



Article

Enhancing the Energy Performance of Historic Buildings Using Heritage Building Information Modelling: A Case Study

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Abstract

Heritage building conservation plays a special role in addressing modern sustainability challenges by preserving the cultural identity, retrofitting, restoring, and renovating these structures to improve energy performance, which is crucial for revitalisation. This research aims to use Heritage Building Information Modelling (HBIM) to increase energy efficiency and environmental sustainability in historic buildings. Retrofitting heritage buildings presents unique challenges and opportunities to simultaneously reduce energy consumption and carbon emissions while maintaining historical integrity. Traditional approaches are often insufficient to meet heritage structures' energy needs. Modern technologies such as information building modelling and energy simulations can offer solutions. HBIM is a vigorous digital framework that facilitates interdisciplinary collaboration and offers detailed insights into building restoration and energy modelling. HBIM supports the integration of thermal and energy efficiency measures while maintaining the authenticity of heritage architecture by creating a comprehensive database. Using a case study heritage building, this research demonstrates how retrofitting the different aspects of heritage buildings can improve energy performance. Evaluating the preservation of heritage buildings' cultural and architectural values and the effectiveness of using HBIM to model energy performance offers a viable framework for sustainable retrofitting of heritage buildings.



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Keywords: energy efficiency; Historic Building Information Modelling (HBIM); retrofitting; sustainability; thermal camera

1. Introduction

Reducing energy consumption is not just a matter of environmental concern but also has a significant financial impact [1]. By 2060, buildings can be expected to increase their overall environmental footprint as the building sector is responsible for almost 40% of energy consumption worldwide [2]. While embodied carbon makes up 10% of global emissions, forecasts indicate that more than half of the total carbon emissions from all new global construction between 2020 and 2050 will come from direct emissions [3]. Immediate action is required to avoid the potentially catastrophic consequences of a 1.5 °C temperature increase by 2030 [4]. In the construction sector, there is a critical demand for a more serious effort to reduce the environmental impact significantly.

Heritage buildings, in particular, face unique challenges and opportunities in this regard. The lack of modern insulation and reliance on outdated Heating, Ventilation, and Air Conditioning (HVAC) systems often cause increases in energy consumption in these structures. However, their high thermal mass offers the potential for improving energy

efficiency through careful retrofitting. The pivotal challenge lies in balancing the need to enhance energy performance while preserving historical and cultural value [5].

Due to their importance and value in unique architectural design, heritage buildings preserve tangible and intangible significance, aesthetics, community connections, and involvement in historical events [6]. Furthermore, it is crucial to devise approaches that address the rising energy requirements of these buildings, promote energy efficiency, and minimise carbon emissions without disturbing their historical architectural integrity [7]. Apart from the substantial energy consumption resulting from their age and the materials used in construction, the lack of regular preservation, and the inefficiency of the energy systems supplying the building, there is a significant deficit in information regarding their energy efficiency. The lack of effective decision-making in these buildings is due to the lack of updating the database, which ultimately prevents the provision of new data [8].

A low-carbon and sustainable future is possible by ensuring the sustainability of New Zealand's heritage buildings for future generations, which can significantly contribute to preserving the country's heritage and play an essential role in nurturing it. Achieving these intertwined goals to protect the distinctive features of historic structures is possible by increasing their energy efficiency and reducing their carbon footprint [9]. Practical and quality considerations are at the heart of the successful retrofit of historic buildings, and using new methods for preserving standards is essential to achieving this. Efforts to better manage energy by reducing energy consumption and emissions often involve adopting new technologies and materials to reduce economic and environmental consequences. However, there has been a lack of attention to linking these to historical buildings. While expertise remains limited to specific sectors, there is potential for a growing disconnect between heritage experts, conservators, life cycle assessment (LCA) professionals, and energy and emissions specialists [10].

Heritage Building Information Modelling (HBIM) offers a promising solution for managing these challenges. As a multi-dimensional tool, HBIM allows the creation of parametric models to provide information in the sixth and seventh dimensions, incorporating sustainability, energy efficiency, and environmental assessment. HBIM can effectively model and manage complex systems in heritage buildings by integrating energy efficiency measures and preserving historical values [8,11]. This paper evaluates the application of HBIM in simulating energy performance in heritage buildings, focusing on a case study heritage building in New Zealand. This HBIM-based approach involves balancing between increasing energy performance and maintaining historic integrity. The methodology consists of creating a digital model of the test heritage spaces, followed by baseline energy analysis, and comparing different insulation materials to achieve this goal. Autodesk Revit's Insight tool was used for energy simulation. Revit's Insight tool operates using Energy Plus engines, which are validated and widely used for dynamic building energy performance simulations. These engines simulate energy use based on input parameters, including climate data, material properties, building geometry, and usage schedules. This research simulates various retrofit strategies, such as shading and roof and wall insulation improvements, within the HBIM environment [12].

The retrofitting of heritage buildings is particularly crucial in New Zealand, where architectural heritage forms a vital part of the nation's cultural identity. This research aims to use advanced technology, such as HBIM, to bridge the gap between heritage conservation efforts and improving sustainability and to propose retrofit strategies that can increase energy efficiency while preserving the cultural significance of these buildings. This research contributes to New Zealand's historic building stock's long-term sustainability and low-carbon future [9,10].

2. Literature Review

Sustainability and heritage are two terms increasingly mentioned together, as cultural heritage—both tangible and intangible—is now viewed not only as a product of a specific society but also as closely tied to broader principles of sustainable development, a perspective embraced by international organisations [13].

Sustainable development, defined by three pillars—economic, social, and environmental—requires careful consideration of modern needs and historical integrity. Heritage buildings embody cultural, historical, and architectural significance and contribute to communities' social and economic vitality. Retrofitting these structures to align with modern sustainability goals (such as energy efficiency and reduced carbon emissions) supports the environmental and economic pillars while maintaining cultural relevance [14].

According to ICOMOS New Zealand, a heritage building is a place that possesses cultural heritage value in New Zealand, including buildings, structures, monuments, and areas. This includes any land, and anything fixed to land, that contributes to an understanding and appreciation of New Zealand's history and cultures [15]. Heritage buildings often face unique challenges when improving energy performance due to their age, construction materials, and historical significance. Energy refurbishment is a significant challenge in a historic building [16]. High energy consumption often occurs in historic structures due to a lack of modern insulation and reliance on outdated systems. Using natural daylight, ventilation, and thermal mass, which follow passive design principles, offers opportunities to improve efficiency [17].

The United Nations Sustainable Development Goals (SDGs), especially those that focus on sustainable cities, responsible climate action, and consumption, are aligned with preserving and restoring heritage buildings. For instance, SDG 11 promotes sustainable towns and communities, which includes protecting cultural heritage [18]. At the same time, SDG 13 encourages measures to combat climate change, a goal where energy-efficient retrofitting of heritage buildings plays a key role. Advanced techniques and a deep understanding of each building's cultural context and heritage are required to minimise environmental impacts without compromising their historical essence [19]. This approach conserves resources and reinforces the buildings' role in contributing to a community's identity, so a sustainable, culturally rich future will happen. Sustainable development and heritage preservation work together to balance the urgent need for environmental responsibility with the conservation of cultural values, ultimately aiming for a comprehensive workflow, including assessment, energy audit, and stakeholder engagement, that enables the achievement of energy-efficient and environmentally friendly spaces in heritage buildings and the preservation of heritage features.

Energy aspects in retrofitting historic buildings are an essential challenge encompassing historical, artistic, and technological facets concerning improving energy output and reassurance [20]. The combination of techniques used for sustainable retrofitting in heritage buildings helps to transform them into environmentally friendly buildings and preserve their historical values over time for future generations. According to Figure 1, 18.7% of all buildings in New Zealand were more than 65 years old in 2022 [21]. Older buildings (i.e., more than 50 years old) may present opportunities for better efficiency [17], especially in reducing energy use. Many structures employ passive design principles that leverage natural elements such as daylighting, solar orientation, and ventilation. The reliance on passive strategies stems from the limited heating and cooling technologies available when these buildings were constructed. Passive survivability ensures optimal conditions are maintained even during a power or fuel failure [22].

