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Review

How Can Scientific Literature Support Decision-Making in the Renovation of Historic Buildings? An Evidence-Based Approach for Improving the Performance of Walls

Valentina Marincioni [1,2,*], Virginia Gori [1], Ernst Jan de Place Hansen [3], Daniel Herrera-Avellanosa [4], Sara Mauri [5], Emanuela Giancola [6], Aitziber Egusquiza [7], Alessia Buda [5], Eleonora Leonardi [4] and Alexander Rieser [8]

1 Bartlett School of Environment, Energy and Resources (BSEER), University College London, London WC1H 0NN, UK; virginia.gori@ucl.ac.uk
2 UK Centre for Moisture in Buildings (UKCMB), London E15 2GW, UK
3 Department of the Built Environment, Aalborg University (AAU), 2450 Copenhagen, Denmark; deplace@build.aau.dk
4 Institute for Renewable Energy, Eurac Research, 39100 Bolzano, Italy; daniel.herrera@eurac.edu (D.H.-A.); eleonora.leonardi@eurac.edu (E.L.)
5 Department of Architecture, Built Environment and Construction Engineering (ABC), Politecnico di Milano, 20133 Milan, Italy; sara.mauri@polimi.it (S.M.); alessia.buda@polimi.it (A.B.)
6 Department of Energy, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), 28040 Madrid, Spain; emanuela.giancola@ciemat.es
7 TECNALIA, Basque Research and Technology Alliance (BRTA), 48160 Derio, Spain; aitziber.egusquiza@tecnalia.com
8 Department of Energy-Efficient Buildings, University of Innsbruck, 6020 Innsbruck, Austria; alexander.rieser@uibk.ac.at
* Correspondence: v.marincioni@ucl.ac.uk

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Abstract: Buildings of heritage significance due to their historical, architectural, or cultural value, here called historic buildings, constitute a large proportion of the building stock in many countries around the world. Improving the performance of such buildings is necessary to lower the carbon emissions of the stock, which generates around 40% of the overall emissions worldwide. In historic buildings, it is estimated that heat loss through external walls contributes significantly to the overall energy consumption, and is associated with poor thermal comfort and indoor air quality. Measures to improve the performance of walls of historic buildings require a balance between energy performance, indoor environmental quality, heritage significance, and technical compatibility. Appropriate wall measures are available, but the correct selection and implementation require an integrated process throughout assessment (planning), design, construction, and use. Despite the available knowledge, decision-makers often have limited access to robust information on tested retrofit measures, hindering the implementation of deep renovation. This paper provides an evidence-based approach on the steps required during assessment, design, and construction, and after retrofitting through a literature review. Moreover, it provides a review of possible measures for wall retrofit within the deep renovation of historic buildings, including their advantages and disadvantages and the required considerations based on context.

Keywords: historic buildings; walls; building performance; retrofit measures

1. Introduction and Scope

More than 30% of residential buildings in Europe have been constructed before the 1950s [1], with national variations depending on the countries' history. Many of these buildings are associated with historical, architectural, or cultural values, and are therefore defined as historic. This definition does not only include listed buildings, but also buildings of historic centres and residential buildings that have a value recognized by the community and are deemed worthy of preservation [2]. These buildings are likely to be preserved and adapted to maximize their life expectancy. As the building stock generates around 40% of global emissions worldwide [3], improving the energy performance of historic buildings can enable climate change mitigation in the cultural built heritage sector, seen by experts as a necessary, although challenging endeavour [4]. Improving the energy efficiency of historic buildings would not only contribute to the reduction of global greenhouse gas emissions, but would also have positive effects on the health and comfort of the occupants and help save the cultural heritage represented by these buildings for future generations.

Acting on the thermal performance of the building envelope in existing buildings plays a major role in terms of reducing their greenhouse gas emissions [5]. There are several retrofit measures for walls available in the market [6], including typologies promoted specifically for historic buildings [7]. The overall performance of a retrofit measure does not only depend on the materials composing the insulation system, but also on the installation method and quality, the properties of the existing wall and its surroundings, and the use of the building. The choice of inappropriate systems in energy-efficient renovation projects can change the hygrothermal performance and reduce the drying potential of a wall, which negatively affects the structural integrity of a building and the health of the occupants. This can occur when new materials or methods are introduced without a sufficient understanding of the possible impacts on the existing construction.

The Deep Renovation of Historic Buildings

The installation of energy efficiency measures in historic buildings is becoming increasingly common [8–10]. Similarly, energy-efficient renovations are progressively seen as contributing to the protection of cultural heritage, since upgrading historic buildings to meet current needs ensures the continued use of these buildings, rather than their neglection and destruction [11,12].

Recently, there has been an increasing interest towards the deep renovation of historic buildings. The IEA-SHC Task 59/ECB Annex 76 project on "Deep renovation of historic buildings towards lowest possible energy demand and CO_2 emission (nearly Zero Energy Buildings—nZEB)" [13] gathered a solid knowledge base on how to cost-effectively save energy in the retrofitting of historic and protected buildings, thanks to the existing research and new findings shared by the partners involved in this interdisciplinary collaboration. In the deep renovation of historic buildings, the IEA-SHC Task 59 argues that each individual building should have a specific energy demand target, depending on the building and its context. The target is defined by a changing "negotiation space" resulting from the intersection between the compatible measures for the specific building and possible measures focused on energy efficiency. According to this approach, "The implementation of all compatible measures included in the negotiation space would achieve the lowest possible energy demand for that building" [14]. The variability and peculiarity of historic constructions make it very hard to identify retrofit strategies that can be applicable at large [15]; therefore, professionals and building users have been voicing the need for support during the decision-making process [16,17]. To this end, a whole-building, integrated framework that can maximise the strengths of the different disciplines contributing to the energy-efficient renovation of historic buildings is necessary. This aspect will be discussed more in detail in a companion paper currently under review in this special issue [18].

