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Improving Energy Performance of Historic Buildings through Hygrothermal Assessment of the Envelope

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Abstract: The intervention on historic buildings through building energy retrofitting has become one of the current challenges of improving energy efficiency. Nonetheless, this building typology presents certain complexities. Among them, one of the most relevant is the protection on their façades due to the historical and/or artistic values of a given façade and, therefore, the addition of external thermal insulation is restricted. However, at the same time, in several of those buildings indoor surfaces do not present that architectural value, and then internal thermal insulation becomes a promising strategy for improving their thermal performance. Nevertheless, its application must be carefully evaluated to avoid possible pathologies caused by moisture problems. This paper aims to identify constructive solutions for interior insulation of walls free from moisture problems. For this purpose, a comprehensive analysis of a series of constructive solutions based on internal insulation has been carried out through hygrothermal simulations. The results show how the application of water-repellent impregnation becomes essential to guaranteeing the integrity of the envelope. In addition, the combination of insulations with or without inner membranes, such as smart vapor retarders or vapor diffusion barriers, has been evaluated detecting the solutions that best fit the objective. Finally, taking advantage of the great potential of 2D simulation tools, the post-processing of the data has been performed to apply the wood decay model, and thus assess the behavior of a very conflictive point in this type of intervention, i.e., the wooden beam-ends. The results in this critical point have shown how the application of the proposed constructive solutions becomes essential to guarantee the integrity of the element and how the application of traditional solutions could lead to a hazard that must be avoided.

Keywords: building energy retrofitting; built heritage; historic buildings; hygrothermal performance; internal thermal insulation composite system (ITICS); wooden beam-ends; wooden decay model

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1. Introduction

Currently, the buildings are one of the main focuses of attention due to their high energy consumption. As they account for 40% of total final energy consumption, improving their energy performance may enable a fulfilment of energy objectives [1]. New buildings can be built under energy efficient designs, however the growth trend of these buildings has depleted due to the impact of the financial crisis in this sector [2]. Therefore, the scope of action is located under the existing buildings. One-third of residential buildings in Europe were built before 1960, and almost 84% are at least 20 years old [3]. With the thesis that the age of the buildings is a clear indicator of their energy consumption [4], the refurbishment of the buildings' envelopes to the present standards supposes a great opportunity for energy and CO_2 emissions savings.

Within this work area, historic buildings with different levels of protection due to their historical or artistic values are also considered. The intervention on them is of great necessity and interest, owing to the positive impact they have in the culture and society [5]. However, the implementation of the European energy efficiency regulations [1] for these historic buildings has been left to each member state [6]. As a consequence, there are few energy retrofit interventions in these kind of buildings. Nonetheless, the research in this area is growing [7] in accordance with the recent regulation [8], and thus showing its relevance for the coming years.

Although the architectural value of a part of the heritage buildings can derive from their external or internal features (rich stuccos, decorated, painted tableaus, etc.) of the walls, many of them do not have remarkable interior values, and therefore can be objects of intervention. For these cases, the reduction in the transmission losses through the application of Internal Insulation Composite Systems (ITICS) becomes a possible way to improve its energy performance. Nonetheless, one of the key issues of these interventions is the assessment of moisture risk, as these solutions could involve the appearance of condensations, mold growth [9,10] and, in extreme cases, a risk of decay [11,12]. These types of assessments are usually carried out through numerical hygrothermal simulations based on combined heat, air, and moisture transfer models [13,14].

These kinds of assessments are able to predict the moisture behavior of buildings' components while avoiding the expensive and time-consuming experimental investigations. In the building sector, the use of the steady-state Glaser method is common when the hygrothermal behavior evaluation of building envelopes is necessary [15–17]. However, the strategies based on this model overlook many of the aspects that substantially affect the system. For example, the process takes into account condensation when the water vapor pressure exceeds that of saturation, as occurs in materials such as glass or metal, but it does not take into consideration the hygroscopic capacity of the porous materials to adsorb or absorb moisture. Due to this, numerical models [18–21] have become more relevant, as they allow a more advanced analysis of buildings' thermal envelopes, taking into account multiple variables that, presenting great relevance in historic buildings, are not considered in the Glaser method. These numerical methods are implemented through Heat, Air, and Moisture (HAM) software, becoming an ideal method for carrying out the hygrothermal assessments, and nowadays there are several available tools for it [22]. Furthermore, various standards and handbooks in this matter serve as support and guides to establish the hygrothermal evaluation criteria of buildings' envelopes [23–26].

Previous research studies carried out in this field have generally focused on the analysis of severe winter climates, with a medium or high precipitation rate and brick assembled masonry walls [27–36]. Nevertheless, there are also other cases that have not been investigated yet. For instance, in some cases where the winter climate is not so severe, usually less moisture risks are presupposed, although in fact, due to their particularities, they present the same risk of problems associated with the hygrothermal behavior of the walls and its components. These cases correspond to situations in which, on the one hand, there is a high rainfall rate and, on the other hand, the material that predominates the composition of the masonry wall is of ashlars with a high coefficient of absorption. This paradigm, despite not being widely evaluated, belongs to the casuistry that can usually be found in the envelopes of heritage buildings. These two factors lead to high moisture contents along the section of the wall and, therefore, to a high risk of pathological processes (damp, mold growth, and/or structural degradation) that have to be avoided in the new proposed designs for the energy retrofits.

This paper's aim is to analyze different constructive solutions to achieve the energy performance improvement of heritage buildings. It focuses on those cases in which the intervention of the thermal envelope could be made from the interior side of the walls. The study has been performed through a series of hygrothermal simulations to detect the most appropriate solutions. It is based on the analysis of different materials that are common in the sector and that, in turn, differentiate themselves from one another due to their hygrothermal behavior. For this, the case to be evaluated should take into account the aforementioned conditions, i.e., a high rate of rain and facade material with high capillary absorption. Additionally, the proposed solution must be a decay safe solution and, to check this issue, an evaluation of a structurally essential element is proposed, the wooden beam-ends. Taking into consideration that energy refurbishment of buildings is one of the main aims of global energy policies, and that the built heritage plays an important role in this, the obtained results can be useful information to support the proper selection of construction solutions in this kind of intervention.

2. Background

2.1. Energy Efficiency and Historic Buildings

The built heritage has become a major issue in recent times. Among others, the historic buildings contribute to maintain the urban identity of neighborhoods [5]. One of the characteristic aspects of built heritage is its impact on culture and society, which is why intervention on this type of building becomes both a challenge and an opportunity. Furthermore, this opportunity can be considered as an investment to improve urban sustainability by improving the energy efficiency of the built heritage [37].

As a result, several papers focused on this issue have been published in the last decade, which shows the relevance of this topic for the upcoming years [7]. Other outcomes include multiple available guidebooks [38–42] and conferences [43,44], whose aim is to serve as a pattern to energy performance interventions in this kind of building. Additionally, ASHRAE and CEN have paid great attention to this type of building through their elaborated guidelines [45–47].

Several interventions, aimed to improve the performance in these buildings, can be identified, such as reducing energy losses through building envelope by adding thermal insulation [48], improving the airtightness [49,50], integration of new RES [51–53], or implementing monitoring systems [54–58]. All these kinds of intervention follow a common criterion, to maintain a balance among energy improvements while its heritage value is preserved. As Arumägi et al. showed [59], this aim is affordable.