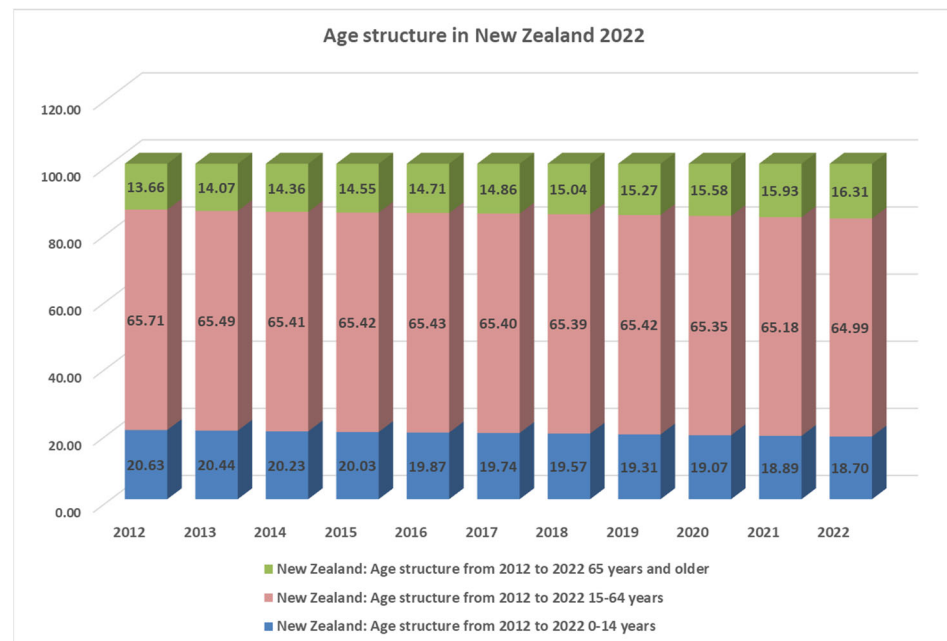


Figure 1. New Zealand: Age structure from 2012 to 2022 [21].

While energy simulation tools are practical and valuable in new buildings and can provide a comprehensive overview of the building's energy demand and consumption through steady-state or dynamic calculations, their use in heritage buildings faces challenges. These challenges are related to the lack of reliable input data for the various components [23] and the limitations of the simulation models. Such limitations include the capacity to accurately describe the geometric peculiarities of heritage buildings, such as the presence of thermal bridges, and heat flow models restricted to one-dimensional flow, which often neglect the hygroscopic phenomena [24] required. IRT can help better define thermal bridges, air leaks, humidity issues, and irregularities in material installation.

BIM has been recognised as the most fundamental transformation related to Information Technology (IT) in the construction industry. Among the diverse capabilities of BIM, visualisation, data management, and cost estimation are invaluable in facilitating energy management, emergency preparedness, and retrofit planning tasks [25]. In the documentation of historic structures, challenges in aligning data acquired through conventional approaches lead to a limited comprehension of the actual state of the building. Within this context, BIM can be considered a suitable platform for preserving heritage buildings due to its ability to document and support data flow in restoration projects [26].

Historic Building Information Modelling (HBIM) commenced around 2007, primarily emphasising architectural surveys or building registration utilising point clouds [27]. Fai et al. (2011) employed Autodesk's Navisworks software to integrate data from diverse sources and georeferenced the semantic features of intangible heritage alongside their digital reconstructions [28]. They underscored the need for additional research in HBIM, emphasising the significance of documenting historical buildings with quantitative data and qualitative information like historical photographs and oral narratives [28].

Volk (2014) stated that HBIM refers to a historic building's dynamic database that enhances the coordination of construction documents [29]. This involves organising and recording the geometry, spatial relationships, geographic information, and other characteristics of building elements in a structured manner [29].

The HBIM model has been developed by incorporating corresponding data on materials, stratigraphy, geometry, and historical information [30]. Counsell and Taylor (2017) highlighted the importance of incorporating detailed information in HBIM models, in-

cluding materials, structural elements, specific challenges, and the evolving social, environmental, cultural, and economic factors that influence the building's use [31]. They suggested that this rich information can be repurposed for managing construction and maintenance projects. Following this approach, similar methodologies could be applied to effectively manage HBIM digital repositories, using filters and tools to analyse and visualise 3D models while gathering user feedback for continuous enhancement [32–34]. Furthermore, integrating Building Information Modelling (BIM) and energy assessment tools can help select appropriate materials to reduce the overall energy consumption of heritage buildings [35].

Tommasi (2016) proposed using HBIM throughout the building life cycle to monitor maintenance activities [36]. Maxwell (2016) [37] pointed out that different recording methods are necessary for various interventions on heritage buildings, such as restoration, maintenance, and reconstruction. Different material parameters should be compared to propose various retrofitting scenarios, integrating them into HBIM and implementing them while considering the cultural heritage value of the buildings. Appropriate materials should be selected based on the buildings' needs and priorities [38]. It was also asserted that the environment surrounding historical buildings should be safeguarded and documented as part of the HBIM methodology [37].

In this context, an integrated, performance-based design and planning workflow is increasingly recognised as essential [39]. The use of integrated digital workflows enables the coordinated optimisation of multiple design parameters, including energy efficiency, decarbonisation, the integration of renewable energy sources, life cycle and circularity considerations, affordability, and indoor air quality, all while maintaining attention to aesthetic and architectural values [40]. The energy performance HBIM model serves as a centralised information repository, supporting the efficient management of large volumes of data, including documents, numerical parameters, and geometrical elements, generated through analysis and simulation processes, improving the energy performance of built heritage. Simulation tools such as Autodesk Revit, Insight, EnergyPlus, and DesignBuilder are utilised to model and analyse various energy use scenarios within the proposed framework. Revit supports the integration of diverse building elements. When combined with Insight for energy analysis, the methodology extends beyond material cost evaluation to encompass comprehensive assessments of annual energy consumption. This includes parameters such as daylighting, occupancy controls, lighting efficiency, and overall energy expenditure, offering a holistic understanding of a building's environmental impact. The integration of cost estimation with detailed energy analysis provides stakeholders with valuable insights for informed decision-making regarding material selection, cost-effectiveness, and sustainability.

Overall, the proposed approach offers a robust and practical solution for optimising building performance, enhancing economic outcomes, and promoting environmental responsibility in contemporary construction practice. Insight, in particular, is considered an interactive tool that supports both clients and designers in selecting appropriate equipment while evaluating associated life cycle costs [41]. Key benefits of the HBIM-based model include its clarity, efficiency, and usability, ensuring that energy performance data remain durable, accessible, and actionable for various stakeholders engaged in preserving and retrofitting heritage buildings [42].

3. Methodology

This study explores the application of Historic Building Information Modelling (HBIM) as a methodological framework for the sustainable retrofitting of heritage buildings in New Zealand. Specifically, the research objectives are as follows:

1. Assess the energy performance of historic buildings using HBIM-based simulation and analysis tools.
2. Examine suitable sustainable retrofit strategies that preserve historical buildings' heritage values and authenticity.

These objectives guide the development and use of an HBIM model of the Fraser Gallery to explore how digital heritage documentation can inform energy-conscious interventions without compromising conservation principles.

A case study methodology was employed. Case studies are commonly used for theory building and serve as singular experiments [43]. Robert Yin's framework was used to justify the case study method in this research, emphasising the suitability of case studies for exploring contemporary phenomena in real-life conditions, especially when the borders between fact and context are not distinctly defined [44]. Yin identifies case studies as a robust method for addressing "how" and "why" research questions, particularly in areas requiring in-depth analysis of complex and multifaceted issues. Given the focus of this research on the application of Heritage Building Information Modelling (HBIM) for retrofitting historic buildings to enhance energy performance and sustainability, the case study method is particularly suitable.

New Zealand's masonry heritage structures were predominantly built before the 20th century. Analysing the age trends of these buildings reveals a surge in construction activity from the early stages of European settlement, peaking around 1930 and then declining. The characteristics of unreinforced masonry (URM) buildings in New Zealand are well defined. Most were constructed between 1880 and 1950 using clay bricks [45]. In the national building database (QV), buildings with a brick veneer but non-masonry load-bearing systems (e.g., timber-framed structures with a brick veneer) are classified as "mixed materials". While it is acknowledged that the label "brick" may also refer to materials like brick veneer, adobe, or rammed earth, the extracted data is considered a legitimate representation of New Zealand's URM building stock [46].

They often cannot be demolished due to their heritage status. Therefore, it is clear that they will have a long lifespan and will still be standing for future generations if preserved [47]. New Zealand's masonry building heritage has a relatively recent origin, from 1833 to the present, totalling less than 200 years. Consequently, examining New Zealand's masonry building inventory has a narrower focus than global benchmarks [46]. The shorter historical timeframe facilitates more accurate documentation and reporting of unreinforced masonry construction practices in New Zealand, which is often not achievable in nations with a more varied history of masonry construction [48].

Many heritage buildings (HBs) have undergone periodic adaptations or revitalisations throughout their life cycle to prepare them for new uses, forming an integral part of their ongoing narrative that necessitates their conservation [5]. Ensuring their viability in the future involves the adaptation (adaptive reuse), repair, rehabilitation, and/or retrofitting of many of these buildings to address contemporary societal challenges. This process considers user expectations related to thermal comfort and energy efficiency [49].

