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Optimisation of the compatible retrofitting measures to enhance the Environmental performance of Heritage Buildings: A DSS-Based Evaluation

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ABSTRACT

This study addresses the challenge of balancing heritage conservation with modern environmental performance requirements by developing a Decision Support System (DSS) to aid in selecting the most effective retrofitting strategies for heritage buildings. The lack of a standardized, adaptable framework for optimizing retrofitting solutions highlights the need for a robust assessment tool.

Despite the availability of multiple retrofitting strategies, heritage buildings require a systematic approach to selecting interventions that align with conservation principles while optimizing environmental performance. Current methodologies lack a decision-making framework that integrates heritage significance and environmental impact, while also considering economic feasibility. This study fills this gap by developing a DSS tailored for heritage retrofitting.

To achieve this, the study employed a mixed-methods approach, integrating both qualitative and quantitative research methods to establish a robust DSS framework. The DSS evaluates various retrofitting options based on three essential criteria: heritage preservation, environmental impact, and economic viability. Additionally, expert insights were incorporated through a structured questionnaire, and the EFFESUS (Energy Efficiency for EU Historic Districts' Sustainability) project methodology was adapted for the scoring and weighting system to enhance the tool's reliability.

The DSS evaluation identified Liquid Waterproofing Membrane as the most effective solution for moisture management, Aerogel Insulation as the optimal choice for thermal regulation, and Double Glazing with Low-E Coating as the best strategy for energy-efficient window retrofitting. These findings confirm the DSS's ability to systematically assess retrofitting measures while preserving heritage integrity.

The study is limited to selected retrofitting interventions within the context of Erbil's heritage buildings, and further validation in diverse heritage settings is required to enhance the DSS's applicability. This research contributes to the expanding field of sustainable architectural conservation, offering practical insights and a strategic framework for optimizing retrofitting interventions in heritage buildings.

1.Introduction

The built heritage fabric stands as a witness for the cultural identity and historical continuity which necessitates the combination of conservation techniques with sustainable development initiatives (Labadi et al., 2021). Adaptive reuse plays a key role in preserving historic buildings while maintaining their functionality (Ismaeel, 2023), (Mafaz and Anwar, 2019). In the realm of heritage buildings, sustainable development encompasses more than just environmental concerns; it seeks to balance economic viability, social equity, environmental management, and cultural enrichment. In the heritage buildings realm, sustainable development sustainable development encompasses more than just environmental concerns; it also seeks to strike a balance between economic viability, social equity, environmental management, and cultural enrichment (Labadi et al., 2021). Retrofitting these historical structures is a commitment to preserving their historical value, promoting sustainable use, and enhancing energy efficiency (Mazzarella, 2015, Martínez-Molina et al., 2016). It emphasises that those environmentally friendly construction practices are still functioning while connecting building conservation to sustainable advancement (Mensah, 2019, LaiDavies and Lorne, 2019, TokedeUdawatta and Luther, 2018). Urban transformation plans are being pursued by many cities to transition from traditional to sustainable urban environments (Klerk-De Klerk, 2021). In order to combat climate change, it is essential to improve the energy efficiency of existing buildings, especially older ones (Fraillon et al., 2020). With the rapid expansion of cities, the high concentration of people and associated demand for services raises concerns about sustainability(Li and Shui, 2015).Retrofitting existing structures is critical in this context, as existing buildings outweigh new development (Asdrubali and Grazieschi, 2020). Particularly challenging in this landscape are heritage buildings, which form a crucial part of our cultural and historical legacy. These buildings require special attention to retrofit in a way that balances historical preservation with modern energy efficiency standards.

Retrofitting need to only act of updating structures but rather to nuanced interplay of enhancing functionality, safety, and energy efficiency while respect heritage values (Chidiac et al., 2024). While retrofitting faces challenges such as cost constraints and technical limitations, strategic assessment tools can support decision-making by prioritizing cost-effective and sustainable solutions (Webb, 2017). However, developing an assessment tool for selecting the most compatible retrofitting measures faces several constraints(Ma et al., 2012, Bostenaru Dan, 2004). In post-conflict settings, heritage conservation becomes even more complex, requiring strategies that balance structural integrity with historical preservation (EldiastyHegazi and El-Khouly, 2021), (Ismaeel and Alabaachi, 2024). Retrofitting is the act of replacing or improving existing infrastructure, features, and structures in existing buildings with the goal of enhancing building performance.

In the following discussion, the study presents the process of developing the design-making assessment tool. This tool will be used for in-depth investigation and exploration of the compatibility of different scenarios of refitting measures within certain strategies. The aim of this study is to determine a comprehensive tool that will be used to assist the professionals, planners, and occupiers to select the most compatible recurrent measures and techniques that are in alignment with the characteristics of heritage and historical buildings. The tool will aim to strike a balance between improving environmental performance with a focus on energy efficiency on the one hand and conserving heritage buildings on the other.This study aims to develop a Decision Support System (DSS) for retrofitting heritage buildings by integrating environmental performance, economic viability, and heritage conservation criteria into the decision-making process. The research further evaluates various retrofitting measures and techniques for optimizing heritage building envelopes and systematically identifies the most compatible retrofitting strategies based on these criteria.To address the research gap, this study follows a structured methodology comprising three key phases, as illustrated in Figure 1:

Figure 1: Study Design Framework Authors' graphical elaboration.

This study presents a novel DSS framework that systematically evaluates retrofitting measures using a structured, multi-criteria decision-making approach. Unlike previous methodologies, this DSS incorporates expert insights, aligns with heritage conservation principles, and quantifies the impact of various interventions.

1.2 Literature review

The process of retrofitting heritage buildings faces unique challenges in enhancing building performance to meet today's environmental need while preserving the building's structural integrity and authenticity. There are many different types of strategies and interventions for retrofitting building with special architectural or historic interest. However, due to the variability of historic constructions it makes challenging to identify universal retrofit strategies that can be applied across all buildings (Buda et al., 2021). Professionals, conservatives and building owners emphasized on the need for developing a decision support tools that is able to navigate this complex process (Li et al., 2021).

Decision support systems can play an important role in the process of selecting and optimizing retrofitting solutions to be compatible and align with unique requirements of with the historical buildings (Li et al., 2021). These systems can evaluate multiple criteria including energy efficiency, conservation principles, and occupants preferences, depending on the scope and objectives of the retrofitting process (Buda et al., 2021).

Several decision-making frameworks have been developed to support heritage building retrofitting, but many existing tools focus on general building stock rather than heritage-specific interventions. For example,Carlos E. Ochoa and I. Guedi Capeluto developed a framework that can be used during the initial stages of façade retrofitting and it's mainly focuses on economic and energy-related factors. This tool was basically designed for existing residential buildings (Ochoa and Capeluto, 2015). However, it lacks specificity for heritage buildings, highlighting a gap in its applicability for comprehensive heritage retrofitting projects.Similarly Rossano Albatici et al. has also develop a DSS for retrofitting actions for social housing and it considers energy efficiency and the occupants comfort criteria (Albatici et al., 2016). This tool has the potential to be used for heritage buildings as well. By incorporating criteria specific to preservation, it can be applied to a border application

The study by Alessia Buda et al explain the IEA-SHC Task 59 Decision Support System (DSS) HiBERtool (Buda et al., 2021). The tool helps to determine the possible retrofit actions that balance energy efficiency and conservation. The EN 16883:2017-compliant tool uses decision trees (Buda et al., 2021). However, it is need to be expanded to remain applicable for different heritage context .

The work by Francesca Roberti and colleagues combined multi-objective optimisation with the Analytic Hierarchy Process. The effectiveness of conservation principles in historic building rehabilitation is assessed using this technique. Their research describes the processes (Roberti et al., 2017).This method reduces energy usage in mediaeval Italian buildings while retaining their history. However, it must modify to be suitable for different needs and other climatic conditions for heritage buildings around the world. Existing tools like the "Responsible Retrofit Guidance Wheel" and "HiBERTool" offer structured approaches to retrofit decision-making but often focus narrowly on specific geographic or architectural contexts.

The table below (Table 1) summarizes key studies in the field of DSS and multi-criteria decision-making (MCDM) for heritage retrofitting. It highlights their methodologies, limitations, and relevance to this study, offering a comprehensive foundation for the proposed DSS framework.

To overcome the limitations in the literature, the study provides a DSS that incorporates criteria that can be adaptable and scalable for different historical and heritage building settings. Thus, it will ensure a thorough assessment that meets the local context of a given building within the environmental goals. Many present models lack the flexibility to evaluate various historic building attributes in different settings. The DSS presented in this offer an effective and adjustable tool for assisting sustainable retrofitting initiatives forr heritage building in Erbil city as a case study. The tool aims to blend historical preservation, cultural sensitivity, and energy efficiency.