However, this kind of building usually presents difficulties as they are built using traditional construction techniques. Moreover, the existing restrictions due to the built heritage protection regulations must also be taken into account. This means that the energy assessment and interventions in these buildings are substantially complex. Therefore, as several studies agree [40,60], further research is needed in this area.

2.2. Hygrothermal Assessment of ITICS Interventions

Currently, multiple materials and constructive solutions can be used to improve the energy efficiency of buildings. However, as mentioned above, the heritage buildings present certain peculiarities in their interventions. Due to this, different guides related to ITICS [61–65] provide keys for these types of interventions.

Internal insulation has become a possible solution for improving the energy performance of heritage buildings. Nevertheless, it presents several risks that must be carefully considered, such as the increase in condensation risk and moisture accumulation behind the insulation layer [63,66]. To solve this issue, the so-called capillary active insulations, CAI, are often employed due to their ability to transport liquid moisture from the wet layer to the indoor surface, thus allowing the drying process through its high water absorption coefficient A_w [67,68]. Various authors [28,69,70] have evaluated this kind of insulation with different approaches, and all of them showed better results compared to traditional insulations. However, as Vereckeen et al. [71] remarked, it is of great importance to distinguish the behavior of different CAIs as, nowadays, there is a wide range of thermal insulation materials with small liquid conductivity and low A_w, and, therefore, there is less dried moisture in the interior. For this reason, the relevance of properly asserting the hygric properties becomes essential, even more so in historic buildings where there is a reliable lack of information about materials´ input parameters [72].

Insulations are not the only materials that take great relevance in interventions with ITICS. As various authors concluded [27,28], the application of internal insulation entails a rise of water content in the wall. Therefore, as to avoid an even greater increase in water due to rain exposure, it is also necessary to apply external water-repellent layers. In these kinds of materials, besides the A_w value, the vapor diffusion coefficient [73,74], δ_p, is of great relevance to allow the proper vapor diffusion to the outdoors and avoid interstitial condensation [75]. Guizzardi et al. [29] analyzed this topic through the evaluation of the effect of application of different external plasters (lime plaster, cement lime plaster, lime cement plaster, and cement plaster) and three kinds of insulation. The conclusion was that, from the evaluated materials, the best combination is the cement plaster, due to its low A_w value, and the calcium silicate, due to its capillary active insulating behavior. However, often, this kind of water-repellents based on external plasters cannot be applied as they alter the heritage value of the facade, as are the cases of stone or brick masonry walls. Due to this, other silicon-based treatments could be an ideal impregnation for external surfaces of historic façades, as their transparency allows the aesthetic appearance to maintain intact. Its properties of low A_w, and high δ_p allow rainwater to be repelled, thanks to the increase in the static contact angle θ [76], which at the same time allows the process of drying the wall. Additionally, it is important to emphasize that if these impregnations are applied in combination with internal insulation, the latter should be installed later, thus allowing excess moisture in the masonry to dry out faster [30].

Other additional materials are the vapor diffusion barriers (VDB) [77] which hinder the vapor diffusion from the interior to the exterior ambience and thus avoid the condensation in the cold layer. However, this also prevents the inward drying process and, therefore, if there is an outdoor source of dampness (high wind-driven rain, broken plumbing, etc.) the problem will be present. To solve this issue, the smart vapor retarders (SVR) were developed allowing inward diffusion in summer through its variable vapor permeability δ_p. Nonetheless, the proper performance of these materials depends heavily on the workmanship quality to ensure the vapor and airtightness continuity.

One of the additional concerns that arises in this type of intervention with internal insulation, and specifically in buildings with wooden structures, are the wooden beam-ends. This fact can lead to a substantial variation of the hygrothermal conditions of these points with respect to the initial conditions, increasing their humidity and reducing their temperature and drying potential, thus increasing decay-hazard (Figure 1).

Figure 1. Wooden beam-end degradation sample in a self-evaluated case.

Different research pieces about this topic can be found in the literature. Morelli et al. [31] and Harrestrup et al. [32,33] showed the suitable behavior of a 200–300 mm insulation gap above and/or below the joint of the beam-end. Thus, an intentional thermal bridge was created to increase the temperatures and reduce the humidity around the beams-ends. However, they also demonstrated how the rain exposure intensity and exposure to the solar radiation through different orientations were fundamental parameters that affect the hazard of mold growth. With a similar concept, Ueno [34] proposed the implementation of the so-called passive heated beam-ends through metallic sheets or by the use of thinner insulation around the beam. He concluded that this system could be a solution, but also that more depth studies through 3D hygrothermal models are necessary due to the complexity of the topic. Ruisigner et al. [35] carried out an exhaustive experimental analysis by monitoring the beam-ends with five different internal insulations (cellulose, insulation plaster, wood fiber, reed, and perlite). They showed how, although there were no major differences in the wooden beams-ends amongst the different insulations, there was a big difference in the cold side of the wall. Only the perlite insulation kept the relative humidity values below the over-hygroscopic range. However, they stated that the favorable conditions of low driving rain load could affect the results. Finally, the existing great complexity to carry out a detailed evaluation of beam-ends was also highlighted, as 3D hygrothermal simulation tools are scarce.

Johansson et al. [36] also evaluated this detail numerically and experimentally, in a laboratory under controlled conditions with a climate simulator and a constructed wall sample. They evaluated the embedded beam-ends in the brick walls with and without the implementation of vacuum insulation panels (VIPs). The research also revealed the utmost relevance of the exterior rain in the wall moisture accumulation rather than the properties of the interior insulation. Nevertheless, it was also pointed out that, in dry periods, the VIP reduces the inward drying capacity, producing higher moisture levels compared to the uninsulated wall. Finally, the importance of the gravity effects along the different height levels in the moisture contents was also remarked.

As observed, energy interventions on historic buildings using ITICS are a complex issue that cannot be addressed through a partial evaluation. All the parameters that affect the behavior of the envelope must be taken into account in a holistic way. Only in this manner the interventions can be carried out and guarantee both the hygrothermal behavior and the integrity of the historical-artistic value of the heritage building typology.

3. Materials and Methods

Interventions on the thermal envelope by means of internal insulation become one of the ways to improve the energy performance of historic buildings. Nevertheless, these actions could involve to the appearance of complexities. As previously mentioned, the research carried out so far has focused on the analysis of case studies in cold climates with masonry brick walls.

To reach the main goal of this paper, the following stepwise method has been carried out. Firstly, another geographical area where a high risk of dampness also exists has been detected. Then, different ITICS solutions, aimed to improve building energy performance without aggravating such moisture problems, have been assessed (Figure 2). The analysis must take into consideration the behavior of different insulation materials in combination with or without internal protective elements such as VDB, SVR, and/or exterior water repellent impregnation. From this series of cases, the most relevant examples have been selected for a subsequent detailed evaluation of the wooden beam-ends.

Additionally, it has been assumed that the workmanship quality is such that allows us to contemplate the following hypotheses. Firstly, there is perfect contact between the materials layers. Secondly, air flow paths through the component that can produce a convective moisture source are omitted, and they are not considered in this analysis. Finally, it is assumed that the membranes are not punched, and they are correctly taped to each other.