The European Standard EN 16883:2017 [2] presents a systematic approach to facilitate decision-making in planning the energy-efficient renovation of historic buildings promoting a joined-up approach from their assessment and design to construction and use. According to the standard, "Any energy performance improvement measures shall be integrated in a long-term management strategy for the whole building". A normative working procedure is provided for the selection of energy efficiency measures, which includes objective-setting, assessment of the building and its context, and assessment and selection of measures. Similar efforts to create processes and frameworks are being made at a national level (e.g., in Italy [19] and in the UK [20]). Despite these efforts, there appears to be limited agreement on valid principles that can guide the holistic assessment and selection of measures for the energy-efficient renovation of historic buildings, which considers multiple, and sometimes contradictory, objectives.

The aim of this paper is to provide a coherent picture of procedural steps and available measures for improving the energy performance of the building envelope, and walls in particular, in historic buildings, according to international literature. The literature review was based on the recent developments in academic literature, with a focus on research that can be applied to historic buildings, and complemented by grey literature published by heritage organisations and policy-makers worldwide. The review builds on the work of a consortium of international experts in the field, involved in the IEA-SHC Task 59/ECB Annex 76 project.

Section 2 provides an overview of the objectives in the deep renovation of historic buildings, based on the framework set out in EN 16883:2017 [2], but common across frameworks developed in similar contexts (e.g., the STBA Whole Building Approach [21], 3EnCult [22], RIBuild [23]). Section 3 highlights the importance of evaluating the existing wall in its context, while Section 4 presents possible ways to address this (i.e., the methods of assessment). An overview of wall-retrofit measures is presented in Section 5, where the different options are grouped according to the main objectives they help address. Finally, Section 6 suggests suitable methods for monitoring the long-term performance of retrofit measures and strategies.

2. Setting the Objectives

An important step for the selection of retrofit measures consists of setting the objectives of the renovation project and relevant criteria to evaluate the adherence of the retrofit strategy to these objectives. These objectives have to be defined in line with the needs and values of the client, who has to be involved in the process and might need guidance to express the objective(s).

The set objectives have an influence on the weighting of the criteria. Striking the balance between the various criteria therefore depends on the objectives set in each renovation project, as well as the impact of each solution on the set objectives. The objectives will be specific to each individual building, as they should take into account the building and its context, including the conditions prior to renovation [23].

Objectives for the Selection of Retrofit Measures for Walls

For the selection of wall retrofit measures, the objectives can be defined based on the following key elements [2]:

- Heritage significance and conservation/protection: A retrofit strategy with heritage significance as objective promotes the maintenance of historical and cultural values. In case of historic buildings, there is a need for preservation of certain building features and the values they convey. These can include a specific construction technique, construction detail, or a wall painting. This might involve the full or partial preservation of the existing wall structure [24] and the reversibility of the retrofit measures implemented, that is, the possibility of removing the measure without damaging the building integrity. It also considers the spatial impact of measures, such as changing the proportions of the building.
- Technical compatibility: This objective consists of preserving the structural or visual integrity of a building. Issues associated with poor technical compatibility in the retrofit of historic walls may lead to damage to the building integrity, including wood rot, corrosion, and fire spread. Mould growth and damp, together with frost damage and algae growth, can negatively affect the building conditions, that is, the structural integrity and the visual appearance of the building [25].
- Low energy consumption: This objective entails the provision of measures that can minimise energy demand of the building, with the aim of minimising the greenhouse gas emissions of the building stock. This is usually regulated at a national level.

- Economic viability: This objective considers the capital and operating costs of the renovated building from a long-term perspective, as well as the economic savings. Economic viability should also consider expenditures required for maintaining the efficiency and reliability levels of the components subject to obsolescence and decay phenomena [2]. A thorough analysis should consider all the elements contributing to a wall retrofit measure, not only the materials involved. For example, it should also consider the workmanship costs, as different measures are associated with different levels of workmanship.
- Indoor environmental quality: This objective entails providing adequate indoor environmental conditions for the health and comfort of users, as well as for the building and the items contained in it, which may include artefacts of historic, social, or cultural value. Issues include effects on health associated with cold homes [26], high indoor temperatures [27], mould growth and damp [28–30], and with the presence of harmful contaminants, such as radon [31] and other pollutants [32].
- Low impact on the wider environment: this objective consists of limiting the rise of greenhouse gas emissions into the atmosphere caused by the renovation process. Considerations include retaining the historic building fabric as much as possible, reusing existing materials [33], and appropriate selection, use, and disposal of construction materials during renovation [34].
- Operational performance: This objective focuses on achieving the design performance after the end of the renovation process. The success of the energy-efficient renovation will not only depend on the effectiveness of the intervention, but also on the maintenance and management practices by users [35].

3. Understanding the Existing Wall in Its Context

After setting the objectives, the selection of retrofit measures for walls requires an assessment of the existing wall and its context. This section presents the main elements for this assessment, which considers an analysis of the building and its context, but also an analysis of the heritage significance of the walls and connected elements, as well as of their hygrothermal characteristics.

3.1. Historic Buildings and Their Context

As it has been recognised since Fathy's [36] studies on vernacular architecture, historic constructions have efficiently used local resources and available energy sources, leading to specific building typologies depending on climate, site location, and local culture. The functioning of historic buildings is deeply linked to their cultural and environmental context, which evolves over time [37]. Historic buildings were designed based on passive indoor climate management strategies, exploiting physical mechanisms such as thermal mass, shading, evaporative cooling, and natural ventilation through walls or window openings. They have been built in periods where mechanical systems for heating, ventilation, and cooling did not exist, and therefore the construction strategy had to take advantage of all the natural elements to make indoor spaces comfortable, both in summer and winter [38]. Ultimately, the environmental qualities and performance of vernacular architecture are intertwined with social, political, and economic aspects, which have to be considered in the analysis of the environmental performance of historic buildings [39].

