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# Using hygrothermal simulations to define safe and robust energy retrofit solutions: interior insulation of a mountain hut with extreme climate conditions

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**Abstract.** Interior insulation is a crucial retrofit measure to improve the energy performance of historical building while preserving their exterior appearance. However, it affects the hygrothermal behaviour of the wall and for this reason it must be planned with a very detailed and careful approach. This becomes even more important when dealing with buildings that are subject to extreme climate conditions such as mountain huts. They are typically exposed to very cold temperatures for all year and to an elevated driving rain load. This paper presents the methodology followed to design the interior insulation intervention of a mountain hut located in Trentino-Alto Adige (Italy). The methodology is centred around the use of hygrothermal dynamical simulations at component level, but several other tools are used to identify the right input for these simulations: the analysis of monitoring data of nearby weather stations to define the exterior climate, simulations at the building level to calculate the interior climate and laboratory measurements to identify the correct material properties.

**Keywords** – Interior Insulation; Hygrothermal Analysis; Historic Buildings; Driving Rain; Dynamical Simulations.

## 1. Introduction

Mountain huts are often beautiful examples of historic buildings. Preserving them means preserving the history and tradition of mountain places. The extreme climate conditions make mountains huts very energy consuming, and their poor reachability makes heating very expensive. Therefore, energy retrofit is the key to keep them alive. The need of combining energy retrofit and preservation of their historical character, makes internal insulation the most effective solution to refurbish their exterior walls. However, the application of internal insulation changes the hygrothermal behaviour of the component and, if not planned correctly, it could lead to moisture related damages [1,2]. The most adequate tool to plan such interventions are hygrothermal dynamical simulations [3,4].

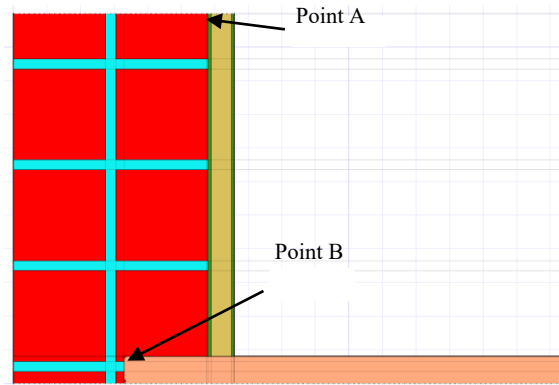
This paper presents the retrofit intervention of a mountain hut located in Trentino-Alto Adige (Italy), “Rifugio Boé”. The focus of the paper is the methodology employed for the design of the interior insulation. It foresees the use of advanced hygrothermal numerical simulation in dynamical regime. A key element to perform accurate and meaningful simulations is the use of correct inputs. The collection of input data is supported by other tools. For the exterior climate, the analysis of monitoring data from meteorological stations is used. The interior climate is provided by simulations at the building level. Finally, the definition of the hygrothermal properties of the materials is supported by laboratory tests.

## 2. The Case Study

“Rifugio Boè” is a mountain hut located at 2871 m above the sea level in the middle of a UNESCO World Heritage Site, the Dolomites (Figure 1). The building is listed and its oldest part of the hut is dated 140 years back. The hut is used only in summer but with poor comfort and high energy costs. The



**Figure 1.** Picture of “Rifugio Boè”. The building consists of two parts: the new extension (left) and the renovated existing part (right)  
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**Figure 2.** Numerical model used for the hygrothermal simulations. The two analysed critical points are also indicated in the figure.