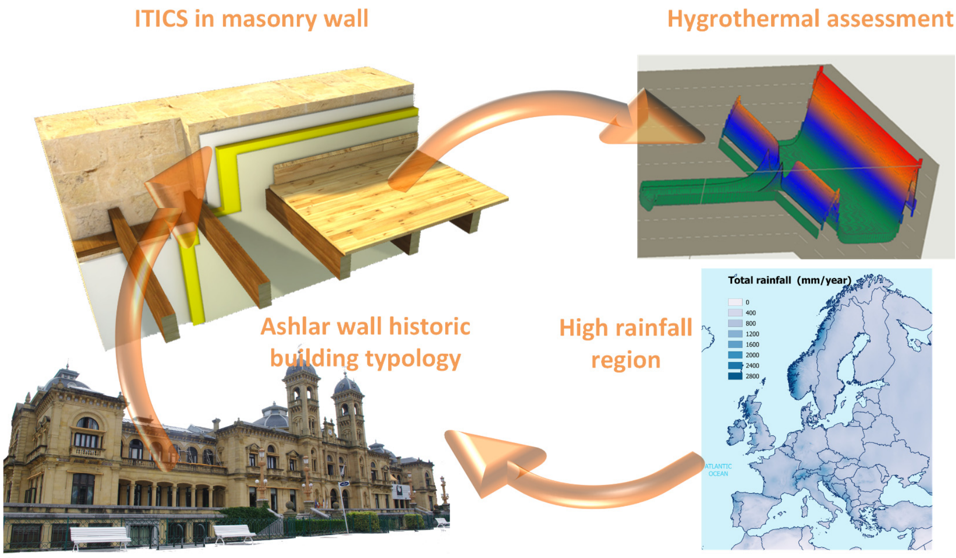

Figure 2. Carried out procedure for the hygrothermal assessment of ITICS solutions.

The rest of this section describes in detail the method followed in this study. The numerical model and general bases considered in the study are presented in Section 3.1. In Section 3.2, simulation model is described and, finally, Section 3.3 describes the main conditions and characteristics of the cases studies evaluated in the simulations.

3.1. Numerical Model

The research carried out is composed of three different parts. The first consists of the simulation process through which the hygrothermal records of the evaluated walls are obtained. Once the results are collated, they are analyzed to detect the inappropriate and appropriate solutions for their implementation in ITICS systems. The second step carries out the post-processing of the records obtained from a group of selected cases, i.e., those considered the most appropriate.

For the hygrothermal simulations, WUFI Pro v.6.2 and WUFI 2D v.4.1 from the Fraunhofer IBP has been used. They are both widely used software programs in this kind of study and are also verified according to the EN 15026 [23]. As analyzed later, the first is used to carry out the set of general simulations and thus be able to obtain some first conclusions. The second software program is used to perform the detailed evaluation of the wooden beam-ends with the solutions that are considered more interesting based on the first obtained conclusions. The reason for not evaluating all the cases in two dimensions is due to the fact that (1) the first software program already detects the general behavior of the different solutions and (2) the volume of data generated in 2D implies high simulation times. The WUFI model is governed according to the following coupled heat and moisture transport equations (Equations (1)–(3)):

$$\frac{\partial \mathrm{H}}{\partial \mathrm{T}}\frac{\partial \mathrm{T}}{\partial t} = \nabla\left(\lambda \nabla \mathrm{T}\right) + h_v \nabla\left(\delta_p \nabla(\phi p_{sat})\right) \tag{1}$$

$$\frac{\partial \mathrm{w}}{\partial \phi}\frac{\partial \phi}{\partial t} = \nabla\left(D_\phi \nabla \phi + \delta_p \nabla(\phi p_{sat})\right) \tag{2}$$

$$D_\phi = D_w \frac{\partial \mathrm{w}}{\partial \phi} \tag{3}$$

where $\partial \mathrm{H}/\partial \mathrm{T}$ is the heat storage capacity of the moist building material (J/kg), $\partial \mathrm{w}/\partial \phi$ is the moisture storage capacity (kg/m^3), w is the moisture content (kg/m^3), λ is the thermal conductivity (W/(m·K)), D_ϕ is the liquid conduction coefficient (kg/(m·s)), D_w is the capillary transport coefficient (m^2/s), δ_p is the water vapor permeability (kg/(m·s·Pa)), h_v

is the evaporation enthalpy of the water (J/kg), p_{sat} is the water vapor saturation pressure (Pa), T is the temperature (K), and ϕ is the relative humidity (%).

Finally, the post-processing of the data will be carried out through the application of the wood decay model. Currently, there are two evaluation models that are the most employed. The first, based on the WTA 6-8 [78], proposes that the daily mean of the relative humidity of the pore air (averaged over the most critical 10 mm of the solid wood product) must not exceed the limit between 95% at 0 °C and 86% at 30 °C (Figure 3). Well-considered exceptions are permissible for individual short-term violations of the limit.

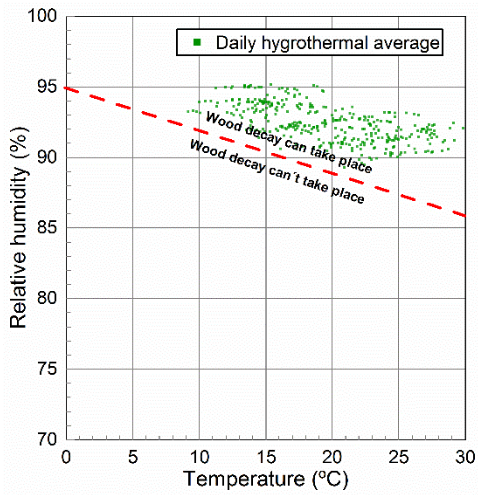

Figure 3. Wood decay assessment based on the WTA 6-8 model.

However, this model does not specify these exceptions, nor does it evaluate the dynamic behavior and its effect on wood. For the purpose of a detailed wooden damage risk evaluation, the Decay Model developed by Viitanen [11,12] can be employed. It is based on the fully developed fungi activation process (α = 1) with which the decay process starts through the mass loss rate (ML), as presented in Equation (4):

$$\alpha(t) = \int_0^t d\alpha = \sum_0^t (\Delta\alpha) \tag{4}$$

The fungi activation only occurs under specific conditions of temperature above 0 °C, and a relative humidity above 95%. If these conditions are not met, the parameter α decreases, and the drying process starts in order to stop the mass loss. However, this is an irrecoverable loss. The time in which α = 0 is assumed to be two years (17,520 h, see Equations (5) and (6):

$$\Delta\alpha = \frac{\Delta t}{t_{crit}(RH,\ T)}\ when\ T > 0\ ^\circ\text{C}\ and\ RH > 95\% \tag{5}$$

$$\Delta\alpha = -\frac{\Delta t}{17520}\ otherwise$$

$$t_{crit}(RH,\ T) = \left[\frac{2.3T + 0.035RH - 0.024T \cdot RH}{-42.9 + 0.14T + 0.45RH}\right] \cdot 30 \cdot 24\ [hours] \tag{6}$$

Fungus activation leads off the mass loss, which is determined by the temperature and relative humidity according to the expression presented in Equations (7) and (8):

$$ML(t\prime) = \int_{t\ at\ \alpha=1}^{t\prime} \frac{ML(RH,T)}{dt} dt = \sum_{t\ at\ \alpha=1}^{t\prime} \left(\frac{ML(RH,T)}{dt} \cdot \Delta t\right) \tag{7}$$

where:

$$ML(RH,T) = -5.96\cdot10^{-2} + 1.96\cdot10^{-4}T + 6.25\cdot10^{-4}RH\left[\frac{\%}{hour}\right] \quad (8)$$

Once the hygrothermal simulations have been performed and analyzed through their post-processing, it will be possible to detect which ITICS solutions adequately fulfill their function. Finally, the conclusions of the study will be obtained, thus allowing us to enumerate guidelines for future energy refurbishment interventions.