The following sections describe some of the elements needed to understand the historic building and its context. These elements include the construction techniques and materials used, the building conditions, the weather, and the indoor environmental conditions.

3.1.1. Construction Techniques and Materials

The materials and construction techniques used for walls are closely related to the local geology and climate, as well as to economic and cultural factors [40]. Historic walls are often made of several building materials; the compositions of the materials in the wall core (e.g., rubble core in a stone masonry wall) are often unknown. Several types of masonry may be involved, reflecting different stages of development. Often bricks were manufactured under uncontrolled temperatures, leading to high variability of material properties. With time, additional layers of construction materials might have been added, sometimes without considering the technical compatibility of measures; for example, hard cement-based mortars were used for pointing, causing damage to the masonry. Inappropriate past interventions should be rectified as much as possible; moreover, choosing retrofit measures that are technically compatible with the original construction technique and materials is essential. For this reason, a knowledge of the materials and, above all, an understanding of the function of the materials is a fundamental requirement for a sustainable renovation.

3.1.2. Building Conditions Prior to Renovation

Together with the climatic boundary conditions, the current state of a wall is one of the most important factors to assess prior to renovation. Knowledge about the pre-retrofit state and the robustness of the external wall and the elements connected to it is important, such as when assessing the rainwater protection of a wall and its ability to dry out before reaching critical moisture levels. This is even more relevant when internal insulation is considered as a retrofit measure, as this measure changes the hygrothermal conditions of the wall. Therefore, any kind of damage needs to be identified and remedial actions need to be taken before deciding what kind of insulation system can be applied. Evaluating whether the wall is sufficiently robust includes an assessment of the rainwater management system, the indoor climate, and the wind-driven rain load [23,41].

3.1.3. Influence of Climate Zone

Climate directly affects the energy performance of buildings, leading to changes in heating and cooling demands. In non-renovated historic buildings, internal temperature is highly dependent on the external temperature, often resulting in lower internal temperatures than those proposed in modern standards for cold climates in winter.

Moreover, future weather may present significant differences compared to historical meteorological conditions due to climate change, potentially with a significant impact on the performance of existing walls that were specifically designed in relation to the specific zonal climate. There is an increasing need for improving historic buildings to adapt to climate change in the coming years, as future climate predictions show heavier rainfall and higher average temperatures [42]. To this end, retrofit measures should be assessed considering future climate scenarios. Recent work has focused on climate change-related exposure of heritage buildings to moisture sources [43] and its impact on the retrofit of walls [44,45]. The impact of a warming climate has also been assessed in relation to the increased risk of overheating in retrofitted historic buildings [46].

3.1.4. Influence of Microclimate

Local climatic conditions were always considered in the design and construction of historic buildings. Even in relatively small regions, variations in the climate due to topography or altitude resulted in the development of different construction typologies [46]. The different exposure of walls to the local microclimate, including direct solar radiation and wind-driven rain, has an important influence on the building performance and wall conditions. Indeed, the hygrothermal performance of walls in a historic building can vary on a wall-by-wall basis, depending on their orientation [47]. Moreover, urban morphology influences the hygrothermal performance of historic walls; buildings in dense areas should not be treated in the same way as standalone buildings, especially regarding radiative exchange [48] and exposure to wind-driven rain.

The installation of insulation systems could exacerbate existing problems or create new ones. Therefore, the selection and design of retrofit measures must take into account the drying-out process, before and after retrofit, as well as the presence of residual moisture and salts [49].

3.1.5. The Indoor Environmental Conditions, Prior to Renovation

The overall behaviour of the building envelope prior to renovation usually depends on the use and occupancy of the buildings, the installation of passive strategies (e.g., ventilation, shading), and other elements (e.g., soft furnishing, tapestries) that can play a role in mitigating indoor environmental conditions. Understanding the role of the existing strategies within the renovation process can help to minimise unnecessary oversizing in design of heating/cooling plants and retrofit measures that could threaten the hygrothermal balance of the building elements.

3.2. Heritage Significance of the Walls and Connected Elements

Cultural heritage depends on the importance (or significance) that a society places on it, and this value has always been the reason underlying heritage conservation [50]. No society makes an effort to conserve what it does not value. It is necessary to gain a detailed understanding of the nature and extent of the significance that a historic building has to a society in order to protect, preserve, and conserve the values of that building and its surroundings. This requires an assessment of the cultural significance of the building, which if not undertaken, could potentially lead to decisions being made that diminish or destroy important aspects of the site [51]. According to the Krakow Charter, cultural significance refers to the aesthetic, historic, scientific (including archaeological), social, or spiritual values for past, present, or future generations [52]. Cultural significance is embodied in the heritage place (or site) itself, its fabric, setting, use, associations, meanings, records, related places, and objects.

The EN 16883:2017 [2] standard specifies that the impact of interventions on the heritage significance of the building should be evaluated considering the risk of physical impact (quantity of material removed), visual impact (perception of the changes made), and spatial impact (impact on the spatial configuration). Among the several examples of heritage significance assessments developed in recent years, a valid method to evaluate the visual, physical, and spatial values of historic environments is outlined by the EFFESUS project [53].

3.3. Hygrothermal Behaviour of Walls

The first step to evaluate the feasibility of wall retrofit measures involves understanding the hygrothermal behaviour of the historic wall prior to retrofit, which presents variability due to its composition and seasonal changes in moisture content. An appropriate estimate of the wall thermal properties supports the selection of measures, with possibly significant effects on the cost-effectiveness of the retrofit, the durability of the building, and on other long-term unintended consequences (e.g., overheating) [54].