This case study focuses on an unreinforced masonry (URM) building currently known as the Fraser Art Gallery and located at 25 Prince Street (Table 1). The Fraser Art Gallery, due to its complex historical context, structural changes, and heritage classification, provides compelling reasons for using HBIM, as the building requires the collection and analysis of detailed structural, historical, and cultural data. The building was initially constructed in 1883 over a gently sloped site and was part of a prosperous neighbourhood created and developed in the 1870s and 1880s. This building was originally the stables of the two-storey building located at 25 Princes Street. This building belongs to the Auckland Council; the ground floor is currently used as an art gallery. There are two flats on the first floor. A

structural upgrade was carried out in 1986, which featured replacing the original timber ground floor with a concrete slab and installing plywood sheets over the first floor of the building. The New Zealand Heritage website classifies the building as a historic structure with a category two heritage value. Internal and perimeter walls are constructed using unreinforced masonry (URM) clay bricks, which support timber joists and floor beams at the first-floor level. Timber rafters with collar ties span between the perimeter walls and support lightweight cladding at the roof level. In the longitudinal and transverse directions, the primary lateral system consists of perimeter three-leaf and internal two-leaf URM walls. The building geometry was determined from a visual inspection and reference to structural drawings in the Auckland Council property file [50].

Table 1. Case study characteristics [50].

Built Year	1883
Architect	Unknown
Current Use	Art Gallery
Former Use	Stable
Cladding	URM walls
Typical Floor Area	98 m ²
Storey	2
Heritage List	Category 2
Status	Partially renovated and unoccupied

This study emphasises the modelling of URM heritage buildings constructed with brick masonry, which, although relatively small in number, represent a significant part of New Zealand’s architectural heritage. According to Russell and Ingham (2010) [46], nearly all URM buildings in the country fall within the 80–130-year age range (as of 2010) and make up approximately 8% of the national building stock by floor area, with an estimated value of NZD 1.5 billion. In urban centres such as Auckland, around 16% of heritage buildings date back to before 1940 and are built with brick masonry, underscoring the importance of their conservation and conditions and the evaluation of sustainable retrofit options. To support this, Polycam software was used for 3D scanning [46]. A building energy simulation was conducted using the Insight plug-in within Autodesk Revit. The Heritage Building Information Modelling (HBIM) was developed using archival and historical documentation, incorporating alterations made throughout the building’s life cycle, as well as data obtained from site visits, photographs, and in situ surveys. As a significant heritage structure that has been adapted for modern use, the building exemplifies the intersection between heritage conservation and contemporary energy efficiency requirements.

3.1. Case Study Description: Fraser Art Gallery

This study focuses on one publicly owned historical case study, the Fraser Art Gallery in Auckland, New Zealand.

3.1.1. Stables (Former)—Exterior

The case study building is a former stable, featuring a one-and-a-half-storey structure with an L-shaped floor plan and a gabled roof clad in corrugated iron, as shown in Figures 2–4. A single-storey extension has been added at the southeast corner, while the rear (west) wall directly abuts Bowen Lane. The exterior is predominantly red brick, accented with horizontal bands of cream-coloured brick that visually connect the door and window

openings. The east façade, which faces the stable yard, includes a central dormer and remnants of a historical hoist mechanism once used to lift goods into the upper-level warehouse. Much of the ground floor on this side has since been incorporated into the newer single-storey extension [51].



Figure 2. External facades of Fraser Art Gallery, 25 Princess Street, 2024, author.

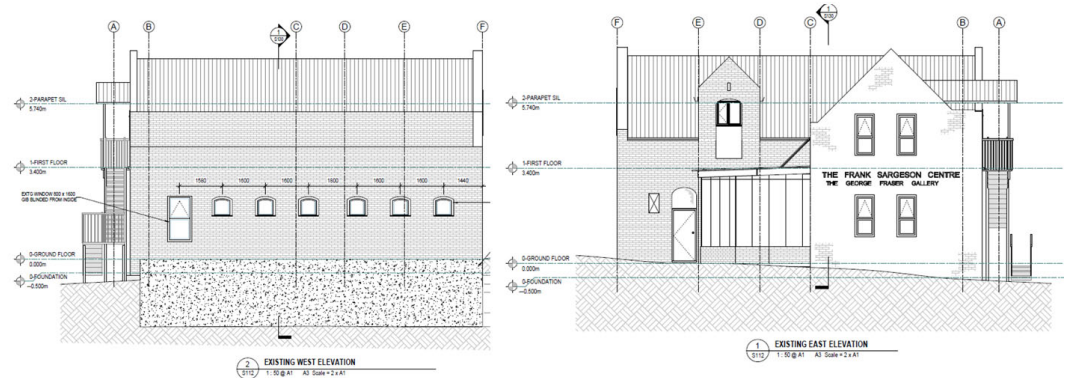


Figure 3. Building’s east and west elevations [52], 2021.

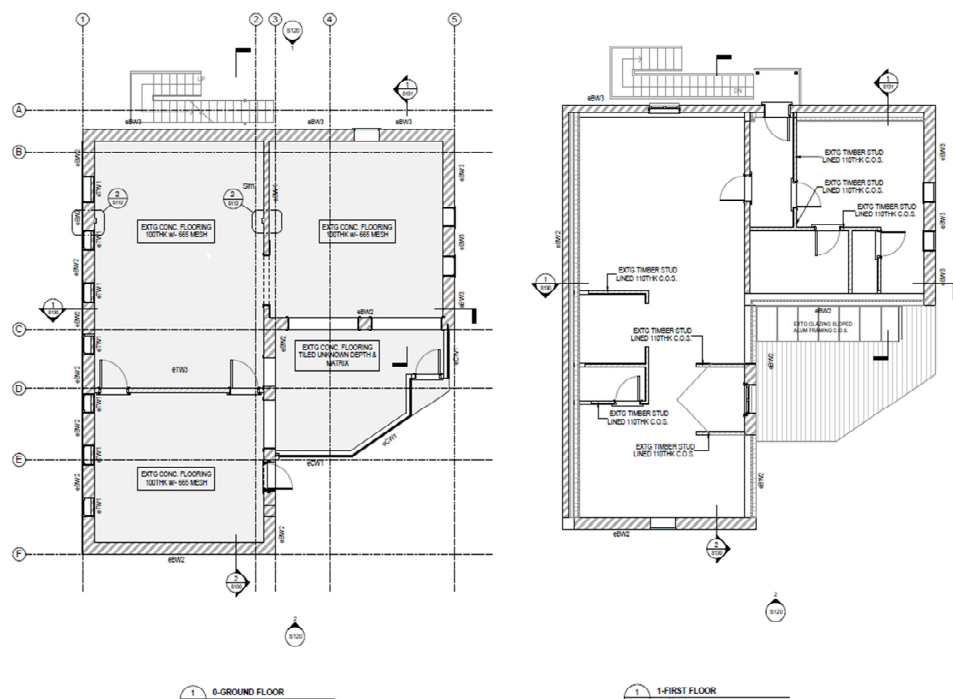


Figure 4. Ground- and first-floor plans [52], 2021.

The north elevation overlooks the adjacent yard at 23 Princes Street. It features a sash window at ground level and a modern door that provides access to two small flats on the upper floor. On the west elevation, six arched windows light the ground-floor stalls. The south elevation is relatively plain, marked only by a single band of cream brickwork [51].

3.1.2. Stables (Former)—Interior

The interior of the former stable has been converted into two large, interconnected exhibition rooms (Figure 5a). The west gallery, originally used as a horse stable, and the east gallery, formerly used for storing horse-drawn vehicles, have been renovated to accommodate their new functions. The west gallery now also contains a small office and kitchen in the southeast corner, and a toilet area has been added in the southwest corner. Several original window and door openings along the west wall have been covered with plywood. In the southern section of the east gallery, glass walls have been introduced, allowing natural light to enter through a skylight. The original brick walls remain exposed and are now painted white, preserving the character of the space while brightening the interior. On the upper floor, two residential flats retain their original windows and exposed timber roof trusses. However, much of the interior has been modernised using contemporary materials, as illustrated in Figure 5b,c.



Figure 5. Fraser Art Gallery, interior space (a), ground floor, (b,c) and first-floor apartments, 2024.

Sustainable retrofitting of heritage buildings often requires innovative solutions to address their unique challenges, including irregular structures, ageing materials, and strict conservation regulations. Previous studies have identified Heritage Building Information Modelling (HBIM) as a valuable tool for integrating thermal and energy performance analysis while supporting historical and architectural values [26]. This research explores the potential of HBIM to assess energy performance, evaluate retrofit strategies, and balance the historical, architectural, and functional significance of heritage structures. Using Yin's case study method, this study provides a comprehensive analysis of the challenges and opportunities involved in retrofitting the Fraser Art Gallery while offering insights that may apply to other heritage contexts [44].

A set of key parameters relevant to energy and environmental analysis was identified and applied to the selected case study building to support the research objectives.

