

Article

Old Buildings' Façades: Fieldwork and Discussion of Thermal Retrofitting Strategies in a Mediterranean Climate

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Abstract: This work is within the scope of thermal retrofitting, applied to old buildings' façades (built between 1700 and 1960) located in Mediterranean climates, such as Portugal. The aim is to increase the sustainability of existing buildings, by reducing their energy consumption needs, for heating and cooling, and the corresponding gaseous emissions, while increasing their users' comfort. Firstly, an analysis of the advantages and disadvantages of several thermal insulation solutions for façades was carried out, supported in current literature. Then, a survey of real retrofitting scenarios and interviews with experts was completed, to allow the selection of the most adequate thermal insulation techniques. Finally, as a result of this study, the discussion of retrofitting strategies was carried out to support the designer's decision process, based on a flowchart with complementary tables, discussing the best thermal retrofitting technique to be implemented on old buildings' façades, case-by-case.

Keywords: façades; old buildings; retrofitting; strategies; thermal insulation

1. Introduction

The demands of modern society, in terms of life quality and comfort conditions, requires a considerable expenditure of energy. This is a trend that, according to the International Energy Agency (IEA), has been increasing exponentially [1]. Portugal uses fossil fuels as the main source of electricity, contributing to emissions of gaseous pollutants such as CO₂ [2], where the construction sector accounts for a large share. Indeed, in Europe, the construction sector spends about 40% of the total energy consumption and emits approximately 30% of greenhouse gases [1].

With the energy consumption and greenhouse gases increase, being responsible for climate changes and global warming, there has been a growing awareness for sustainability, energy efficiency and environmental preservation [3]. To this end, the European Union imposed a limit on CO₂ and other gaseous emissions into the air. Each state member that committed to fulfill those requirements, including Portugal, is obliged to reduce emissions of harmful gases into the environment, particularly in buildings, to comply with the agreed targets [2].

Currently, Decree-Law no. 118/2013 of August 20 (Energy Certification of Buildings (SCE), Regulation of Energy Performance of Residential Buildings (REH) and Regulation of Energy Performance of Buildings Trade and Services (RECS)) is in force in Portugal, revised by the Law no. 52/2018 of August 20 (5th alteration to the Decree-Law 118/2013) and the Decree-Law 95/2019 of June 18 (6th alteration to the Decree-Law 118/2013), requiring a minimum buildings' envelope thermal

performance. In this sense, opaque elements of the envelope are subject to compliance with limit values for the thermal transmission coefficient, which varies according to the type of element, and the winter climatic zone (I1, I2 or I3 (Dispatch n.º15793-F/2013: Climate zoning)—the former corresponding to a less extreme and the latter to a more adverse and demanding climatic zone). However, in the case of existing buildings, Decree-Law no. 53/2014 of April 8 (Exceptional regime for buildings' rehabilitation), Decree-Law no. 194/2015 of September 14 (Republication of the Decree-Law n.118/2013), and Decree-Law 95/2019 of June 18 (already referred), provide an exceptional regime. In this exceptional regime, interventions on buildings or fractions, whose construction has been completed for at least 30 years or located in urban renovation areas, are exempt from the minimum energy efficiency and thermal quality requirements whenever the buildings are for residential use and if there is no feasibility of technical, functional, architectural or economic nature, however with some scales of retrofitting demanding the fulfilment of some requisites (Statute 297/2019—4th alteration to Statute 349-B/2013, presenting the requisites for small scale retrofitting interventions). According to some authors [4,5], buildings with architectural and historical value should be exempted from energy efficiency standards, since the implementation of those measures could compromise their cultural value.

However, in any retrofitting strategy, the possibility of adopting thermal measures should always be considered, even if there is no legal obligation [6,7]. As previously mentioned, environmental concerns are recent, and Decree-Law no. 40/90 of February 6 (Regulation of the Thermal Performance's Characteristics of Buildings (RCCTE)) was the first legal document in Portugal to demand the conditions of thermal comfort in buildings. Thus, during the construction of old buildings, there was no awareness of the need for energy efficiency or sustainability [8]. In this sense, there must be an improvement in the comfort conditions and energy performance of old buildings [9,10] to meet the increasingly demanding requirements established by modern society [11,12].

In Portugal, energy efficiency certificates encourage the adoption of measures that set the modern energy efficiency parameters not only for new buildings but also for the old building stock, turning the thermal rehabilitation of the building stock into an important parameter for consumers. This way, improving the energy performance of buildings has become one of the current challenges of construction and should be seen as a need, for the construction of new buildings and for the rehabilitation of the existing ones [13–15]. Since a part of the energy expenditure in buildings is used for indoor climate control, it is necessary to reduce the use of air conditioning (heating and cooling) equipment, without compromising the desired levels of thermal comfort. Improving the thermal insulation of the envelope is one of the most efficient measures to reduce the energy consumption of buildings [8,16] and should be a priority to guarantee the energy efficiency of old buildings, leading to a decrease of the economic and environmental costs [17,18]. It is through the façades that part of the heat exchanges are made with the exterior, so the application of thermal insulation in the façades contributes significantly to the overall thermal performance of buildings [19].

Therefore, this research aims to discuss retrofitting strategies in order to support the decision process on which action should be taken to improve the thermal performance of old buildings' façades, considering the restraints involved in this type of buildings. The main goals of this study are: (a) determining the advantages and disadvantages of several commonly used thermal retrofitting solutions, taking into consideration the constraints involved in the interventions; (b) getting a portrait of the current situation regarding the feasibility and the actual implementation of thermal retrofitting of façades on old buildings in Portugal; (c) discuss retrofitting strategies in order to support the designers in the selection of the thermal retrofitting solutions that should be adopted in each case based on technical assumptions.

To achieve those goals, a study based on current literature was made to determine the generic pre-existing thermal behaviour of the façades, and the advantages and disadvantages of several thermal insulation solutions, when applied to old buildings' façades. It was also carried out fieldwork to compare and validate the collected data, through inspections in real building rehabilitation sites. The discussion of retrofitting strategies was carried out to support the building's designers in the

selection of adequate thermal solutions. With that aim, an innovative methodology which systematises the decision process in thermal rehabilitation of old buildings is proposed.

2. Research Methods

This research work was based on a literature review—cases studies, and presents a framework proposal method. Firstly, reference literature was searched for to identify the main types of façades of old buildings and the current thermal retrofit solutions. The advantages and disadvantages of each solution were also summarised.

To validate the referred review, 32 ongoing building retrofit interventions were contacted, and twelve were selected using the professional network of the authors. The aim was to have a sufficient sample of buildings with and without thermal retrofitting solutions applied on existing outer walls. For each intervention, an interview with the site manager and/or with the retrofit designer was done. Then, an inspection and a characterisation file were filled, and documentation related to the retrofit intervention was provided. It was also possible to visit the construction site in most of the cases.

This fieldwork was complemented with guided interviews of the authors with experts in the thermal and structural retrofit of old buildings (two recognised Portuguese Civil Engineers, Researchers and Professors with more than 30 years of experience each and a recognised Portuguese Architect, Researcher and Professor with more than 15 years of experience in thermal performance of buildings). Finally, a decision-support method for buildings thermal retrofitting is proposed based on the theoretical and practical information previously collected.