building owner decided to build a new extension and renovate the existing part upgrading its energy performances and comfort. The focus of this paper will be on the renovation of the historical part of the hut. It consists of two floors: on the ground floor there are a dining room, a big multifunctional room, a drying room for shoes and clothes and the bathrooms, on the first floor there are the sleeping rooms and additional bathrooms. In order to preserve the external aspect of the existing hut, it was decided to use internal insulation. The existing wall is made by dolomite stones and has a variable thickness with a maximum of 58 cm. The analysed retrofit solution foresees the addition of a 6 cm mineral insulation board, whose commercial name is “Multipor”. The roof has been demolished and reconstructed, as well as the ground floor slab and the intermediate ceiling. The roof is a timber pitched insulated roof; the ground floor slab is an insulated suspended floor slab. The intermediate ceiling is a timber ceiling with main and secondary beams. The simulated wall structure is represented in Figure 2. It is composed by a thick existing stone wall (58 cm), then there is a glue mortar layer (1 cm), the mineral insulation panel (6 cm) and finally the interior lime plaster (0.8 cm). Additionally, there is the main wooden beam that is 16 cm high and enters the masonry for a depth of 25 cm.

### 3. Methods

The main tool that is employed to analyse the effect of interior insulation on the hygrothermal behaviour of the wall are numerical simulations in dynamic regime [3,4]. More precisely the simulations are performed with the software DELPHIN 6.0 [5] that can be used to simulate the combined transport of heat and moisture in construction elements both with one-dimensional and two-dimensional geometries. In the next sections we present in detail how the simulations are structured and how inputs are selected.

#### 1.1. Geometrical model and materials

The geometrical model used for the simulations is showed in Figure 2. A cutting plane has been inserted into the numerical model which cuts the wooden beam exactly in half on an axis of symmetry. This allows to speed up the numerical simulations without affecting its accuracy. For most of the simulations presented in the paper, the historical wall, which is made of stones and mortar joints, is simplified as a single layer of stone, to reduce simulation times. An additional calculation, to understand the role played by the mortar joints is also carried out, using the geometry represented in Figure 2. Also, this is a simplification of reality: mortar joints are in fact represented with a regular structure, to allow an efficient discretization of the geometrical model. The joints are represented with a thickness of 3 cm, while the stones have a dimension of approximately 27 cm. However, it is expected that this simplification has a minor impact on the final results [6,7].

The selection of the materials is a crucial step when setting up a hygrothermal model. All materials are selected from the DELPHIN 6.0 database. For new materials (Insulation, Internal Plaster and Glue

Mortar), a perfect correspondence was possible. In fact, all materials used in the retrofit intervention are present in the database. Regarding existing materials (stone, historical mortar and wood), we selected those that were as similar as possible to the one present on-site, based on the available information. Particular attention is dedicated to the selection of the stone since it is expected to affect the most the final hygrothermal behavior of the wall. The walls of the hut are realized with dolomite stone which is not present in the database. Therefore, the support of laboratory tests is used to measure some basic properties of the stone and to identify the most suitable selection within the database. The stone was sampled on site and brought to the lab where the following basic parameters were measured: apparent density  $\rho = 2696 \pm 33 \frac{kg}{m^3}$ , thermal conductivity  $\lambda = 2.6 \pm 0.3 \frac{W}{mK}$ , specific heat capacity  $C_p = 791 \pm 121 \frac{J}{kgK}$ , water uptake coefficient  $A_w = 0.0032 \pm 0.0004 \frac{kg}{m^2 \cdot \sqrt{s}}$ . A full hygrothermal characterization of the stone was not possible due to time and budget limitations. The stone which was more consistent with these values was selected from the database and it is a limestone. Table 1 presents the list of the materials used in the simulations and their corresponding hygrothermal parameters. Another stone, a type of sandstone, is used in additional simulations to show the impact that a wrong choice of materials can have on the final evaluation. The hygrothermal properties of the selected sandstone are reported in the last row of Table 1.

