# Energy retrofit strategies of built heritage: using Building Information Modelling tools for streamlined energy and economic analysis.

To cite this article: S Thravalou *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1196** 012115



# Energy retrofit strategies of built heritage: using Building Information Modelling tools for streamlined energy and economic analysis.

**S Thravalou[1,2], A Michopoulos[1], K Alexandrou[2] and G Artopoulos[3]**

[1]Department of Architecture, University of Cyprus, 75 Kallipoleos Av., 1678, Nicosia, Cyprus
[2] Energy, Environment and Water Research Center, The Cyprus Institute, 20 Konstantinou Kavafi Street, 2121, Aglantzia, Nicosia, Cyprus
[3] Science and Technology in Archaeology Research Center, The Cyprus Institute, 20 Konstantinou Kavafi Street, 2121, Aglantzia, Nicosia, Cyprus

sthraval@gmail.com

**Abstract**. Dynamic simulation tools are widely used in the workflow of energy retrofitting historic buildings as they contribute to the development of an optimised, cost-effective renovation strategy. Additionally, Building Information Modelling (BIM) applied in heritage buildings can provide a holistic platform that improves collaboration between different stakeholders involved in the management, restoration and energy-retrofit of heritage buildings, by facilitating data sharing and project coordination. However, the use of BIM for energy simulation is rarely implemented due to emerging technical complexities regarding data interoperability. In response to the above shortcomings, the paper addresses the challenges of integrating a) dynamic energy performance analysis and b) financial feasibility analysis, using Heritage-BIM (H-BIM) tools. Insights and knowledge acquired through the case of a deep renovation of a historic building in ruin condition is presented. Specifically, an integrated H-BIM approach was developed by the authors in order to propose cost-effective energy efficiency upgrade measures. 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. The economic feasibility study is based on widely used financial indicators, including life cycle cost analysis (LCCA). The proposed workflow aims to become a useful methodological tool for public authorities, assisting the attraction of financing mechanisms for the restoration and energy-upgrade of the historic building stock.

## 1. Introduction

In the case of built heritage, energy retrofits are often described in the literature as an act of balancing multiple criteria, among which conservation and energy efficient prevail [1]. Despite the lack of a regulatory framework for minimum energy performance requirements in historic dwellings, the potential of energy savings and emissions' reduction by retrofitting this sensitive category of building stock has been widely acknowledged through the work of several research programs (e.g. SECHURBA, CLIMATE FOR CULTURE, 3ENCULT, RIBUILD, EFFESUS) [2–6] and studies [1,7–9]. In this

IOP Conf. Series: Earth and Environmental Science 1196 (2023) 012115 doi:10.1088/1755-1315/1196/1/012115

framework, the ambitious Renovation Wave strategy, which forms a part of the European Green Deal agreement, addresses sustainability of built environment and the challenges of cultural heritage [10,11]. The aim is to boost deep renovation and meet the objective of doubling the annual energy-retrofit rate of existing buildings by 2030. Yet, accessibility to funding and financial sustainability is a common challenge for governments and third sector organizations working in heritage conservation [12]. The need to increase cooperation among public, private sectors, and civil society organisations to meet this aim, is highlighted in UN-Habitat's 2006 Istanbul Declaration on Human Settlements [13]. Indeed, over the last decades, Private-Public Partnership (PPP) schemes and Energy Performance Contracts[1] (EPC) have gained in popularity as a potential mechanism for leveraging funds for heritage renovation [14]. Furthermore, recent pilot studies for renewable energy systems integration in historic buildings are being implemented widely, which indicates future developments in the sector [15].

Dynamic energy simulation is widely used as a decision-making tool for estimating energy savings and optimising energy-efficiency measures [1,16–18]. Yet, developing as-built building energy models (BEM) implies time-consuming and costly modelling and necessary data input, such as local weather data, construction materials, thermal bridges, system characteristics, general occupancy profile, etc. [17,19]. As reported in the literature, the major limitations of BES in historic buildings concern: i) the lack of reliable thermo-physical data of envelope components, ii) simplifications in the representation of geometric features (e.g., presence of thermal bridges) and (iii) the adoption of inaccurate models of certain physical phenomena, such as decay of historical buildings [1,20]. An additional challenge concerns the calibration of the BEM in order to reduce uncertainty of the predicted outputs [21]. While the validation of dynamic hygrothermal simulation models is traditionally based on energy consumption data, an increasing use of microclimatic parameters for calibration and validation purposes is reported in heritage BES [22]. This is attributed to the absence of heating/cooling systems, which is often the case for many historical buildings, or due to difficulties in retrieving energy consumption data (e.g., due to abandonment or partial use). For this reason, in the case of non-airtight building envelopes (e.g., historic buildings in severe static condition), the verification of the BEM is based on assumptions and future needs and requirements, which implies further uncertainties for private investors to proceed with financing energy improvement projects. Understanding the assumptions that lie behind predictions of different software allows for a more accurate and thorough understanding of a building's energy use and its associated costs and emissions.

Additional recent initiatives of European Commission also encourage Member States to digitise by 2030 all monuments and sites that are at risk of degradation and recommends the creation of a common European data space for cultural heritage [23,24]. The International Council on Monuments and Sites (ICOMOS), although is not referring directly to the application of Building Information Modelling (BIM) technologies in conservation, it stresses the importance of digitalisation as a means for avoiding incoherence and the duplication of efforts [25]. Considering the challenge of handling information which is dispersed across different disciplines and stakeholders, BIM tools applied in heritage buildings (H-BIM) can provide a holistic platform improving collaboration between different stakeholders involved in the management, restoration and energy-retrofit of heritage buildings, by facilitating data sharing and project coordination [25]. Furthermore, BIM tools can also help the professionals in estimating more accurate costs and energy savings in post-retrofit buildings, which supports the building owners in investing in energy efficiency measures [26]. Given these benefits, the Directive 2014/24/EU requires the adoption of BIM tools in public projects when public procurement value exceeds certain thresholds [27]. However, the application of BIM in heritage refurbishment projects is challenging [28,29]. This is mainly attributed to emerging complexities of heritage building geometry, the absence of standardised processes, namely the scan-to-BIM intensive modelling process, and finally the inadequate data exchange between native BIM and Building Energy Simulation (BES) software [30–33].