3. Thermal Retrofitting of Old Buildings

This study is focused on old buildings constructed in the period between 1700 and 1960. The evolution of the building construction technology in Portugal, namely in the Lisbon region, can be divided into the following stages: *pre-Pombalina* construction (before 1755); *Pombalina* construction (1755–1880); *Gaioleira* construction (1880–1930); and Mixed construction (1930–1960). In the first two stages, the outer walls usually played a structural role, being generally made of stone masonry, but could also be made of brick masonry or mixing materials (or even more than one material), with a significant thickness (0.50–0.90 m) (Figure 1). However, Mixed construction represents a period of transition from traditional construction to modern buildings, with the introduction of elements of concrete (namely in floors). This resulted in changes in the typology of façades, leading to the implementation of double walls, in 1950, losing their structural resistant role as time went by.

In order to improve the thermal behaviour of old buildings' façades, there are many solutions in the market, with a potential application, which leads to the need of analysis, case-by-case, so it can be possible to determine the adequate solution.

The façades of old buildings are typically in stone masonry with strong thermal inertia because they are elements of high mass and thickness, but without any thermal insulation [20]. Thermal inertia is a relevant phenomenon in buildings located in Mediterranean climates, such as Portugal, whose daily temperature range is significant [21] since it can time-shift and flatten out heat flow fluctuations (6 to 8 h) [22]. In this way, it is possible to guarantee a temperature of the interior space with oscillations inferior to those existing in the exterior [23].

Therefore, the masonry stone walls, with their strong thermal inertia, guarantees satisfactory comfort conditions, preserving a dry and cool indoor environment during the summer, but present a poor thermal behaviour in the winter, due to the lack of thermal insulation [20]. This requires an increase in the thermal resistance of these façades to guarantee the interior comfort temperature during the winter [22].

In the case of a masonry wall with a thickness of approximately 0.40 m, its thermal transmittance (U) may not comply with thermal insulation requirements [22], depending on the type of masonry. Even in other traditional constructions, with thicknesses up to 1 m, the thermal requirements are not ensured without a thermal insulation layer in the façades [22,24].



Figure 1. Examples of Portuguese facades from building built on periods of 1880–1930 (a–d) and before 1755 (e,f).

Old building's double walls (built between 1950 and 1960), in addition to being usually thicker than the current double-leaf air cavity walls, have a cavity, which increases the thermal resistance of the wall, thus being thermally more efficient. However, these walls also require a thermal insulation layer in order to increase its thermal resistance to fulfil the current thermal requirements [22].

Another parameter to consider is related to the existence of thermal bridges in the façades, such as connections between the façade and floors, ceilings, interior walls and window and door contours, that significantly compromise the heat exchanges of the surroundings with the exterior [8,11]. Also, thermal bridges are subject to the occurrence of surface condensation, which is why they are favourable elements for the formation and development of biological colonisation, thus creating black spots on the walls [8,25] and degrading the building elements.

The advantages and disadvantages of each thermal retrofitting solution were searched in the literature to determine which one should be applied, based on the restrictions of each intervention, and to compare them with the decisions made in practical rehabilitation cases. Table 1 presents the summary of the research made, based on the information gathered from previous works [11,26–30] and from the interviews with experts.

Table 1. Summary of the advantages and disadvantages of each thermal insulation solution for façades [11,26–30].

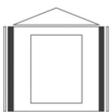
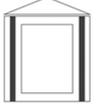
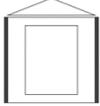
Solution	Advantages	Disadvantages
<p>ETICS (External Thermal Insulating Composite System)</p> 	<ul style="list-style-type: none"> • High thermal efficiency • Correction of thermal bridges and consequent reduction of the risk of condensation • Preservation of thermal inertia • Quick and simple application in façades with few architectural features • The convenience of the occupants during the execution • The inner area remains intact • Provides an exterior aesthetic renovation • Works as a protective barrier against atmospheric agents 	<ul style="list-style-type: none"> • There are frequently durability issues with the system’s coating (occurrence of anomalies) • Does not allow the aesthetical preservation of buildings with architectural or heritage value • Finishing execution complexity due to architectural constraints • High-cost investment • Vulnerability to mechanical stresses (impacts) • Execution exposed to the weather conditions, which can compromise the performance of the thermal retrofitting solution • More complex and expensive application in façades with ascending humidity and/or for very porous façades
<p>Ventilated Façade</p> 	<ul style="list-style-type: none"> • High thermal efficiency • Correction of thermal bridges • Preservation of thermal inertia • The convenience of the occupants during the execution • The inner area remains intact • Provides an exterior aesthetic renovation • Works as a protective barrier against atmospheric agents • Reduces the risk of internal condensations in the walls, in winter, and air renovation, decreasing façade temperature, in summer • Easy maintenance • High durability 	<ul style="list-style-type: none"> • Does not allow the aesthetical preservation of buildings with architectural or heritage value • Finishing execution complexity due to architectural constraints • The highest investment cost • Execution exposed to the weather conditions • Risk of fire spreading between floors, because of the system’s ventilated chamber, if it is not correctly sectioned • The wall’s support (masonry) must have enough resistance, stability, and cohesion
<p>Thermal insulation injection in the cavity of double-leaf walls</p> 	<ul style="list-style-type: none"> • Preservation of the original internal and external appearance of the façades • The inner area remains intact 	<ul style="list-style-type: none"> • Does not protect the façade from outside actions caused by atmospheric agents • Reduces the thermal inertia, but does not eliminate it • Does not eliminate thermal bridges • Requires skilled labour, because the injection must be entirely homogeneous to seal the cavity • The execution might have some complexity, depending on the façade features • The efficiency of its implementation depends on the existing conditions in the cavity

Table 1. Cont.

Solution	Advantages	Disadvantages
<p>Internal thermal insulation</p> 	<ul style="list-style-type: none"> • Preservation of the appearance of old buildings with architectural or heritage value • Quick and easy application 	<ul style="list-style-type: none"> • The inner area is reduced • Constraints for the occupants during its execution • Does not work as a protective barrier against atmospheric agents • Avoids taking advantage of the thermal inertia of the existing wall • Does not eliminate thermal bridges • Some care should be taken to the effect in terms of building physics, since it can increase moisture-related problems such as frost damage, interstitial condensation, and mould growth. Each solution must be therefore designed by an expert to avoid e.g., polymeric insulation materials and prevent decreasing the water vapour diffusiveness of the wall.
<p>Render with improved thermal performance</p> 	<ul style="list-style-type: none"> • Easiest execution in all surfaces, including with architectural constraints (e.g., curved surfaces) • Permeability to water vapour 	<ul style="list-style-type: none"> • Thermally less efficient than most solutions, so it can be recommended to use as a complementary solution of other thermal retrofitting solutions

It is essential to point out that one of the main conclusions referred by numerous authors [9–12,20,31,32] is that although an external thermal retrofitting solution (Figure 1) such as the External Thermal Insulation Composite System (ETICS) is considered one of the most thermally efficient systems, since it can minimise thermal bridges and enables the preservation of the thermal inertia of the façades, it presents some constraints when applied in old buildings’ façades. The architectural and historical value, frequently associated with these buildings, prevents the use of external thermal retrofitting solutions, as it would lead to the loss of the façades’ cultural value. Therefore, the same authors present the internal thermal retrofitting solution (Figure 2) as an alternative, being nevertheless necessary to take into consideration the limitations of this solution, such as the elimination of the strong thermal inertia of the existing façades [33,34], which results from a thickness equal or greater than 60 cm, causing a decrease of the indoor thermal comfort, particularly in summer; the lack of thermal bridges correction [22]; and the reduction of the indoor floor area. Other limitation of ETICS can be the application in façades with frequent rising damp and salt crystallisation [35], for which renders with improved thermal behaviour can be a better option.