Most of the historic buildings are made of materials that allow the moisture balance between wetting and drying, provided by a combination of water vapour and liquid transfer, storage, and evaporation. Such materials include lime and/or earth mortars, renders, and plasters. They act as a buffer for moisture and allow for the redistribution of absorbed rainwater, as well as drying via evaporation. Additional rainwater protection could have been provided by means of lime-based renders, or cladding, as well as eaves, overhangs, canopies, and balconies. It is important to consider the impact of the retrofit measures on these elements, such as the reduction of depth of the existing eaves.

When insulating a historic wall, it is crucial to find a solution that is compatible with the hygrothermal characteristics of the existing wall, as systems designed for modern construction might not be appropriate for historic buildings [49].

4. Assessment and Selection of Measures

Retrofit strategies can entail different levels of intervention, based on the impact that the measure is allowed to have on the building, its occupants, and the wider environment. After a thorough understanding of the context, it is necessary to decide the allowed level of intervention for the specific wall in its context, by means of a holistic assessment of the retrofit measures, which includes their impact on heritage, on the integrity (technical compatibility) of the building fabric, on the health and comfort of occupants, and on the environment.

This section presents an overview of assessment methods that can support the selection of retrofit measures for historic walls. As the assessment of the measures depends on the context, it varies case by case.

4.1. Assessment of the Heritage Impact of Retrofit Measures

The Heritage Impact Assessment (HIA) can be used as a tool to evaluate the acceptability of impacts caused by new interventions on cultural heritage assets, comparing the heritage significance of the impacted elements with the changes caused by the required intervention. In the guide developed by the International Council on Monuments and Sites (ICOMOS) for World Heritage properties [55], the negative and positive effects of the proposed interventions are contrasted with the heritage significance values (as defined in Section 3.2).

The EFFESUS project developed a framework to check the eligibility of measures, matching the level of heritage significance with the impact evaluation [53]. The heritage significance level is defined on a scale of 0–4 (from neutral or negative significance to exceptionally outstanding significance), and it is used to evaluate the vulnerability/significance of the building elements, such as walls, roofs, and urban spaces. In parallel, a numerical value from 0 to 4 expresses the heritage impact produced by a repository of retrofit measures (heritage impact level). The eligibility of measures can be defined by the matrix composed by the significance and impact levels. This method can be scaled to the building fabric level and support the assessment of the heritage significance of walls.

The EFFESUS approach has been applied to evaluate early-stage energy efficiency interventions in historical environments considering the improvement of the energy performance of historic buildings as a positive impact on their heritage significance [56]. The types of heritage impact include:

- Material impact: The possible alteration of the existing materials (i.e., the addition/removal of an element or a portion of the building components). An analysis can be done measuring or estimating the quantity of material added or removed.
- Constructional and structural impact: Linked to the stability of the construction (i.e., creating a new opening in a load-bearing masonry).
- Visual impact: The degree of perception by an observer of the changes made by the intervention on the building. The degree of visual impact depends on multiple factors, linked to the conflicting juxtaposition between the new material and the existing building elements. This evaluation is not easily assessable, as it is subjective. It can be evaluated through the assignment of acceptability ranges.
- Spatial impact: Impact on the spatial configuration of the building (external and internal); for example, retrofitting a wall with thick insulation will change the spatial configuration of the building envelope, leading to a possible conflict if there is a window or a balcony.
- Reversibility: In case the insulation system is intended to provide reversibility, the ease of reversibility will be evaluated, assessing the use of hard materials for bonding and the use of mechanical fixings. To this end, the risk of visual damage to the existing interior finish due to mould growth or condensation will be evaluated.

4.2. Assessment of the Technical Compatibility of Retrofit Measures

Although there is not an agreed set of criteria associated with the technical compatibility of measures, some principles for the assessment of technical compatibility can be defined.

4.2.1. Building Conditions and Integrity

First, an assessment of the existing wall has to be carried out. If the wall is in poor conditions, this has to be dealt with before considering any retrofit measure, with the aim of preventing any moisture infiltration due to cracks and gaps. Aspects like the type of finish (e.g., plaster, ashlar, cladding) and its status of conservation, along with the state and efficacy of the rainwater management system, will influence the protection of the wall from wind-driven rain.

4.2.2. Hygrothermal Risks

In traditional walls, it is essential to consider that rainwater is highly likely to be absorbed by the wall. Therefore, moisture risk in walls can be minimized by ensuring that any moisture that has been accumulated within the element is able to dry out. Hygrothermal simulations according to EN 15026:2007 [57] can be performed to evaluate the ability of retrofit measures (e.g., insulation systems) to dry in relation with the existing wall; this assessment requires the knowledge of boundary conditions for simulations (in particular, wind, rainfall, and solar radiation) and of the most relevant material properties [58]. The assessment of the technical compatibility includes the assessment of the likelihood of moisture accumulation within the retrofitted wall, considering indoor and outdoor moisture sources. Excess moisture accumulation can introduce other risks that in turn may lead to structural issues. For example:

- Wood rot, if there are timber elements (e.g., lintels) within the historic wall, or the wall is connected to timber elements (e.g., floor joists).
- Frost damage, if the historic wall has structural elements that are susceptible to frost (e.g., brittle masonry).
- Corrosion, if there is metalwork within the historic wall (e.g., structural ironwork).
- Salt efflorescence, which can occur if the wall has a past history of excess wetting and subsequent evaporation [59] (e.g., water infiltration, rising damp). Sources of salt can originate from the building materials or from pollutants in the surrounding air and soil [23].
- Biological attack, including mould and algae growth. Mould growth can be found on internal cold surfaces or on the surfaces of building materials composing the wall; it can be detrimental to occupants' health if the surfaces are in contact with the indoor environment [60].

These hygrothermal risks can also be assessed by means of hygrothermal simulations if suitable failure criteria and degradation models are known.

4.2.3. Robustness and Buildability of Retrofit Measures

Robustness and buildability need to be explored to ensure that the retrofit measure is performing as intended (i.e., as per design). Robustness represents the ability of a system to deal with uncertainty and variability of hygrothermal properties; this should be considered for a thorough assessment of retrofit strategies.