3.2. Simulation Model

The simulation model must be a reflection of the most widespread element throughout the historic buildings' typology. These kind of buildings are characterized by thick masonry walls and wooden structure. As the evaluation of the wall is essential, as it conforms the thermal envelope, this point, along with the connection to the wooden structure, is chosen to be the evaluation detail.

To assess this construction type, a reference must be taken as a case study. This must meet the below mentioned requirements:

- It must be a heritage construction typology (load walls and wood structure).
- The intervention of energy retrofit through thermal insulation must be carried out inside the wall.
- The wall must have a high water absorption coefficient.
- There must be a high rainfall rate.
- Winter severity must not be very high.

Keeping in mind these requisites, an oceanic climate or a Cfb climate according to the classification of Köppen–Geiger [79] could turn into the application case. This climate is characterized by very moderate temperatures throughout the year and a high concentration of relative humidity and precipitation. In the first instance, it can be noted that the west coast of the United Kingdom, Ireland, and Norway and the north coast of Spain meet these requirements, being the regions with the highest rainfall rate of the European territory (see Figure 4).

As previously observed, some hygrothermal research pieces have already focused on the areas of the UK, Ireland, and Norway [36,63]. Furthermore, in these sites, the use of brick for a masonry wall is very widespread. It can be said that this material is not one of those that offers the worst protection against capillary suction of rainwater. In this way, the northern coast of Spain has not yet been evaluated, and therefore becomes a suitable candidate for the case study, specifically, the city of Donostia-San Sebastián located in the territory of the Basque Country near the French frontier. The choice of this city, aside from having first-hand knowledge of the area, is justified for two reasons. On the one hand, the architecture of the environment is characterized by the predominant use of sandstone walls with high capillary absorption [80] that leads to great moisture problems, which are further punished by the high precipitation rate in the area. On the other hand, there is a high risk of decay of wooden structures. Through the well-known Scheffer Index (SI) [81], a quick assessment of the danger of wood structures can be made through the monthly climatic records of temperature and number of rainy days. According to the SI values obtained in various references [82,83], the city, due its climatic characteristics, belongs to one of the sites with the greatest hazard for wood decay in Europe. Therefore, from a macroclimatic perspective level that makes it possible to reflect this parameter, it seems reasonable to focus the hygrothermal assessment in this city due to the high existing risk, and then make a detailed evaluation of the wooden beam-end component through the specific simulation models.

The city of Donostia-San Sebastián, characterized by its great built heritage, is known as Le Petit Paris due to the clear influence of French architecture on their design [84]. Part of the city center is protected by the municipal regulation [85] that controls the interventions in these historic buildings and thereby prevents the gradual decay of the city. Therefore, from the architectural heritage point of view, it could be proper example as the solutions of energy improvement of the main facades can only be performed from the interior side of the walls.

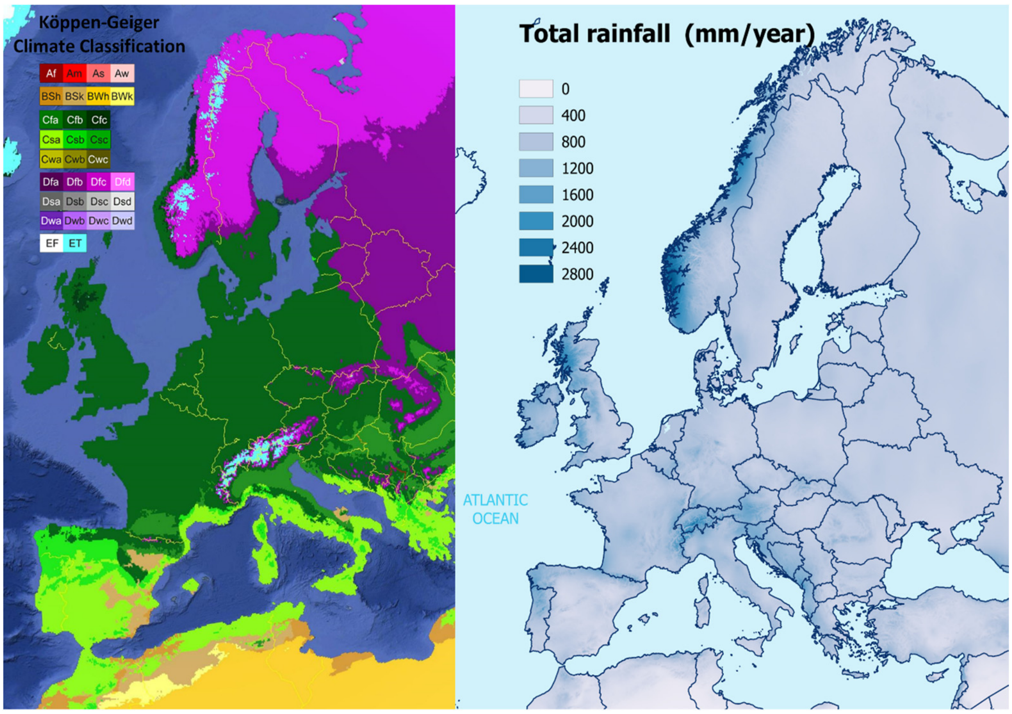

Figure 4. Köppen–Geiger climate classification and annual total rainfall rate of European territory (Maps derived from [79,86]).

Regarding the constructive characteristics of the city buildings, they are composed of sandstone ashlar stonework walls with a normally comprised thickness of 40 to 70 cm, as previously cited. Figure 5 shows the composition of the masonry wall to which the proposed ITICS is added. Additionally, the typical connection of the wooden beam-ends in the wall with the load bearing beam is represented.

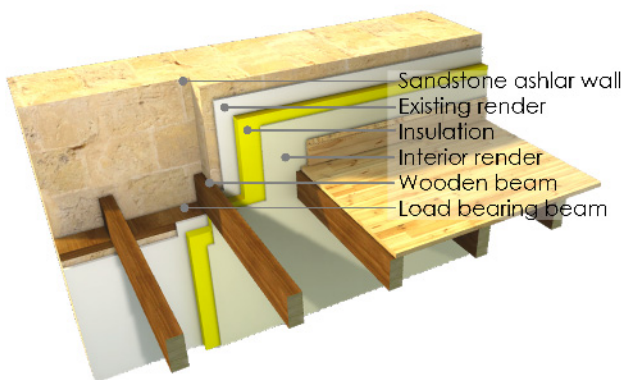

Figure 5. Geometrical description of the simulation model.

As explained previously, the model is going to carry out a simulation with different kinds on insulations in order to detect the overall hygrothermal behavior of these solutions. For the selection of the insulations, it is going to take into account the general classification of insulation according to its hygrothermal behavior [64]. It classifies the insulations into three types: those that are permeable to water vapor, those that offer sufficient resistance to vapor diffusion, and finally those that, in addition to being permeable to water vapor, offer a high capillary absorption capacity, that is, the CAIs.