[1] EPC is a contractual arrangement between the beneficiary and the provider, an Energy Service Company (ESCO), for delivering energy efficiency or a renewable energy project, where investments are paid for in relation to a contractually agreed level of energy efficiency improvement.

In this context, this research aims to present a thorough workflow for energy and economic analysis of energy improvement measures for built heritage, promoting the use of BIM tools. An enhanced BIM to BES interoperability workflow is presented in this paper, addressing the challenges of simulating the energy performance of historic buildings that are not occupied or lie in decay. The widespread economic indicator Life Cycle Cost Analysis (LCCA) is used for the financial evaluation of the refurbishment project, aiming to foster the access of public administration to credit from private financial services. The results of this research reflect the case of energy refurbishment of a characteristic historic building in the Mediterranean and semiarid climate types ($C_{sa}$ and $B_{Sh}$) [34].

## 2. Methodology

### *2.1. Building documentation and environmental analysis*

Preliminary analysis of the case study building involved the identification of legislative information, national zoning plans and other regulations regarding the designation of heritage and technical documentation of the building geometry. Critical historical, architectural and environmental attributes of the pilot building were identified, diagnosed and collected according to international guidelines and practices of architectural surveying and energy improvement of built cultural heritage [35–37]. Specifically, the documentation entailed the geometrical survey, the assessment of the building's heritage significance, the conservation state analysis, but also the climate analysis of the site, the indoor environmental monitoring and the building energy audit.

Both traditional and digital surveying techniques were used, i.e., topography, technical documentation and terrestrial laser scanning or photogrammetry, heat flux meter analysis and environmental monitoring techniques. An image-based survey was also performed to capture in detail the decorative elements of the building. This type of 3D survey assisted the authors to digitally represent the detailed stone artefacts and stone wall pediment details located in the interior and exterior spaces of the building. Non-destructive methods were used to identify i) the stratigraphy of the building envelope, ii) the thicknesses and dimensions of building components, as well as iii) the thermal properties of building materials. More specifically, the underlying materials of the walls, rising damp, as well as the emissivity of the original plasters were identified through infrared techniques. The thermal transmission properties of the opaque building elements were measured through the heat flow meter method described in ISO 9869, while simplifications were made in the calculation of the thermal transmission of the windows and doors, according to ISO 10077 [38,39]. Outdoor environmental conditions such as air temperature, relative humidity, wind speed and direction, and solar radiation, were monitored through the installation of a weather station in the vicinity of the building.

### *2.2. H-BIM model creation*

Terrestrial photogrammetry supplied an accurate 3D point cloud with the critical representation of its graphical rendering and a validated two-dimensional drawing file; comprising in this way, the resources for the H-BIM modelling initiation [40–42]. The widely used BIM software *Autodesk Revit 2022* was employed in this research [33,43]. The authors used ad-hoc family types and existing BIM ontologies for the creation of the particular building components (H-BIM), based on existing standardised BIM ontologies, to avoid modelling customisations and maintain model consistency and clarity. In addition to geometric representation of building components, the thermal properties of the building materials were added in the BIM library and assigned to the respective opaque multilayer elements. Opaque and transparent envelope elements (BIM nested families) have been configured as schematic types and linked to manually registered entries of the analytical properties pre-sets.

### *2.3. Data interoperability between H-BIM and BES*

The whole-building energy simulation analysis was performed through *EnergyPlus 9.4* and the comprehensive graphical interface of *Design Builder V.7,* listed as the third most used software for BES worldwide [33,44]. The authors implemented a semi-automatic H-BIM to BES workflow through the gbXML data exchange schema. The online gbXML viewer platform, *Spider gbXML Viewer,* was used prior to importing the model to the BES interface, in order to confirm the consistency of the exported building geometry and its compliance with the BEM's planar surface requirements [45]. The BIM model geometry was further corrected through an iterative process, until the appropriate planar surfaces were appropriately generated by the export operation.

The imported gbXML file was analysed in the BES interface to identify potential missing data and geometry mismatches. The option of *Model data grid view* was used to display the imported data, enabling the export of *Visible data grid view* to a comma separated file (.CSV). The CSV file was accessed using the *Dynamo*[2] plug-in tool and missing values were manually added/substituted by the actual data located in the BIM model. The necessary input data for the energy simulation model included: location and related weather data; geometry, materials and types of spaces; thermal zones, based on spaces' definition; occupants, appliance and lighting loads; HVAC components; other specific simulation parameters required by the simulation model. Finally, the updated CSV file was imported to Design Builder through the tool *Data grid dialog* in order to perform the energy performance analysis. The schematic representation of the adopted workflow is illustrated in Figure 1.

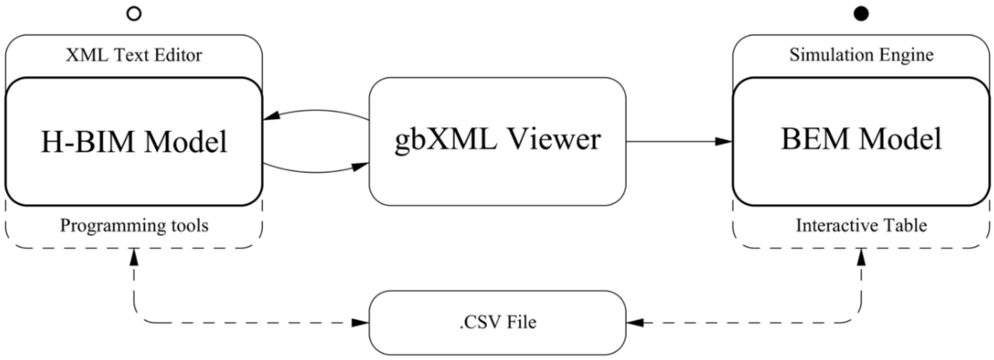



**Figure 1**. Schematic representation of the adopted H-BIM to BES workflow.

## 2.4. Dynamic energy simulation

*2.4.1. The baseline model – existing case-study building:* The baseline model (BL) reflects the case-study building which is located in Nicosia, close to Paphos Gate and the Venetian walls of the historic centre. The selected historic building has a significant architectural and historic value which lies in the combination of colonial-style building features – such as the angular stone turret on the northwest, pitched roof and corner pediments [46,47] – and typical elements of Cypriot urban vernacular architecture, e.g., the typological elements of the internal courtyard, along with covered semi-open spaces and a portico entrance hall [48,49] (Figure 2). It was built in the second half of the 19th century as the club of the British cavalry and during the 20th century it was converted into barracks for the Danish Canadian military detachment in Cyprus. The pilot building remained in use until the 1970ies and currently faces severe structural damages caused by the lack of maintenance and the long-term abandonment.