Table 1 Summary of Key Studies on DSS for Heritage Retrofitting (by authors)

Ismaeel (2023)	D&C technique as an MCDM tool for heritage value assessment in post-war cities	Multi-criteria decision-making (MCDM), heritage value assessment, post-war conservation	D&C technique as an MCDM tool for heritage value assessment in post-war cities
Seghezzi (2018)	A decision support framework for technology-related choices in façade retrofit	Façade retrofit DSS focusing on technology and morphology	Proposes a decision framework considering façade morphology and lifecycle cost
GigliarelliCalcerano and Cessari (2017)	An integrated approach using Heritage BIM, numerical simulations, and DSS for retrofitting historic buildings.	Heritage-BIM platform, Numerical Simulations, Decision Support System (DSS), Analytical Hierarchy Process (AHP), Computational Design, Graphical Algorithmic Modelling.	Potential complexity in integrating Heritage-BIM with numerical simulations; dependency on computational tools and expertise.
(Si, 2017)	Multi-Criteria Decision Making (MCDM), Life Cycle Assessment (LCA), Energy Performance Modelling.	Focuses on non-domestic buildings; limited applicability to historic structures; lacks case studies in heritage conservation.	Demonstrates the role of MCDM in retrofit decision-making, providing insights for heritage building sustainability strategies.
EgusquizaBrostrom and Izkara (2022)	Incremental decision-making for energy retrofitting in historic urban areas using the EFFESUS Decision Support System (DSS).	EFFESUS DSS, Multi-criteria Decision Analysis (MCDA), Geographic Information Systems (GIS), Energy Performance Simulation.	Challenges in balancing energy efficiency with heritage conservation; complexity in integrating diverse datasets for decision-making.
CecconiKhodabakhshian and Rampini (2022)	Data-driven Decision Support System (DSS) for energy retrofit policies in building stocks.	Data-driven DSS, Machine Learning, Energy Performance Simulation,	Dependence on large datasets for accurate decision-making;

		Statistical Analysis.	challenges in policy implementation across diverse building typologies.
Massafra et al. (2023)	Integration of Building Information Modeling (BIM) and Building Performance Simulation (BPS) for Decision Support Systems (DSS) in heritage building operations.	BIM-based DSS, Energy Performance Simulation, Digital Twin Technology, Data-Driven Analysis, Interactive Dashboards.	Challenges in data integration; reliance on high computational resources; requires expertise for implementation.
(Amaripadath et al., 2024)	Multi-criteria decision support framework for climate change-sensitive thermal comfort evaluation in European buildings.	Multi-Criteria Decision Analysis (MCDA), Climate-Sensitive Thermal Comfort Assessment, Energy Performance Simulation.	Applicability limited to European climate conditions; challenges in adapting framework to diverse building typologies.

1.3 The heritage building Retrofitting Decision Support System DSS.

A Decision Support System (DSS) is a comprehensive, interactive framework designed to assist in complex decision-making scenarios(Ada and Ghaffarzadeh, 2015). It integrates a variety of inputs including data, insights, and models to tackle challenges, particularly those with incomplete information (Insua and French, 2010, French and Geldermann, 2005). The 'Heritage Building Retrofitting Assessment Tool,' a specialized Decision Support System (DSS), is designed to enhance decision-making in retrofitting heritage buildings. This system employs Multi-Criteria Decision Analysis (MCDA) to align with the EN 16883:2017 standard, focusing on critical factors

that influence retrofit decisions [84].

This tool's value is significantly enhanced by a detailed comparative analysis outlined in appendix table 1 Comparative Analysis of Retrofitting Tools. This table evaluates several existing tools, including the 'Responsible Retrofit Guidance Wheel', 'HiBERTool', 'exDSS', and 'Effesus DSS/RE2H'. While these tools provide valuable frameworks, they often exhibit limitations in geographic and architectural scope and do not fully mitigate risks crucial to heritage buildings, such as interstitial condensation and fabric decay. This assessment aligns with the findings of Seddiki et al. (2021), highlighting the gaps in current methodologies that the DSS effectively bridges (Seddiki et al., 2021).

The DSS overcomes these challenges by providing a framework that not only evaluates these critical risks but also adapts to the unique environmental and architectural characteristics of each heritage site. This adaptability is crucial for implementing retrofitting solutions that are both effective and sensitive to the preservation of cultural heritage. The effectiveness of this approach is demonstrated through its application in various strategies that are proposed for heritage building in Erbil city as a case study, showing a robust and adaptable approach compared to more traditional tools.

2.Methodology

2.1 Overview

This section presents the foundational methodology employed in this study, including literature review and criteria development for the DSS. The methodology begins with a comprehensive literature review to identify the key factors that influence the retrofitting of heritage buildings. This foundational stage ensures a thorough understanding, which is crucial for developing a flexible Decision Support System (DSS) adaptable to various heritage buildings, regardless of their specific (Figure 2) .

After establishing the key influencing factors from the literature, specific criteria are selected and defined to act as dependent variables. These criteria are essential for evaluating retrofitting interventions, ensuring that they meet both conservation goals and modernization needs across different heritage settings.

To prioritize these criteria, a survey involving experts in architecture and heritage conservation is conducted. Their insights help establish a weighted evaluation framework within the DSS, facilitating a balanced and prioritized assessment of retrofitting measures**.** This process includes administering a structured questionnaire to these experts to assess and weight the qualitative criteria, ensuring that the evaluation framework is robust and nuanced.

A scoring system, inspired by the EFFESUS project, is then implemented to categorize the impacts of each criterion. This quantitative assessment ensures that each retrofitting measure is evaluated against a consistent and transparent set of benchmarks, making the DSS robust and applicable in diverse settings.

2.2 DSS Framework Development

2.2.1 Structure and Components of DSS

The Decision Support System (DSS) developed in this study is an **evaluative decision-making framework,** not a standalone software tool. It employs a structured **multi-criteria decision-making approach (MCDA)** to systematically assess and prioritize retrofitting measures for heritage buildings. The DSS integrates **quantitative scoring and expert evaluations,** using a **weighted decision-making system inspired by the EFFESUS project.**

2.2.2 Scoring System for Retrofitting Interventions

The scoring system operates on a scale of 0 to 4 across three dimensions: Heritage Significance Level (HSL), Environmental Impact Level (EIL), and Economic Criteria (EC). Each level reflects the measure's impact, ranging from 'Neutral or Negative' to 'Exceptional Outstanding Impact.' This scoring approach allows practitioners to balance heritage conservation, environmental sustainability, and economic viability. The structured scoring system supports the thorough evaluation of retrofitting measures, enhancing energy efficiency while preserving cultural heritage.

2.2.3 Integration of Heritage Conservation and Economic Viability

While the primary focus of this study is on optimizing environmental performance, the DSS framework also incorporates economic viability and heritage conservation as essential evaluation criteria. Economic assessments include long-term cost savings, operational costs, and maintenance expenditures, while heritage conservation principles are embedded through compatibility assessments, minimum intervention principles, and historical value preservation.

2.3 Weighting Methodology

2.3.1 Expert Questionnaire Design

To prioritize the criteria, a survey involving experts in architecture and heritage conservation was conducted. Their insights helped establish a weighted evaluation framework within the DSS, facilitating a balanced and prioritized assessment of retrofitting measures. The questionnaire was specifically designed to assess the importance of each criterion and was not intended as a qualitative data collection tool.

2.3.2 Expert Selection Process

To ensure the reliability and relevance of the DSS, experts were selected based on the following criteria:

1. Minimum of 10 years of professional experience in heritage conservation or sustainable building practices.
2. Academic qualifications in architecture, urban planning, or environmental sustainability.
3. Active involvement in heritage preservation or sustainable development, including teaching or research roles.

The experts were mainly drawn from universities and professional institutions in Iraq and the Kurdistan region, primarily consisting of professors and academics. A total of 30 experts meeting these criteria were invited to participate, and 26 responses were received. Their insights were gathered through structured questionnaires, and their evaluations were systematically weighted to ensure objectivity and accuracy in the DSS.

2.4.2 Statistical Analysis and Validation

The statistical approaches used to analyse the collected data include normalization of expert weightings to ensure consistency and comparability. The weighted scoring calculations were conducted to prioritize retrofitting measures effectively. The EFFESUS project scoring system was employed to standardize the impact levels of each criterion. This quantitative assessment ensures that each retrofitting measure is evaluated against a consistent and transparent set of benchmarks, making the DSS robust and applicable in diverse settings.

2.3 DSS Validation and Application

The DSS validation process involves applying a selected range of retrofitting measures that have been previously identified as required for heritage buildings in Erbil City to prevent building deterrence and improve its environmental performance. These options were tested to make sure they selected the most applicable and effective strategy for the selected case study. This process employs an iterative approach, starting from selecting criteria, designing the tool, receiving feedback through testing phases, and continuously refining and optimising the retrofitting procedures. This adaptive process ensures the interventions remain effective and relevant to the conservation needs of heritage buildings globally, achieving a balanced integration of heritage preservation and sustainability objectives.