Mostly, ITICS interventions are performed with the first type of insulations through mineral wool insulation (MW) and, in some cases, with the addition of an interior VDB. As these solutions do not allow the inward diffusion of the condensed moisture, the behavior of the SVRs and CAIs is alternatively evaluated to verify if their response is adequate. On the other hand, the appraisal of non-vapor permeable insulation is also carried out using one of the materials commonly used in these cases, expanded polystyrene (EPS). Finally, the effect of an exterior water-repellent protection (H) is taken into consideration so as to reduce the rain absorption and thus reduce the damp accumulation in the wall.

3.3. Materials, Properties, Climate, and Surface Transfer Conditions

The external conditions taken into consideration for the simulation, as well as the internal conditions, can be found in Figure 6. Considered internal boundary conditions will be in accordance with Section 4.2 of the WTA 6-2 [25]. In this model, the indoor air temperature is in function of the outside temperature, as well as the indoor air humidity (see Figure 7). As the present study is based on a design phase, it has taken into account the case of Medium Moisture Load, increasing its coefficient by 5% in order to offer a safety margin. In addition, the external conditions have been obtained from the Meteonorm database [87].

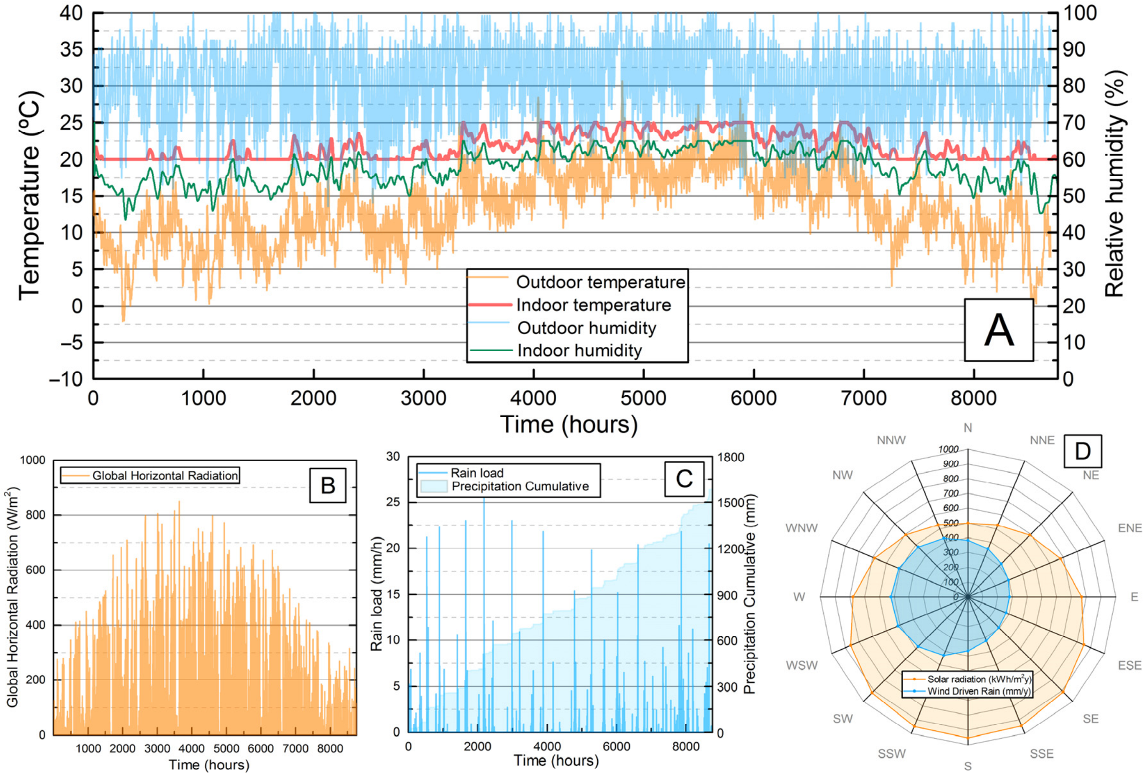

Figure 6. External and internal environmental conditions for the simulation model: (**A**) temperature and humidity, (**B**) solar radiation, (**C**) precipitation, and (**D**) wall radiation and wind-driven rain.

As pointed out above, the climate, although characterized by moderate temperatures, is notable for its high humidity throughout the year (Figure 6A) as well as its high rate of precipitation (Figure 6C). It is essential to analyze the actual exposure of the vertical planes of the facades (Figure 6D), as the choice of the orientation to be evaluated will later depend on it. As shown, the west facade is the most affected by the rain, so this has been the orientation taken into account in the simulations in order to analyze the most adverse scenario.

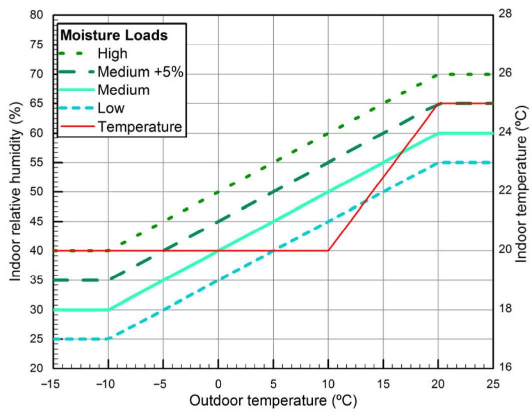

Figure 7. Derived room air temperature and humidity of living spaces as a function of the outside air temperature according to the WTA 6-2.

Following the boundary conditions, the considered surface transfer coefficients definitions for heat transfer coefficient α (W/(m^2·K)) are α_e = 17 and α_i = 8 for the exterior and interior surfaces, respectively. On the other hand, in relation to water vapor transfer coefficient β_p (kg/(m^2·s·Pa)), the WUFI model establishes that there is a relationship between the vapor transfer coefficient and the convective component of the heat transfer coefficient. In this way, β_p is obtained through the following expression: $\beta_p = 7 \times 10^{-9} \cdot \alpha_c$. To consider the surface effects of short-wave radiation absorptivity (a_s) and long-wave radiation emissivity (ε), the value of 0.9 (-) was considered for both coefficients according to the data offered by the software for sandstone material. In order to consider the effect of the driving rain load on the vertical surface of the façade, it was employed the proposed model by WUFI of the ASHRAE Standard 160-2009. The considered model factors of rain exposure (FE) and rain deposition (FD) have been 1.4 (-) and 0.5 (-), respectively. Additionally, the adhering fraction coefficient value has been considered in order take into account the splash effect of rain when hits the wall and is not available for capillary absorption. The considered value has been of 0.7 (-) as proposed by the hygrothermal model for vertical components.

It should be noted that the initial hygrothermal conditions considered have been constant throughout the components of the model, taking the reference value of 80% for relative humidity and 20 °C for temperature.

