Indoor Air Quality), enhancing artifact preservation efforts.

Heritage building digital twin (HBDT). IoT-based, physics and data-driven automation in heritage buildings faces barriers with traditional BMS systems. Thus, management relies on simplistic controls. The HBDT utilizes sensors to gather real-time data, calibrating continuously and forecasting weather, occupancy and demand profiles to optimize building operations. These adjustments are implemented via IoT actuators. The DT can adapt to pursue stable conditions, comfort or energy efficiency. This approach offers unprecedented control in historic buildings, allowing for reversible testing and validation of operational changes before implementation, ensuring the preservation of cultural heritage.

Heritage district digital twin (HDDT). The HDDT maps all historic buildings within a district-level DT, including construction details, energy consumption and constraints. It synthesizes data into actionable information, supporting diverse user groups. By integrating building data with other sources like energy networks and sociocultural indicators, it creates a cross-sector digital representation of the community, aiding decision-making while preserving cultural heritage.

Modules and end-user services

This service bundle engages final users, aiding informed decisions to optimize energy performance and predictive maintenance of buildings. It balances energy savings, hygiene, comfort and sustainability. It includes the following: *building operations management and optimization module* analyzes operational data and DTs to optimize heritage building energy efficiency, user comfort and artifact preservation. It manages demand flexibility while considering user preferences and artifact constraints using IoT data and three DTs (HSUDT, HMADT and HBDT). The tool identifies critical areas for energy waste reduction and occupant comfort improvement, automating alternative strategies for energy consumption profiles. *Building maintenance optimization module* provides a comprehensive approach to building maintenance, considering structural and operational performance interdependencies, stakeholder priorities and intervention costs. *Intervention/renovation optimization module* enables users to assess DT models and create decarbonization roadmaps, balancing costs, energy targets, historic value preservation and environmental impact. Leveraging energy efficiency measures, it supports renovation activities, considering cost-effectiveness and heritage value. The balance weights generator ensures optimization by weighing sub-objectives. Leveraging DT models, it enables users to optimize interventions at both building and district levels, starting from a district level and scaling up to optimize interventions.

Conclusions

Utilizing a heritage dynamics method, this study can effectively address the intricate characteristics of historic buildings and neighborhoods, drawing insights from the literature review. By applying a "Whole Building" approach, the research integrates socio-technical considerations and dynamic relationships between various elements. Conducting empirical analyses to validate the conceptual framework could achieve people-centered heritage management guided by a nuanced understanding of non-linear interconnections. Preserving and renovating heritage buildings requires balancing modernization with conservation, incorporating modern amenities while preserving historical authenticity. Challenges include a lack of comprehensive documentation and potential conflicts among stakeholders. Heritage building renovation demands an interdisciplinary approach to navigate complexities and ensure preservation while making buildings functional and sustainable. Introducing a multi-level framework of DTs enables comprehensive comprehension and integration of complex heritage contexts. A data-rich digital representation facilitates optimal renovation solutions by replacing static design data with dynamic sensor data and simulations. SD offers a holistic approach, enabling proactive strategies for conservation and sustainable development. Testing the effectiveness of the framework at diverse pilot sites can provide practical insights for heritage professionals. However, limitations include the lack of empirical analysis to demonstrate the framework's practical implementation and the need for a clearer methodology. Future research should focus on integrating empirical analysis and refining the methodology to enhance the study's robustness and applicability.

References

Adams, C., Douglas-Jones, R., Green, A., Lewis, Q. and Yarrow, T. (2014), "Building with history: exploring the relationship between heritage and energy in institutionally managed buildings", *The Historic Environment: Policy and Practice*, Vol. 5 No. 2, pp. 167-181, doi: 10.1179/1756750514Z.00000000053.

Al-Masri, R.A., Spyridopoulos, T., Karatzas, S., Lazari, V. and Tryfonas, T. (2021), "A systems approach to understanding geopolitical tensions in the Middle East in the face of a global water shortage", *International Journal of System Dynamics Applications (IJSDA)*, Vol. 10 No. 4, pp. 1-23, doi: 10.4018/IJSDA.289431.

Alam, K.M. and El Saddik, A. (2017), "C2PS: a digital twin architecture reference model for the cloud-based cyber-physical systems", *IEEE Access*, Vol. 5, pp. 1-1, doi: 10.1109/ACCESS.2017.2657006.

Bobrova, Y. and Fouseki, K. (2018), "Understanding the change of heritage values over time and its impact on energy efficiency decision-making at residential historic buildings through system dynamics", *The 3rd International Conference on Energy Efficiency in Historic Buildings*, EEHB, Visby, Sweden, available at: http://eehb2018.com/ (accessed 2 August 2023).

Burra Charter & Practice Notes | Australia ICOMOS (2013), available at: https://australia.icomos.org/publications/burra-charter-practice-notes/ (accessed: 2 August 2023).