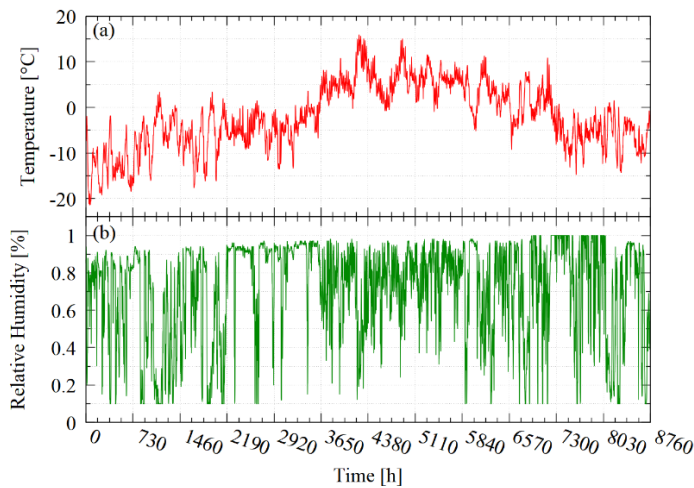
**Table 1.** Basic hygrothermal properties of the materials used for the numerical simulations. Starting from the left column: material description and corresponding ID number in the DELPHIN 6.0 database, apparent density, thermal conductivity, specific heat capacity, vapour diffusion resistance factor and water uptake coefficient.

Description [Database ID]	$\rho \left[ \frac{kg}{m^3} \right]$	$\lambda \left[ \frac{W}{m^2K} \right]$	$C \left[ \frac{J}{kgK} \right]$	$\mu [-]$	$A_w \left[ \frac{kg}{s^{0.5}m^2} \right]$
Glue Mortar [77]	830	0.16	815	13.0	0.003
Interior Plaster [681]	1245	0.38	1026	8.4	0.045
Insulation - Multipor [643]	99	0.04	1331	3.0	0.006
Limestone [464]	2440	2.30	850	140.0	0.0034
Pine Wood [714]	554	0.21	2775	4.5	0.017
Lime Cement Mortar [143]	1570	0.70	1000	11.0	0.176
Sandstone [567]	2032	1.410	717	25.9	0.083

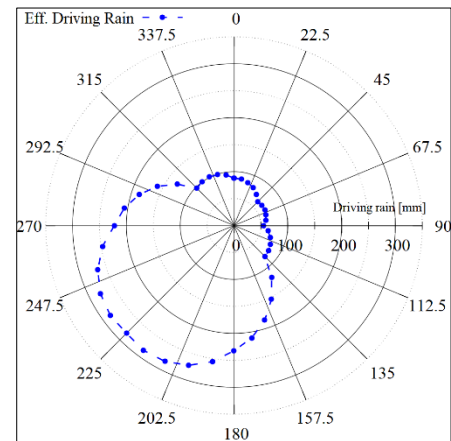
## 1.2. External Climate

The exterior climate dataset required for an hygrothermal simulation consists of hourly data of temperature, relative humidity, short wave radiation, long wave radiation, rain on the horizontal plane, wind speed and wind direction. This dataset is derived starting from the measured data of nearby weather stations and it is integrated with the radiation data extracted from satellite data. All the ground stations data are obtained through the tool Meteo Browser South Tyrol [8] that relies on the meteorological time series of the Open Data Catalogue of the Province of Bolzano [9]. The used stations are Cima Pisciadù (2985 m / ~2 km distance from the hut) for temperature, relative humidity, wind direction and speed and Seiser Alm (2055 m / ~10 km distance from the hut) for rain data. The satellite data are instead extracted from the software Meteonorm [10] and are used for short and long wave radiation data.