There are some works, like the one presented by Fernandes et al. [30], which presents a proposal for architectural integration measures of ETICS in retrofitting, using solutions such as: reducing the thickness of the thermal insulation next to the window/door frames; removal and replacement of the window/door frames after placing the thermal insulation on the façades; extending the existing sill, through the application of ETICS reinforced with metal profiles, among others. However, the scope of this research is focused on residential buildings built since the second half of the 20th century, being more complex the preservation of the exterior appearance of façades of buildings built before this period, since they usually have more complex architectural features and higher historical value, restraining the integration of ETICS.

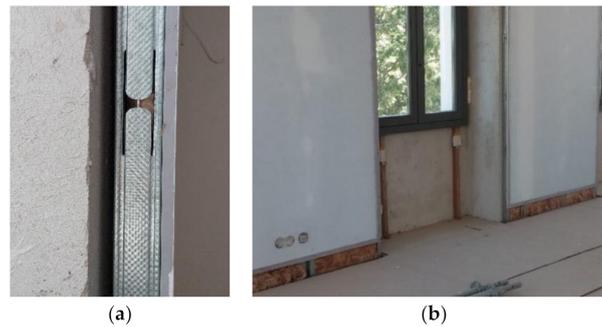


Figure 2. Application of an internal thermal retrofitting solution: (a) insulating boards of mineral wool coated with gypsum plasterboard; (b) auxiliary structure which leads to the creation of a cavity between the wall and the thermal insulation (case B).

After the initial characterisation of the building's walls and the thermal insulation techniques more commonly used, it was searched in the current literature, if there was any methodology available to support, case-by-case, the decision process involved in the thermal rehabilitation of old buildings' façades.

The majority of the already referred works was only focused on the study of specific solutions for detailed cases, like the one developed by Zagorskas et al. [36]. These authors considered that, in the case of buildings with cultural interest, the only solution available was the interior thermal insulation. Biseniece et al. [37] also only considered the internal thermal insulation on historic buildings. Finally, the review made by Martínez-Molina et al. [1] summarises studies made in several buildings with different uses, concluding that these older buildings greatly benefited from thermal retrofitting, usually made in the interior and lowering emissions and energy consumption, but without referring any method associated to the choice of the thermal insulation techniques to apply for each case.

The review of literature allowed to conclude that the application of thermal insulation on the façades of old buildings is of crucial importance to drop the energy consumption and consequently the associated gaseous emissions while increasing the users' comfort. Moreover, depending on the buildings' characteristics, the thermal insulation technique to apply should be judiciously chosen. However, it was verified the lack of consistent guidance and decision-making processes for selecting an adequate thermal retrofit solution on a case-by-case basis, as recently stated by Webb [38], namely, to avoid the risks described in Table 1.

A lack in knowledge was identified and a methodology which systematises the decision process, integrating the concerns and the different problems that one can face when in a thermal rehabilitation scenario, in necessary, to guide on the best solution to apply. This, therefore, justifies the interest and contribution of the present work to discuss the intervention strategies based on real case studies.

4. Fieldwork and Results' Discussion

The main aim of the fieldwork carried out was the analysis of the current practice of the thermal rehabilitation of the façades of old buildings. It was essential to understand if the thermal retrofitting solutions were being applied on façades when the retrofitting of old buildings occur, and, if not, which were the reasons that prevented their application. Secondly, this fieldwork determined, for different case studies, the reasons that lead to the selection of specific thermal retrofitting solutions, instead of other available solutions, their advantages and disadvantages and the involved constraints.

This research analysed 12 case studies of old buildings rehabilitation (built up to 1960). Some of these cases included thermal retrofitting solutions applied on existing outer walls (case studies A to E), while others did not include any thermal retrofitting of existing façades (case studies F to L). Their selection was based on direct contacts of the authors and on the diversity of interventions.

Retrofitting works included in this fieldwork were mostly located in the Lisbon district (Portugal), except for one case, which was located in Coimbra (Portugal). Whenever possible, contact with the site manager and/or with the retrofit designer was established.

4.1. Mediterranean Climate

According to Koppen-Geiger climate classification, Mediterranean climates are warm temperate climates with dry summer (Cs), in which monthly mean temperatures of the coldest months are between $-3\text{ }^{\circ}\text{C}$ and $+18\text{ }^{\circ}\text{C}$ [39]. In the south of Portugal, the summers are hot with the monthly mean temperature of the warmest month above $22\text{ }^{\circ}\text{C}$ (Csa). In the north, with warm summers, at least four months have a mean monthly temperature above $+10\text{ }^{\circ}\text{C}$ (Csb). The majority of the case studies are located in Lisbon which has a heating season of 5.3 months with 1071 heating degree-days (HDD; base $18\text{ }^{\circ}\text{C}$), $10.8\text{ }^{\circ}\text{C}$ mean outdoor temperature of the coldest month and $150\text{ kWh}/(\text{m}^2\cdot\text{month})$ of mean monthly solar energy received on a south-facing vertical surface. The cooling season, considered having a four-month duration by the Portuguese energy codes, has a mean outdoor temperature of $21.7\text{ }^{\circ}\text{C}$ and $840\text{ kW}/\text{m}^2$ of accumulated solar energy received horizontally [7].

4.2. Critical Analysis of the Case Studies with Thermal Retrofitting of Existing Façades

The following solutions were identified in the case studies: internal thermal insulation coated with gypsum plasterboards and fixed to a supporting structure, allowing the existence of a ventilated cavity between the thermal insulation and the wall (Cases A and B); ETICS applied in some regions of the façades (Case C) or throughout the whole facade (Case D); and injection of insulating material in the cavity of double-leaf walls (Case E). These were identified as the most economically and technically viable solutions for each case. Table 2 summarises the main constraints involved in each intervention and the advantages and disadvantages associated with the chosen solutions.

Table 2. Summary of the critical analysis of case studies A to E.

Summary of the Critical Analysis of the Cases with Thermal Rehabilitation of Existing Façades					
Case Studies	Period of Construction	Main Constraints of the Building	The Thermal Retrofitting Solution Adopted	Main Advantages	Main Disadvantages
Case A (Figure 3a)	1880–1930	Need to maintain the external appearance of the façades to preserve the architectural and heritage value of the building	Internal thermal insulation composed by MW (mineral wool) boards coated with gypsum plasterboards Figure 3	Preservation of the original aesthetic of the façades	Eliminates the thermal inertia of the existing outer walls and decreases the useful indoor area
Case B (Figure 3b)					
Case C					
Case D	1930–1960	-	External Thermal Insulation Composite System (ETICS) Figure 4	Exterior aesthetic renovation Highest energy efficiency	It might have the disadvantage of the mischaracterisation of the building architecture, but, in this case, the need for architectural preservation, does not exist
Case E (Figure 3c)		Need to maintain the exterior aesthetic of the façades to preserve the architectural features	PUR (polyurethane foam) injection in the whole cavity	Preservation of the original internal and external appearances of the façades	Complex application and difficulty in ensuring the efficiency of the solution