Chondrogianni, D. and Karatzas, S. (2023), "A systems approach for managing risks with complex interactions in urban spaces", *City and Environment Interactions*, Vol. 20, 100117, doi: 10.1016/j.cacint.2023.100117.

Cornaro, C., Puggioni, V. and Strollo, R. (2016), "Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study", *Journal of Building Engineering*, Vol. 6, pp. 17-28, doi: 10.1016/j.jobe.2016.02.001.

Ćosović, M. and Maksimović, M. (2022), "Application of the digital twin concept in cultural heritage", *VIPERC*, available at: https://api.semanticscholar.org/CorpusID:253398672

Fouseki, K. and Cassar, M. (2014), "Energy efficiency in heritage buildings — future challenges and research needs", *The Historic Environment: Policy and Practice*, Vol. 5 No. 2, pp. 95-100, doi: 10.1179/1756750514Z.00000000058.

Fouseki, K., Newton, D., Murillo Camacho, K.S., Nandi, S. and Koukou, T. (2020), "Energy efficiency, thermal comfort, and heritage conservation in residential historic buildings as dynamic and systemic socio-cultural practices", *Atmosphere*, Vol. 11 No. 6, p. 604, doi: 10.3390/atmos11060604.

Fufa, S.M., Flyen, C. and Flyen, A.-C. (2021), "How can existing buildings with historic values contribute to achieving emission reduction ambitions?", *Applied Sciences*, Vol. 11 No. 13, p. 5978, doi: 10.3390/app11135978.

Galassi, V. and Madlener, R. (2017), "The role of environmental concern and comfort expectations in energy retrofit decisions", *Ecological Economics*, Vol. 141, pp. 53-65, doi: 10.1016/j.ecolecon.2017.05.021.

Heritage Dynamics (2022), "UCL press", available at: https://www.uclpress.co.uk/products/155755 (accessed 2 August 2023).

Historic England - Championing England's heritage | Historic England (2023), available at: https://historicengland.org.uk/ (accessed 2 August 2023).

Historic Environment Scotland (2023), available at: https://www.historicenvironment.scot/ (accessed 2 August 2023).

Hou, H.(C.), Lai, J., Wu, H. and Wang, T. (2023), "Digital twin application in heritage facilities management: systematic literature review and future development directions", *Engineering, Construction and Architectural Management*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/ECAM-06-2022-0596.

ISO/IEC 21823-4 (2022), "ISO", available at: https://www.iso.org/standard/84773.html (accessed 2 August 2023).

Jouan, P. and Hallot, P. (2020), "Digital twin: research framework to support preventive conservation policies", *ISPRS International Journal of Geo-Information*, Vol. 9 No. 4, p. 228, doi: 10.3390/ijgi9040228.

Karatzas, S. and Chassiakos, A. (2020), "System-theoretic process analysis (stpa) for hazard analysis in complex systems: the case of 'Demand-Side Management in a Smart Grid'", *Systems*, Vol. 8 No. 3, p. 33, doi: 10.3390/systems8030033.

Khan, M.S., Bughio, M., Talpur, B., Kim, I. and Seo, J. (2022), "An integrated HBIM framework for the management of heritage buildings", *Buildings*, Vol. 12 No. 7, p. 964, doi: 10.3390/buildings12070964.

Koukou, T. and Fouseki, K. (2018), "Heritage values and thermal comfort in Neoclassical residential buildings of Athens, Greece: tension or co-existence?", in: *Conference Report – The 3rd International Conference on Energy Efficiency in Historic Buildings* (pp. 463-471). Uppsala University: Visby, Sweden. (2018). The 3rd International Conference on Energy Efficiency in Historic Buildings (EEHB2018), Visby, Sweden: Uppsala University, available at: http://eehb2018.com/conference-report/ (accessed 2 August 2023).

Laing, R. (2020), "Built heritage modelling and visualisation: the potential to engage with issues of heritage value and wider participation", *Developments in the Built Environment*, Vol. 4, 100017, doi: 10.1016/j.dibe.2020.100017.

Marra, A., Gerbino, S., Greco, A. and Fabbrocino, G. (2021), "Combining integrated informative system and historical digital twin for maintenance and preservation of artistic assets", *Sensors*, Vol. 21 No. 17, p. 5956, doi: 10.3390/s21175956.

Mylonakou, M., Chassiakos, A., Karatzas, S. and Liappi, G. (2023), "System dynamics analysis of the relationship between urban transportation and overall citizen satisfaction: a case study of Patras City, Greece", *Systems*, Vol. 11 No. 3, p. 112, doi: 10.3390/systems11030112.

Newton, D. and Fouseki, K. (2018), “Heritage values as a driver or obstacle for energy efficiency in Victorian and Edwardian buildings”, *Energy Efficiency in Historic Buildings*, available at: https://www.diva-portal.org/smash/get/diva2:1297062/FULLTEXT01.pdf

Ni, Z., Eriksson, P., Liu, Y., Karlsson, M. and Gong, S. (2021), “Improving energy efficiency while preserving historic buildings with digital twins and artificial intelligence”, *IOP Conference Series: Earth and Environmental Science*, Vol. 863 No. 1, 012041, doi: 10.1088/1755-1315/863/1/012041.