The final climate dataset used in the simulation refers to the year 2019. To obtain a multiyear simulation the same dataset is repeated yearly. The more relevant parameters of the climate dataset are reported in Figure 3 and Figure 4. In particular, Figure 3 shows the evolution of the temperature and relative humidity data during the year and Figure 4 shows the total yearly driving rain for the different wall orientations. The driving rain data are extracted from the horizontal rain and wind data according to the following equation [11]  $R_D = \sum_i^8 R_i^{\frac{8}{9}} w_{s,i} \cos(w_{D,i} - \Theta)$ , where  $R_D$  is the total yearly driving rain expressed in  $mm$ ,  $R_i$  is the horizontal rain at hour  $i$  expressed in  $\frac{mm}{h}$ ,  $w_{s,i}$  is the wind speed at hour  $i$  in  $\frac{m}{s}$ ,  $w_{D,i}$  is the wind direction at hour  $i$  and  $\Theta$  the wall orientation. The summation is taken over all hours for which  $\cos(w_D - \Theta)$  is positive and the external temperature is larger than  $-2 \text{ }^\circ\text{C}$  [12], otherwise



**Figure 3.** External Temperature (a) and Relative Humidity (b) of the external air as a function of the hour of the year.

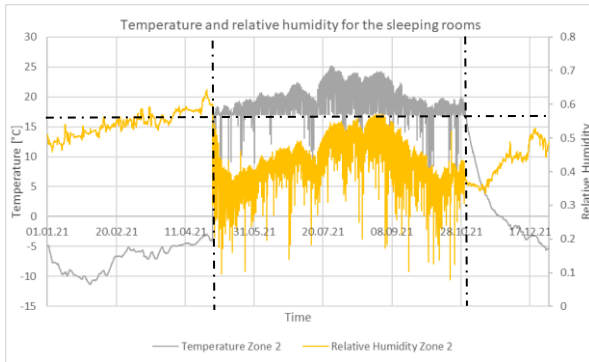


**Figure 4.** Total yearly driving rain as a function of the wall orientation  $\theta$ .

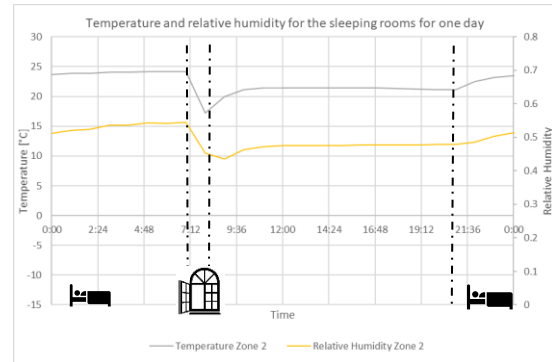
rain is assumed to be snow and not included in the calculation of the total yearly driving rain. The relevant wall orientations for the considered case study are  $46^\circ$  (North-East),  $136^\circ$  (South-East),  $226^\circ$  (South-West) and  $316^\circ$  (North-West).

### 1.3. Internal Climate

Simplified models for internal climate extracted from standards and recommendations [3,4,13] are not suitable for this case study for many reasons. First of all, there is the need to calculate accurate internal climate profiles also in winter, when the hut is closed, which relevantly influence the wall behaviour. Furthermore, also in summer, due to the specific usage of the building, standard assumptions on occupation profiles, as well as on moisture and heat loads are not realistic. Therefore building simulations are carried out using WUFI Plus [14], which is a heat and moisture dynamical simulation tool. The peculiarity of the tool is that it combines energetic building simulations with hygrothermal component simulations and allows for the assessment of indoor climate, hygienic conditions, thermal comfort, indoor air quality and energy consumptions. The external climate used in the simulations is the one described in the paragraph 1.2. The used materials are taken from the WUFI Database. Two different thermal zones are modelled, the ground floor and the first floor. The ground floor is considered with usage profiles for dining room, while the first floor for sleeping room, neglecting in this way the different profiles happening in the bathrooms. The internal loads profiles are personalized for the hut usage depending on the year period and on the daily time. The hut is simulated to be open from beginning of May to end of June, with the touristic peak season going from the middle of July until the middle of September. The daily profile consists of three internal loads in the ground floor corresponding to breakfast, lunch and dinner and a night load for the first floor. The internal loads are assumed according to [15] for heat loads and mets, according to [16] for  $\text{CO}_2$  loads and according to [17] for moisture loads. The temperature set point is fixed at  $20^\circ\text{C}$  for the dining rooms and  $17^\circ\text{C}$  for the sleeping rooms. The infiltration losses are calculated with the air change rate, the opening of the windows is defined with profiles. Since no mechanical ventilation is planned, different simulations were carried out varying the ventilation strategy. The different outputs in terms of temperature and relative humidity are used as inputs for the hygrothermal simulations in Delphin. Depending on the results in Delphin, indications are provided to the building users on the most suitable ventilation strategy. The recommended ventilation strategy foresees the windows fully opened for one hour after the meals in the ground floor and one hour in the morning in the first floor. The most critical profiles are the ones obtained for the sleeping rooms. In Figure 5 and Figure 6 the temperature and relative humidity for the sleeping room (thermal zone 2) for respectively one year and one day (1st August) are shown. In the second plot the influence of the