[2] Dynamo is an open-source visual scripting platform for computational design, integrated in the BIM software Revit.


**Figure 2.** The case study building in a) 1934, b)1964, and c) 2013.

Several building materials and construction techniques demonstrating various historic layers and construction phases were identified during the visual inspection of the site. According to the findings, the predominant structural system is load-bearing stone masonry, 50 cm in thickness. Additional vertical building components include timber walls constructed using a lath and plaster technique (mainly interior curtain walls), as well as adobe masonries resting on stone foundations [50]. Lime and gypsum-based plasters are used on the exterior and interior layers of the external walls, respectively. The thermal transmittance (U-value) of the exterior walls, $U_{walls}$, is 0.89 W/m$^2$K. The inclined roof ($_{Roof\_1}$) is a timber structure with a thin reed layer and compacted earth and clay tiles as an external finishing. Respectively, the pitched roof ($U_{Roof\_2}$) is a timber structure covered with ceramic tiles. The U-value of the inclined and pitched roofs are 3.07 and 1.79 W/m$^2$K respectively. The floor covering materials on the ground floor are ceramic tiles, local stone (*gypsomarmaro*) or timber planks, while interior floors on the first level are wooden. Finally, windows are assumed with wooden frames and dividers, as well as single glazing (Solar Heat Gain Coefficient (SHGC) and Light Transmission (LT) approximately 0.76 and 0.81 respectively). The total floor area of the BL model shown in Figure 3, is 506 m$^2$, the Window to Wall area (WTW) is 0.11, and the Compactness Ratio, A/V (i.e., the Area of the building's external envelope to its inner Volume) is 0.68.

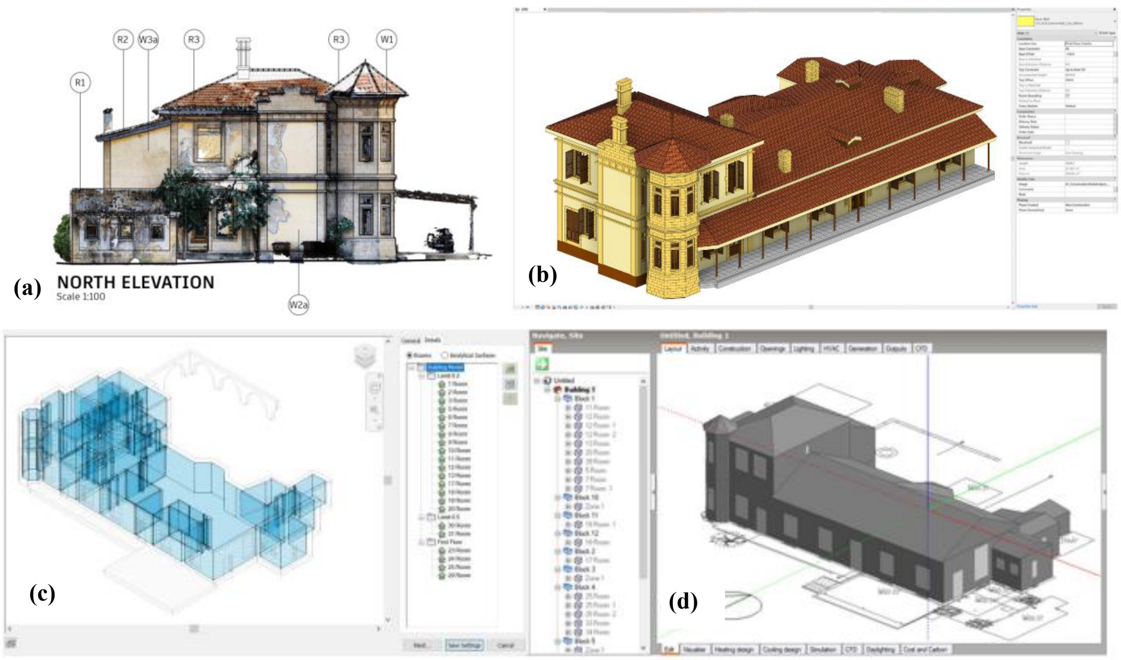



**Figure 3**. a) Thematic maps illustrating the conservation state of the pilot building; b) the H-BIM model; c) BIM analytical model defined using Revit *Spaces*; d) BEM in Design Builder software.

*2.4.2. Energy improvement measures:* Four energy retrofit scenarios are examined comparatively. As summarised in Table 1, these scenarios comprise of a set of energy improvement measures regarding a) passive means for upgrading the envelope's thermal transmission, b) active means for efficient heating, cooling and lighting, and c) the incorporation of renewable energy systems. The first scenario, SC1, corresponds to interventions upgrading the thermal transmittance of the building envelope, such as: P1, the application of plaster based on lime and expanded perlite *[51]*; P2, the installation of rock wool on the roof; and P3, the substitution of the transparent envelope with double, Low-E glazing and wooden frames with thermal break. The second scenario, SC2, involves active systems for heating and cooling, efficient equipment and lighting. Specifically, measure A1 refers to the installation of air-to-brine heat pumps (VRV/ VRF systems) with local heat reclaim ventilator (HRV/ VAM) units (Seasonal Coefficient of Performance (SCOP) and Seasonal Energy Efficiency Ratio (SEER) equal to 4.46 and 4.86 respectively). In spaces with hygiene interest, e.g., toilets, kitchens, or storage usage, the HRV/ VAM units are replaced by common exhaust fans. These configurations with the aid of local thermostats allow the independent regulation of the desired indoor temperature is any space according to its specific requirements or working conditions. Measure A2 involves the substitution of indoor lighting with highly efficient light-emitting diode (LED) light panels, and measure A3 refers to the substitution of the electrical and electronic equipment. Finally, scenario SC3 involves the installation of renewable energy systems (RES). Specifically, photovoltaic panels (PV) are foreseen on the roof of an independent structure which serves as shelter for the parking, at the east part of the plot. The shelter of the parking corresponds to an area of 460 $m^2$, where 32 PV panels (1716 x 1023 mm) of nominal capacity of 340 Wp can be installed, with a total capacity of 10.88 kWp. Eventually, scenario SC4 covers all the proposed energy improvement measures.