Building material

Building age and size

Architectural details

Historical and current use

To address Objective 1, a detailed digital HBIM model of the case study building was developed. This model facilitated an assessment of the building's energy perfor-

mance and supported appropriate sustainable retrofit strategies. It accurately captured the historical and physical characteristics of the building, including construction materials and key architectural features [53]. For Objective 2, various retrofit scenarios, such as window shading, internal wall insulation, and roof and floor insulation enhancements, were tested within the HBIM environment. These interventions were evaluated based on their potential to improve energy performance while balancing multiple building values, including energy savings, architectural and historical significance, aesthetic integrity, and functional or economic viability [2]. To conduct the energy performance analysis of the Fraser Gallery, Autodesk Revit Insight was selected due to its strong interoperability with BIM environments and its capability to provide real-time feedback on energy consumption. Insight allows a seamless transition from the HBIM model without requiring additional geometry simplification, which ensures data consistency and reduces modelling errors. It is particularly suitable for early-stage performance analysis, offering cloud-based simulation features and parametric adjustments for design optimisation, including solar gain and daylighting [54].

In addition to digital simulation, infrared thermography was employed to examine the building envelope's current thermal performance. This non-invasive technique enables the identification of thermal bridges, moisture infiltration, and areas of heat loss—especially important in heritage buildings where intrusive analysis is not permitted. The decision to combine these tools reflects recommendations in recent HBIM and sustainable retrofit research, where integrated workflows are emphasised for holistic decision-making [55]. This approach ensures that the selected retrofit strategies are informed by both digital prediction and on-site empirical evidence, balancing conservation needs with performance targets.

After comparing the outcomes, the most effective retrofit strategies were selected based on their ability to improve energy efficiency without compromising the building's heritage value. These strategies were further tested by adjusting relevant building features within the HBIM model to optimise performance. The resulting findings are presented in the following section, and the overall research process is illustrated in Figure 6.

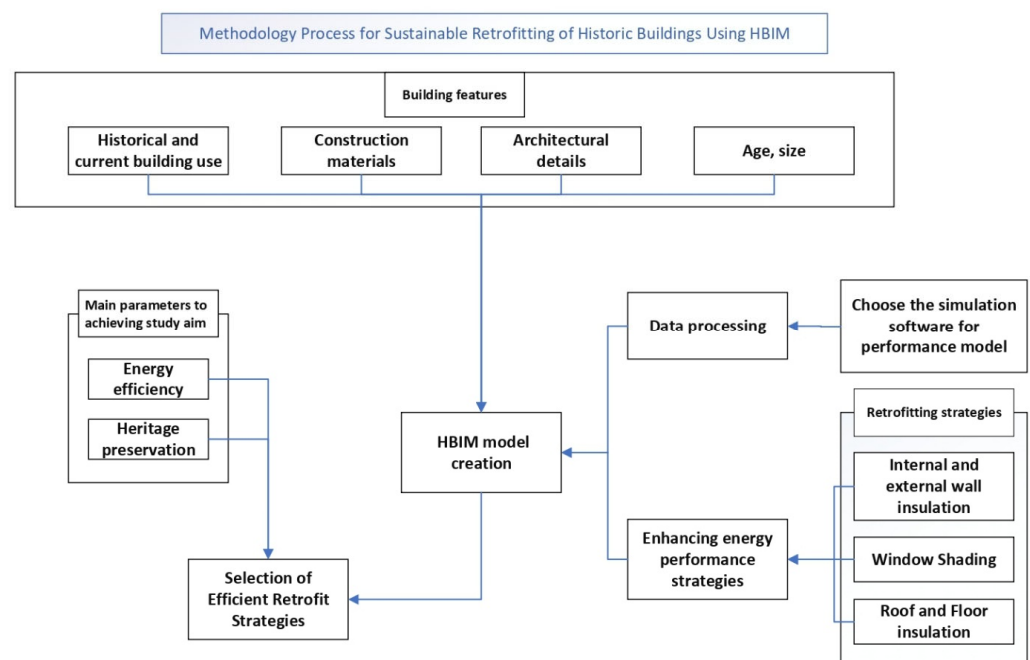


Figure 6. Research diagram showing the methodological approaches.

4. Results and Discussion

4.1. HBIM Model

The existing documentation, provided as 2D drawings in .dwg and .pdf formats, indicated that the case study masonry building—Fraser Art Gallery—had undergone several restoration and conservation interventions over time. As shown in Figure 7, various materials were introduced throughout the building’s life cycle to improve structural performance and accommodate functional needs. Laser scanning was conducted and integrated with the existing 2D documentation to develop a detailed digital model. The resulting data were imported into Autodesk Revit to create the HBIM model (Figure 8). Although laser scanning was used to capture the existing geometry of the Fraser Gallery, in this research, scanning and Building Information Modelling (BIM) were treated as distinct processes with separate functions. The laser scans were used to capture accurate geometric and spatial data for reference, while the HBIM model was developed manually in Autodesk Revit using multiple data sources, including archival documents, structural drawings, site surveys, and photographs. These tools were used in parallel but were not directly linked through automated processes. For Building Energy Modelling (BEM) purposes, the model incorporated key building information, including construction year, gross floor area (GFA), volume, and characteristics of the building envelope [54]. The completed HBIM model of the case study is presented in Figure 9.

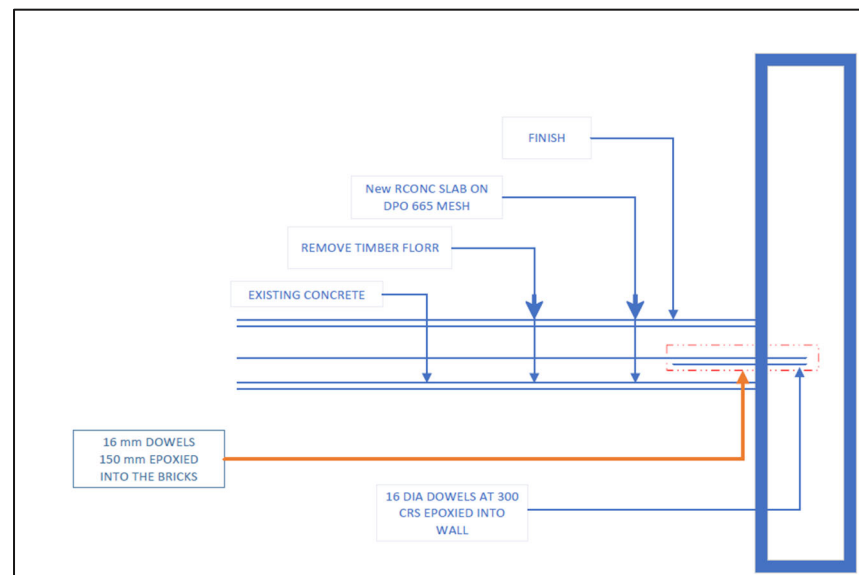


Figure 7. The original timber ground floor has been changed to a 100 mm concrete slab on grade reinforced with 665 mesh. Fill with a minimum depth of 100 mm has been provided below the slab. The slab is connected to the URM walls with D16 dowels [50].

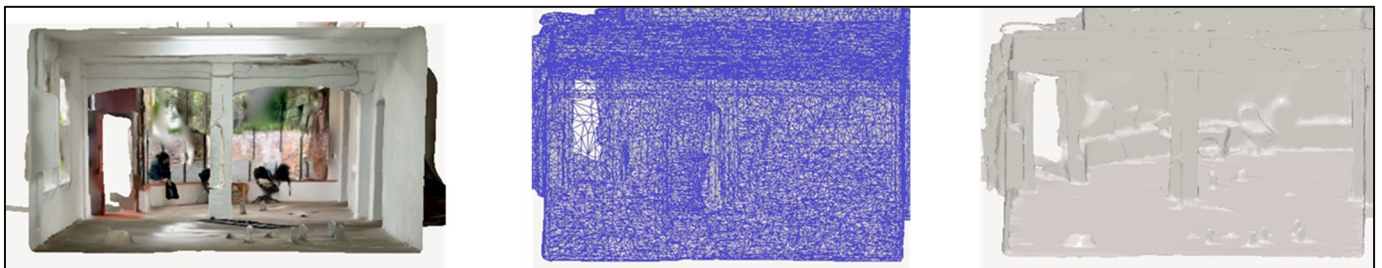


Figure 8. Gouraud shaded (**Right**), triangulated mesh (**middle**), 3D scans (**left**).