As the employed software has a comprehensive material base, it is considered opportune to use it in the simulations carried out. The hygrothermal properties of the materials are reflected in Figure 8 and Table 1. Firstly, the different behaviors of the materials can be observed. The water content (Figure 8A) shows the large moisture storage capacity offered by materials such as spruce, the sandstone, the original interior gypsum, or the new interior plaster, and on the contrary the null or low capacity of storage for the sheet materials (VDB and SVR) and the EPS. Due to the great variation of moisture content in the over hygroscopic range, a second axis at the top and dash lines have been added to reflect this with greater definition. Regarding the vapor diffusion resistance (Figure 8B) the great difference between the sheets and the rest of the materials is highlighted. At the same time, it allows the fundamental characteristic of the SVR, the variation of its diffusion coefficient, to be observed. On the other side, the behavior of liquid transport (Figure 8C), the difference in transport activity of the CAI with respect to the rest of the materials, is noticeable. The inability of materials such as EPS, mineral insulation, and sheets should also be noted. Finally, as proposed by Fraunhofer IBP [88], in order to take the effect of the impregnation of the water repellent in the simulation model into account, a thin layer of 1 cm thick was adjusted on the outer face of the sandstone wall considering a typical water absorption coefficient of 0.05 (kg/(m^2·h$^{0.5}$)).

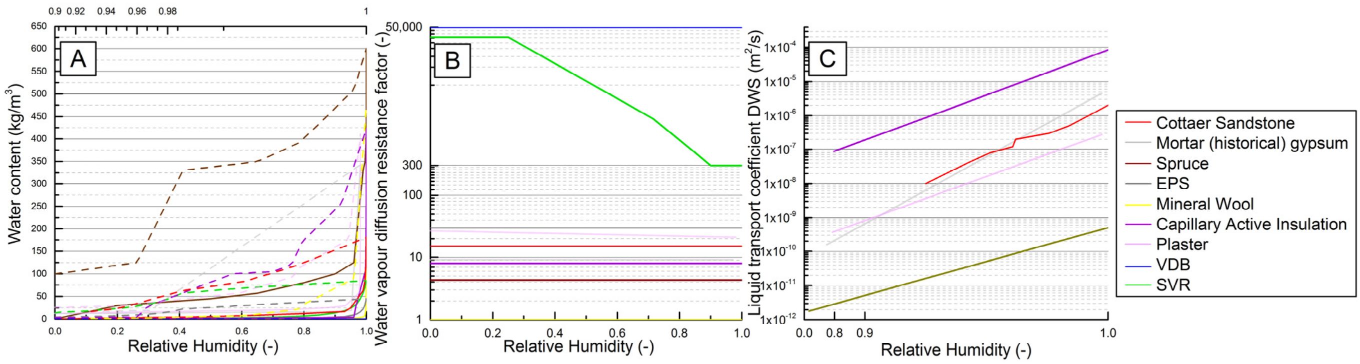

Figure 8. Hygrothermal properties of the employed materials: (**A**) moisture storage function, (**B**) water vapor diffusion, (**C**) liquid transport coefficient.

Table 1. Basic material data used for the developed model.

Material	Bulk Density (kg/m^3)	Porosity (m^3/m^3)	Spec. Heat. Capacity (J/kg·K)	Thermal Conductivity (W/(m·K))
Cottaer Sandstone	2050	0.22	850	1.8
Mortar (historical) gypsum	915	0.64	850	0.52
Spruce	455	0.73	1400	0.23
EPS	30	0.95	1500	0.04
Mineral Wool	32.5	0.95	840	0.032
CAI	100	0.96	850	0.042
Plaster	1330	0.5	850	0.87
VDB	130	0.001	2300	2.3
SVR	85	0.086	2500	2.4

4. Results and Discussion

This section presents the detailed evaluation of the model and its results. In the first place, a prior analysis of the previously discussed possibilities is carried out in order to detect the interventions with greater viability and detect anomalous behavior through WUFI Pro. Later, a more detailed analysis is made in the wood beam-end with WUFI 2D with the solutions selected in the previous analysis and with those that are not recommended in order to show the hazard that they entail if they are carried out. For that, the proposed wood decay model is applied, and its evolution analyzed to determine the suitability of the solution.

It is worth mentioning a relevant topic related to the insulations' evaluation thickness. Although it seems logical to use materials with the same thickness, this would mean that, on the one hand, there would be a difference in terms of the obtained energy improvement, and on the other, that the temperatures along the wall section of the different solutions would be different. This last fact would bring with it that, when applying the decay model, the different cases would be evaluated with temperature differences, and therefore could not be comparative cases. Taking into account that a high thickness would lead to an appreciable loss of the useful surface, it is considered appropriate to take 40 mm of thickness from a traditional insulation such as mineral insulation. This would lead to the need to use 50 mm for the case of EPS and 52 mm for the CAI due to its higher thermal conductivity.

4.1. One-Dimensional Analysis

Figure 9 shows the results obtained in the simulations campaign carried out with WUFI Pro. In them, certain tendencies can be distinguished. The first is related to the solutions that do not have any protection, either on the outside, with the water-repellent impregnation (H), nor on the inside face, with a membrane. Firstly, it can be observed that the hygrothermal equilibrium state is reached immediately as a result of being more exposed to indoor and outdoor moisture sources. As can be seen, the three ITICS solutions result in a higher relative humidity than the original wall. The reason is twofold: on the one hand, the rain acts as an external moisture focus that easily penetrates the wall; and on the other hand, the drying capacity of the wall has been reduced as the temperature along the cross section of the wall also has been reduced after the application of the insulation. Regarding the insulations, it can be observed that in the case of the MW and the CAI, in comparison with the EPS, the hygrothermal profile of the valleys and peaks is more pronounced as a consequence of the greater water vapor permeability. This characteristic allows that, during the summer periods, the moisture accumulated during the cold periods is able to be reduced. However, and in accordance with the specifications set by WTA 6-5 [65], none of the solutions can be recommended, as they exceed the 95% limit of relative humidity and therefore there is a risk of excess moisture in the envelope.

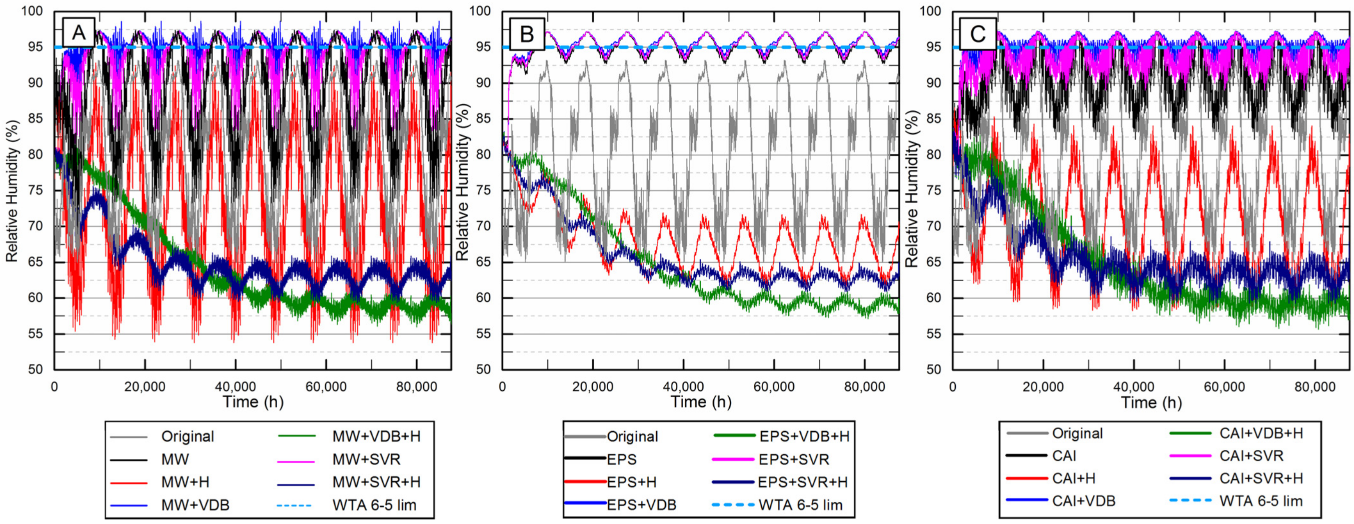

Figure 9. Relative humidity profiles behind the insulation surface: (**A**) Mineral Wool (MW), (**B**) EPS, and (**C**) Capillary Active Insulation (CAI).