**Table 1.** Energy improvement measures and scenarios

| | **Energy Improvement Measures –** Technical specifications | **Retrofit Scenario** SC1 | SC2 | SC3 | SC4 |
|---|---|---|---|---|---|
| P1 | **Thermal plaster application** Hydraulic lime plaster with perlite, λ=0.15 W/mK | x | x | | x |
| P2 | **Roof Insulation** Rock wool 8mm, λ=0.033 W/mK | x | x | | x |
| P3 | **Window substitution** Wooden frame with thermal break, double glazing 6/13/6mm Air, Low-E, SHGC: 0.38, LT: 0.62 | x | x | | x |
| A1 | **Installation of VRV/VRF system with HRV** Heating/Cooling capacity: 88/ 75 kW, SCOP: 4.46, SEER: 4.86 | | x | | x |
| A2 | **Lighting system substitution with LED panels** | | x | | x |
| A3 | **Electrical and Electronic equipment substitution** | | x | | x |
| R1 | **PV installation** Total capacity: 10.88kWp | | | x | x |

*2.4.3. Economic and environmental analysis:* The annual mass (Kg) of carbon dioxide ($CO_2$), $C_{PV}$, saved in each retrofit scenario was calculated according to the Decree 33/2015 *[52]* and the formula: $C_{PV} = Q_{PV} * c_D$, where $Q_{PV}$, the annual saved electric power (kWh) and $c_D$ the emission factor of the region; i.e. 0.794 kg $CO_2$/kWh (220.55556 g/MJ) *[52]*.

Respectively, for the evaluation of the financial feasibility of the examined energy retrofit scenarios SC2 and SC4, the analysis of the life cycle cost has been performed considering an economic lifespan of 15 years. This analysis includes the initial investment cost, $C_{in}$, in association with the maintenance cost $C_{m,j}$, the equipment replacement cost $R_{m,j}$, the energy consumption $EC$ and energy cost $C_{el,j}$, and the salvage value $SV_k$, as shown in the following equation.

$$LCC = -C_{in} - \sum_{j=1}^{n} \frac{C_{m,j}}{(1+i)^j} - \sum_{j=1}^{n} \frac{R_{m,j}}{(1+i)^j} - \sum_{j=1}^{n} \frac{EC \cdot C_{el,j}}{(1+i)^j} - \sum_{k=1}^{x} \frac{SV_k}{(1+i)^n}$$

## 3. Results and discussion

### *3.1. BIM-based energy retrofitting workflow*

In the present paper, a BIM-based energy-retrofit workflow has been employed for the environmental, energy and economic analysis of the heritage building under study. Although the BIM to BES interoperability framework is under investigation and remains uncertain in terms of the geometry conversion and non-geometrical data exchange, yet it offers great benefits to the overall retrofit design process. These benefits include the parametric representations and economic indicators in BIM that enable credible decision-making. The federal model workflow and improved coordination between the involved actors minimise the risks occurring during the remodelling or re-registration of building information. The integration of all building data into a single digital environment is of great accountability to all involved professionals, as everyone gets direct access to the relevant information necessary for providing their consultation. By extend, energy engineers can provide feedback and suggestions to the design team from the early conceptual to the concluding detailed design phase, thus minimizing time-consuming practices of the past and eliminate the staining of the project budget. In the long run, the implementation of time-effective design practices allows for the involved professionals to utilise their resources on enhancing the final project quality [53].

### *3.2. Energy simulation results*

As mentioned, the existing building is naturally ventilated. As no HVAC systems are installed, the energy consumption of BL model corresponds mainly to lighting and equipment. The energy source is electricity, and its total amount is estimated at 28,843.6 kWh, i.e., 57 kWh/m$^2$ of indoor spaces. Considering the monthly cooling and heating demands, as illustrated in Figure 4, the annual final energy demand of BL model is 261.5 MWh, which corresponds to 516 kWh/m$^2$ of indoor spaces.

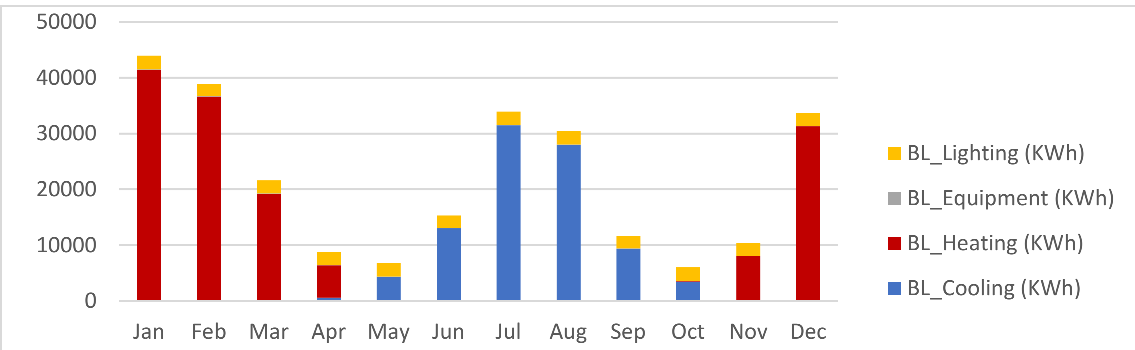



**Figure 4**. Monthly final energy demand (kWh) of the existing building (BL model).

IOP Conf. Series: Earth and Environmental Science 1196 (2023) 012115 doi:10.1088/1755-1315/1196/1/012115