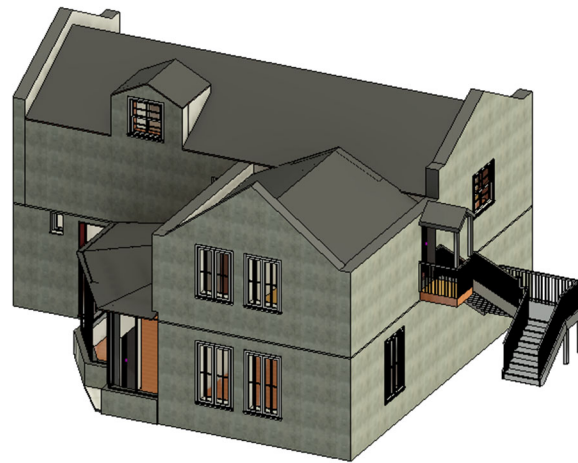


Figure 9. Three-dimensional model of the case study, 25 Princess Street (Revit, 2023).

Based on the information in the 2D plans, an architectural model of the case study building was developed using the BIM design platform Autodesk Revit 2003 (Figure 9) [56]. Each historical component was carefully modelled to reflect the building's existing architectural features. Revit includes a range of standard elements commonly found in historic structures, which were incorporated where appropriate to represent actual building components. Various 3D parametric models were also linked to ensure a multidisciplinary and integrated approach, enabling the incorporation of geometric and technical characteristics of the building's components and systems into the HBIM model.

When modelling existing buildings, particularly historic ones, a standard limitation is the incomplete availability of accurate input data. As a result, the HBIM model required continuous updates to reflect the building's evolution across its various life stages and to ensure accuracy and performance. The developed as-built model represents the correct stratigraphy of changes throughout the building's life cycle [57], with each architectural component, including customised historical elements, faithfully reproduced to maintain historical integrity [58].

4.2. Objective 1: Assess the Energy Performance of Historic Buildings Using HBIM-Based Simulation and Analysis Tools

The foundation for accurate solar radiation modelling is built on key environmental parameters of the building, such as geographic location, weather data, latitude, longitude, and seasonal variations. Building-specific parameters, such as actual north orientation and facade geometry, are also factored into this analysis, ensuring that the unique characteristics of the Fraser Gallery are accurately accounted for.

4.2.1. Solar Analysis and Energy Performance

By leveraging HBIM, the simulation accurately captures the building's existing conditions and orientation. It gives a comprehensive perspective on energy performance analysis using the Insight 360 plug-in, including different analyses.

The solar analysis, performed using the solar analysis tool in Revit, provided energy performance details such as the analysis grid density, solar study type (radiation and heat gain), and seasonal periods (Figure 10). The results show seasonal solar radiation peak variations on the east and south facades.

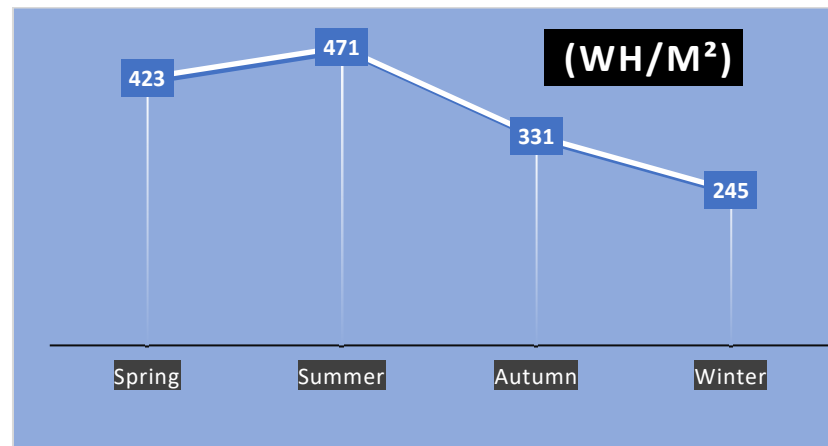


Figure 10. Summarises the solar radiation variations across seasons, author.

Spring: Radiation increases compared to winter, peaking at 423 Wh/m².

Summer: High sun angles and clear weather produce peak solar radiation levels of approximately 471 Wh/m².

Autumn: Moderate levels of radiation, peaking at 331 Wh/m².

Winter: Lower sun angles and shorter daylight hours reduce the peak to 245 Wh/m².

These findings provide initial data for designing sustainable retrofit interventions, such as improved shading systems and insulation, that enhance energy efficiency while preserving the building's heritage. Such strategies will ensure that the Fraser Gallery maintains and achieves its historic integrity while focusing on increasing energy efficiency and sustainability.

4.2.2. Infrared Thermography for Assessing Energy Loss

In addition to the HBIM-based solar analysis, infrared thermography (thermal imaging) was used to assess energy loss through the building envelope of the Fraser Gallery. This non-invasive technique enables the detection of temperature variations across large surface areas, making it particularly useful for identifying thermal bridges, insulation gaps, and material deficiencies—key issues in heritage buildings where preserving the original structure is essential [59].

As HBIM focuses on accurately modelling historic structures based on laser scans, photogrammetry, and archival research, the geometry, material properties, thermal characteristics, and orientation of the Fraser Gallery in Figures 11 and 12 are precisely captured in the HBIM model, ensuring that energy simulations reflect real-world conditions [60]. HBIM-based solar analysis identifies excessive solar gain areas, leading to improved shading designs [61]. HBIM uses simulation before actual intervention to ensure that interventions respect the original architectural context while increasing energy performance. This method ensures that modifications meet energy efficiency goals and heritage conservation requirements.

The building was surveyed using a Testo 865 thermal imaging camera (Testo SE & Co. KGaA, Titisee-Neustadt, Germany), focusing on the internal envelope, including walls, ceilings, doors, and windows, as shown in Figures 11 and 12. The thermal scans revealed significant loss, particularly along the perimeter walls and through the timber doors and single-glazed windows. Materials commonly used in buildings from this period, such as brick and plaster, exhibit high emissivity, making them well-suited for thermographic analysis. These findings confirm that thermography is an effective diagnostic tool for identifying problem areas and evaluating the effectiveness of retrofitting interventions, especially when integrated into a broader HBIM-based energy assessment strategy [62].

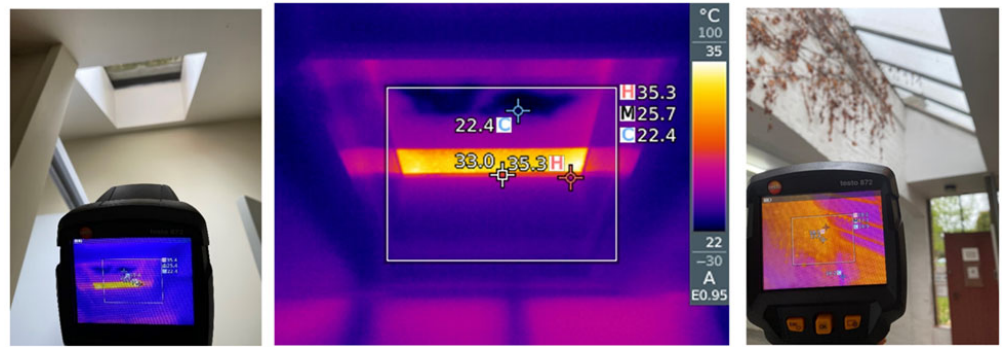


Figure 11. Thermographic image of skylights, author, 2024.

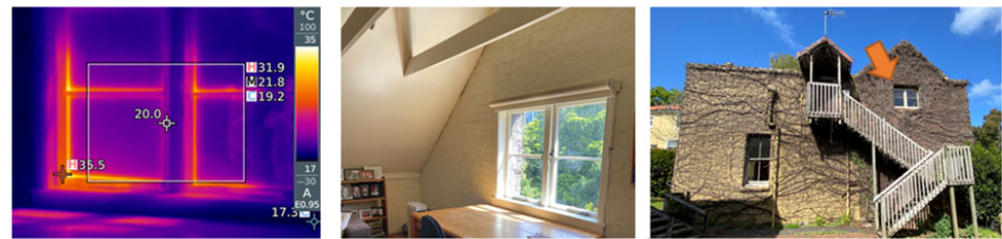


Figure 12. Thermographic image of internal walls and windows, which is indicated by the arrow in the image, north-facing, author, 2024.

4.2.3. Thermal Performance and Energy Simulation Using HBIM

HBIM provides an effective platform for analysing thermal performance and supporting the design of energy-efficient retrofit interventions in heritage buildings. By integrating with energy simulation tools such as Autodesk Revit's Energy Analysis and Insight 360 (powered by Energy Plus), HBIM enables detailed assessments of solar gain, shading effects, and overall energy performance [58].

For the Fraser Gallery case study, an energy model was created in Revit using inputs such as building geometry, location, weather data, and thermal properties obtained through archival documentation and site visits. This model was used to perform seasonal energy simulations, considering New Zealand's climatic variations and the orientation of the building (Figures 13 and 14). Figure 13 shows the onsite climatic variations of the heritage building, while Figure 14 provides an overview of the environmental parameters in relation to the building's location.