**Figure 5.** Temperature and relative humidity resulted from the building simulation for the sleeping rooms



**Figure 6.** Temperature and relative humidity resulted from the building simulation for the sleeping rooms during one day (1st August).

ventilation strategy and the occupation profile on temperature and relative humidity can be clearly identified.

#### 1.4. Other Simulation parameters

In Table 2 a list of all the parameters related to the boundary conditions used in the DELPHIN simulations are reported. The parameters are chosen according to the prescriptions contained in various standards and recommendations [3,4,13,18]. The duration of the simulations is always larger than 3 years or anyway long enough to obtain a yearly periodic behavior of the construction detail.

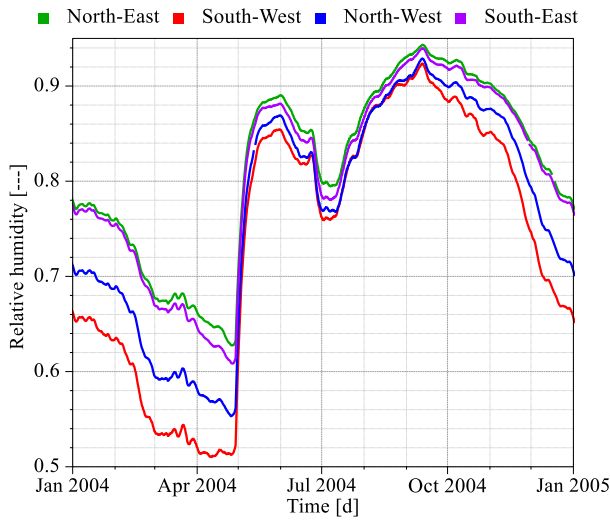
**Table 2.** Parameters used in the DELPHIN simulation to describe the coupling of the wall with the exterior and the interior environments.

Boundary Conditions Exterior	<i>Heat Exchange Coefficient (convective)</i>	20 W/m <sup>2</sup> K
	<i>Vapour Exchange Coefficient</i>	$7.5 \times 10^{-8}$ s/m
	<i>Short-Wave Radiation Absorptivity</i>	0.6
	<i>Long-Wave Radiation Emissivity</i>	0.9
	<i>Adhering Fraction of Rain</i>	0.7
Boundary Conditions Interior	<i>Heat Exchange Coefficient (convective)</i>	4 W/m <sup>2</sup> K
	<i>Vapour Exchange Coefficient</i>	$2.5 \times 10^{-8}$