Similar behavior, but more aggravated, is perceived in those cases in which only an inner sheet (VDB or SVR) is included with the insulation. The use of the sheets involves the reduction in the inward drying capacity of the existing high moisture, and therefore becomes trapped.

On the other hand, the effect of using only the water-repellent impregnation improves exceptionally for the case of the EPS, notably for the case of the CAI and with appreciable improvements in the case of mineral insulation. This result agrees with the vapor diffusion behavior of the insulations. Although the external moisture source has been prevented from taking effect in all cases, the internal moisture source and the resistance to vapor diffusion of the insulation are what generates the differences existing at the evaluation point. As the vapor diffusion resistance of the insulation decreases, the humidity increases at the evaluation point. For this particular case, all the solutions could be taken into consideration as they do not set the 95% limit imposed. However, it must be noted that, in the case of mineral insulation, special attention should be paid as it is close to the limit and, therefore, there is a contingency that preferably should be avoided.

Finally, the solutions that have technically shown the best results in the simulations have been those that include an inner sheet in addition to the water-repellent. It can be seen how the equilibrium regime is reached in a longer period of approximately four years. This fact occurs as the wall is more dissociated from the internal moisture sources by the use of the sheets and, progressively, the initial moisture is released. The appreciable difference between the VDB and the SVR is worth noting. The first sheet offers, in all three cases, a lower and flatter moisture profile as it allows less moisture to enter the interior of the wall section. However, cases with SVR result in higher humidity and a steeper profile in which higher seasonal variations are observed. That is, the crests and valleys along the registered humidity profiles are more noticeable and are due to the drying process towards the interior that allows the SVR as a consequence of its greater vapor permeability in the summer period. It should be noted that, in the case of EPS, the ridges and valleys are not as pronounced, as the insulation itself acts additionally and lightly as a vapor flow barrier. As previously mentioned, although VDB have technically shown the best behavior, it must be taken into account that, if there is an uncontrolled moisture focus (installation error or lack of maintenance of the exterior water repellent impregnation, leaks in water pipes, etc.), it would accumulate moisture at that point, generating a difficult problem to solve. Furthermore, in the case of CAI insulation, it must be taken into account that the use of these sheets is not recommended, as once the insulation has performed its capillary function with the moisture on the condensed face, by distributing it towards the inside face of the enclosure, it would meet the barrier and therefore another conflicting point could be generated.

In order to demonstrate the specific behavior at the critical point of the wooden beam-end, a selection of case studies has been made to evaluate in the next section. The selection criteria chosen are based on evaluating different hygrothermal behaviors, so those that have proven to offer similar profiles are not considered, thus avoiding repeats. In the first place, EPS + VDB and MW + VDB cases are chosen, as they are two of the most obvious solutions that may present pathologies. Secondly, the CAI case is also considered interesting, as it exceeds the 95% relative humidity barrier punctually, but it is not known if the time that exceeds this limit is wide enough to activate the fungus phase ($\alpha = 1$) and then start the rotting process. Just as the CAI case, the MW+H solution occasionally reaches relative humidity peaks close to the maximum limit values. In order to guarantee that the constructive solution is moisture safe in the beam, and the results are not aggravated in this point, the proposed solution requires a more in-depth analysis through 2D analysis. Finally, there are those cases in which the results of the 1D simulations have shown the nonexistence of any risk; however, in order to verify it, the cases of CAI + H, MW + H + SVR, and EPS + H are also taken as examples.

4.2. Two-Dimensional Analysis

Once the assessment of the general behavior of the different solutions has been carried out, a detailed evaluation using WUFI 2D proceeds it. Figure 10 shows the developed model for the two-dimensional simulation, showing the position of the evaluated monitoring point on the wooden beam-end. The beam head is embedded 10 cm into the wall, and a 20 mm air gap is included between the wall and the beam head.

The achieved results (presented in Figure 11) show a similar behavior to the previously carried out 1D simulations. The original wall results show that peaks of moisture occasionally overcome the limit of 95%. However, these do not produce in a prolonged manner, and therefore can hardly carry a risk that may cause the beginning of wood decay. The heat flow transferred along the wall section, as a consequence of the absence of insulation, allows lower moisture levels to be maintained compared to insulated and non-waterproofed walls. Regarding the latter, they have shown a hygrothermal profile similar to the original, but with more moisture. This profile leads to a risk as it exceeds the 95% in a prolonged time and therefore there is a decay hazard. In addition, through this evaluation, it is shown more clearly that the case of the CAI is hazardous as it shows a higher profile of moisture in the wooden beam than that obtained in the 1D simulation after the insulation layer. The reason is that behind the face of the insulation (1D simulation), there is the possibility that the capillary absorption property performs its function, thus reducing the accumulated moisture, while in the wooden beam-end where the insulation is not found, said moisture is retained. Nevertheless, in the case of the previous doubt of the MW + H, the results show that the moisture profile at this point is significantly reduced, thus offering exceptional behavior, as well as the rest of the cases that behave very similarly.

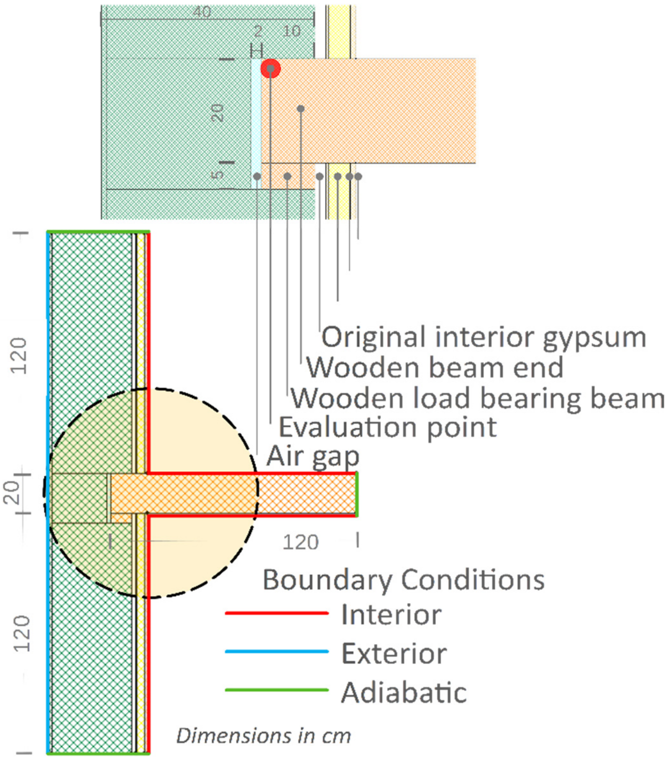

Figure 10. Considered 2D hygrothermal model, evaluation point, and boundary conditions.