The buildability of retrofit strategies is an important, but often overlooked point. Examples from the construction industry showed that poor buildability can lead to poor workmanship [61]. In particular, ease of insulation at junctions should be preferred to ensure thermal continuity of the fabric; the evaluation of moisture risk at junctions must consider the risks of surface mould growth and condensation due to lower insulation thicknesses in those locations. Ease of connections (e.g., sealing of vapour control layer) and required maintenance over time is also important.

4.3. Assessment of the Impact of Retrofit Measures on the Environment

The renovation of historic buildings provides a unique opportunity to act on climate change mitigation, by adopting measures with reduced environmental impact. These measures should aim at acting on energy demand and carbon emission reduction, both during the renovation and operative phases.

If the building use will remain unchanged after renovation, the potential energy demand reduction allowed by different retrofit strategies can be evaluated by using the current energy performance of the building (e.g., from in situ measurements, energy meters, or bills) as baseline. Conversely, if the renovation also aims at introducing a change of use of the building, benchmark values can be used for the assessment.

Furthermore, the environmental impact of the renovation can be reduced by adopting low-carbon solutions using natural, local, and recycled materials. These can have a positive impact on the Life Cycle Analysis of the building and help retain its constructive heritage.

4.4. Assessment of the Impact on Occupants' Health and Comfort

The building envelope of historic buildings often has high thermal mass, which can contribute to the health and comfort of occupants by shifting and dampening the indoor temperature peaks. The loss of thermal mass associated to the internal insulation of solid masonry walls is an aspect that should also be considered in some cases, especially in climates with cold winter and warm summers. The tradeoff between both seasons should be studied to avoid creating a cooling load in summer that offsets the benefits of insulation during the coolest part of the year.

The location of insulation in respect to the existing wall can determine a different thermodynamic behaviour. Internal wall insulation can decouple the thermal mass of the heated spaces and allow faster space heating, which can be beneficial in the case of intermittent occupancy. External wall insulation allows to retain the thermal mass, which allows to stabilise the indoor temperature.

4.5. In Situ Evaluation to Support the Assessment of Retrofit Strategies

An evaluation of the wall by means of visual inspection and in situ measurements is essential to assess its thermal performance and allow for a baseline characterization prior to renovation, which accounts for the context (e.g., climate zone and microclimate, building use) and state of conservation. In situ measurements are able to depict the performance of the whole existing wall rather than the sum of the individual elements, and to account for the interaction of the building with the surrounding environment. The in situ measurement of the heat flux across a wall provides an accurate estimation of its thermal transmittance (U-value) [23,62]; these measurements will lead to more informed decision-making during retrofitting [63]. The in situ measurement of the airtightness and the heat loss of the whole building could contribute to gaining a clearer picture of the building prior to renovation, and therefore inform the assessment of retrofit measures.

Laboratory measurements of key wall material properties can also support the hygrothermal risk assessment by providing some input data for hygrothermal simulations. Laboratory measurements include the gravimetric method, to gain some understanding on the initial moisture content of the building, and the measurement of both the water absorption coefficient and the water vapour diffusion resistance (or water vapour permeability) [23]. Such laboratory measurements are expensive, invasive, and time-consuming. Therefore, they are rarely performed outside academia. Non-invasive methods for the on-site testing of water uptake and moisture content (e.g., the Karsten tube method and microwave reflection measurements) in buildings are available [64–66] and allow for a quantification of the wall performance in those cases where sample removal is not possible, or time or budget constraints prevent further analysis [67].

5. Retrofit Measures for Historic Walls

After the assessment of the impact of retrofit measures on the heritage, technical compatibility, and environment, it is possible to select suitable retrofit measures based on the objectives which were set initially. Retrofit measures can be grouped into three types, based on the objective that they prioritise. It is of utmost importance to point out that the suitability of a measure is a function not only of the set objectives, but also of the impact of the measure on those objectives. The first group concerns measures that prioritise heritage conservation, that is, conservative options that are reversible, compatible, and non-invasive. The second group concerns measures that prioritise technical compatibility—they are not necessarily reversible, may be invasive to some extent, but are generally compatible with the historical material consistency. In the third group, measures that prioritise the wider environment are clustered; this group includes measures that prioritise a reduction in energy demand, but also measures made of low-carbon materials. Every retrofit measure must be considered in combination with the initial repair.

Table 1 provides a summary of the objectives addressed by each retrofit measure. It is worth mentioning that, for each type of retrofit measure, several systems are available in the market, and they may be designed to address specific issues thanks to their engineered material properties. It is not the aim of this paper to analyse the differences among proprietary systems.

Table 1. Summary of objectives addressed by the retrofit measures. Natural and local materials can also be part of other retrofit measures in the table (e.g., thin IWI with natural materials); in that case, the objectives in bold also apply to those measures.

Objectives		Prioritising Heritage	Prioritising Technical Compatibility					Prioritising the Environment		
		Reversible lining	Reversible EWI	IWI with Insulating Plaster	EWI with Insulating Render	Thin IWI	Thick EWI	Thick IWI	Natural Materials	Local Materials
Heritage	External appearance	✓		✓		✓		✓		
	Internal proportions	✓		✓	✓	✓	✓			
	Reversibility	✓								
	Material impact								**✔**	**✔**
Thermal comfort	Higher indoor temperature	✓	✓	✓	✓	✓	✓	✓		
	Fast thermal response (e.g., for discontinuous use)			✓		✓		✓		
	Original thermal mass effect (dampening temperature peaks)	✓	✓		✓		✓			
Energy and environment	Energy demand reduction		✓		✓			✓		
	Resources								**✔**	**✔**
	Thermal bridges reduction				✓					
Technical compatibility	Protection from wood rot		✓		✓		✓			
	Protection from frost damage		✓		✓		✓			
	Surface mould reduction		✓	✓	✓	✓	✓	✓		
	Interstitial mould reduction (within the wall)		✓		✓		✓			

5.1. Repairing the Existing Wall

Repairing the existing wall prior to any retrofit intervention is necessary for the improvement of wall durability. The correct intervention depends on the materials and construction techniques of the wall. For example, repairing masonry consists of cleaning, re-pointing, and replacing decayed elements of the construction. This measure aims at keeping a hygrothermal balance of the wall, keeping the wall dry, and allowing drying if needed. On its own, this measure does not improve the energy efficiency of the building, but it is necessary in combination with every other measure.