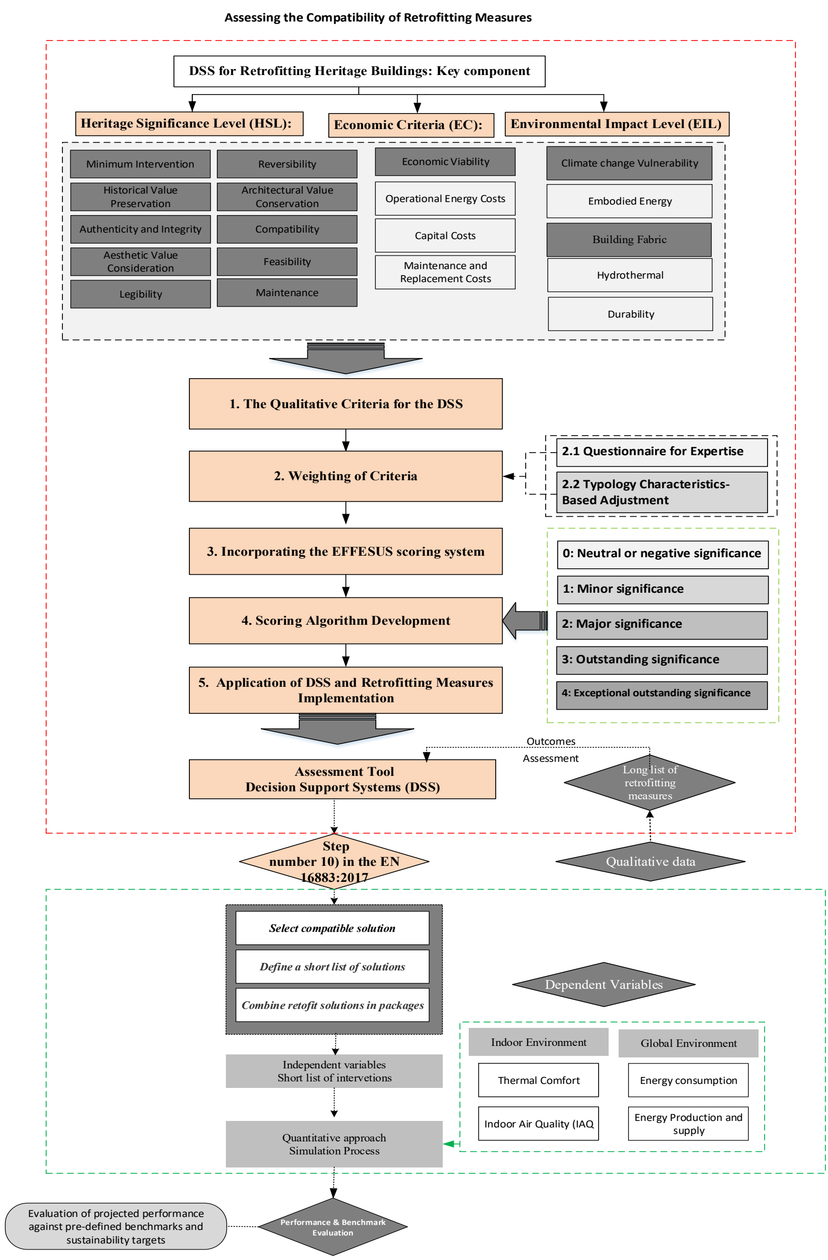


Figure 2: Diagrammatic Representation of the Iterative Retrofitting Decision-Making Framework for Heritage Buildings (by authors).

3.Theoretical background

The study theoretical framework will be built around the main concepts which they are environmental retrofitting strategies, sustainable development in heritage buildings, and heritage building preservation principles. These components are essential in defining the criteria and sub-criteria for the Decision Support System (DSS), guiding our comprehensive analysis and strategic decision-making in heritage building retrofitting

3.1 Sustainable Development: Balancing Multiple Dimensions

Sustainable development in heritage buildings refers to practices that meet the needs of the present without compromising the ability of future generations to meet their own needs (Lucchi et al., 2024). In the context of heritage buildings, this involves balancing the need for modernization and environmental performance improvements with the preservation of cultural and historical values (Munarim and Ghisi, 2016).

Sustainability traditionally consists of three pillars: environmental, social, and economic (PurvisMao and Robinson, 2019). However, this study will focus primarily on environmental performance due to its specific aim. The social and broader economic aspects are acknowledged but will not be the primary focus. Some criteria related to economic viability that have a direct impact on the selection of retrofitting measures will be included.

3.1.1 Environmental sustainability

Environmental sustainability, a core principle in this study, extends beyond simple energy consumption and conservation. It involves a broad spectrum of sustainability criteria that include the global environment, building materials, indoor conditions, and economic impacts (Webb, 2017).Each component significantly influences the selection of retrofit strategies, offering a holistic approach to sustainability.

Table 2 summarizing the key components related to the environmental sustainability in retrofitting heritage buildings, with a focus on economic viability:

Table 2: Key Components of Environmental Sustainability: Qualitative Criteria for Retrofitting Performance Indicators by the authors.

Category	Criteria	Metrics	References
Global Environment	Energy Consumption	- Annual Energy Consumption (kWh or MJ/year) - Annual CO2 Emissions (kg or t/year)	(Lidelöw et al., 2019, Cho et al., 2020, Lyudmila and Julia, 2023, Liang et al., 2022, Seddiki et al., 2021)
	Energy Production and Supply	- Proportion of Demand Met by Renewables (%) - - Operational CO2 Emissions Reduction (kg or t/year)	(Lidelöw et al., 2019) (Lyudmila and Julia, 2023, Liang et al., 2022)
	Climate Change Vulnerability	- Resilience to Environmental Risks - Exposure to Hazardous Conditions	(Cantatore and Fatiguso, 2021, ChieffoFormisano and Miguel Ferreira, 2021)
	Embodied Energy	- Amount of Original Fabric Preserved (%) - Energy Used in New Material (MJ or kWh/unit)	(Lidelöw et al., 2019, Cabezade Gracia and Pisello, 2018, Piccardo et al., 2020)
Building Fabric	Hydrothermal Performance	- U-value (W/m²K) - Specific Heat Capacity (J/kgK) - Linear Thermal Transmittance (W/mK) - Moisture Buffering Capacity (kg/m²) - - Air Tightness (m³/hm² at 50 Pa)	(Dias PereiraSaraiva and Soares, 2023, PosaniVeiga and de Freitas, 2021) (Huerto-Cardenas et al., 2021, Martín-Garín et al., 2021)
	- Durability	- Drying Capacity (kg/m²s) - Freeze-Thaw Cycles Survived - Interstitial Condensation (%) - Decay of Embedded Elements	(Martín-Garín et al., 2021)

Indoor Environment	Thermal Comfort	- Mean Radiant Temperature - Relative Humidity - Air Temperature	(Standard, 1992, Luciani, 2013, Ibrahim et al., 2021, Seddiki et al., 2021)
	Indoor Air Quality (IAQ)	- Ventilation Efficiency - Pollutant Concentration Levels - Moisture Control - O2 Concentration - Occupant Satisfaction	(FrascaCornaro and Siani, 2019, Luciani, 2013, Seddiki et al., 2021)
Economic Viability	Capital Costs	- Total Initial Investment Costs (currency)	(Seddiki et al., 2021)
	Operational Energy Costs	- Annual Energy Costs (currency/year)	(Buda et al., 2021, Galatioto et al., 2019)
	Maintenance and Replacement Costs	- Sum of Periodic Maintenance and Replacement Costs (currency)	(Galatioto et al., 2019)

This table aligns the economic considerations with the principles of environmental sustainability, emphasizing measures that have a direct impact on the retrofitting process while respecting the historical significance of heritage building

3.2 Heritage Preservation and Its Integration with Sustainable Retrofitting

Heritage preservation forms a crucial aspect of sustainable retrofitting in historical buildings, emphasizing the balance between maintaining physical and cultural integrity and implementing modern updates for better energy efficiency and environmental sustainability. This concept is further elaborated in various sources, notably the "Monuments and Sites 1 Charters" and additional scholarly works such as those by (Petzet, 2004, ICOMOS, 2004), (Taher Tolou DelSaleh Sedghpour and Kamali Tabrizi, 2020) (LiangAhmad and Mohidin, 2023), (Mohamed and Marzouk, 2023), (Nury and Haykal, 2023), (Ismael, 2024) which provide extensive principles and evolving methodologies for integrating new technologies, minimal interventions, and respecting the cultural narratives of heritage structures. Table 3 presents a detailed examination of these principles and methodologies under the qualitative criteria for heritage preservation.

Table 3 Qualitative Criteria for Heritage Preservation principles (By authors).

Principle	Description	
Minimum Intervention	Interventions should be discreet and limited to what is necessary for the preservation of the building, ensuring minimal impact on the historical substance.	(Petzet, 2004, ICOMOS, 2004)
Reversibility	Retrofitting measures should be reversible, where possible, to allow for the removal or alteration of interventions without damaging the original structure.	(Petzet, 2004, ICOMOS, 2004)
Authenticity and Integrity	Preserve the genuine character and historical authenticity of the building, maintaining its integrity as a testament to its era and cultural significance.	(Petzet, 2004, ICOMOS, 2004, Taher Tolou DelSaleh Sedghpour and Kamali Tabrizi, 2020)
Compatibility	This principle involves ensuring retrofitting measures are in harmony with the heritage building, encompassing structural compatibility (respecting original structural systems), material compatibility (using materials that are in line with the building's historical context), and technical compatibility (techniques and methods that align with the building's heritage value).	(Petzet, 2004, ICOMOS, 2004)
Historical Value	Protect and interpret the building’s history throughout the retrofitting process.	(LiangAhmad and Mohidin, 2023, Taher Tolou DelSaleh

Preservation		Sedghpour and Kamali Tabrizi, 2020)
Architectural Value Conservation	Enhance or at least maintain the architectural features of the building through retrofitting techniques.	(LiangAhmad and Mohidin, 2023, Taher Tolou DelSaleh Sedghpour and Kamali Tabrizi, 2020)
Aesthetic Value Consideration	Ensure retrofitting interventions preserve the visual appeal and character-defining elements of the heritage building.	(LiangAhmad and Mohidin, 2023, Taher Tolou DelSaleh Sedghpour and Kamali Tabrizi, 2020)
Feasibility	Assess the practicality and viability of retrofitting interventions.	(Mohamed and Marzouk, 2023).
Legibility	Distinguish new work from original materials and features, and preserve the building's historical character.	(Mohamed and Marzouk, 2023).
Maintenance	Regular care and maintenance to prevent deterioration and maintain the building's historical character.	(Mohamed and Marzouk, 2023).

3.3. The Qualitative Criteria for the DSS

This step involves developing the criteria for the DSS based on theoretical foundations established in sections above. The criteria are systematically organized into three categories as it shown in table 4:

Table 4: Qualitative Criteria for the DSS and Corresponding Evaluation Questions (By authors).