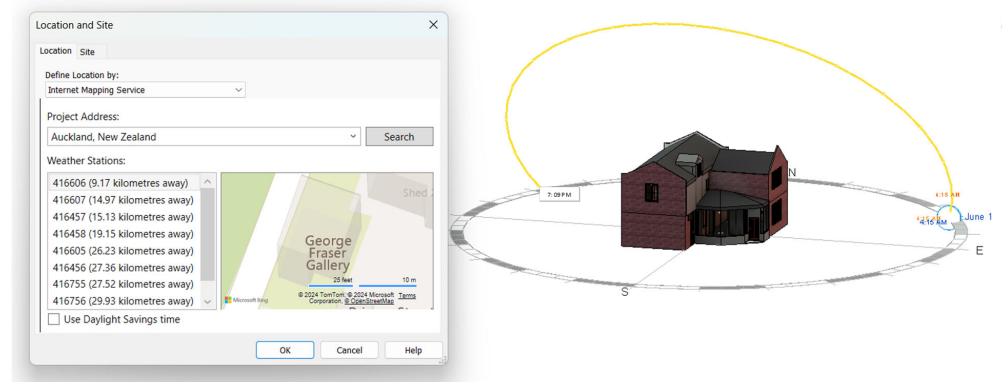


Figure 13. Location and sunlight direction, Revit 2023, author.

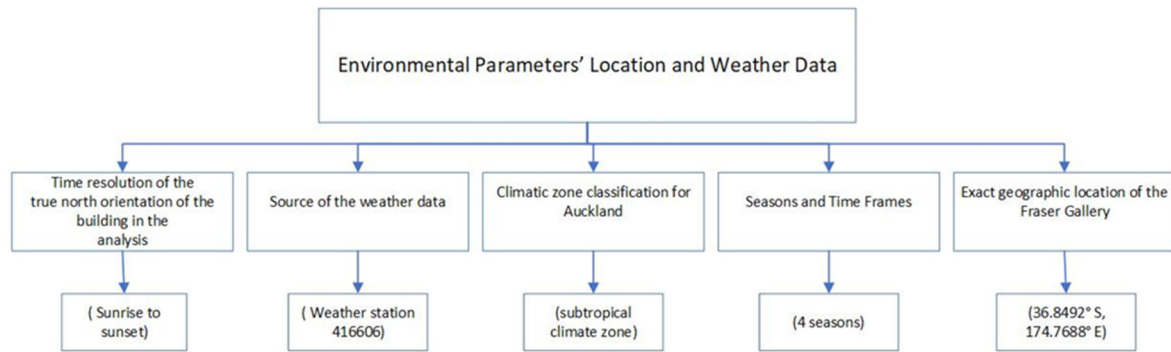


Figure 14. Environmental parameters' location and weather data.

Using Insight 360, the cumulative insolation on façades and windows was analysed to identify areas of significant heat gain and loss. Figures 15–18 illustrate this analysis across seasons, where yellow areas indicate surfaces with high solar exposure and purple areas represent low-exposure zones. This helped identify key problem areas, such as thermal bridging and insufficient insulation, which informed the selection of appropriate retrofit strategies.

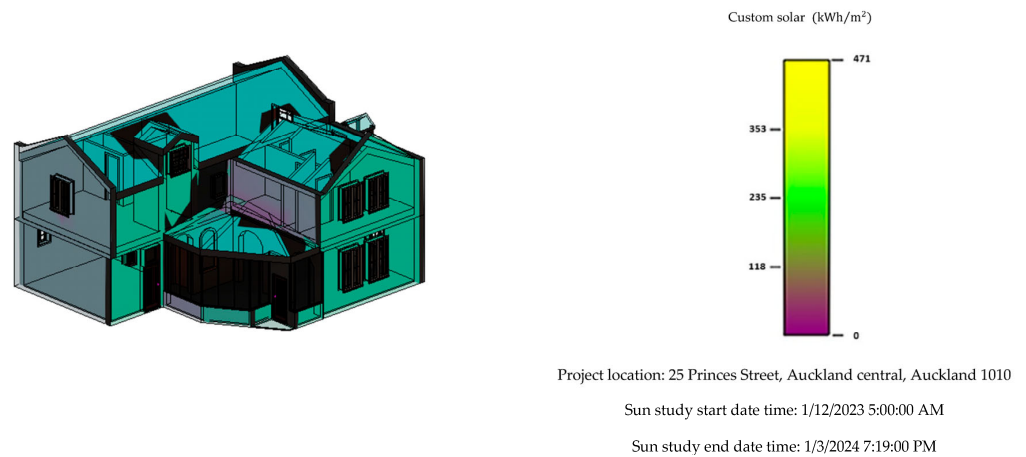
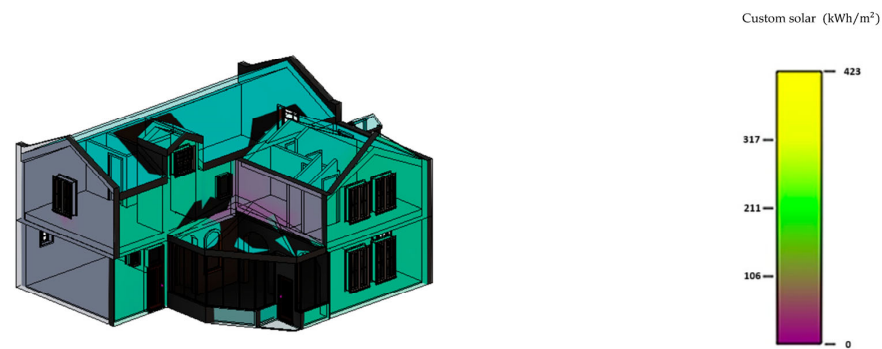


Figure 15. Summer season analysis. Yellow = walls directly exposed to sunlight; purple = walls with minimal solar exposure.



Figure 16. Winter season analysis. Yellow = directly exposed to sunlight; purple = walls with minimal solar exposure.

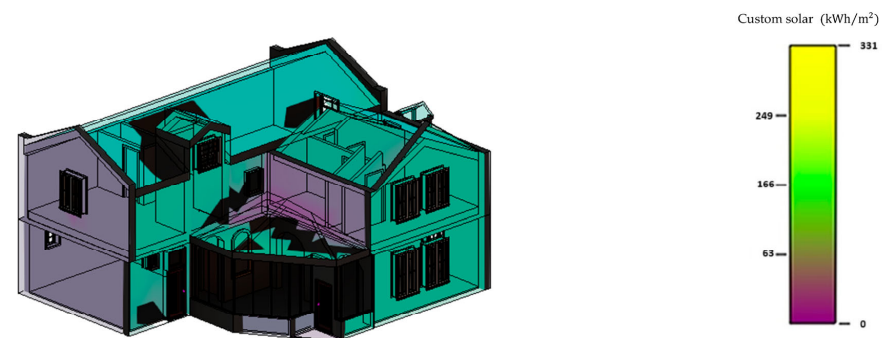


Project location: 25 Princes Street, Auckland central, Auckland 1010

Sun study start date time: 1/9/2024 6:47:00 AM

Sun study end date time: 1/12/2024 5:56:00 PM

Figure 17. Spring season analysis. Yellow = directly exposed to sunlight; purple = walls with minimal solar exposure.



Project location: 25 Princes Street, Auckland central, Auckland 1010

Sun study start date time: 1/3/2024 6:10:00 AM

Sun study end date time: 1/6/2024 6:57:00 PM

Figure 18. Fall season analysis. Yellow = walls directly exposed to sunlight; purple = walls with minimal solar exposure.

The energy simulation and performance analysis carried out within the HBIM environment played a critical role in the optimisation of retrofit solutions, ensuring they align with both sustainability goals and heritage conservation principles [55].

Summer Analysis

During the summer season, the building was exposed to significant solar irradiance due to Auckland's high sun angles and predominantly clear weather conditions. Revit's solar analysis revealed a maximum solar energy gain of approximately 471 Wh/m^2 , while shaded surfaces received as little as 0 Wh/m^2 . Figure 15 illustrates the summer heat gain distribution across the east and south façades.

Winter Analysis

The winter analysis showed a notable reduction in solar exposure, consistent with Auckland's lower sun angles and shorter daylight hours. The maximum solar energy received on window surfaces was approximately 245 Wh/m^2 , which is just over half the summer maximum. Figure 16 presents the winter heat gain distribution for the east and south façades.

Spring Analysis

In spring, solar insolation increased compared to winter but remained lower than summer levels, reflecting the transitional nature of Auckland's climate. The maximum irradiance measured on building surfaces was approximately 423 Wh/m^2 , with shaded areas again recording 0 Wh/m^2 . Figure 17 shows the spring heat gain analysis for the east and south façades.

Autumn Analysis

The autumn analysis indicated lower solar exposure than in spring and summer. The maximum solar energy recorded was approximately 331 Wh/m^2 , while shaded surfaces remained at 0 Wh/m^2 . Figure 18 displays the autumn heat gain analysis for the east and south façades.