5.2. Prioritising Heritage

The retrofit measures that prioritise heritage allow some changes to the appearance internally, and little or no changes to the materiality of the envelope.

Reversible Interior Lining of Walls

Lining interior walls with reversible systems, such as tapestries, is a method that was widely used in the past. Over the centuries, in fact, many cultures have developed components for indoor use to cope with harsh outdoor climatic conditions [68]. Tapestries were used in some cultures to cover everything, even canopies, and they were used as curtains to be removed during the summer periods.

Besides their main decorative purpose, traditional interior lining devices contribute to the thermal insulation, to the improvement of thermal comfort, and to the control of the radiant temperature of the wall surface at low cost. They are also easily removable, reusable, can be installed seasonally, and have flexible and manageable elements. However, there are concerns related to the mould growth risk behind the lining, especially in case of low thermal performance of walls or in cold climates, and the final performance of the wall can only be improved to some extent. Additionally, if used to decorate historic buildings, they could interfere with internal ornamental elements, such as fixed furnishing and wall paintings.

5.3. Prioritising Technical Compatibility

The retrofit measures that prioritise technical compatibility aim at minimising risk associated with the structural and visual integrity of the walls; these measures lead to changes to the appearance and materiality of the envelope, but to little or no changes of its spatial characteristics.

5.3.1. External Wall Insulation Systems with High Reversibility

External wall insulation (EWI) systems with high reversibility (shown in Figure 1) consist of prefabricated façade elements that can be fixed to the existing uneven façade by means of compensation rails; the resulting cavities can be filled with loose fill insulation, such as cellulose. In this way, the measure installed allow an increase of the overall thermal resistance to Passivhaus standard and a protection of the façade from wind-driven rain.

The advantages of this solution include reversibility, and therefore, the preservation of a large part of the original façade; only the holes drilled for the compensation rails will be visible after dismantling. Additionally, this solution can be installed and completed quickly due to the high degree of prefabrication, and provides a high level of energy demand reduction.

With this approach, however, the original façade is completely covered after renovation, and the proportions of the building are changed. ThisAlthough more expensive, this solution offers an alternative to a conventional exterior insulation, due to its reversibility although more expensive, but; however, it has to be questioned with regard to the preservation of historical values.

Figure 1. Example of reversible external wall insulation: picture (**left**) and cross-section ((**right**), layers presented from inside to outside) [69].

5.3.2. Internal Wall Insulation with Insulating Plaster

The application of insulating plaster as a means for internal wall insulation (IWI) allows for an improvement of the overall thermal performance of the envelope while maintaining the appearance and materiality of the wall externally and replicating it internally. The use of thin layers ensures respecting the original spatial characteristic of the wall and room, while facilitating replication of the original appearance of the wall (if the original internal surface was plastered) by reproducing any pre-existing unevenness, as shown in Figure 2.

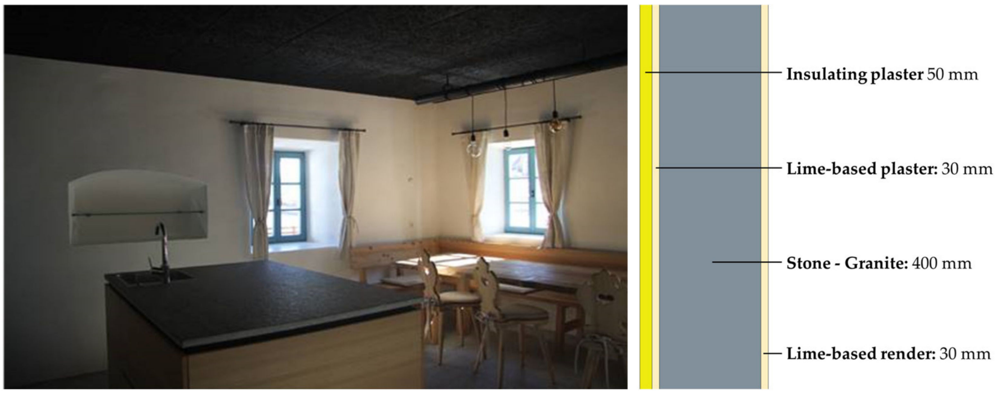

Figure 2. Example of internal wall insulation with insulating plaster: picture (**left**) and cross-section ((**right**), layers presented from inside to outside) [70].

Improving the thermal transmittance of the wall, even slightly, can result in a significant increase of the surface temperature of the wall leading to improved thermal comfort and reduced risks of mould growth (especially around cold areas and thermal bridges, like window reveals [71]). The use of capillary active materials (e.g., lime) will ensure a suitable hygrothermal performance of the wall.

The thermal performance of the measure will depend greatly on the aggregate and thickness used, and there is a wide range of aggregates (e.g., perlite [72], polystyrene, aerogel [73,74], cork, or other bio-based aggregates [75,76]). In many cases, reduced thickness of the insulating plaster is chosen for conservation and practical reasons, and thus, the final performance of the wall can only be improved to some extent, unless high-performing materials like aerogel [77] are used in the plaster. Aerogel, however, is still fairly expensive and might not be suitable in every case. Thicker layers of insulating plaster are likely to change the proportions of the windows, and the visual impact of this measure must be considered. Additionally, the use of insulating plaster might not be feasible in the presence of important decorations like wall paintings or wooden paneling.