The set of measures examined in SC1 corresponds to the upgrade of the building envelope, improving the thermal transmittance of the building components. More specifically, through the interventions P1 and P2, the U-value of the roofs were improved by $\Delta U_{roof\_1}$: 2.73 W/m²K and $\Delta U_{roof\_2}$:1.45 W/m²K, while the contribution of the thermal plaster s in the walls was moderate with $\Delta U_{walls}$:0.16 W/m2K. As observed in Figure 5, intervention P3, i.e., window substitution with low emission coating and double glazing, introduces contradictory results as it leads to an increased heating demand in the winter, however, it significantly reduces direct solar gains during the summer period, thus decreases cooling demand. This effect is also discussed in the literature [54]. In this case, indoor air temperature in the main exhibition area of the ground floor is reduced by 1°C in the summer. Compared to the BL case, the interventions in SC1 increase the heating demand of the dwelling by 717.7 kWh, whereas cooling demand is reduced by 27,344.4 kWh. Considering all the aforementioned passive interventions in the envelope, the annual energy demand of the dwelling in SC1, as illustrated in Figure 6, is 239.4 MWh, and corresponds to 473.1 kWh/$m^2$ of indoor spaces. The improvement regarding the existing building (BL) is 43 kWh/$m^2$. These measures not only decrease the annual energy demand of the building by 8.5 % but also improve the indoor conditions in terms of operational temperature and thermal comfort, decrease the possibility of condensation on the interval surfaces of the building elements and increase the protection of the building envelope against the exposure to weather conditions. This is in line with relevant literature investigating energy efficiency measures in building envelopes in the Mediterranean climate [55].

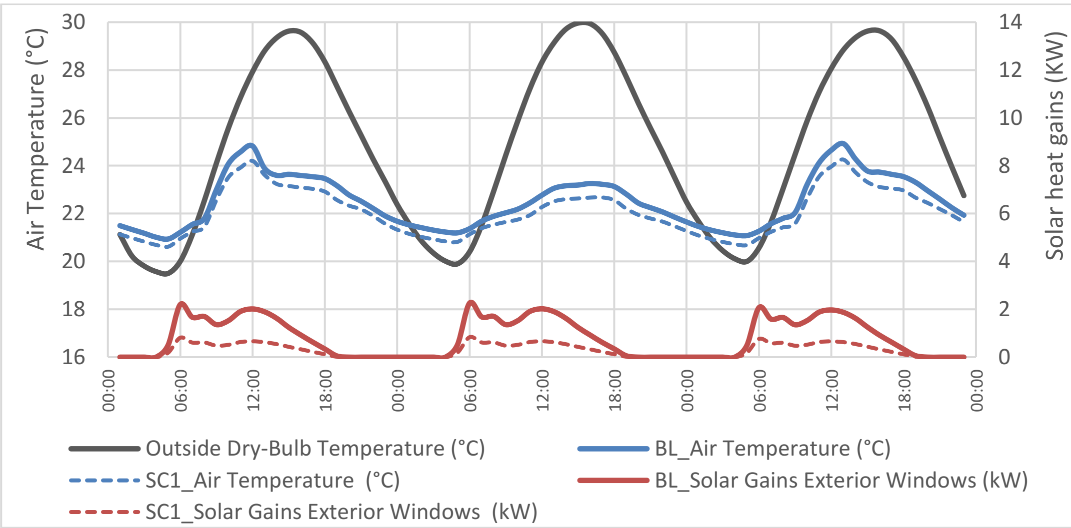



**Figure 5.** Air temperature (°C) and solar heat gains (kW) during June in the main, ground floor exhibition area, in the case of the baseline model (BL) and SC1 (upgraded envelope).

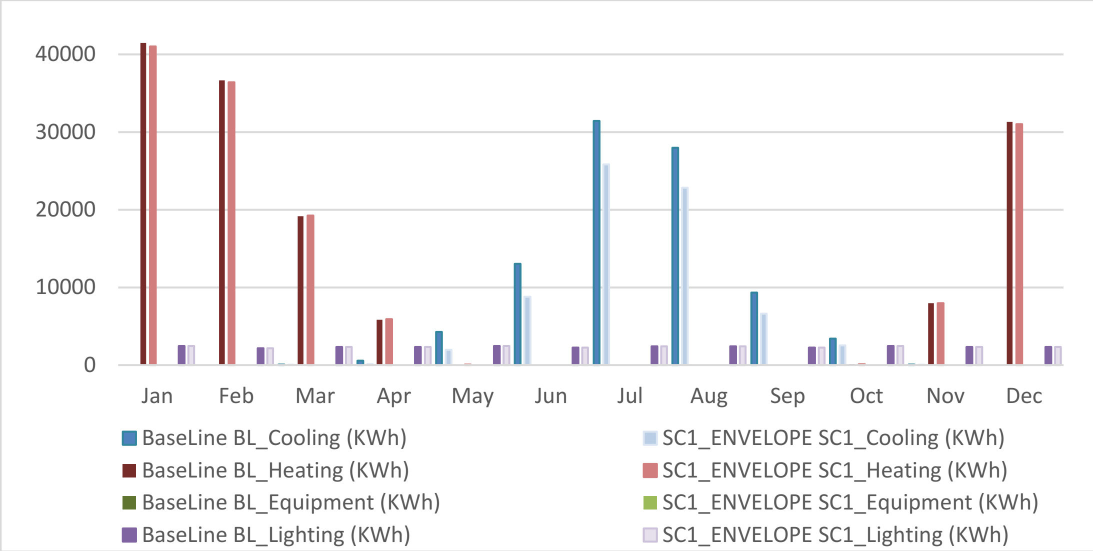
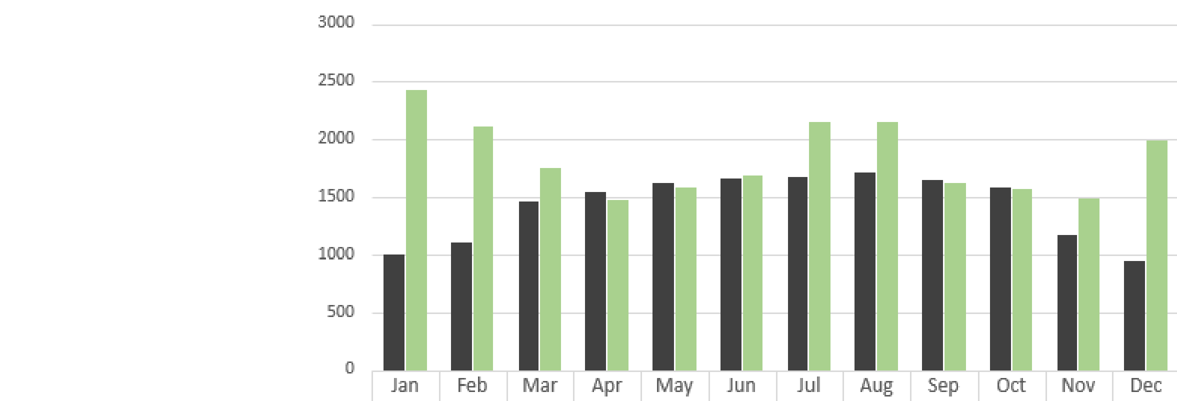