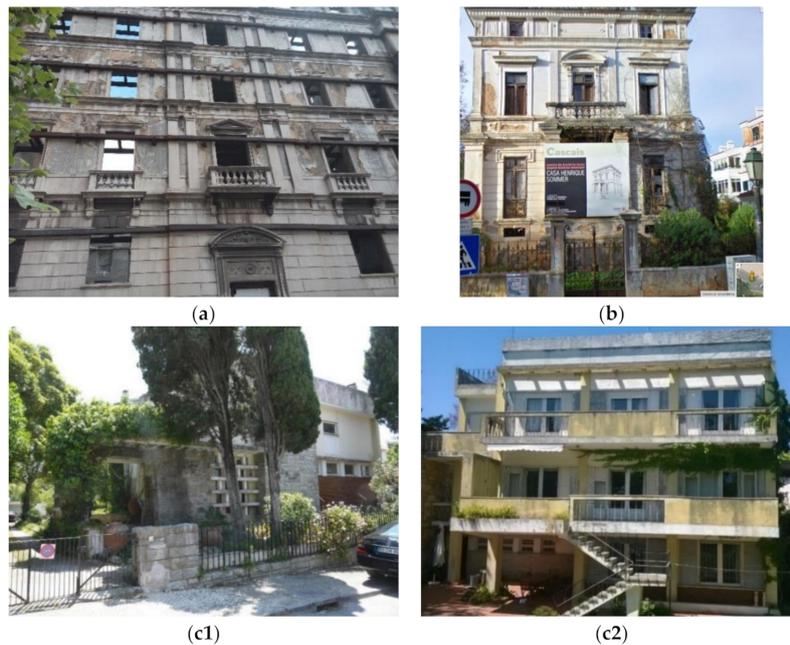


Figure 3. Facades in which it was necessary to maintain the external appearance, before retrofit: (a) case A; (b) case B; and (c1,c2) case E.

It is possible to conclude that, in the older buildings' rehabilitation (built in the period 1880–1930), there is usually an architectural and heritage value that prevents the adoption of external thermal insulation solutions throughout the façades (Figure 3). Therefore, in case studies A, B and C, the use of external thermal retrofitting solutions on the façades were limited.

It was possible to adopt, in cases A and B, an internal thermal insulation solution, which increased the thermal resistance of the façades and preserved the exterior appearance of those buildings. However, there are disadvantages, as described before, that compromises the performance of this solution. Moreover, it is a less efficient thermal solution compared to one applied on the outside, but more viable for old buildings, due to the cultural constraints.

In case C, the building also has an architectural and heritage value, since it is in an area protected by UNESCO. In this case, the adopted solution was not sufficiently thermal efficient: even though being applied on the outer face of the façades (ETICS), it was only used in certain areas, leaving the remaining parts of the façades without any thermal retrofitting solution. Therefore, the envelope could not present a good overall thermal performance.

In buildings built between 1930 and 1960, like the one in case D (Figure 4), there is usually more freedom to change the appearance of the façades, because there are no constraints associated with their authenticity and historical identity. This allowed, in case D, the use of a more thermally efficient solution, as the ETICS. Even though the building from case E was built between 1930 and 1960, its exterior aesthetics and architectural features had to be preserved. In this case, it was possible to take advantage of the fact that the façades were composed by double-leaf walls allowing the injection of insulating material in their cavity. This way, it was possible to maintain the outside and inside appearance. However, the injection process had to be carefully made, due to the risk of compromising the performance of the thermal solution (guarantee of complete filling application and over time).

The records made during the inspections, as well as the comments made by the responsible for each studied retrofitting strategy, pointed out several other interesting characteristics associated with the thermal insulation solutions, leading to the results presented in Tables 1 and 2. In those Tables, the main constraints identified in the analysed buildings, which lead to the selection of each thermal retrofitting technique, as well as the associated advantages and disadvantages, were in agreement with the literature review already presented.



Figure 4. ETICS with ICB (insulation cork board) application (case D).

4.3. Critical Analysis of the Case Studies without Thermal Retrofitting of Existing Façades

Case studies with façades not thermally retrofitted were also critically analysed (Figure 5). The aim was to understand the reasons leading to the absence of thermal improvements and to confirm if there were thermal retrofitting measures implemented in other envelope’s elements.

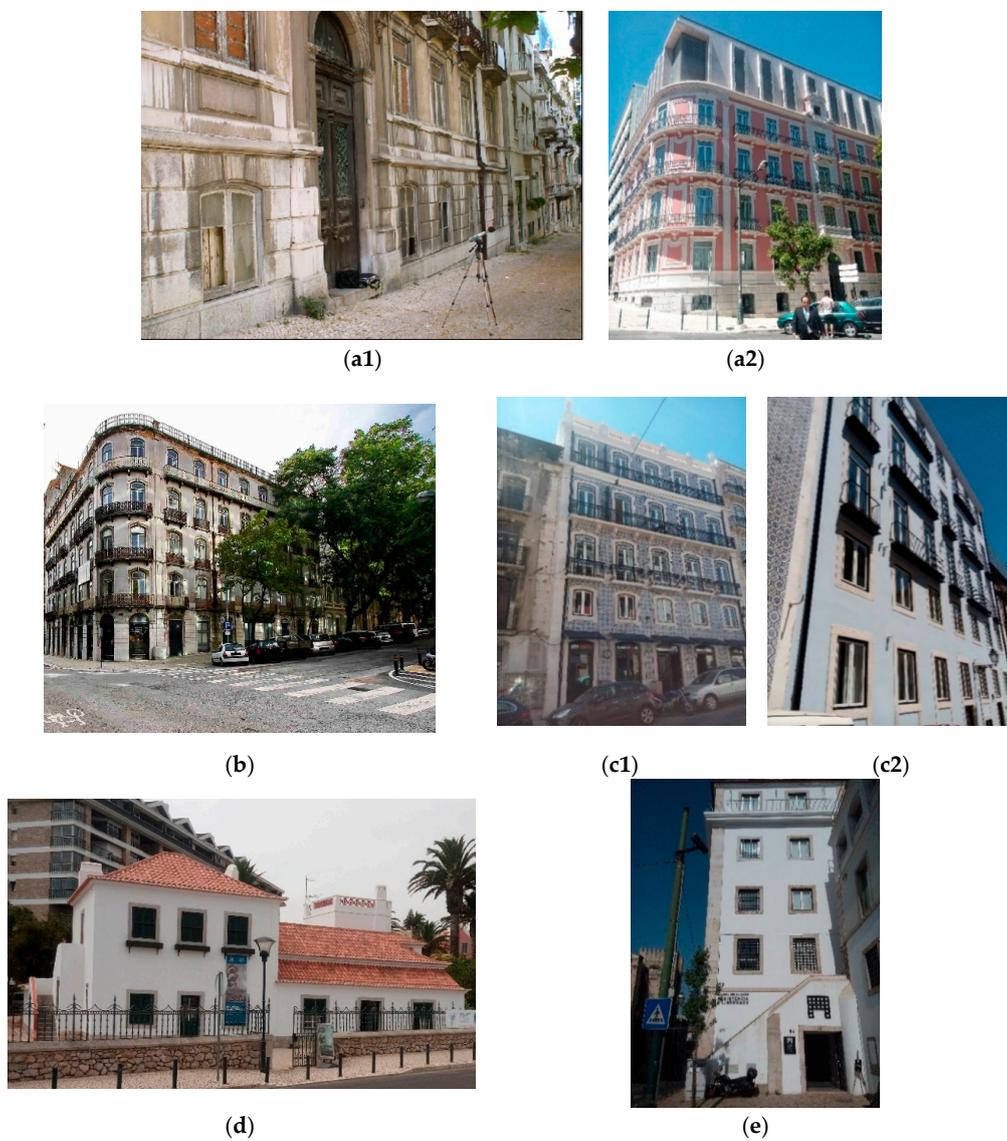


Figure 5. Facades in which thermal insulation was not applied: (a1,a2) case G before and after retrofit; (b) case H before retrofit; (c1,c2) case J after retrofit; (d) case K after retrofit; (e) case L after retrofit.