Qualitative Criteria for the DSS		
1.Category HSL	**Sub-category**	**Description**
I. Minimum Intervention	Structural Integrity	Does the retrofit maintain the structural integrity of the building with minimal alterations?
	Historical Fabric Preservation	Are historical materials and construction techniques preserved
	Non-invasive Techniques	Are the methods employed non-destructive to the original fabric?"
II. Reversibility	Removability,,	Can new additions be removed without trace?
	Future Adaptability	Does the retrofit allow for future changes or reversions?
	Non-permanent Alterations	Are interventions easily reversible?
III. Authenticity and Integrity	Historical Accuracy,	Does the retrofit reflect the building's original time and place?
	Material Authenticity,	Are materials historically appropriate and sourced?
	Original Design Preservation	Is the original design narrative preserved?
IV. Compatibility	Structural Compatibility,	Can the retrofit be incorporated without altering the existing structural framework?
	Material Compatibility,	Will the new materials age or weather consistently with the existing materials?
	Aesthetic Compatibility	Does the retrofit uphold the building's historical aesthetic and character?
V. Historical Value Preservation	Conservation of Historic Façade:	Does the retrofit preserve the facade's architectural style and structural elements?
	Material Authenticity and Aging	To what extant the retrofit's impact on preserving the facade's architectural style and structural elements?
	Detail Preservation and Integration:	Are facade details and ornamentation retained and harmoniously integrated?
VI. Architectural Value Conservation	Architectural Features Maintenance	Are the original architectural features maintained properly?
	Style Preservation	Does the retrofit preserve the historical style of the building?.

		Enhancing Architectural Character	Does the retrofit enhance the building's unique architectural character?
VII.	Aesthetic Value Consideration	Visual Impact	Is the visual impact of the retrofit in harmony with the heritage context?
		Character-Defining Elements	Are character-defining elements of the building preserved?
		Landscape Integration	Does the retrofit integrate well with the surrounding landscape?
VIII.	Feasibility	Cost-Effectiveness	Is the retrofit financially viable?
		Implementation Practicality	Is it practical to implement the retrofit measures?
		Availability of Materials/Techniques	"Are the necessary materials and techniques readily available?"
IX.	Legibility	Distinction between Old and New	Is there a clear distinction between the original and new additions?
		Interpretability	"Does the retrofit facilitate the interpretation of the building's history?
		Documentation of Changes	Are all retrofit-related changes thoroughly documented?
X.	Maintenance	Ease of Care	Are the retrofit measures easy to maintain?
		Long-term Sustainability	Will the retrofit measures be sustainable in the long term?
		Preservation Techniques	Are appropriate preservation techniques employed for ongoing maintenance?
2. Category EIL		Metrics	Description
a)	Embodied Energy	Amount of Original Fabric Preserved (%)	To what extent does the retrofit consider conserving the original building fabric and minimizing the energy footprint of new materials?
		Energy Used in New Material (MJ or kWh/unit)	To what extent does the retrofit utilize energy-efficient materials?
b)	Hydrothermal Performance	U-value (W/m^2K)	To what extent does the retrofit improve the thermal performance of the building envelope?
		Specific Heat Capacity (J/kgK)	To what extent does the retrofit regulate temperature effectively?
		Linear Thermal Transmittance (W/mK)	To what extent does the retrofit manage moisture levels for better thermal control?
		Moisture Buffering Capacity (kg/m^2)	To what extent does the retrofit enhance moisture buffering capacity?
		Air Tightness (m^3/hm^2 at 50 Pa)	To what extent does the retrofit improve airtightness?
c)	Durability	Drying Capacity (kg/m^2s)	To what extent does the retrofit improve the drying capacity of materials?
		Freeze-Thaw Cycles Survived	To what extent are the materials resilient to natural weathering?
		Interstitial Condensation (%)	To what extent does the retrofit control moisture within building structures?
		Decay of Embedded Elements	To what extent does the retrofit assess and address the decay of embedded elements?
3. Category Economic criteria EC		Sub-category	Description
a)	Capital Costs	Total Initial Investment Costs (currency)	To what extent is the upfront investment for retrofitting measures manageable?
b)	Operational Energy Costs	Annual Energy Costs (currency/year)	To what extent are the annual energy costs post-retrofit reasonable?
c)	Maintenance and Replacement Costs	Sum of Periodic Maintenance and Replacement Costs (currency)	To what extent are the long-term costs for maintenance and potential replacement of retrofit components sustainable?

3.4 Scoring of the retrofitting interventions

The scoring system operates on a scale of 0 to 4 across three dimensions: Heritage Significance Level (HSL), Environmental Impact Level (EIL), and Economic Criteria (EC). Each level reflects the measure's impact, ranging from 'Neutral or Negative' to 'Exceptional Outstanding Impact,' enabling practitioners to balance heritage conservation, environmental sustainability, and economic viability. This approach supports thorough evaluation of retrofitting measures, enhancing energy efficiency while preserving cultural heritage (Figure 3).

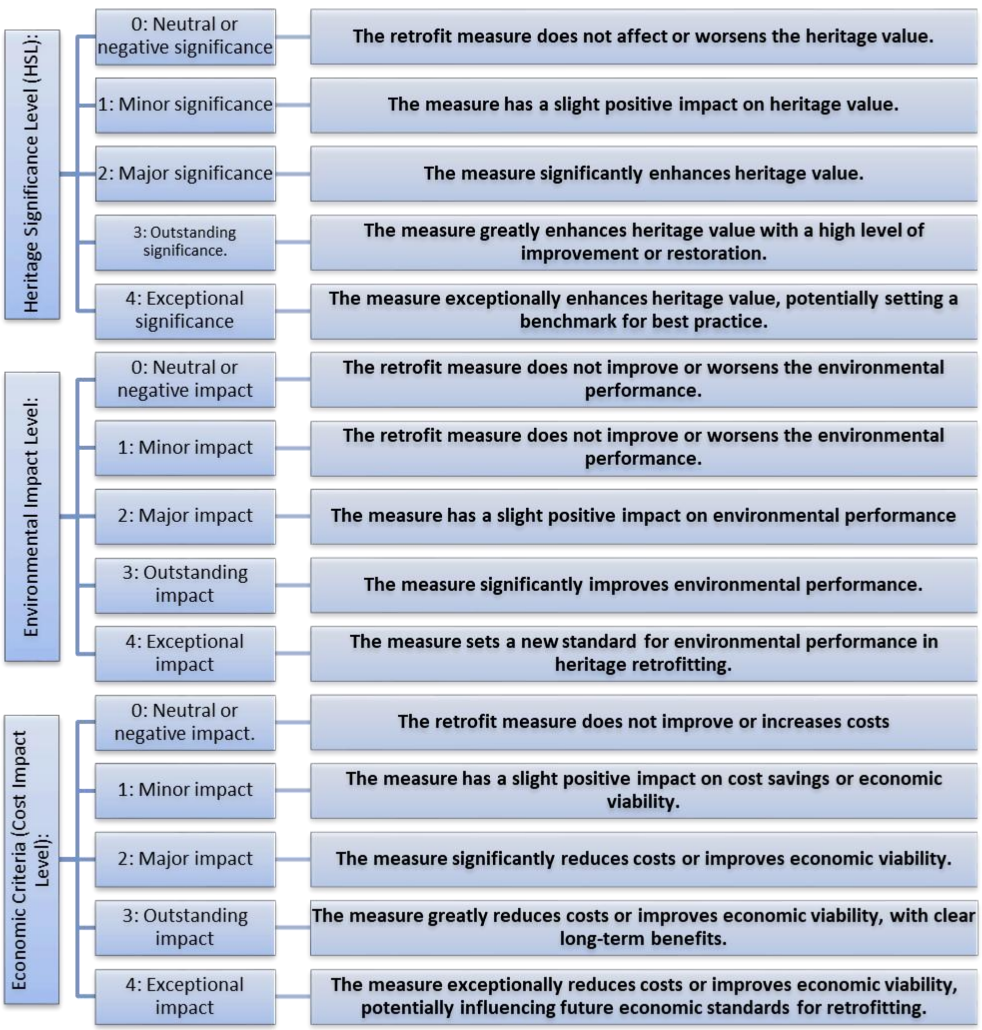


Figure 3 : Scoring Dimensions Based on the EFFESUS Project (by Authors).

3.5 Weighting Methodology in the Heritage Building Retrofitting DSS

The DSS for heritage building retrofitting employs a comprehensive weighting methodology informed by the EFFESUS project (Rettberg et al., 2013), UNESCO conservation guidelines (Biörnstad, 2020), and ICOMOS principles(PatiwaelGroote and Vanclay, 2019). This approach integrates q questionnaire process to establish weightings for criteria used in assessing retrofitting measures: The DSS is the primary evaluation tool in this study, designed to assess retrofitting measures based on criteria derived from literature and theoretical analysis. Unlike qualitative field data collection, this study relies on a structured decision-making framework where expert input was used solely for weighting the predefined criteria, ensuring objective prioritization of retrofitting strategies.

3.5.1 Expert Questionnaire Methodology:

The DSS's expert questionnaire methodology is a systematic approach to quantifying the qualitative aspects of heritage building retrofitting. This process entailed:

- Translating retrofitting criteria into structured queries (Refer to appendix table 2).
- Gathering assessments from 30 field specialists who rated each criterion's importance on a scale from 1 ('Not Important') to 5 ('Very Important').
- Analyzing expert responses to establish initial weightings, which were then normalized to reflect their relative importance

The questionnaire was designed specifically for this study, based on the criteria developed for the DSS. Each criterion was reformulated as a structured question to allow experts to assign weightings, ensuring an objective prioritization process. The primary purpose of the questionnaire was to determine the relative importance of each criterion within the DSS framework, rather than to introduce new variables.

To ensure consistency, a pilot review was conducted with five senior heritage conservation specialists, who verified the clarity and applicability of the questions. The final weightings were normalized to maintain balance and minimize bias, ensuring that all criteria were proportionally represented in the DSS evaluation process.