**Figure 6**. Monthly energy demand (kWh) of the baseline model (BL) and SC1 (upgraded envelope).

The installation of active systems (i.e., scenario SC2) which involves efficient HVAC systems with heat recovery, as well as lighting and equipment substitution, results in an annual energy consumption of 22 MWh, that corresponds to 43.5 kWh/m$^2$ of indoor spaces. The monthly energy consumption in the case of SC2 is shown in Figure 7. The monthly electric power generation produced in SC3 from the installation of PV panels, is also presented in Figure 7.

Considering SC4, which combines the passive and active means, coupled with RES, the annual energy consumption of the building drops to 4.87 MWh, which corresponds to 9.6 kWh/ m$^2$ of indoor spaces. The annual generation of electricity from the PV (i.e., cases SC3 and SC4) is 17,122.5 kWh. Thus, adopting a holistic approach by implementing all the examined measures, i.e., case SC4, instead of focusing on the active systems, i.e., SC2, there is 77.8% savings in annual energy consumption, i.e., 17.1 MWh of electricity, which corresponds to 13.6 tons of $CO_2$ emissions reduction.




| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SC3_Energy generation (KWh) | 1001.4 | 1105.8 | 1458.1 | 1538.7 | 1623.3 | 1663.4 | 1680.3 | 1711.1 | 1641.6 | 1577.0 | 1168.7 | 953.2 |
| SC2_Final energy consumption (KWh) | 2430.2 | 2104.2 | 1750.8 | 1471.4 | 1575.5 | 1684.4 | 2154.2 | 2148.3 | 1626.2 | 1572.9 | 1488.7 | 1987.3 |

**Figure 7.** Final energy consumption (kWh) in SC2 (passive and active interventions) and energy generation in scenario SC3 (installation of PV).

### 3.3. Economic analysis results

The financial feasibility results of the economic analysis are presented in Table 2. It appears that the life cycle cost is significantly high in both SC2 and SC4 renovation scenarios, with a reduction of 16,000 € when implementing the second one, due to the use of PV electricity. This finding indicates the significant cost of the restoration measures in heritage buildings and the need for generous financial mechanisms accompanied with challenging business plans, that can ensure the economic viability of the restoration project. It is worth noticing that, as the pilot building does not comprise any mechanical systems for heating, cooling and ventilation, and thus the energy consumption is restricted to the consumption of the office equipment; the energy improvement measures focusing on the building envelope and the incorporation of efficient HVAC systems, such as SC1 and SC2, do not suggest any feasible financial indicator such as payback time (PBT), net-present value (NPV), return of investment (ROI), etc. This fact indicates that more long-term financing mechanisms, such as concession contracts, may be feasible and more appealing to potential investors instead of energy performance contracts (EPC). In the EPC approach, the building owner transfers the technical risks to the ESCO, based on performance guarantees given by the former. In other words, the ESCO remuneration is based on a demonstrated performance: the level of energy savings. For this reason, in the case of abandoned or non-airtight historic buildings, defining a baseline model and a starting point for energy consumption is based on a series of critical assumptions, therefore is highly challenging.

**Table 2.** Economic analysis of the examined energy retrofit scenarios

| | BL | SC1 | SC2 | SC3 | SC4 |
|---|---|---|---|---|---|
| Overall Investment Cost [€] | - | 164,920 | 375,920 | 20,000 | 395,920 |
| Total Energy Production from RES (kWh/annual) | - | - | - | 17,122.5 | 17,122.5 |
| Average annual energy cost over the project's life span[3] (15 years) (€/annual) | - | - | 7,811.1 | - | 2,369 |
| Maintenance cost (€) | - | 3,298 | 9,400 | 400 | 9,800 |
| Discount rate (%) - (*average weighted)* | - | - | 9% | - | 9% |
| LCCA (€) | - | - | 481,000 | - | 465,000 |

## 4. Conclusions

This research presented a thorough workflow for energy and economic analysis of energy improvement measures for built heritage, supported by the use of BIM tools. Building survey and reality capture 'as is' documentation, environmental analysis as well as 3D modeling tools were used to create an H-BIM model of the heritage building under study. The workflow adopted in this research aims to enhance collaboration and facilitate data exchange management across different disciplines and stakeholders, involved in an energy retrofit project. Through hands-on experience of dealing with BIM to BES interoperability issues, the authors acknowledge that it is hard to standardise a protocol of step-wise operations for the accurate transitioning of the building geometry between said software environments. Further development of plug-in tools aiming at more accurate geometry and data transition between software would contribute to a wider adoption of BIM tools for BES and energy retrofit projects in the built heritage. Expanding on disseminated results of this research [56], the workflow presented in the paper handled the energy-related data exchange between the BIM (Revit) and BES (Design Builder) software, through the use of a Dynamo script.