4.2.4. Integrating HBIM-Based Solar Analysis and Infrared Thermography for Energy Efficiency Assessment

Integrating HBIM-based solar analysis with infrared thermography (thermal imaging) provides a comprehensive evaluation and enhancement of the energy efficiency of heritage buildings. HBIM solar analysis provides insights into areas of solar heat gain, particularly during warmer seasons, by simulating sun exposure across building façades and glazing elements. This allows for a thorough understanding of how different surfaces respond to sunlight over time. Complementing this, thermal imaging offers a more detailed view of thermal inefficiencies within the building envelope. It detects temperature variations, identifying issues such as insulation gaps, air leakage, and thermal bridges, which may not be fully captured through simulation alone.

In the case of the Fraser Gallery, HBIM simulations indicated high levels of solar gain on the north façade and through skylights during summer months. Thermal imaging validated these findings, revealing corresponding temperature anomalies and insulation weaknesses in the same areas. Together, these two methods provide a multi-layered diagnostic approach, strengthening the accuracy of energy assessments and informing more targeted and conservation-sensitive retrofit strategies.

4.3. Objective 2: Examine Suitable Sustainable Retrofit Strategies That Preserve the Heritage Values and Authenticity of Historical Buildings

HBIM has emerged as a valuable tool for guiding interventions and energy rehabilitation in historic buildings. By identifying, compiling, and integrating semantic building data into a unified digital environment, HBIM supports effective collaboration among professionals involved in conservation and retrofitting projects [39].

To achieve this objective, digital tools and workflows were adapted with sensitivity to heritage values, enabling the evaluation of how renovation strategies impact energy efficiency and preservation goals. Data collected from energy simulations and thermal imaging were embedded within the HBIM model, enabling structured data organisation and the creation of a functional digital library for use in energy simulation software. This integration ensures the completeness of analysis and strengthens the model's utility as a decision-support tool in sustainable heritage retrofitting.

4.3.1. Energy Analysis and Retrofit Strategies

It was also important to investigate the sustainable retrofit strategies suitable for the Fraser Gallery. As such, the HBIM model was developed and enhanced to integrate key energy-related features, including solar analysis, lighting simulations, and infrared thermography. This integration of both visual and numerical data enabled the generation

of accurate and reliable information, supporting efforts to improve energy efficiency and aiding in the selection of context-sensitive retrofit strategies.

This study focused on retrofit approaches that address heat gain, energy loss, and the performance of potential insulation materials. Key interventions identified for the Fraser Gallery included the application of insulation to walls, roofs, and floors, the retrofitting of skylights with shading devices, and the use of advanced materials to enhance energy performance.

Improving the energy efficiency of heritage buildings presents unique challenges, particularly when preserving cultural and architectural values is a core priority. This study adopted an integrated approach, focusing primarily on passive retrofit strategies [63,64]. By leveraging BEM in a passive design context, it becomes possible to enhance energy performance with minimal intervention, making it well-suited for heritage structures where physical alterations must be limited. Incorporating passive strategies within an HBIM framework also facilitates informed decision-making, allowing conservation professionals to evaluate retrofit options based on accurate building geometry, materials, and historical context. Additionally, HBIM enables the simulation and visualisation of passive interventions before implementation, helping to reduce the risk of damaging historically significant features.

4.3.2. Passive Retrofit Design and Material Selection

The purpose of this phase of the workflow was to develop energy and environmental improvement strategies and design retrofit scenarios that require minimal physical intervention. Passive retrofit measures were selected for the Fraser Gallery due to their practicality, cost-effectiveness, and alignment with heritage conservation principles. These strategies were chosen for their compatibility with the historical character of the building and their ability to enhance the building's passive thermal performance without compromising its heritage value. The proposed interventions focused on minimising alterations to the original architectural features while improving energy efficiency.

This study identified thermal insulation as a key intervention to reduce heat loss during winter and mitigate heat gain during summer. Thermal insulation refers to materials that reduce the rate of heat transfer by conduction, convection, and radiation. It lowers heat loss through walls by decreasing thermal transmittance (U-value) while also offering additional benefits such as increased internal surface temperatures and reduced air permeability. Insulation materials were evaluated based on thermal conductivity, density, and specific heat capacity (Table 2). Three categories of insulation materials were considered:

Mineral-based insulation: Offers good thermal performance but has a relatively high environmental impact due to emissions during production [65].

Fossil-based insulation: Provides high efficiency but requires specialised recycling processes [66].

Plant-based insulation: Materials such as cork are renewable and biodegradable but may have lower mechanical strength and durability [67].

Table 2. Comparison of insulation materials for improving the thermal performance of the heritage building [68].





The Characteristics of the Insulating Materials					
Type of Insulation	Thermal Conductivity [W/mK]	Density [kg/m ³]	Specific Heat [J/(kg K)]	Steam Resistance	Compressive Strength [kPa]
Calcium silicate	0.076	200	840–1030	1_2	n.d.
Cork	0.045	120	1560–1800	1_10	100–250
Wool fiber	0.05	165	1600–2400	2_10	40–200

Table 2. Cont.

The Characteristics of the Insulating Materials					
Type of Insulation	Thermal Conductivity [W/mK]	Density [kg/m ³]	Specific Heat [J/(kg K)]	Steam Resistance	Compressive Strength [kPa]
Kenaf and hemp	0.038	40	1500–2200	1_2	n.d.
Limecrete	0.3	2000	840		45.5
Aerogel	0.024	1000–1900	1800		35.7–199.3

Calcium silicate was selected as the primary material for wall insulation due to its compatibility with traditional masonry, moisture-regulating properties, and thermal effectiveness (Table 3). Its ~0.06 W/m·K thermal conductivity provides effective insulation without compromising structural integrity [66]. Its capillary-active nature allows it to absorb and release moisture, preventing condensation and long-term damage to historic masonry [69]. Furthermore, calcium silicate is non-combustible, vapour-permeable, and chemically stable, making it especially suitable for heritage contexts where reversibility, breathability, and fire resistance are critical factors [70]. A 70 mm thickness was applied to achieve an optimal balance between thermal performance and moisture control [71].

Table 3. Potential passive retrofit strategies. Source: Author.

Passive Retrofit Strategy (Low Intervention, High Energy Efficiency)			
Strategies	Key Interventions	Method 1	Method 2
	Internal Wall Insulation	Applying breathable aerogel-based insulation (e.g., silica-based panels) behind existing plaster layers to improve thermal resistance (reducing U-values).	Using hemp–lime or calcium silicate boards to allow moisture permeability, preventing damp issues common in masonry buildings.
	Roof Insulation Enhancement	Natural wool, cork, or rigid board insulation is added under the Gibraltar Board to reduce heat loss and improve thermal inertia.	Implementing vapour-permeable reflective membranes to mitigate overheating during summer.
	Ground Floor Insulation and Thermal Mass Optimization	Installing cork-based or calcium-silicate insulation boards over the existing concrete to enhance thermal resistance while ensuring breathability.	Using limecrete flooring as a sustainable alternative to modern concrete, improving heat retention and reducing heat loss through the ground.
	Adding movable and fixed shading devices for internal and external applications reduces energy consumption through windows and skylights	<p>Fixed Shades</p> <p>External: Using perforated wooden façade panels to reduce solar heat gain while maintaining ventilation and natural light.</p> <p>Internal: Solar control window films are used to minimise infrared and UV radiation while maintaining visibility.</p>	<p>Movable Shades</p> <p>External: Using adjustable external blinds or shutters, which can be tilted to control sunlight and ventilation dynamically</p> <p>Internal: Adding roller blinds with reflective coatings to manage heat gain and glare efficiently</p>

Method 1 refers to the strategy implemented in the building energy simulation model. Method 2 indicates an alternative retrofit option that can be considered in similar heritage contexts, offering comparable performance with different materials or applications.

For the roof insulation, cork was chosen to insulate the existing corrugated iron roofing of the Fraser Gallery. Cork offers a strong balance between thermal performance, moisture management, and sustainability while remaining sympathetic to the building's heritage character (Table 4). With a ~ 0.04 W/m·K thermal conductivity, cork significantly reduces heat transfer through the roof, enhancing indoor comfort. In addition, cork is a renewable, biodegradable, and low-emission material, making it an environmentally responsible option [68]. It is also lightweight and rot-resistant and exhibits good acoustic insulation properties, adding benefits for retrofitting heritage buildings [72].

Table 4. The construction material.