3.5.2 Questionnaire Results and Expert Insights

The questionnaire designed to gather expert insights on retrofitting criteria for heritage buildings provided invaluable data from 26 specialists in heritage architecture and conservation from Iraq and the Kurdistan region. The results, synthesized into spider diagrams for each criterion category (Figures 4, 5, and 6), highlight the nuanced priorities set by these experts.

The radar charts convey the relative importance of sub-criteria within each broader category, from the preservation of architectural authenticity to economic viability. 'Authenticity and Integrity' and 'Historical Value Preservation' are highly valued in the heritage preservation category, aligning with the overarching goals of retrofitting within Erbil's Citadel.

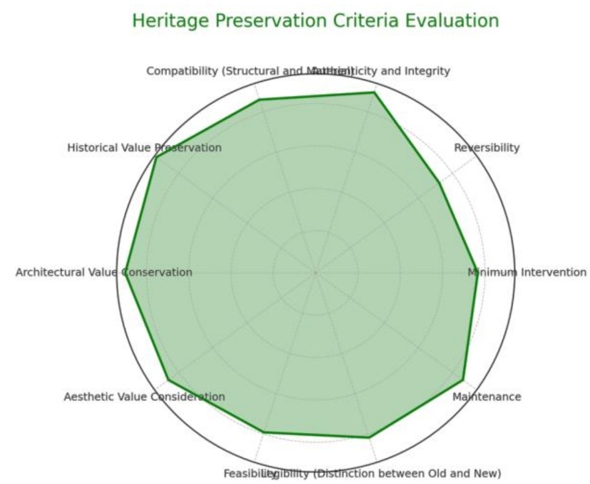


Figure 4: Heritage Preservation Criteria Evaluation (By the authors).

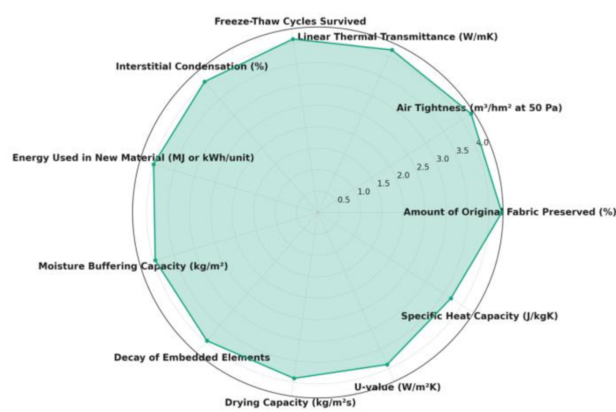


Figure 5: Environmental Performance Criteria Evaluation (By the authors).

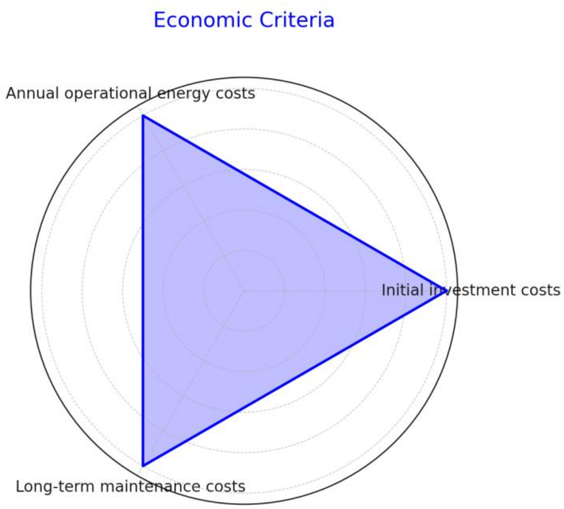


Figure 6 : Economic Criteria Evaluation (By the authors).

The quantitative scores from the expert questionnaire have been normalized and translated into a weighting system, with a cumulative weight sum of 100, ensuring proportional representation and impact of each criterion in the DSS (Appendix table3). This conversion from qualitative assessments to a quantifiable weighting system is crucial for the DSS's nuanced assessment capabilities, allowing it to align closely with retrofitting objectives and capture both conservation and modernization needs.

3.6 Application of the DSS and selection of Optimal Interventions

The application of the DSS involves a systematic process:

- **Case Study Selection:** The heritage buildings of Erbil City are selected as the case study, focussing on retrofitting needs for Erbil City heritage buildings.
- **Evaluation of Retrofitting Measures**: The retrofitting measures were selected based on strategies suggested by previous published research by (Miran and Husein, 2024).A short list of intervention options was chosen for each strategy. These strategies are categorised under efficient envelope retrofitting.
- **Utilising the DSS:** Evaluate each option across the main criteria of the study, which are environmental performance, economic viability, and heritage preservation standards.
- **Selection of Optimal Interventions:** based on the assessment the measures will select the highest scores across all criteria, tailored to the distinctive characteristics of each of the selected case studies.

The validation process involved applying the DSS to various retrofitting strategies for selected case studies in Erbil City. This ensured that the interventions would be chosen based on their best performance concerning the criteria and scores.

3.7 case study selection.

The selection of case studies was based on specific criteria, including historical and architectural significance, degree of deterioration, and representativeness of Erbil's heritage buildings. The study by Miran and Husein (2024) highlighted the rapid deterioration these buildings endure due to multiple factors, such as exposure to severe environmental conditions and the loss of protective elements like shading and canopies which they previously had (Miran and Husein, 2024). Other factors affecting the structural deterioration of these buildings include rapid urban development and the economic prosperity the city has experienced, which has led to the neglect of these old structures and focuses more on adopting global architectural trends. thus, it's important to retrofit the heritage buildings to preserve them form the degradation and to maintain their authenticity (Miran and Husein, 2023). Figures 7 and 8 shows two of the selected case studies, illustrating the level of architectural detail and the extent of deterioration that the retrofitting aims to address by balancing preservation and promoting sustainability within the heritage sector.

Figure 7: The Citadel of Erbil – Preserving Heritage amidst Urban Expansion.

Figure 8: Heritage Building Envelope in Erbil City (By the authors).

4.Result and discussions

4.1 Optimization Strategies for Building Envelope Retrofitting in Erbil City's Heritage Buildings

The selection of retrofitting measures in this study is based on a structured process informed by prior research on the deterioration causes and defect patterns in heritage buildings in Erbil City (Miran and Husein, 2024). This research provided a data-driven foundation for identifying key areas requiring retrofitting interventions, ensuring that the selected measures align with heritage conservation needs, environmental performance goals, and economic feasibility. The Decision Support System (DSS) in this study builds upon these findings, serving as an optimization tool to systematically evaluate and prioritize the most effective retrofitting solutions. The DSS employs a weighted scoring system to assess measures based on multiple criteria, ensuring their compatibility and applicability in the context of Erbil's heritage buildings. Figure 9 illustrates the categorized retrofitting strategies integrated into the DSS.

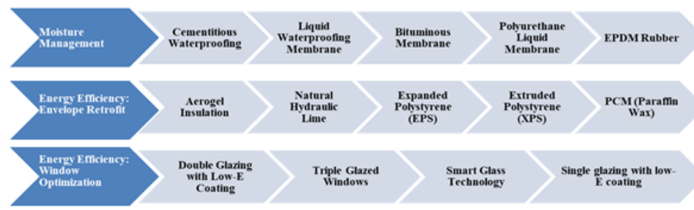


Figure 9: the list of the retrofitting measures and interventions to be applied in the DSS (By the authors).

4.1.1. Intervention 1: Envelope Retrofit for Moisture Management.

A critical aspect of retrofitting the envelope for energy efficiency and preservation of the building is the selection of appropriate waterproofing solutions, which aim to manage the infiltration of moisture and water from the roof. Moisture penetration through the roof has a significant negative impact on the structure and aesthetic value of the building's interior and exterior elements. Table 5 presents the selected materials, evaluated through a comprehensive literature review and aligned with the specific requirements of heritage structures. This table details their characteristics, including thickness, density, water vapour resistance factor, and fire reaction class. These properties are essential for ensuring the durability, compatibility, and safety of the interventions.

Table 5: Selected Measures and Materials for Waterproofing and Moisture (By the authors).
The material properties are based on standards such as EN 13501-1 for fire classification (EN, 2009)and ISO 10456:2007 for hydrothermal properties(Normalización, 2007), as well as manufacturer datasheets and technical manuals .

Material Type	Thickness	Characteristics	Density [kg/m³]	Suitable for Roof Type	Water Vapor Resistance Factor (μ)	Reaction to Fire Class
Cementitious Waterproofing	2-4 mm	Rigid, durable, seamless	2100-2300	Flat and sloped	> 10,000	A1 (non-combustible)
Liquid Waterproofing Membrane	1-2 mm	Highly flexible, seamless, versatile	1100-1300	Flat and sloped	Moderate	E
Bituminous Membrane	3-4 mm	Self-adhesive, robust	1100-1300	Flat and sloped	Low to moderate	E
Polyurethane Liquid Membrane	1.5-2 mm	Highly elastic, chemical resistant	1200	Flat and sloped	Low	B2 (flammable)
EPDM Rubber	1-2 mm	UV resistant, flexible	1200-1300	Flat and slightly sloped	Very high	E

The analysis has identified the Liquid Waterproofing Membrane as the most suitable material in compare with other types. This is because this material has the minimum visual impact, high flexibility and easy to be implemented which make it achieve the higher score heritage impact level as it can be seen in figure 10. This material is an ideal material for preserving the structural integrity while providing a good level of protection again rainwater infiltration which it make it more compatible to historical characteristic of Erbil heritage buildings(Movilă et al., 2021, Yu and Sun, 2017). Additionally, it scored highly in the Environmental Impact Level (EIL) due to its compatibility with traditional materials and its effective capabilities for managing moisture.