A set of energy improvement measures focusing on passive and active means, as well as integration of RES were analysed in terms of energy and economic feasibility. Specifically, the paper focused on the challenges of simulating the energy performance of heritage buildings that are not occupied or lie in

[3] Estimated running cost of electric energy 0.40 c€/kWh, and assuming a reduction of 2% every second year.

decay presenting a workflow that was implemented to overcome the challenges introduced by the current building state. The results of the dynamic energy analysis indicate that the insulation of the building envelope and the replacement of windows with more efficient ones may improve the energy performance up to 8.5% (43 kWh/m$^2$). Adopting a more holistic approach (SC4) which combines the passive and active means, coupled with RES, was able to cover 78% of the total energy needs of the building. The research also showed that the energy/economic balance of energy improvement measures focusing on the building envelope, despite having a beneficial effect in the energy demand of the building, they present financial ineffectiveness. The same applies for the installation of HVAC systems in the case of naturally ventilated heritage buildings with no mechanical heating and cooling systems. This fact indicates that more long-term financing mechanisms, such as concession contracts, may be feasible and more appealing to potential investors instead of energy performance contracts (EPC), which is based on the level of energy savings. These findings, coupled with the presented methodology through the BIM workflow, are expected to facilitate the decision-making process for energy retrofitting of heritage and boost potential mechanisms for leveraging funds for heritage renovation.

**References**

[1] Webb AL. Energy retrofits in historic and traditional buildings: A review of problems and methods. Renewable and Sustainable Energy Reviews. 2017 Sep;77:748–59.
[2] De Santoli L. Reprint of “Guidelines on energy efficiency of cultural heritage”. Energy and Buildings. 2015 Maggio;95:2–8.
[3] Historic England. Energy Efficiency and Historic Buildings, how to improve energy efficiency. Historic England; 2018.
[4] D’Ambrosio FR, Mazzarella L, Bellia L, Filippi M, De Santoli L, Romagnoni P. Energy Efficiency in Historic Buildings [Internet]. REHVA; 2018. Available from: https://www.rehva.eu/eshop/detail/energy-efficiency-in-historic-buildings
[5] GBC. GBC Historic Building [Internet]. Green Building Council Italia; 2017. Available from: http://gbcitalia.org/documents/20182/157656/Sistema+di+verifica+GBC+HB_2016-mag17.pdf/7d185808-b994-45fe-a6af-218e81a8fe27
[6] Troi A, Bastian Z. Energy efficiency solutions for historic buildings. A handbook. Basel: Birkhauser; 2015.
[7] Laine A, Davies J, Buchanan K, Warren K, Turtinen J. Heritage Research Matters. Case studies of research impact contributing to sustainable development [Internet]. 2019. Available from: http://jpi-ch.eu/wp-content/uploads/Heritage-Research-Matters.pdf
[8] Martínez-Molina A, Tort-Ausina I, Cho S, Vivancos JL. Energy efficiency and thermal comfort in historic buildings: A review. Renewable and Sustainable Energy Reviews. 2016 Aug 1;61:70–85.
[9] Berg F, Flyen AC, Godbolt ÅL, Broström T. User-driven energy efficiency in historic buildings: A review. Journal of Cultural Heritage. 2017 Nov 1;28:188–95.
[10] European Parliament. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 on energy efficiency, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU. Official Journal of the European Union. 2018;(L156, 19.06.2018):75–91.
[11] Li Y, Kubicki S, Guerriero A, Rezgui Y. Review of building energy performance certification schemes towards future improvement. Renewable and Sustainable Energy Reviews [Internet]. 2019 Oct 1 [cited 2022 Mar 16];113. Available from: https://www.sciencedirect.com/ science/article /pii/ S1364032119304447
[12] Galatioto A, Ricciu R, Salem T, Kinab E. Energy and economic analysis on retrofit actions for Italian public historic buildings. Energy. 2019 Jun;176:58–66.
[13] United Nations. Istanbul Declaration on Human Settlements [Internet]. Instabul, Turkey; 1996 [cited 2022 Dec 1]. (Conference on Human Settlements (Habitat II)). Available from:

https://www.un.org/en/development/devagenda/habitat.shtml
[14] Macdonald S, Cheong C. The Role of Public-Private Partnerships and the Third Sector in Conserving Heritage Buildings, Sites, and Historic Urban Areas. Los Angeles, USA: The Getty Conservation Institute; 2014.
[15] Durante A, Lucchi E, Maturi L. Building integrated photovoltaic in heritage contexts award: an overview of best practices in Italy and Switzerland. IOP Conf Ser: Earth Environ Sci. 2021 Oct 1;863(1):012018.
[16] Cornaro C, Puggioni VA, Strollo RM. Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study. Journal of Building Engineering. 2016;6(Journal Article):17–28.
[17] Akkurt GG, Aste N, Borderon J, Buda A, Calzolari M, Chung D, et al. Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions. Renewable and Sustainable Energy Reviews. 2020 Feb 1;118:109509.
[18] Martínez-Molina A, Tort-Ausina I, Cho S, Vivancos JL. Energy efficiency and thermal comfort in historic buildings: A review. Renewable and Sustainable Energy Reviews. 2016 Aug;61:70–85.
[19] Patiño-Cambeiro F, Bastos G, Armesto J, Patiño-Barbeito F. Multidisciplinary Energy Assessment of Tertiary Buildings: Automated Geomatic Inspection, Building Information Modeling Reconstruction and Building Performance Simulation. Energies. 2017 Jul 19;10(7):1032.
[20] Macdonald IA. Quantifying the effects of uncertainty in building simulation. University of Strathclyde; 2002.
[21] ASHRAE Guildeline 14. Guideline 14, Measurement of Energy and Demand Savings. ASHRAE; 2014.
[22] Huerto-Cardenas HE, Leonforte F, Aste N, Del Pero C, Evola G, Costanzo V, et al. Validation of dynamic hygrothermal simulation models for historical buildings: State of the art, research challenges and recommendations. Building and Environment. 2020 Aug;180:107081.
[23] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS 2030 Digital Compass: the European way for the Digital Decade [Internet]. 2021 [cited 2022 Nov 15]. Available from: https://eur-lex.europa.eu/legal-content/en/ TXT/?uri=CELEX%3A5202 1DC0118
[24] European Commission. Europeana: Discover Europe’s digital cultural heritage [Internet]. 2021 [cited 2022 Nov 15]. Available from: https://www.europeana.eu/en
[25] Nieto-Julián JE, Antón D, Moyano JJ. Implementation and Management of Structural Deformations into Historic Building Information Models. International Journal of Architectural Heritage. 2020 Oct 20;14(9):1384–97.
[26] D’Angelo L, Hajdukiewicz M, Seri F, Keane MM. A novel BIM-based process workflow for building retrofit. Journal of Building Engineering. 2022 Jun;50:104163.
[27] Directive 2014/24/EU [Internet]. L 94/65, 2014/24/EU Feb 26, 2014 p. 65–242. Available from: http://data.europa.eu/eli/dir/2014/24/oj/eng
[28] Piselli C, Romanelli J, Di Grazia M, Gavagni A, Moretti E, Nicolini A, et al. An Integrated HBIM Simulation Approach for Energy Retrofit of Historical Buildings Implemented in a Case Study of a Medieval Fortress in Italy. Energies. 2020 Jan;13(10):2601.
[29] Gigliarelli E, Calcerano F, Martinelli L, Artopoulos G, Thravalou S, Alexandrou K. Methodology for the energy renovation of heritage buildings using BIM. Guidelines for the development of an Energy Efficient Heritage Building Information Model (EE-HBIM). Gigliarelli E, Calcerano F, Martinelli L, editors. Roma: Consiglio Nazionale delle Ricerche; 2022. 156 p.
[30] Chiaia B, Davardoust S, Osello A, Aste N, di Milano P, Mazzon M, et al. BIM and interoperability for energy simulations. In: Building Simulation Applications. 2015. p. 93–7.