In case-studies F to L, no thermal retrofitting solutions were considered in the rehabilitation of the existing façades. Table 3 summarises the similarities identified in these cases, using the information gathered in the fieldwork and also from experts.

Table 3. Summary of the critical analysis of case studies F to L.

Summary of Key Data Collected from Case Studies without Thermal Insulation of Existing Façades							
Case Studies and Construction Period	High Thermal Inertia of Existing Façades ¹	New Façades Complying with Current Thermal Requirements	Application of Thermal Insulation on the Roof		Thermal Correction of Glazed Areas	The Thermal Regulation was Followed ²	Acoustic Concerns More Relevant than Thermal Concerns
			New Construction	Existing Structure			
F: 1880–1930	x	x	x		x		x
G: 1902 Figure 5a	x	x	x		x	x	x
H: 1880–1930 Figure 5b	x	x	x		x	x	x
I: 1755–1880		x	x		x	x	
J: 1880 Figure 5c	x	x	x		x	x	x
K: 1880–1930 Figure 5d	x		x		x		
L: 1700–1755 Figure 5e	x			x	x		x

Legend: ¹—Main reason given for not using an internal thermal insulation solution on the existing façades; ²—The intervention respects the thermal regulation.

From Table 3, it can be concluded that, in most cases, no measures were taken to improve the thermal resistance of the façades, since there was a perception that they have good thermal behaviour in summer, thanks to their thickness (between 0.40 m and 1 m). Therefore, their strong thermal inertia (mainly for buildings built before 1930) was the main reason for not applying thermal retrofitting solutions. Thus, thermal insulation was just applied in new building elements, such as new façades and roofs. In fact, and since the roof and glazed areas are the most fragile thermal elements of the envelope [29], there is a more significant trend in intervening in these elements, with the acoustic concern also potentiating those interventions [3].

5. Discussion of Thermal Retrofitting Strategies on Old Buildings

In this section, a comparative analysis between the values of the thermal transmittance for each retrofitting solution and the maximum values imposed by thermal regulation was performed. The former was calculated, for each façade, considering: the thickness of each layer of material collected from each case study; the thermal transmittance of each material provided by the Portuguese reference publication of the Energy Certification System of Buildings (Pina dos Santos, C.A.; Matias, L. *U-values of building envelopes elements*; Laboratório Nacional de Engenharia Civil: Lisbon, Portugal, 2006). Figure 6 presents the comparison between the values of the thermal transmittance (U) calculated for each constructive solution of the façades of case studies A and I (which exemplify case studies with and without thermal insulation application on facades) and the maximum values imposed by thermal regulations for Portugal (Decreets-Law 95/2019 and 195/2015, already referred). As expected, existing façades with thermal retrofitting solutions (Façades 1 to 4 in case study A), and the new façades built in case I with thermal insulation solutions (Façades 3 and 4), have lower U-values than existing façades without any thermal retrofitting solution on the case I (Façades 1, 2 and 5).

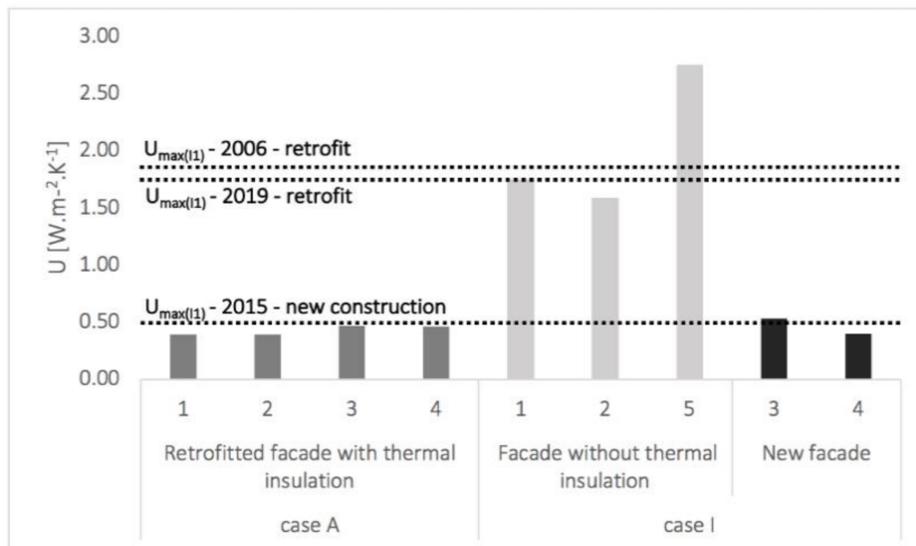


Figure 6. Comparison between the values of the thermal transmittance (U) of each constructive solution of the façades from case studies A and I, and the maximum values allowed by thermal regulations for climate zone I1, through the years.

The buildings of these case studies were located in Lisbon (classified as a climate zone I1). The U-values of existing façades, without thermal insulation, from case I, are below the maximum value of $1.80 W \cdot m^{-2} \cdot K^{-1}$, which was imposed by the thermal regulation of 2006 (Decree-Law no. 80/2006 Regulation of the Thermal Behaviour of Buildings) for this climate zone, except Façade 5 from Case I: it has 0.20 cm of thickness, which is lower than typical façades of old buildings, where thickness usually varies between 0.40 m and 1 m, according to the case studies analysed in the fieldwork. The U-values of these façades can also be below the maximum value of $1.70 W \cdot m^{-2} \cdot K^{-1}$, except Case I Façade 5, which was imposed by the thermal regulation of 2019 (Statute 297/2019 already referred) for smaller-scale retrofitting. However, thermal requirements have been increasing, and the current regulation, which is in force since 2015 (Statute 379-A/2015—1st alteration to Statute 349-B/2013, presenting the thermal insulation requisites for buildings), imposes a maximum value of $U = 0.50 W \cdot m^{-2} \cdot K^{-1}$ for the I1 climate area but only for new buildings and for deep retrofitting. Therefore, the thermal performance of existing façades, without thermal insulation, from case I, do not comply with the current allowable values (but complied with the ones on-force at the time of the intervention, except for Façade 5). Existing façades with thermal insulation, from case A, are still able to comply with the maximum value of $U = 0.5 W \cdot m^{-2} \cdot K^{-1}$, imposed by the current thermal regulation.

In the fieldwork carried out, many case studies and interviews with experts were analysed, which lead to the conclusion that measures to encourage buildings thermal retrofitting, as well as to support a more informed and sustained choice of the used technique, must be taken. In Figure 7 and Table 4, the intervention strategies are discussed in a structured way and based on the fieldwork. This approach can be used in a decision-support method, including critical decision points supported by Table 4, which presents additional information, assisting the selection process.