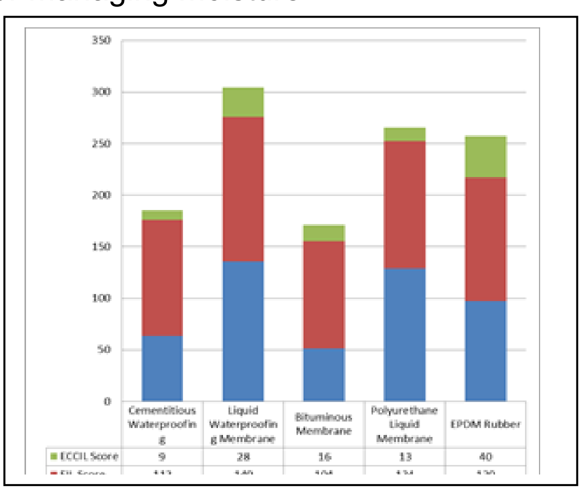


Figure 10 Comparison of DSS scores across different waterproofing materials.

The high elasticity and chemical resistance of the polyurethane liquid membrane were the key factors that contributed to its high performance with regard to the environmental impact level. However, the maintenance and replacement of this membrane may be more complex or invasive in the context of heritage conservation, and this complexity increases with the use of traditional methods, making it less preferred compared to other options. While EPDM rubber is UV resistant and flexible, its impact on visual appearance and high density resulted in a lower score compared to other alternatives. This was due to its potential impact on the structural load of heritage buildings, particularly those with a higher risk of structural default (Chandrasekaran, 2010).

4.1.2 Intervention two: Thermal Control and Energy Efficiency retrofitting for building envelop:

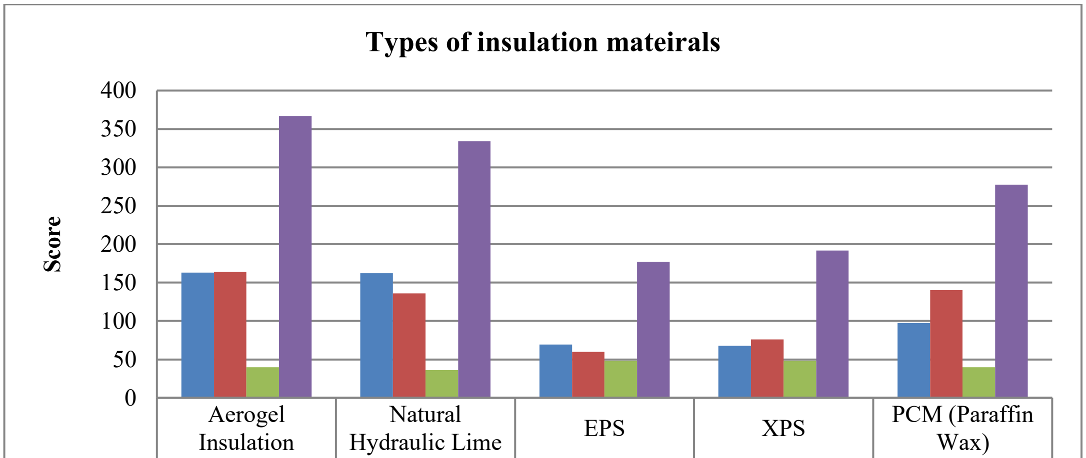
There is a need for optimizing the building envelope in order to improve its thermal resistance and provide more insulation for the building. Not only that, but we are also improvising thermal insulation materials for older buildings to address their potential degradation due to exposure to severe climatic conditions. Table 6 presets the specification and properties of the selected material to provide thermal insulation for building envelope (wall and roof). These materials will be tested and evaluated using the developed DSS.

Table 6: Properties of Selected Insulation Materials for Building Envelope Retrofitting(Pérez, 2012, Inc, 2021),(Walker, 2009, Normalización, 2007), (YucelBasyigit and Ozel, 2003, Company, 2021),(Corning, 2021, CaiZhang and Cremaschi, 2017), (Cabeza et al., 2011, Simon et al., 2024).

Insulation Material	Thickness (m)	Thermal Conductivity (W/mK)	Thermal Resistance (m²K/W)	Key Characteristics
Aerogel Insulation	0.01	0.014	0.714	High-performance, breathable insulation; ideal for traditional structures
Natural Hydraulic Lime	0.02	0.9	0.022	Moisture-regulating layer; enhances durability and compatibility with heritage materials
Expanded Polystyrene (EPS)	0.1	0.038	2.63	Alternative insulation material; significant thermal resistance but less breathability
Extruded Polystyrene (XPS)	0.1	0.028	3.57	High insulation value; similar to EPS, less compatible with traditional methods
PCM (Paraffin Wax)	0.02	0.21	0.095	Thermal buffer against temperature fluctuations; beneficial in varying climates

The results from the DSS analysis as it can be seen in figure 11 indicates the following

- **Aerogel Insulation**: has achieved the higher score make it the most compatible material to be used for the roof and the wall of the heritage building in Erbil city. The main factors that lead to the high score is its thermal proprieties and the minimal ecological footprint which is aligned with sustainability goals. The study by Ganobjak et al. (2020) also confirmed the effectiveness of the Aerogel insulation material for heritage buildings due to its minimal thickness. Furthermore, the design of Aerogel as a non-invasive application form, such as renders and boards, makes it ideal for preserving the structural and historical integrity of buildings(GanobjakBrunner and Wernery, 2020).
- **Natural Hydraulic Lime**: It is preferred for its natural qualities and the level of moisture management that it provides, making it essential for the structural duration, particularly in older buildings. Its use is well-documented by Forster and Carter (2011), highlighting its suitability in preserving the aesthetic and structural integrity of historic masonry (Forster and Carter, 2011).
- **Phase Change Materials (PCM)**: Although PCM like Paraffin Wax offers innovative temperature regulation by absorbing and releasing heat, its integration must be carefully considered. Delgado et al. (2018) emphasize PCM's potential to reduce energy usage effectively, which must be balanced with preserving historical authenticity as discussed by Nair, Verde, and Olofsson (2022), (Del Curto and Cinieri, 2020),(NairVerde and Olofsson, 2022)
- **EPS and XPS**: While these materials provide good insulation, they are less favored due to their potential visual impact and challenges in integrating with traditional building materials.



	Aerogel Insulation	Natural Hydraulic Lime	EPS	XPS	PCM (Paraffin Wax)
HSL	163	162	69	68	97
EIL	164	136	60	76	140
ECCIL	40	36	48	48	40
total	367	334	177	192	277

Figure 11: Comparison of DSS Scores for Different Insulation Materials (By the authors)

This DSS evaluation guides the selection of insulation materials by assessing their compatibility with heritage preservation goals, environmental impact, and economic viability, thus aiding in enhancing energy efficiency while respecting historical integrity.

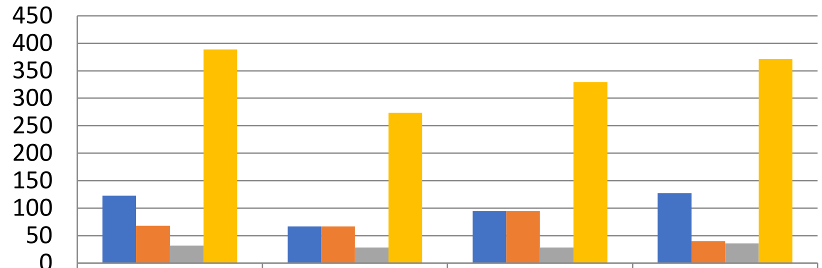
4.1.3 Intervention 3: Efficient Window Strategies for Heritage Buildings

Window retrofit strategies are essential for enhancing energy efficiency while preserving the architectural integrity of heritage buildings (NairVerde and Olofsson, 2022). The selected window technologies aim to balance modern performance demands with the conservation of historical aesthetics (Table 7).

Table 7: Properties of Selected Window Technologies for Retrofitting (By the authors).

Window Technology	U-value (W/m²K)	Sound Insulation (dB)	Light Transmission (%)	Key Features	Ref.
Double Glazing with Low-E Coating	1.2 - 1.8	30 - 35	70 - 80	Reflects heat back into the room, reducing energy needs.	(Somasundaram et al., 2020),(Al-Sakkaf et al., 2021)
Triple Glazed Windows	0.5 - 0.8	Over 40	60 - 75	Multiple layers of glass and coatings for superior insulation.	(Miran, 2020, Ide et al., 2022)
Smart Glass Technology	Variable	Comparable to double glazing	10 - 80	Adjusts light transmission dynamically for energy optimization.	(Casini, 2014)
Single Glazing with Low-E Coating	2.5 - 3.5	20 - 25	80 - 90	Improves over standard single glazing but less efficient than multi-pane options.	(MarzoukElSharkawy and Eissa, 2020)

These window technologies have been compared against each other using the DSS, rather than being evaluated for each typology individually. This approach ensures a comprehensive assessment that identifies the best overall solution. The results as it can be seen in figure 12 indicate the following result.



	Double Glazing with Low-E Coating	Triple Glazed Windows	Smart Glass Technology	Single Glazing with Low-E Coating
1 Heritage conservation critera HSL (0-4)	122.35	66.66	94.67	127.53
2. Enviromantl Criteria EIL(0-4)	68	66.66	94.67	40
3. Economic critera ECCIL (0-4)	32	28	28	36
TOTALLY	388.7	273.32	329.34	371.06

Figure 12. Evaluation of Different Window Technologies within the window efficient strategy (By the authors).