5.3.3. External Wall Insulation with Insulating Render

The application of an external insulating render can considerably improve the thermal performance of the wall by lowering its thermal conductivity while retaining the thermal mass. This solution is particularly suitable for stone masonry constructions, especially when the pre-existing render needs to be replaced.

Regular maintenance of the envelope is key in avoiding any water ingress and ensuring the long-term performance of the masonry, as seen in Section 4.2.1. Historic buildings with damaged renders might present a good opportunity to improve the thermal and hygric performance of the wall. Furthermore, external thermal renders can replicate the appearance of the existing finish, resolve problems of thermal bridges and ensure a watertight surface while maintaining the net floor area of the building and minimizing the disruption to occupants.

However, using an insulating render is likely to affect the appearance and materiality of the building, depending on the thickness of the insulating render. Thicker layers of insulating render can affect the visual and spatial characteristics of the building, and thus should only be used when the heritage significance of the building and its surroundings allow for these changes. Moreover, thicker external wall insulation leads to a change of proportions at the roof eaves, potentially leading to moisture issues.

5.3.4. Thin Internal Wall Insulation

A thin layer of insulation (e.g., 2–4 cm) can be applied internally on walls in a wide range of historic buildings [76]. It allows to preserve the external appearance of the wall and the internal proportions of the rooms while improving the energy efficiency of the wall and the thermal comfort of the occupants due to increased surface temperature. When applying internal insulation, the thermal capacity of the heated space mainly consists of the internal air, partition walls, and furniture, and not of the external walls. This leads to a faster heating-up of the indoor spaces, which is desirable in the case of buildings which are not permanently occupied. This solution may also be suitable in the case of internal wooden paneling or lath and plaster, as the cavity that is usually present behind the existing lining could be filled in with insulation, as shown in Figure 3.

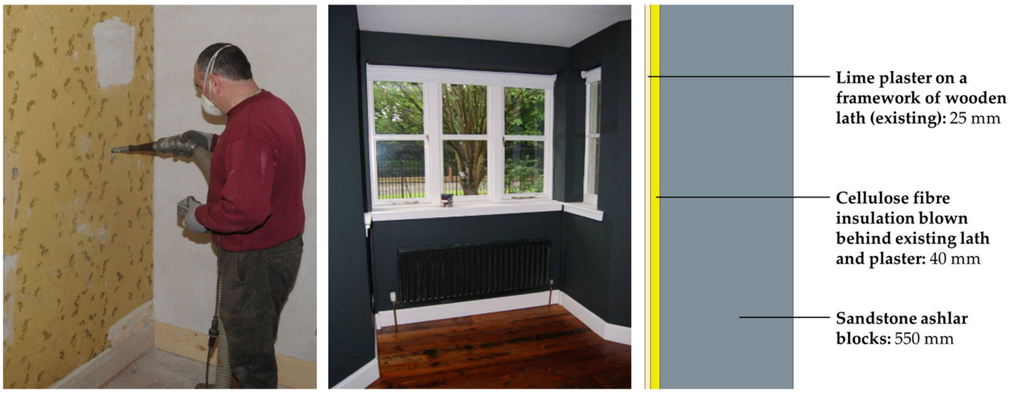

Figure 3. Process of blowing cellulose behind existing lath and plaster (**left**), resulting internally insulated wall (**centre**) and cross-section ((**right**), layers presented from inside to outside) [78].

The solution does not have the potential to save a large amount of energy because of little improvement of thermal transmittance (unless insulation with high thermal resistance such as aerogel is used) and cannot be used in case of internal decorations on the wall. However, because of the lower thermal resistance, thin internal wall insulation can lead to better hygrothermal performance than thicker internal wall insulation systems [79].

5.4. Prioritising Low Environmental Impact

The retrofit measures that prioritise a low environmental impact can be grouped into measures that allow for energy demand reduction and measures with low embodied carbon. They are likely to lead to changes in the aesthetic, material, and spatial properties of the envelope, as well as low reversibility. Moreover, some of these measures are associated with high hygrothermal risks. Concerning embodied carbon, some materials can have lower embodied carbon than others. Low-carbon materials can be used for many of the retrofit measures described in this paper.

5.4.1. Thick External Wall Insulation

A thicker layer (e.g., more than 8 cm) of external insulation than in Section 5.3.3 can be applied on the façade of the building. This leads to large energy savings and improvement of the occupants' thermal comfort. Avoiding thermal bridges is less complex than with internal wall insulation and hygrothermal risks decrease significantly. The use of removable systems allows for preservation of the wall. The wide choice between insulation materials and systems increases the possibility to meet economic needs and wishes of the client. This solution is suitable in the case of a non-valuable external appearance of the façade and need of façade refurbishment.

This insulation measure reduces heat losses caused by transmission, minimises thermal bridges, and improves thermal comfort. It retains the beneficial thermal mass of solid walls, and therefore moderates the air temperature fluctuations, allowing the wall to achieve thermal equilibrium with the internal spaces. The measure can be installed while the building remains in occupation, and does not reduce the floor area of the room. Finally, it can increase the lifespan of walls by protecting masonry.

Among the disadvantages, the measure affects the external appearance of the building and the proportion of original details. The detailing and implementation of the solution should be considered carefully before its implementation as roof eaves, window reveals, or projections of rain pipes and services might represent a challenge for its correct installation [80,81]. It is highly likely to require alteration to the rainwater collection system and extension of the roof line for careful design and installation to avoid risk of water penetration and trapping, especially at junctions [25]. Finally, the use in historic buildings may be restricted due to existing decorative features or building details.