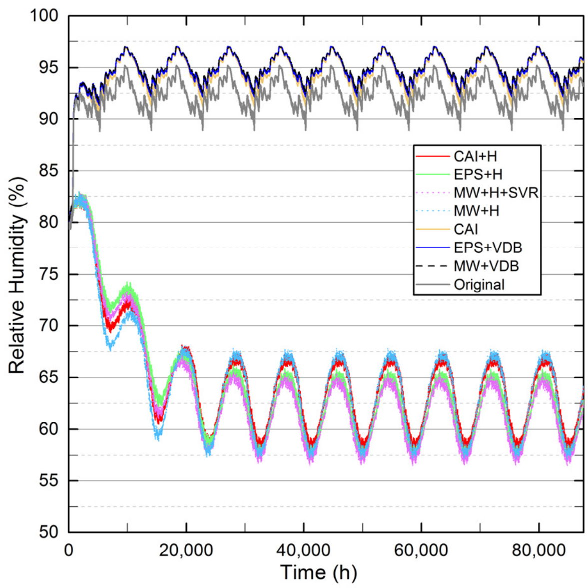

Figure 11. Relative humidity profiles in the wooden beam-end derived from the 2D hygrothermal simulation.

4.3. Wooden Decay Risk Analysis

The last step corresponds to implementing the results of the 2D simulation in the wood rot model. Although the cause of potential problems could already be intuited in the previous simulation cases, the risk cannot be quantified only using hygrothermal profiles. Therefore, implementation of the wood rot model developed by Viitanen was carried out.

Figure 12 shows the results obtained after the implementation of the model, both the activation phase of the fungus (α) and the evolution of decomposition of the wood after the activation of the fungus. As presented, none of the solutions that had water-repellent impregnation show a wood decomposition process; even the development of the fungus does not occur. This is due to the fact that none of the cases in the simulation reached 95% of the relative humidity. However, it can be observed on the original wall, which reached this limit punctually, the development phase of the fungus begins but only reaches maximum values of $\alpha = 0.15$ and, therefore, it does not pose a danger for the decomposition of the wood. Nevertheless, this behavior does not occur in the solutions without water repellent impregnation. It can be observed that, in just over a year, the activation of the fungus has completely occurred and, therefore, the decomposition of the wood begins. As the hygrothermal records of the simulation of these cases are similar, the same happens with the evolution of wood decay. Only a slightly lower forward speed is observed in the case of the CAI compared to the cases of MW + VDB and EPS + VDB.

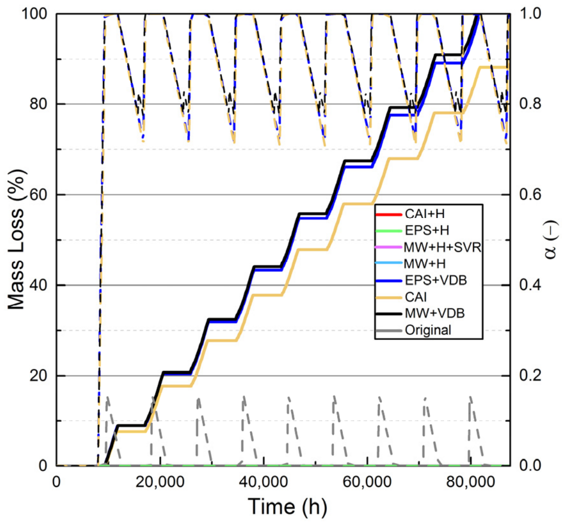

Figure 12. Decay development and fungi activation process during the simulation period based on the Viitanen model.

In this way, it can be concluded that all ITICS solutions that do not have water-repellent impregnation pose a danger in buildings' energy retrofit interventions. As observed, although the original wall allows us to guarantee the integrity of the structure as a consequence of the drying process that allows the own heat leakage along the wall, it does not happen in the same way in the solutions with ITICS. Therefore, the external protection of the wall becomes an essential element in the energy envelopes interventions of the built heritage.

5. Conclusions

This research has carried out an assessment of different ITICS solutions in order to guarantee hygrothermal behavior of the energy performance retrofits of historic buildings. For it, the influence of three types of thermal insulations has been evaluated. Completely different behaviors of the refurbished thermal envelope have been observed due to the difference of the hygrothermal properties between the proposed solutions. In order to reduce the effect of indoor and outdoor moisture sources on the wall, the application of moisture barriers, such as exterior water-repellent impregnation and interior VDB and SVR sheets, has been analyzed. The effect of these types of interventions has also been evaluated in a detailed manner on a very conflictive and typical point in this building typology, the embedded wooden beam-ends.

In all evaluated cases, it has been evidenced that the lack of application of exterior water-repellent leads to a risk for the envelope. The reduction in the drying capacity of the wall, as a consequence of the decrease in the transmitted heat flow due to the application of interior insulation and the persistence of the rain entrance, leads to those high levels of moisture registered in the cold face of the envelope. Solutions with VDB and rain protection showed proper behavior; however, it is also important to keep in mind that, if a damp source occurs, it could produce an accumulation problem behind the insulation (i.e., a similar result to what could be obtained with solutions without water-repellent could occur). It should be added that the correct functioning of the VDBs depends very closely on the quality of taping between the different sheets. Otherwise, water vapor would flow between the VDBs and produce an additional moisture accumulation. Due to all this, the same solution, but with SVR, would be the ideal system if an ITICS solution with internal membranes is proposed. Although the results show a slightly higher humidity profile compared to the case of VDB, the SVR, in the event of any leakage of water, would not allow accumulation to occur due to its variable vapor permeability. It should also be pointed out that, even if a good result has also been obtained in the case of the CAI, this solution with VDB or SVR would be counterproductive, as it would be a barrier, and would not allow the correct performance of the insulation.

The application of the wood decay model has proved to be a successful method for a detailed beam-end evaluation. While the original wall was maintained without the risk of rotting the wood, the modification of the hygrothermal conditions as a result of the implementation of ITICS systems can lead a structural danger disintegrating the wood. In this case, the implementation of the water repellent is also more relevant than the type of insulation to be used to ensure the correct behavior of beam-end.

Throughout the development of this study, certain areas related to the subject have been detected. The application of ITICS solutions leads to a modification in the thermal behavior of the wall in relation to its thermal inertia. A loss of thermal damping that allowed the original masonry wall is produced, and therefore a possible loss of comfort is experienced. That is, after the application of the ITICS, any interior temperature peak generated by a high internal load could, as a consequence, generate a rapid rise in the interior temperature. One of the possible research lines could be the application of internal Phase Change Materials (PCMs), e.g., through gypsum boards that allow the storage of that surplus heat. However, hygrothermal behavior should also be taken into consideration, as if, for example, it were a barrier to the CAI, it could jeopardize the correct functioning of the complete system. Other research lines could be the evaluation of thermally modified timber (TMT) [89] such as the ThermoWood® or Plato® processes in building energy retrofits. These treatments improve the properties of the wood, among which is the resistance to decay fungi. This could be an additional solution to apply with the aim of guaranteeing the integrity of the wooden beam-ends in those cases where the external water repellent cannot be applied. Finally, as mentioned in the background section, the application of three-dimensional hygrothermal simulation models is another of the current lines of work scarce developed. Recently, and as an example, the COMSOL Multiphysics software incorporated the specific module of heat and moisture transfer in building materials, thus becoming an alternative with a wide range of possibilities that could be applicable for detailed analysis.

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