- **Double Glazing with Low-E Coating**: This technology excels in heritage conservation by minimizing structural alterations and maintaining historical integrity. It offers excellent insulation (low U-value), enhancing breathability and lifespan. Economically, high initial costs are offset by long-term energy savings and reduced maintenance. Overall, it provides a balanced approach, improving insulation and energy efficiency while preserving heritage aesthetics, making it the preferred choice.
- **Triple Glazed Windows:** While offering superior insulation, this technology may significantly alter the building's appearance, compromising heritage goals. It matches double glazing in environmental performance but is less adaptable to traditional aesthetics. High initial costs may not yield proportional benefits, limiting its economic attractiveness. Thus, despite energy benefits, its impact on heritage aesthetics and costs reduces its suitability.
- **Smart Glass Technology:** This option scores lower in heritage conservation due to potential visual changes. It excels in dynamic light and energy management but may not suit all heritage settings due to its modern look. High-tech features increase initial costs without equivalent heritage benefits. While innovative in environmental control, it may compromise historical essence, making it less ideal for heritage retrofitting.
- **Single Glazing with Low-E Coating:** Maintaining a traditional look, this technology lacks in thermal and acoustic enhancement. It provides minimal environmental benefits and is less effective for energy conservation. Economically, lower initial costs lead to higher long-term expenses due to poor insulation and energy inefficiency. Overall, it fails to meet comprehensive retrofitting needs, making it less suitable for heritage buildings.

5.Discussion

This study systematically evaluated retrofitting strategies for heritage buildings in Erbil City, focusing on moisture management, thermal insulation, and energy-efficient window strategies. The results, analyzed using the Decision Support System (DSS), provided quantitative assessments of each intervention based on heritage significance, environmental impact, and cost-effectiveness. This section critically discusses these findings in relation to the research objectives and previous studies.

Addressing the Research Objectives

- **Objective 1: Evaluating the Compatibility of Retrofitting Scenarios**

The study systematically assessed the compatibility of different retrofitting scenarios within predefined strategies. The DSS facilitated a structured evaluation process, ensuring that interventions align with heritage conservation principles while optimizing environmental performance.

- **Objective 2: Developing a Decision Support System (DSS) for Retrofitting**

The DSS was designed as a comprehensive decision-making tool that integrates heritage significance, energy efficiency, and economic viability. By incorporating expert insights and a structured weighting system, the DSS ensures that professionals, planners, and building occupants can select the most appropriate retrofitting strategies.

- **Objective 3: Evaluating Retrofitting Measures and Their Impact**

5.1 Moisture Management in Heritage Buildings

The DSS analysis identified Liquid Waterproofing Membrane as the most effective material for moisture management due to its high flexibility, seamless application, and minimal visual impact (Figure 10). This finding aligns with Martínez-Garrido et al. (2018) and AlfanoPalella and Riccio (2023), who emphasize the importance of using non-invasive waterproofing solutions that preserve the aesthetic and structural integrity of historic buildings.

However, despite its high performance, this material requires periodic maintenance to ensure long-term durability. Alternative solutions, such as polyurethane liquid membranes and EPDM rubber, were found to be less favorable due to either heritage impact concerns or increased structural load. These results underscore the need for balance between preservation and durability in moisture management strategies.

5.2 Thermal Performance and Energy Efficiency

Among insulation materials, Aerogel Insulation ranked highest in DSS analysis due to its high thermal resistance, minimal thickness, and non-invasive nature (Figure 11). This confirms the findings of Ganobjak et al. (2023) who demonstrated aerogel's effectiveness in improving thermal comfort without altering historic facades. Their research highlighted how aerogel-based insulation solutions effectively reduce heat transfer and condensation risks, contributing to better indoor environmental quality while maintaining aesthetic and structural heritage value.

Similarly, Aien (2021) investigated the thermal and hygro-thermal performance of aerogel-containing plaster as a retrofit solution for historic building façades. Aien's study emphasized that aerogel-based plasters provide a high level of insulation while addressing moisture-related issues, ensuring both thermal efficiency and long-term material durability. Natural Hydraulic Lime was the second most preferred material due to its moisture-regulating properties and historical compatibility (Apostolopoulou et al., 2020). In contrast, EPS and XPS insulation, though thermally effective, were found to be less compatible with heritage structures due to visual and material integration challenges.

The findings suggest that a hybrid insulation approach, combining aerogel with lime-based materials, could offer both energy efficiency and material compatibility.

5.3 Energy-Efficient Window Strategies

The DSS analysis revealed that Double Glazing with Low-E Coating was the most effective solution for window retrofitting due to its balance between energy efficiency and heritage preservation (Figure 12). This aligns with studies by Nur-E-Alam et al. (2024), which emphasize Low-E coatings as an optimal solution for historic buildings due to their ability to enhance insulation without altering aesthetics.

Although Triple Glazed Windows provided superior insulation, they were deemed less suitable due to their high cost and visual impact on heritage buildings. Similarly, Smart Glass Technology, while offering dynamic light control, was ranked lower due to aesthetic alterations and high maintenance costs.

These results indicate that window retrofitting in heritage buildings should prioritize solutions that enhance energy performance while maintaining historical authenticity.

5.4 Overall Impact and Practical Implications

The findings demonstrate that carefully selected retrofitting strategies can significantly enhance energy efficiency and indoor comfort in heritage buildings without compromising their historical integrity. The DSS provided a structured evaluation framework that allowed decision-makers to assess interventions based on multi-criteria analysis.

Furthermore, this research highlights the importance of non-invasive retrofitting approaches, particularly in historic districts where strict conservation regulations apply. The integration of advanced materials and simulation tools facilitates data-driven decision-making for sustainable retrofitting in Erbil and beyond.

5.5 Challenges in Retrofitting Heritage Buildings

The study identified several constraints that must be addressed in heritage retrofitting:

- **Heritage preservation constraints:** Retrofitting options must maintain historical integrity while improving performance.
- **Material compatibility:** Ensuring that modern materials blend seamlessly with traditional construction techniques.
- **Energy efficiency improvements:** Enhancing thermal comfort while minimizing structural alteration.
- **Economic feasibility:** Weighing the cost-effectiveness of retrofit solutions against long-term benefits.

5.6 The Role of the Decision Support System (DSS) in Retrofitting Strategies

The validated DSS provides a structured methodology to facilitate sustainable retrofitting decision-making. It contributes to conservation efforts by:

- Offering a replicable, evidence-based approach for assessing retrofit compatibility.
- Prioritizing energy-efficient solutions that align with heritage preservation principles.
- Enhancing transparency and consistency in retrofitting decision-making.

5.7 Policy and Legislative Considerations

The study underscores the need for regulatory frameworks that facilitate sustainable retrofitting while preserving cultural heritage. The EN 16883:2017 standard could serve as a reference for developing heritage-specific retrofitting policies in Erbil and similar contexts. Implementing financial incentives and legal guidelines would further encourage sustainable conservation strategies.

5.8 Novelty and Contributions:

This study presents a novel **Decision Support System (DSS)** specifically designed for the sustainable retrofitting of heritage buildings in **Erbil City.** Unlike previous approaches, the DSS systematically integrates **heritage conservation principles, environmental performance metrics, and economic viability assessments** into a unified framework. The innovative scoring and weighting methodology offers a **transparent and replicable approach** to evaluate retrofitting strategies, making it applicable to various heritage contexts. Furthermore, the study contributes to the field by demonstrating the **practical applicability of the DSS** through a real-world case study in Erbil, addressing the **lack of tailored retrofitting frameworks** for heritage structures in hot, semi-arid climates. By optimizing thermal comfort and energy efficiency while preserving cultural integrity, the study bridges the gap between **sustainability and heritage conservation,** offering a practical and adaptable tool for future retrofitting initiatives.

5.9 Limitations and Future Research

While this study presents a comprehensive assessment of retrofitting solutions, several limitations should be acknowledged:

- **Cost Considerations:** Some materials (e.g., aerogel) offer high thermal performance but remain expensive, requiring further analysis of cost-benefit trade-offs.
- **Long-Term Performance Validation:** Future research should focus on monitoring post-retrofit performance to validate the DSS predictions.
- **Integration with Renewable Energy:** Future studies could explore solar-integrated window technologies or passive cooling systems to enhance energy efficiency further.

By addressing these areas, future research can expand the applicability of sustainable retrofitting frameworks for diverse heritage contexts.

6Conclusion

This research contributes to the ongoing efforts in sustainable retrofitting by presenting a validated DSS framework that systematically evaluates energy-efficient interventions for heritage buildings. The findings emphasize the importance of an integrated, multidisciplinary approach where conservation experts, architects, and policymakers collaborate to achieve optimal retrofit solutions.