5.4.2. Thick Internal Wall Insulation

A thicker layer (e.g., more than 6 cm) of internal wall insulation than in Section 5.3.2 or Section 5.3.4 can be applied on the internal surface of the wall, leading to an improvement of the thermal transmittance of the element and occupants' thermal comfort. The increasingly common use of these systems and the large number of challenges in technical compatibility led to an increasing number of possible solutions and to more widespread knowledge of these systems. There are several options for this type of internal wall insulation, including systems based on capillary active materials.

Downsides of thick IWI are the reduction of the interior floor space, which can be problematic in small rooms, and the fact that thermal bridges may be more pronounced, leading to potential surface condensation issues [82]. This insulation system is also associated with a consistent reduction of thermal mass on the inner side of the wall, leading to potential summer overheating problems due to faster heating of the room. Due to hygrothermal risks [83] and the presence of thermal bridges, a detailed hygrothermal risk assessment is often needed for these systems. Some disruption is associated to the removal and replacement of things such as skirting boards or door frames, and occupants might need to vacate the building. Finally, the use of thick IWI in historic buildings may be restricted due to existing important decorations (e.g., wall paintings).

5.4.3. Natural Materials

Improving the sustainability of historic buildings goes beyond the thermal performance of the envelope. The use of natural materials is sometimes favored to promote more sustainable measures due to their lower embodied carbon. However, a careful evaluation should include not only their embodied carbon, but also other aspects, like associated environmental impacts [84], end-of-life processing, hygrothermal compatibility [85], or even the transient thermal performance of the material. Bottino-Leone et al. [86] developed a holistic performance-based evaluation method applied to a conservation and rehabilitation case of a residential building. Results show that natural-based materials have the lowest initial environmental impact; however, due to the higher moisture storage properties of these materials, they also present the highest increase in thermal transmittance. However, all retrofit variants tested in the study dramatically reduced the overall environmental impact of the building.

5.4.4. Local Materials

The use of local materials is valid from a Life Cycle Analysis point of view, and is also part of the constructive heritage, as they also take into account local techniques that could be considered as part of the intangible heritage. The wide adoption of solutions based on local skills and materials can help to keep the cultural identity, enhance the use of local resources, and activate the surrounding territory. This indicator was used in the ENERPAT project in order to select solutions that were not only efficient, but also locally rooted [87].

6. After Renovation

6.1. Monitoring

The risks associated to retrofit measures sometimes cannot be minimized; this is the case when conflicting objectives are at stake. In this case, monitoring can help in evaluating whether the retrofit strategy has fulfilled the objectives in the long-term. To evaluate the retrofit effectiveness from a technical point of view, it is possible to monitor moisture accumulation in critical areas of the building fabric. Some critical areas can be monitored visually, while others are hidden within the wall structure. Critical hidden areas include the interface between IWI and the existing wall and joist ends [88–92].

6.1.1. Spot Measurements of Moisture Content

The possibility of examining the moisture conditions between the interior insulation and the existing wall is a great advantage, especially for constructions that are vulnerable to moisture risk. Unfortunately, monitoring systems are rarely installed during the construction phase, as they are difficult to install and often expensive. Especially with historic timber buildings, the examination of wood moisture at the boundary layer is important, since here, it is not only mould that can occur, but in the worst case, even wood rot is possible.

Simple spot measurements in hidden timber can be facilitated by the installation of stainless-steel wood screws. Installing wood screws at a distance of approx. 30 mm, it is possible to measure the current moisture content of timber at any time using standard resistance moisture meters.

6.1.2. Long-Term Monitoring

Long-term monitoring can be used post-retrofit to evaluate the performance of certain interventions, and for quality assurance. Long-term monitoring of the indoor environmental conditions before and after an energy retrofit provides useful information for the evaluation of the suitability and outcome of an intervention, respectively [93,94].

Long-term monitoring of hygrothermal conditions can help deepen the understanding of the performance of insulated walls. Relative humidity and temperature probes (and, less frequently, moisture content sensors) have been installed at various depths of insulated walls. This has been used in the assessment of the suitability of internal wall insulation systems for historic buildings (e.g., [47,76,95–100]).

6.2. Use, Management, and Maintenance

User behaviour, including the way users interact with the building and its services, is crucial in the final success of a renovation project. The users should be involved in the renovation from the start and participate in the decision-making process during and after retrofit, as the relationship between buildings and users is co-evolving [101]. During renovation, the retrofit measures must be chosen considering the occupants' needs and values. After retrofit, there are tools available to enable the users to understand the influence of their behaviour on conservation, energy consumption, and cost, so that they can act upon it. Examples include installing simple meters that users can follow to learn about energy and moisture levels. However, the roll-out of these meters comes with socio-technical challenges; occupants need to be engaged and empowered through necessary dialogue, clear communication, advice, and support [102].

Significant energy savings may be achieved through the change of user behaviour without altering the building. However, when energy-performance improvement measures are implemented in a historic building, they may not save as much energy as anticipated [103,104]. In this sense, decision-making in the deep renovation of historic buildings should favour ease of control and maintenance, robustness (i.e., limited influence from unintended changes of conditions, including behaviour and weather), and security of energy supply.

7. Conclusions

This paper presented an overview of the steps required for improving the performance of walls in historic buildings during and after the renovation, drawing from the literature in building physics and conservation. Moreover, it provided an overview of possible measures for wall retrofit within the deep renovation of historic buildings (see Section 5), including their potential advantages and disadvantages from the points of view of heritage, technical compatibility, environmental impact, and indoor environmental quality. Therefore, this paper can complement national and international guidelines for improving the energy performance of historic buildings by providing further understanding of the reasons behind relevant procedural steps and examples of possible retrofit measures.

However, the appropriate selection of the retrofit measures depends on the context of each individual renovation project. Therefore, the role of building and heritage professionals is to devise a retrofit strategy that is based on the latest evidence in building physics and conservation, but that also considers the social, cultural, economic, and environmental context of the building and its deep renovation, in accordance with the underlying principles of sustainable construction [105].

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