Material	Thickness (mm)	Conductivity (W/ (m.k))	Specific Heat (J/(kg.K))	Density (kg/m ³)
Internal Walls				
Cement//plaster/mortar/plaster	20	0.35	840	950
Two-leaf brick	230	0.9	950	1850
calcium silicate *	50	0.7	950	200
Cement//plaster/mortar/plaster	20	0.35	840	950
Ground Floor				
Gibraltar	12.5	0.21	1.17	800
Cork insulation *	50	0.04	1800	140
Cement//plaster/mortar/plaster	20	0.35	840	950
Existing concrete	100	2	0.9	2300
Roof				
Corrugate iron	1	50	470	7800
Air gap with timber	25	0.04	1	1.2
Cork insulation *	100	0.04	1800	140
Gibraltar board	9.5	0.17	1.12	700

* Green rows show insulation materials suggested in this study.

Installing cork-based insulation boards over the existing concrete on the ground floor is a suitable retrofit strategy for heritage buildings like the Fraser Art Gallery. This method ensures minimal intervention, preserving the original concrete slab, a critical requirement in heritage conservation where structural alterations are discouraged. Cork boards are reversible, meaning they can be removed without damaging the original fabric, aligning with ICOMOS conservation principles. Additionally, this material is vapour-permeable, allowing moisture to pass through and preventing damp accumulation within historic masonry. From a performance perspective, cork's performance is 0.04 W/m·K [18,72].

In addition to thermal insulation, window shading devices, such as external louvred blinds, play a significant role in optimising energy performance in heritage buildings. These blinds extend perpendicularly from the window surface, with a width equal to the window height and a depth proportionate to it. Depending on the specific dimensions applied, such shading systems can contribute to a measurable reduction in energy consumption. The effectiveness of window blinds is influenced by various factors, including window size, orientation, and solar heat gain characteristics. In this study, the model analysed louvre configurations with $1/6$ of the window height. These configurations produced optimal results for windows facing all cardinal directions, highlighting the potential of shading devices as a low-impact, passive strategy that complements insulation efforts while preserving the building's historical character [73]. Table 3 outlines the recommended strategies, particularly suitable for projects with budget constraints that demand low-impact solutions.


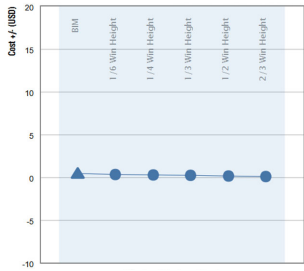
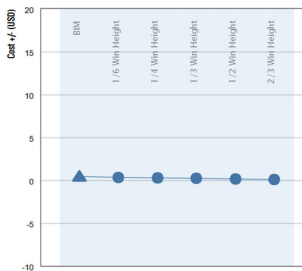
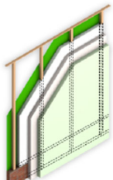
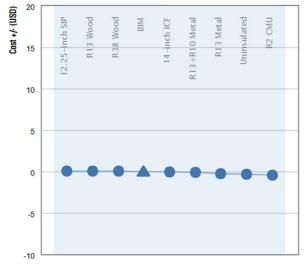
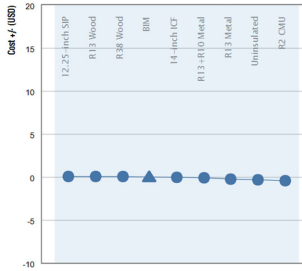
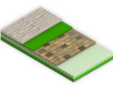
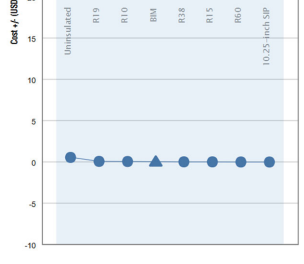
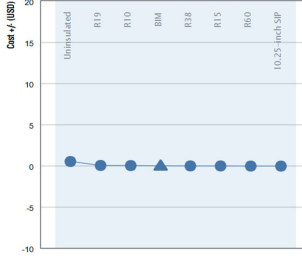
4.3.3. Energy Performance Evaluation and Implications for Sustainable Retrofitting

The passive retrofit strategies proposed in this study were evaluated through energy simulations made possible by HBIM interoperability. Autodesk Insight was used to assess

the impact of various retrofit scenarios on the energy performance of the Fraser Gallery, using data exported from the HBIM model. The simulations demonstrated significant improvements in energy efficiency, particularly through the application of thermal insulation to the building envelope.

Table 5 presents a comparison of envelope efficiency factors before and after the proposed interventions, while Table 4 outlines the thermophysical characteristics of the building materials used. The insulation materials introduced in this study are highlighted in green in Table 4. Figure 19 compares U-values for key architectural elements before and after retrofit implementation, clearly illustrating performance gains.

Table 5. Comparison of building envelope efficiency factors: current vs. proposed.

Efficiency Factor	Current Conditions	Proposed Condition
<p>Shades can reduce HVAC energy use. The impact depends on other factors, such as window size and solar heat gain protection</p>  <p>Window Shades North</p>		
<p>Represents the overall ability of wall constructions to resist heat losses and gain</p>  <p>Wall Construction</p>		
<p>Represents the overall ability of roof constructions to resist heat losses and gain</p>  <p>Roof Construction</p>		

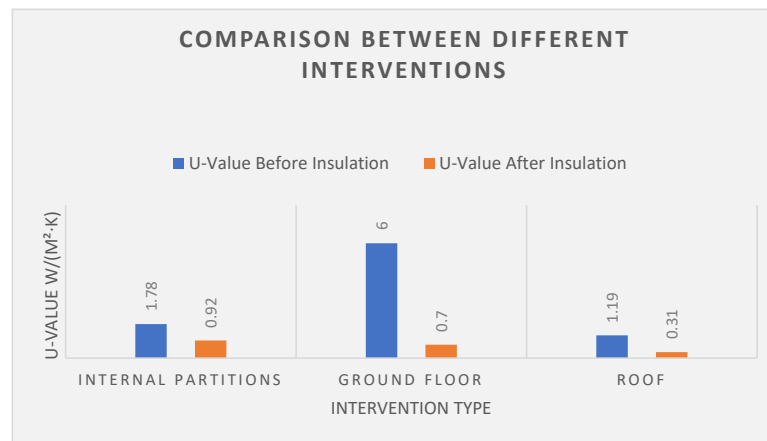


Figure 19. U-value before and after insulation intervention in architectural elements of the heritage building.

The findings confirm that passive retrofit strategies can effectively reduce energy consumption while maintaining the historic character of the building. The use of HBIM, with its ability to generate building models from predefined templates, proved valuable for simulating and evaluating optimal energy-saving solutions. This integrated workflow allows for efficient adaptation within the BIM environment and supports ongoing advances in energy performance modelling [73]. Beyond technical enhancements, the results underscore the necessity of adopting a standardised yet context-sensitive approach to retrofitting heritage buildings. Careful consideration of material compatibility, thermal performance, and moisture dynamics is essential to ensure that retrofit strategies are both effective and respectful of the unique characteristics of historic structures.

Furthermore, the integration of HBIM and energy simulation tools provides a robust foundation for informed, conservation-sensitive decision-making. Incorporating indicators that encompass the three pillars of sustainability—environmental, economic, and social—alongside those reflecting aesthetics, craftsmanship, and cultural identity allows for a more holistic understanding of the multifaceted values inherent in heritage buildings [74]. By focusing on a case study in New Zealand—a region underrepresented in current HBIM research—the findings offer a valuable reference point for integrating conservation principles with energy performance goals in historic masonry buildings.

5. Conclusions

This study demonstrates that Heritage Building Information Modelling (HBIM) can serve as an integrated digital framework that consolidates historical documentation, visual inspection, and energy performance simulation to guide energy-efficient and conservation-sensitive retrofitting of historic buildings. Using the Fraser Gallery in Auckland as a case study, HBIM was used to structure and manage data collected through archival research, infrared thermography, and dynamic simulation, enabling the evaluation of multiple passive retrofit scenarios.

The simulation results showed that applying internal wall insulation using calcium silicate boards could reduce heat loss by approximately 35%, while roof insulation using cork contributed to a 28% improvement in overall building envelope performance. Infrared thermography helped identify key areas of thermal bridging and energy loss, confirming the effectiveness of the proposed interventions. Window shading strategies also proved beneficial in reducing solar gain during summer months. These outcomes were achieved without compromising the building's heritage fabric, validating the selection of low-impact, reversible, and breathable materials for use in historically significant environments.

This study also highlights the practical advantages of using HBIM as a centralised platform for integrating energy modelling tools, such as Autodesk Insight, within the retrofit decision-making process. By allowing scenario testing and visual performance feedback within a unified environment, HBIM enhanced both the precision of retrofit planning and the potential for long-term performance monitoring.

While the absence of in situ environmental sensors limited the ability to validate simulation data with actual measurements, the methodology still provided clear evidence of performance gains. Future studies should incorporate environmental monitoring to further verify outcomes and apply the framework to a wider range of building types and climates across New Zealand.

This research confirms that HBIM offers a structured, scalable, and conservation-sensitive approach to improving the energy performance of unreinforced masonry heritage buildings, contributing to the development of sustainable retrofit strategies tailored to New Zealand's historic building stock.

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