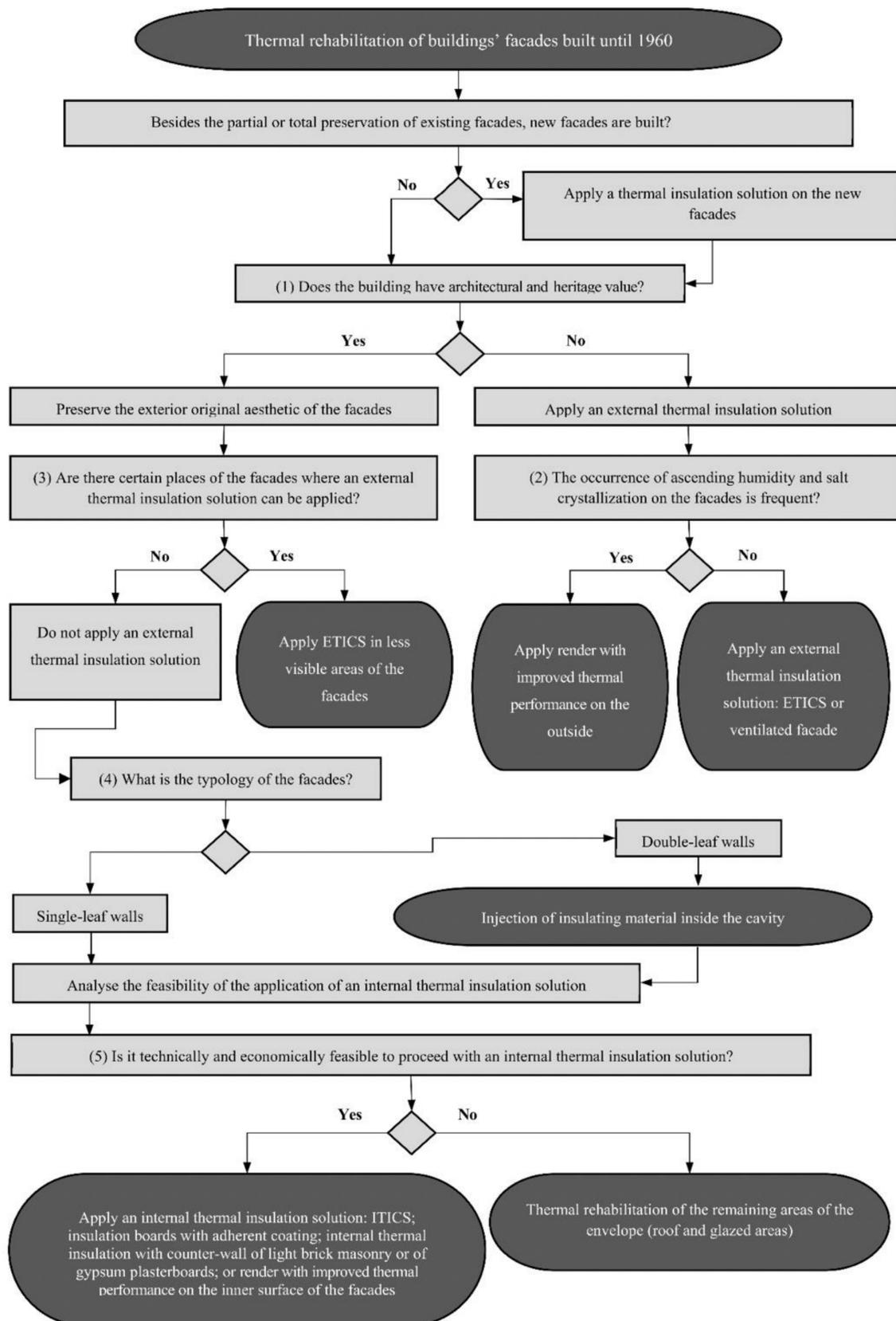


Figure 7. Flowchart to discuss thermal retrofitting strategies of old buildings' façades.

Table 4. Detailed information about the critical points of the Flowchart.

(1) Does the Building Have an Architectural and/or Heritage Value ?	
<p>Is there an intention to preserve the original exterior aesthetic of the façades? or Do the façades have complex architectural features, such as salient elements and window/door frames?</p>	<p>Yes. → The application of an external thermal retrofitting solution is not recommended since it could mischaracterise the external aesthetic of the building. Furthermore, its application is difficult on the system edges.</p> <p>No. → The application of an external retrofitting solution is the most appropriate since it is possible to take advantage of its benefits.</p>
(2) Is the Occurrence of Ascending Humidity and Salt Crystallisation on the Façades Frequent?	
<p>When it occurs, the thermal insulation solution must not create a barrier to the passage of the water with dissolved salts, because that would lead to the creation of a tension field between the wall and the thermal insulation solution, compromising the durability of the insulation material and the system’s adherence to the wall.</p>	<p>Yes. → The application of a render with improved thermal performance is several times recommended for this case. Besides, specific measures to remove or minimize ascending humidity action and effects on the wall have to be applied, if possible. However, this solution has less thermal resistance than other thermal insulation solutions, but innovative thermal renders (e.g., aerogel based-renders [40–42]) can improve this limitation.</p> <p>No. → It is recommended the use of a more thermally efficient solution: ETICS or ventilated façade. These are the solutions that allow the correction of the thermal bridges, maintain the thermal inertia of the façades, and provide exterior aesthetic renovation of the façades. The ETICS is a solution more common than the ventilated facade in the rehabilitation field, possibly because the second one has the highest investment cost associated. The choice of the insulating material of the ETICS system is also significant, and materials more permeable to the water vapour should be used, such as MW and ICB, since those are more suitable for the application in façades of old buildings and because these façades are made of porous elements, usually stone masonry.</p>
(3) Are there Certain Places of the Façades where an External Thermal Insulation Solution can be Applied?	
<p>It is intended to preserve the original aesthetic of the building. The possibility of the application of ETICS in low visible areas of the façades should be analysed if its application does not mischaracterise the building’s architecture.</p> <p>Although ETICS is a very thermally efficient solution, when it is only applied in some regions of the façades, the thermal behaviour of the remaining areas of the façades is not improved. Therefore, it should be analysed if an internal thermal retrofitting solution offers a better improvement of the thermal behaviour of the façades.</p>	<p>Yes. → Application of ETICS in less visible areas of the façades.</p> <p>No. → Do not apply an external thermal insulation solution.</p>

Table 4. Cont.

(4) What is the Typology of the Façades?	
<p>If it is not possible to apply an external thermal retrofitting solution, such as ETICS, it should be considered the possibility of the application of another solution, which should be the one that is more appropriate to the typology of the façade.</p>	<p>Double-leaf wall. → The injection of insulating material inside the cavity, such as PUR’s foam, is recommended because it allows the preservation of the internal and external appearance of the façades. However, it must be ensured that the cavity filling process is correctly made. Another aspect to consider is the water vapour permeability of the used material, since a lower water vapour permeability can potentiate the appearance of humidity issues.</p> <hr/> <p>Single-leaf wall. → For this case, there are several internal thermal retrofitting solutions, so the feasibility of its application must be examined.</p>
(5) Is it technically and economically feasible to proceed with an internal thermal insulation solution?	
<p>The constraints of an internal thermal retrofitting solution, such as the loss of thermal inertia of the façades and the reduction of the useful inner area, do not override the benefits, such as the increase of thermal resistance, of the façades? or An economic limitation does not prevent its application?</p>	<p>No. → After analysing the advantages and disadvantages, if it is not possible to apply a thermal retrofitting solution on the façades, given the constraints involved, thermal rehabilitation measures should be taken in the remaining envelope (roof and glazed areas).</p> <hr/> <p>Yes. → Apply one of the following internal thermal insulation solutions: ITICS; insulation boards with adherent coating; internal thermal insulation with counter-wall of light brick masonry or gypsum plasterboards; render with improved thermal performance on the inner surface of the façades.</p>

Mediterranean Specificity

Most of the energy guides assume the internal thermal insulation solution as the most suitable for traditional buildings due to restrictions of external appearance changes. Moisture associated risks are pointed out as the main caution to be taken into consideration when prescribing this solution. This subject is widely and comprehensively address in the recent RIBuild guide [43] which brings together contributions from members mainly from countries with cold climates. Nonetheless, the significant increase of the risk of overheating in summer due to the elimination of the thermal inertia of the building facades is only briefly mentioned.