The study demonstrates that energy efficiency improvements can be successfully implemented without compromising historical integrity, reinforcing the importance of scientific, data-driven assessment tools in heritage conservation strategies

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Appendix 1 Table 1: Comparative Analysis of Retrofitting Tools by the researcher

Tool Name	Context	Authors	Date of	Connection to the EN 16883:2017	Methodology	Link	Limitations	Parameters Measured	Methodology Description
Responsible Retrofit Guidance Wheel	UK	Sustainable Traditional Buildings Alliance (STBA)	2013 (2020)	Identifies retrofit solutions(10.3-10.4; selects and assesses packages);(10.6-10.7)	Wheel structure for exploring retrofit solutions.	Responsible Retrofit Guidance Wheel	Locally focused (UK and France), mainly considers traditional buildings,	Evaluates technical efficiency, heritage preservation, and energy performance;	Utilizes a wheel structure where each segment corresponds to a specific retrofit solution. Users input data regarding the building's context, heritage value, condition, etc., to explore the implications of various retrofit solutions, including energy savings and risk levels.
French version of the Responsible Retrofit Guidance Wheel	France	STBA; Centre Rehabilitation du Bâti Ancien (CREBA)	2018	Identifies retrofit solutions(10.3-10.4; selects and assesses packages);(10.6-10.7)	Similar structure to UK version, adapted for French context.	French Version	Locally focused, mainly considers traditional buildings,	- Similar parameters as the UK version	Shares the methodology of the UK version but requires adaptation to the French context, focusing on traditional French buildings.
HiBERT ool - Historic Building Energy Retrofit Tool (Atlas)	Alpine space	Interreg AS ATLAS / IEA-SHC TASK 59	2021	Identification of the retrofit solutions (10.3-10.4); Assessment of remaining solutions (10.5)	Detailed assessment of retrofit solutions.	HiBERTool	Dependent on a restricted number of documented solutions, focused on traditional regional alpine architecture, may require adaptation to other contexts	- Detailed assessment for retrofit solutions - Long list of possible retrofit solutions - Shortlist selection for viable solutions	Provides a database of retrofit solutions with detailed assessments. Users can access a list of solutions and evaluate them to create a prioritized shortlist based on documented solutions, applicable to alpine architecture.

exDSS - Climate for Culture	Europe	Climate for Culture project	2014	From Collection of relevant information (7) to Identification of the retrofit solutions (10.3-10.4)	Assumed methodology for assessing hygrothermal risks	exDSS	Limitations not explicitly mentioned in the provided text	- Hygrothermal risk assessment of retrofit solutions	Although specific parameters are not mentioned, it is assumed that the tool assesses the impact of retrofit solutions on the hygrothermal performance of historic buildings, which is crucial for preserving their condition and heritage value.
Effesus DSS/RE2H	Europe	TECNALIA	2015 (2020)	From Initiating the planning process (6) to Urban district level	Presumably supports urban scale energy planning and renovation.	Effesus DSS/RE2H	Limitations not explicitly mentioned in the provided text	- Urban scale energy planning and renovation measures	The tool likely incorporates a variety of parameters tailored for urban district-level planning, focusing on the integration of retrofitting strategies within broader urban energy plans.

Appendix 2 Questionnaire (Heritage Building Retrofit Assessment: Expert Evaluation of Criteria Importance)
We are researcher form Department of Architecture, College of Engineering at Salahaddin University in Erbil. I am engaged in research that focuses on updating and improving heritage buildings to meet current environmental and energy standards – a process known as retrofitting. Your specialized knowledge is essential to help identify the most critical factors in this process. By participating in this survey, you are contributing to a pivotal aspect of my dissertation, aimed at preserving our architectural heritage in a sustainable manner.
Thank you for your valuable participation.
Not important, (2) slightly Important, (3) Moderately Important, (4) Important, and (5) Very Important

Category HSL	Sub-category	Description	1	2	3	4	5	Note
Minimum Intervention	Structural Integrity	Is the building's structural core maintained with minimal alterations?"						
	Historical Fabric Preservation	Are historical materials and construction techniques preserved						
	Non-invasive Techniques	Are the methods employed non-destructive to the original fabric?"						
Reversibility	Removability,,	"Can new additions be removed without trace?"						
	Future Adaptability	"Does the retrofit allow for future changes or reversions?"						
	Non-permanent Alterations	Are interventions easily reversible?						
Authenticity	Historical Accuracy,	Does the retrofit reflect the building's original time and place?"						

and Integrity									
	Material Authenticity,	Are materials historically appropriate and sourced?							
	Original Design Preservation	Is the original design narrative preserved?							
Compatibility	Structural Compatibility,	"Can the retrofit be incorporated without altering the existing structural framework?"							
	Material Compatibility,	"Do the retrofit materials match the original in appearance and physical properties?" "Will the new materials age or weather consistently with the existing materials?"							
	, Aesthetic Compatibility	"Does the retrofit uphold the building's historical aesthetic and character?" "Is the visual impact of the retrofit in harmony with the building's architectural style?"							
Historical Value Preservation	Conservation of Historic Façade:	Evaluates the retrofit's impact on preserving the facade's architectural style and structural elements.							
	Material Authenticity and Aging	Evaluates the retrofit's impact on preserving the facade's architectural style and structural elements.							
	Detail Preservation and Integration:	Examines the retention and harmonious integration of facade details and ornamentation.							
Architectural Value Conservation	Architectural Features Maintenance	"Are the original architectural features maintained properly?"							
	Style Preservation	"Does the retrofit preserve the historical style of the building?"							
	Enhancing Architectural Character	"Does the retrofit enhance the building's unique architectural character?"							
Aesthetic Value Consideration	Visual Impact	"Is the visual impact of the retrofit in harmony with the heritage context?"							
	Character-Defining Elements	"Are character-defining elements of the building preserved?"							
	Landscape Integration	"Does the retrofit integrate well with the surrounding landscape?"							
Feasibility	Cost-Effectiveness	"Is the retrofit financially viable?"							
	Implementation Practicality	"Is it practical to implement the retrofit measures?"							

	Availability of Materials/Techniques	"Are the necessary materials and techniques readily available?"						
Legibility	Distinction between Old and New	"Is there a clear distinction between the original and new additions?"						
	Interpretability	"Does the retrofit facilitate the interpretation of the building's history?"						
	Documentation of Changes	"Are all retrofit-related changes thoroughly documented?"						
Maintenance	Ease of Care	"Are the retrofit measures easy to maintain?"						
	Long-term Sustainability	"Will the retrofit measures be sustainable in the long term?"						
	Preservation Techniques	"Are appropriate preservation techniques employed for ongoing maintenance?"						
Embodied Energy	Amount of Original Fabric Preserved (%)	Maintaining the originality building fabric and the energy footprint of new materials.						
	Energy Used in New Material (MJ or kWh/unit)	Using energy-efficient materials in heritage building retrofitting						
Hydrothermal Performance	U-value (W/m^2K)	Ensuring a low U-value for optimal thermal performance in heritage building retrofits						
	Specific Heat Capacity (J/kgK)	Regulating temperature effectively during heritage building retrofitting						
	Linear Thermal Transmittance (W/mK)	"Lowering thermal bridging in heritage building retrofitting for better thermal control."						
	Moisture Buffering Capacity (kg/m^2)	Managing moisture levels in retrofitting historical buildings for better thermal control						
	Air Tightness (m^3/hm^2 at 50 Pa)	Ensuring airtightness when retrofitting heritage buildings to maintain their integrity						
- Durability	Drying Capacity (kg/m^2s)	Significance of materials' drying capacity in retrofit durability						
	Freeze-Thaw Cycles Survived	Material resilience to natural weathering						
	Interstitial Condensation (%)	Evaluate the importance of controlling moisture within building structures						
	Decay of Embedded Elements	Assessing the decay of embedded elements in the durability of retrofitted heritage buildings						
Capital Costs	Total Initial Investment	Calculates the upfront investment required for						

	Costs (currency)	retrofitting measures.						
Operational Energy Costs	Annual Energy Costs (currency/year)	Estimates the annual costs associated with the energy consumption post-retrofit.						
Maintenance and Replacement Costs	Sum of Periodic Maintenance and Replacement Costs (currency)	Projects the long-term costs for maintenance and potential replacement of retrofit components.						

Appendix 3. DSS Tool Weighting Criteria Based on Expert Questionnaire

Qualitative Criteria for the DSS	Column1	Weight	M 1	WS 1	M 2	WS 2
Heritage conservation criteria HSL (0-4)						
Minimum Intervention	Structural Integrity	1.33		0		0
	Historical Fabric Preservation	1.33		0		0
	Non-invasive Techniques	1.33		0		0
Reversibility	Removability,,	1.33		0		0
	Future Adaptability	1.33		0		0
	Non-permanent Alterations	1.33		0		0
Authenticity and Integrity	Historical Accuracy,	1.5		0		0
	Material Authenticity,	1.5		0		0
	Original Design Preservation	1.5		0		0
Compatibility	Structural Compatibility,	1.5		0		0
	Material Compatibility,	1.5		0		0
	Aesthetic Compatibility	1.5		0		0
Historical Value Preservation	Conservation of Historic Façade:	1.67		0		0
	Material Authenticity and Aging	1.67		0		0
	Detail Preservation and Integration:	1.67		0		0
Architectural Value Conservation	Architectural Features Maintenance	1.68		0		0
	Style Preservation	1.68		0		0
	Enhancing Architectural Character	1.68		0		0
Aesthetic Value Consideration	Visual Impact	1.5		0		0
	Character-Defining Elements	1.5		0		0

	Landscape Integration	1.5		0		0
Feasibility	Cost-Effectiveness	1.33		0		0
	Implementation Practicality	1.33		0		0
	Availability of Materials/Techniques	1.33		0		0
Legibility	Distinction between Old and New	1.33		0		0
	Interpretability	1.33		0		0
	Documentation of Changes	1.33		0		0
Maintenance	Ease of Care	1.5		0		0
	Long-term Sustainability	1.5		0		0
	Preservation Techniques	1.5		0		0
2. Environmental Criteria EIL(0-4)						
Embodied Energy	Amount of Original Fabric Preserved (%)	4		0		0
	Energy Used in New Material (MJ or kWh/unit)	4		0		0
Hydrothermal Performance	U-value (W/m²K)	4		0		0
	Specific Heat Capacity (J/kgK)	4		0		0
	Linear Thermal Transmittance (W/mK)	4		0		0
	Moisture Buffering Capacity (kg/m²)	4		0		0
	Air Tightness (m³/hm² at 50 Pa)	4		0		0
Durability	Drying Capacity (kg/m²s)	4		0		0
	Freeze-Thaw Cycles Survived	4		0		0
	Interstitial Condensation (%)	4		0		0
	Decay of Embedded Elements	4		0		0
3. Economic criteria ECCIL (0-4)						
Capital Costs	Total Initial Investment Costs (currency)	4		0		0
Operational Energy Costs	Annual Energy Costs (currency/year)	4		0		0
Maintenance and Replacement Costs	Sum of Periodic Maintenance and Replacement Costs (currency)	4		0		0