[31] Gigliarelli E, Calcerano F, D'Uffizi F, Di Biccari C, Mangialardi G, Campari M. From heritage BIM to BPS, a computational design-based interoperability approach. Building Simulation Conference Proceedings. 2019;1:129–36.
[32] Kamel E. Review of BIM's application in energy simulation_ Tools, issues, and solutions. Automation in Construction. 2019;97:164–80.
[33] Di Biccari C, Calcerano F, D'Uffizi F, Esposito A, Campari M, Gigliarelli E. Building information modeling and building performance simulation interoperability: State-of-the-art and trends in current literature. Advanced Engineering Informatics. 2022 Oct;54:101753.
[34] Peel MC, Finlayson BL, Mcmahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci. 2007;13.
[35] Cappa M, De Angelis D, Pecci A, Barba L, Cura M, Crisci GM, et al. Thermographic Survey at Hagia Sophia: Main Arches, Pendentives and Tympana. International Journal of Architectural Heritage [Internet]. 2016 [cited 3AD Feb 1];(Journal Article). Available from: http://dx.doi.org/10.1080/15583058.2015.1104400
[36] CEN/TC 346. EN 16096:2012 Conservation of cultural property - Condition survey and report of built cultural heritage. EN 16096:2012 2012.
[37] CEN/TC 346. EN 16883:2017 Conservation of cultural heritage - Guidelines for improving the energy performance of historic buildings. EN 16883:2017 2017.
[38] CEN. ISO 10077-1:2017 Thermal performance of windows, doors and shutters — Calculation of thermal transmittance — Part 1: General [Internet]. ISO 10077-1 :2017 2017. Available from: https://www.iso.org/obp/ui/#iso:std:iso:10077:-1:ed-3:v2:en
[39] CEN. ISO 9869-1:2014 Thermal insulation — Building elements — In-situ measurement of thermal resistance and thermal transmittance — Part 1: Heat flow meter method [Internet]. ISO 9869-1:2014 2014. Available from: https://www.iso.org/obp/ui/#iso:std:iso:9869:-1:ed-1:v1:en
[40] Historic England. BIM for Heritage: Developing a Historic Building Information Model [Internet]. 2017. Available from: https://historicengland.org.uk/images-books/publications/bim-for-heritage/
[41] Bienvenido-Huertas D, Nieto-Julián JE, Moyano JJ, Macías-Bernal JM, Castro J. Implementing Artificial Intelligence in H-BIM Using the J48 Algorithm to Manage Historic Buildings. International Journal of Architectural Heritage. 2020 Sep 13;14(8):1148–60.
[42] Sztwiertnia D, Ochałek A, Tama A, Lewińska P. HBIM (heritage Building Information Modell) of the Wang Stave Church in Karpacz – Case Study. International Journal of Architectural Heritage. 2021 May 4;15(5):713–27.
[43] Amoah E, Nguyen T. Optimizing the usage of Building Information Model (BIM) interoperability focusing on data not tools. In Banff, Canada; 2019 [cited 2022 Mar 23]. Available from: http://www.iaarc.org/publications/2019_proceedings_of_the_36th_isarc/optimizing_the_usage_of_building_information_model_bim_interoperability_focusing_on_data_not_tools.html
[44] Durdyev S, Dehdasht G, Mohandes SR, Edwards DJ. Review of the Building Information Modelling (BIM) Implementation in the Context of Building Energy Assessment. Energies. 2021 Jan;14(24):8487.
[45] Spider gbXML Tools [Internet]. Spider gbXML Tools. 2018 [cited 2022 Jul 20]. Available from: https://www.ladybug.tools/spider-gbxml-tools/#README.md
[46] Georghiou C. BRITISH COLONIAL ARCHITECTURE IN CYPRUS: The Architecture of the British Colonial Administration, 1878-1960. [Internet]. Nicosia: En Tipis Publications; 2013 [cited 2021 Jan 29]. Available from: https://www.nasisbooks.com/shop/english-books/architecture/architectural-theory-history/british-colonial-architecture-in-cyprus/
[47] Georghiou C. The Architecture of Cypriots during British Rule 1878 – 1960. Nicosia, Cyprus: En Typois Publications; 2018. 477 p.
[48] Demi D. The Walled City of Nicosia, A Typology Study. Nicosia Master Plan. Nicosia: UNDP United Nations Development Programme; 1997. 136 p.