As previously mentioned, the main reason given by designers for not applying any thermal insulation on facades (in 6 out of 12 case studies) was to be able to continue to take advantage of the high thermal inertia of existing facades. This is particularly important in old buildings with wooden floors, such as the ones built until 1930, since the main heat storage capacity are in external walls. This represents around 8% of total Portuguese accommodations [44].

Data from 2010 indicates that 22% of energy household consumption is dedicated to indoor climate, with only 0.5% specifically to cooling [44]. However, most of the Portuguese estimated energy needs do not correspond in fact to consumption but to absence of heating or cooling and continuous thermal discomfort. Although Mediterranean weather is considered soft (see Section 4.1), 28% of the Portuguese population cannot keep their homes adequately warm in winter [45] in contrast with the European average of 11%. But energy poverty in Portugal is even more evident in summer, with 36% of Portuguese living in not sufficiently cool housing [46]. Climate change represents an added challenge, namely heat waves, that are expected to be longer and more frequent [47], being more likely to cause building performance failures [48].

When retrofitting, care should be taken to avoid exacerbating overheating risk which could lead people to resort to HVAC systems. This would lead to an increase in CO₂ emissions resulting not only

from the cooling energy consumption but also from equipment's embodied energy. This is contrary to the initial purpose of increasing the sustainability of existing buildings by reducing their energy consumption needs and the corresponding gaseous emissions, while increasing their users' comfort.

The presented flowchart (Figure 7) as a pre-design tool for decision support reflects the described Mediterranean specificity. The final step, with the remaining option of internal thermal insulation, also considers not thermally intervening at all in external walls in order to avoid overheating.

6. Conclusions

With the research results herein presented, it can be concluded that there is still much to do in Portugal, and Europe, concerning the thermal retrofitting of old buildings' façades. There are already legal rules to be followed, but old buildings can be an exception if adequately justified. For this reason, thermal retrofitting strategies are commonly absent from most interventions, and the rules are not integrally accomplished. However, this paper highlights that existing walls on old buildings' facades can be insufficient to guarantee thermal comfort in Lisbon, Portugal, and also in other locations and weather conditions in the Mediterranean area.

Also, the fieldwork and interviews with experts highlighted the paramount importance of thermal insulating this type of buildings with suitable strategies. Therefore, the thermal retrofitting of old buildings' façades should be encouraged.

Different issues and scenarios that must be considered in the selection process of the insulation techniques to be adopted in the façades, to improve their thermal behaviour, were summarised in this paper, based in the literature. The application and the advantages and disadvantages of these techniques were evaluated and validated, studying real retrofitting cases in a Mediterranean Climate and conducting interviews with experts.

The selection of the most adequate solution for the thermal retrofitting of a façade depending on: the architectural feasibility of applying an external insulating solution throughout the whole façade (e.g., if the building has or not cultural value) or in some regions of the façade (corresponding to less visible areas); the occurrence of frequent rising damp and salt crystallisation on the façades (leading to the analysis of the application of renders with improved thermal performance as a possible solution); the typology of the façades (since it should be analysed the possibility of injection of an insulating material inside the cavity, in case of double-leaf walls); the technical and economic feasibility to proceed with an internal thermal insulation solution.

This study also presents the specificity of thermal retrofitting interventions in the Mediterranean context. The case studies are in Portugal and the decisions made on the thermal rehabilitation of the facades had in mind the constructive (strong thermal inertia of the facades of old buildings) and climatic (cooling needs / risk of overheating) features. In more than 50% of the case studies, the option taken was to not apply thermal insulation to facades. In cases where the only option would be to apply thermal insulation from the inside, the designer preferred not to do so in order to continue taking advantage of the strong thermal inertia of the walls. This issue is preponderant in old buildings with a light floor and roof (wood) structure, for which the only element that contributes as a thermal damper is the thick walls of the facades. The flowchart presented to support the decision reflects this same reality.

This paper contributes to a better discussion of the factors that influence the decision process and to a more frequent thermal retrofitting of old building façades, based on a fieldwork and supported with literature. Adequate interventions contribute to a lower energy consumption and greenhouse gas emissions, while increasing the comfort of the occupants, and minimising the aesthetic impact of the retrofit. Further research is needed to complement the study with thermal retrofitting solutions more common in other European countries and climates, for example, innovative solutions (e.g., aerogel-based boards or vacuum insulation panels) where in-service performance over time is not yet fully understood.

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References

1. Martínez-Molina, A.; Tort-Ausina, I.; Cho, S.; Vivancos, J.-L. Energy efficiency and thermal comfort in historic buildings: A review. *Renew. Sustain. Energy Rev.* **2016**, *61*, 70–85. [[CrossRef](#)]
2. Brás, A.; Rocha, A.; Faustino, P. Integrated approach for school buildings rehabilitation in a Portuguese city and analysis of suitable third party financing solutions in EU. *J. Build. Eng.* **2015**, *3*, 79–93. [[CrossRef](#)]
3. Pedroso, M.; de Brito, J.; Dinis Silvestre, J. Characterization of walls with eco-efficient acoustic insulation materials (traditional and innovative). *Construct. Build. Mater.* **2019**, *222*, 892–902. [[CrossRef](#)]
4. De Santoli, L. Guidelines on energy efficiency of cultural heritage. *Energy Build.* **2015**, *86*, 534–540. [[CrossRef](#)]
5. Mazzarella, L. Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. *Energy Build.* **2015**, *95*, 23–31. [[CrossRef](#)]
6. DGGE. *Energetic Rehabilitation of Residential Building Envelopes*; DGGE: Lisboa, Portugal, 2004; p. 40. (In Portuguese)
7. Loli, A.; Bertolin, C. Towards Zero-Emission Refurbishment of Historic Buildings: A Literature Review. *Buildings* **2018**, *8*, 22. [[CrossRef](#)]
8. Sallée, H.; Quenard, D.; Valenti, E.; Galan, M. VIP as thermal breaker for internal insulation system. *Energy Build.* **2014**, *85*, 631–637. [[CrossRef](#)]
9. Murgul, V.; Pukhkal, V. Saving the Architectural Appearance of the Historical Buildings due to Heat Insulation of their External Walls. *Procedia Eng.* **2015**, *117*, 891–899. [[CrossRef](#)]
10. Arumägi, E.; Pihlak, M.; Kalamees, T. Reliability of Interior Thermal Insulation as a Retrofit Measure in Historic Wooden Apartment Buildings in Cold Climate. *Energy Procedia* **2015**, *78*, 871–876. [[CrossRef](#)]
11. CCE. *Energy Rehabilitation Methodology for Buildings Located in Urban Areas—A SAVE II Programme Action*; CCE: Amadora, Portugal, 2000.
12. Ganobjak, M.; Brunner, S.; Wernery, J. Aerogel materials for heritage buildings: Materials, properties and case studies. *J. Cultur. Herit.* **2019**. [[CrossRef](#)]
13. Altan, H.; Mohelnikova, J. Energy Savings and Carbon Reduction due to Renovated Buildings. *Int. Rev. Mech. Eng.* **2009**, *3*, 833–836.
14. Lechtenböhmer, S.; Schüring, A. The potential for large-scale savings from insulating residential buildings in the EU. *Energy Eff.* **2011**, *4*, 257–270. [[CrossRef](#)]
15. Malanho, S.; Veiga, M.d.R. Bond strength between layers of ETICS—Influence of the characteristics of mortars and insulation materials. *J. Build. Eng.* **2020**, *28*, 101021. [[CrossRef](#)]
16. El-Darwish, I.; Gomaa, M. Retrofitting strategy for building envelopes to achieve energy efficiency. *Alex. Eng. J.* **2017**. [[CrossRef](#)]
17. Tadeu, S.; Rodrigues, C.; Tadeu, A.; Freire, F.; Simões, N. Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions. *J. Build. Eng.* **2015**, *4*, 167–176. [[CrossRef](#)]
18. Sulakatko, V.; Lill, I. The economic relevance of on-site construction activities with the External Thermal Insulation Composite System (ETICS). *Int. J. Strateg. Prop. Manag.* **2019**, *23*, 213–226. [[CrossRef](#)]
19. Walker, R.; Pavía, S. Thermal performance of a selection of insulation materials suitable for historic buildings. *Build. Environ.* **2015**, *94*, 155–165. [[CrossRef](#)]
20. De Berardinis, P.; Rotilio, M.; Marchionni, C.; Friedman, A. Improving the energy-efficiency of historic masonry buildings. A case study: A minor centre in the Abruzzo region, Italy. *Energy Build.* **2014**, *80*, 415–423. [[CrossRef](#)]

21. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [[CrossRef](#)]
22. Canha da Piedade, A.; Braga, A.; Moret Rodrigues, A. *Thermal Behaviour of Buildings (In Portuguese: Térmica de Edifícios)*, 1st ed.; Editora ORION: Lisboa, Portugal, 2009.
23. Ahmed, A.; Qayoum, A.; Mir, F.Q. Investigation of the thermal behavior of the natural insulation materials for low temperature regions. *J. Build. Eng.* **2019**, *26*, 100849. [[CrossRef](#)]
24. Mistretta, F.; Stochino, F.; Sassu, M. Structural and thermal retrofitting of masonry walls: An integrated cost-analysis approach for the Italian context. *Build. Environ.* **2019**, *155*, 127–136. [[CrossRef](#)]
25. Dumitrescu, L.; Baran, I.; Pescaru, R.A. The Influence of Thermal Bridges in the Process of Buildings Thermal Rehabilitation. *Procedia Eng.* **2017**, *181*, 682–689. [[CrossRef](#)]
26. Alves, S.; Ferreira, C.; Freitas, V.P.d.; Guimarães, A. *Existing Buildings-Improvement Measures of Energy Performance and Indoor Air Quality*; ADENE: Miraflora, Portugal, 2011. (In Portuguese)
27. Gagliano, A.; Nocera, F.; Aneli, S. Thermodynamic analysis of ventilated façades under different wind conditions in summer period. *Energy Build.* **2016**, *122*, 131–139. [[CrossRef](#)]
28. APFAC. *ETICS-Application Manual*; APFAC: Lisbon, Portugal, 2015. (In Portuguese)
29. Appleton, J. *Old Buildings Rehabilitation*, 2nd ed.; Editora ORION: Lisboa, Portugal, 2011. (In Portuguese)
30. Fernandes, C.; de Brito, J.; Cruz, C.O. Architectural integration of ETICS in building rehabilitation. *J. Build. Eng.* **2016**, *5*, 178–184. [[CrossRef](#)]
31. Finken, G.R.; Bjarløv, S.P.; Peuhkuri, R.H. Effect of façade impregnation on feasibility of capillary active thermal internal insulation for a historic dormitory—A hygrothermal simulation study. *Construct. Build. Mater.* **2016**, *113*, 202–214. [[CrossRef](#)]
32. Sulakatko, V. Modelling the Technical–Economic Relevance of the ETICS Construction Process. *Buildings* **2018**, *8*, 155. [[CrossRef](#)]
33. Wójcik, R.; Bomberg, M. On interior rehabilitation of buildings with historic facades. *J. Build. Phys.* **2016**, *40*, 144–161. [[CrossRef](#)]
34. Lourenço, P.B.; Luso, E.; Almeida, M.G. Defects and moisture problems in buildings from historical city centres: A case study in Portugal. *Build. Environ.* **2006**, *41*, 223–234. [[CrossRef](#)]
35. Sulakatko, V.; Vogdt, F. Construction Process Technical Impact Factors on Degradation of the External Thermal Insulation Composite System. *Sustainability* **2018**, *10*, 3900. [[CrossRef](#)]
36. Zagorskas, J.; Zavadskas, E.K.; Turskis, Z.; Burinskienė, M.; Blumberga, A.; Blumberga, D. Thermal insulation alternatives of historic brick buildings in Baltic Sea Region. *Energy Build.* **2014**, *78*, 35–42. [[CrossRef](#)]
37. Biseniece, E.; Žogla, G.; Kamenders, A.; Purviņš, R.; Kašs, K.; Vanaga, R.; Blumberga, A. Thermal performance of internally insulated historic brick building in cold climate: A long term case study. *Energy Build.* **2017**, *152*, 577–586. [[CrossRef](#)]
38. Webb, A.L. Energy retrofits in historic and traditional buildings: A review of problems and methods. *Renew. Sustain. Energy Rev.* **2017**, *77*, 748–759. [[CrossRef](#)]
39. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263. [[CrossRef](#)]
40. Pedroso, M.; Flores-Colen, I.; Silvestre, J.D.; Gomes, M.G.; Silva, L.; Ilharco, L. Physical, mechanical, and microstructural characterisation of an innovative thermal insulating render incorporating silica aerogel. *Energy Build.* **2020**, 109793. [[CrossRef](#)]
41. Pedroso, M.; Flores-Colen, I.; Silvestre, J.D.; Gomes, M.G.; Silva, L.; Sequeira, P.; de Brito, J. Characterisation of a multilayer external wall thermal insulation system. Application in a Mediterranean climate. *J. Build. Eng.* **2020**, 101265. [[CrossRef](#)]
42. Pedroso, M.; Flores-Colen, I.; Silvestre, J.D.; Gomes, M.G. Nanomaterials’ Influence on the Performance of Thermal Insulating Mortars—A Statistical Analysis. *Appl. Sci.* **2020**, *10*, 2219. [[CrossRef](#)]
43. Project RIBuild—Robust Internal Thermal Insulation of Historic Buildings. Written Guidelines for Decision Making Concerning the Possible Use of Internal Insulation in Historic Buildings. 2020. Available online: <https://static1.squarespace.com/static/5e8c2889b5462512e400d1e2/t/5f04215c5b6cfa0aa7baa5b1/1594106230146/Written+guidelines+for+decision+making+concerning+the+possible.pdf> (accessed on 25 August 2020).
44. INE, DGEG. *Survey to Energy Consumption in Residential Sector*; INE, DGEG: Lisbon, Portugal, 2011. (In Portuguese)

45. Eurostat. Inability to Keep Home Adequately Warm (SILC). 2013. Available online: http://ec.europa.eu/eurostat/web/products-datasets/-/ilc_mdcs01 (accessed on 15 May 2018).
46. Eurostat. Share of Population Living in a Dwelling Not Comfortably Cool during Summer Time by Income Quintile and Degree of Urbanisation. Source of Data. Available online: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_hcmp03&lang=en (accessed on 15 February 2018).
47. IPCC. *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Pachauri, R.K., Reisinger, A., Eds.; Climate Change 2007: Synthesis Report; IPCC: Geneva, Switzerland, 2007.
48. Herrera, M.; Natarajan, S.; Coley, D.A.; Kershaw, T.; Ramallo-González, A.P.; Eames, M.; Fosas, D.; Wood, M. A review of current and future weather data for building simulation. *Build. Serv. Eng. Res. Technol.* **2017**, *38*, 602–627. [[CrossRef](#)]

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