Nieto-Julián, J.E., Farratell, J., Bouzas Cavada, M. and Moyano, J. (2023), “Collaborative workflow in an HBIM project for the restoration and conservation of cultural heritage”, *International Journal of Architectural Heritage*, Vol. 17 No. 11, pp. 1813-1832, doi: 10.1080/15583058.2022.2073294.

OVERVIEW | Energy Efficiency in Historic Buildings: A State of the Art | BUILD UP (no date), available at: https://build-up.ec.europa.eu/en/resources-and-tools/articles/overview-energy-efficiency-historic-buildings-state-art (accessed 2 August 2023).

Piselli, C., Romanelli, J., Di Grazia, M., Gavagni, A., Moretti, E., Nicolini, A., Cotana, F., Strangis, F., Witte, H.J.L. and Pisello, A.L. (2020), “An integrated HBIM simulation approach for energy retrofit of historical buildings implemented in a case study of a medieval fortress in Italy”, *Energies*, Vol. 13 No. 10, p. 2601, doi: 10.3390/en13102601.

Rieder, E., Larson, L.R., ’t Sas-Rolfes, M. and Kopainsky, B. (2021), “Using participatory system dynamics modeling to address complex conservation problems: tiger farming as a case study”, *Frontiers in Conservation Science*, Vol. 2, 696615, doi: 10.3389/fcosc.2021.696615.

Rohdin, P., Milic, V., Wahlqvist, M. and Moshfegh, B. (2018), *On the Use of Change-Point Models to Describe the Energy Performance of Historic Buildings*.

Santamouris, M. and Vasilakopoulou, K. (2021), “Present and future energy consumption of buildings: challenges and opportunities towards decarbonisation”, *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, Vol. 1, 100002, doi: 10.1016/j.prime.2021.100002.

Soufivand, M. (2012), “Enhancement of tourism service delivery performance through value co-creation: a system dynamic approach: case study: cultural heritage sector in Sicily”, available at: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-118826 (accessed 25 January 2024).

Standards, E. (2017), “BS EN 16883:2017 Conservation of cultural heritage. Guidelines for improving the energy performance of historic buildings”, available at: https://www.en-standard.eu/bs-en-16883-2017-conservation-of-cultural-heritage-guidelines-for-improving-the-energy-performance-of-historic-buildings/ (accessed 2 August 2023).

Tao, F., et al. (2019), “Five-dimension digital twin model and its ten applications”, *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS*, Vol. 25, pp. 1-18, doi: 10.13196/j.cims.2019.01.001.

Thravalou, S., Michopoulos, A., Alexandrou, K. and Artopoulos, G. (2023a), “Energy retrofit strategies of built heritage: using Building Information Modelling tools for streamlined energy and economic analysis”, *IOP Conference Series: Earth and Environmental Science*, Vol. 1196 No. 1, 012115, doi: 10.1088/1755-1315/1196/1/012115.

Thravalou, S., Alexandrou, K. and Artopoulos, G. (2023b), “A simulation-based approach for defining energy retrofit strategies of built heritage through the use of H-Bim tools”, in Sayigh, A. (Ed.), *Mediterranean Architecture and the Green-Digital Transition: Selected Papers from the World Renewable Energy Congress Med Green Forum 2022*, Springer International Publishing (Innovative Renewable Energy), Cham, pp. 545-555, doi: 10.1007/978-3-031-33148-0_43.

Vuoto, A., Funari, M.F. and Lourenço, P.B. (2023), “Shaping digital twin concept for built cultural heritage conservation: a systematic literature review”, *International Journal of Architectural Heritage*, Vol. 0 No. 0, pp. 1-34, doi: 10.1080/15583058.2023.2258084.

Webb, A. and Castele, D. (2019), “Insulating the walls of historic buildings: a systematic review of existing guidance”, *APT Bulletin*, Vol. 50, pp. 37-44.

Wu, Z. and Xu, J. (2013), "Predicting and optimization of energy consumption using system dynamics-fuzzy multiple objective programming in world heritage areas", *Energy*, Vol. 49, pp. 19-31, doi: 10.1016/j.energy.2012.10.030.

Xu, H. and Dai, S. (2012), "A system dynamics approach to explore sustainable policies for Xidi, the world heritage village", *Current Issues in Tourism*, Vol. 15 No. 5, pp. 441-459, doi: 10.1080/13683500.2011.610499.

Yarrow, T. (2016), "Negotiating heritage and energy conservation: an ethnography of domestic renovation", *The Historic Environment: Policy and Practice*, Vol. 7 No. 4, pp. 340-351, doi: 10.1080/17567505.2016.1253149.

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