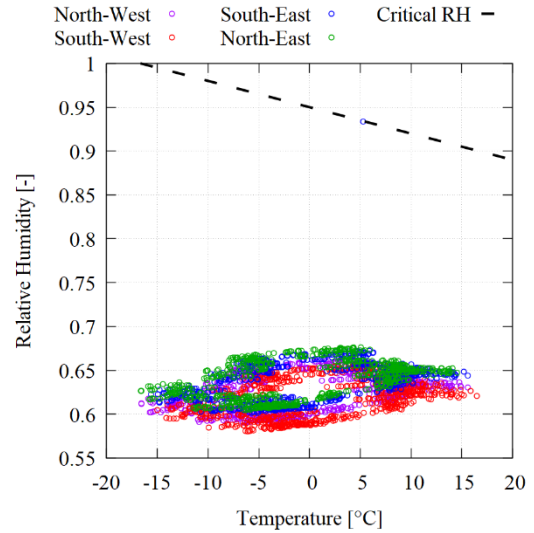
## 4. Results

The hygrothermal analysis presented in this paper focuses on two critical points of the construction: A) the interface between the existing stone and the insulation layer and B) the beam head of the intermediate ceiling. The first (point A), represents the point of the construction where interstitial condensation is most likely to accumulate, while the second (point B) considers a detail where wood is involved, a material subject to degradation when placed in humid environment, and, at the same time, relatively exposed to the effect of driving rain. In order to evaluate the hygrothermal risk two different indicators are used for the two critical points. For point A the relative humidity is analysed and a maximal value of 95% is accepted [18]. For point B the WTA wood degradation model is used. This method consists in plotting the hourly data points of combined temperature and humidity. They must not exceed a critical curve in a Relative Humidity-Temperature graph as defined in the WTA Recommendation [19].

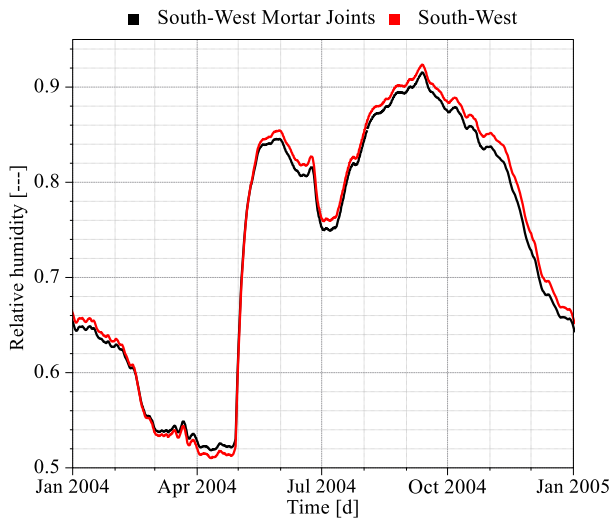
Firstly, the analysis of the two critical points is shown in Figure 7 and Figure 8, for the 4 different orientations of the walls of the hut. The result is visualized just for the last simulation year in a regime where the simulation reaches a yearly periodic behaviour. In Figure 9 and Figure 10 the role played by mortar joints is investigated. In these figures the two selected indicators are represented for exactly the



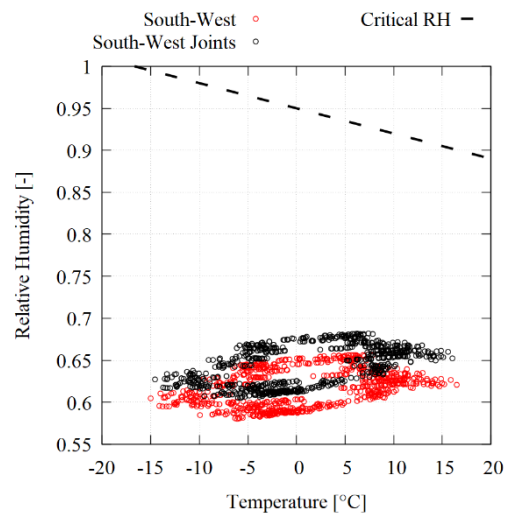
**Figure 7.** Relative humidity at the interface between insulation and existing wall (point A) for simulations with different wall orientation



**Figure 8.** WTA wood degradation model applied at the wooden beam head (point B) for different wall orientations.



**Figure 9.** Relative humidity at the interface between insulation and existing wall (point A) for simulations without and with mortar joints.



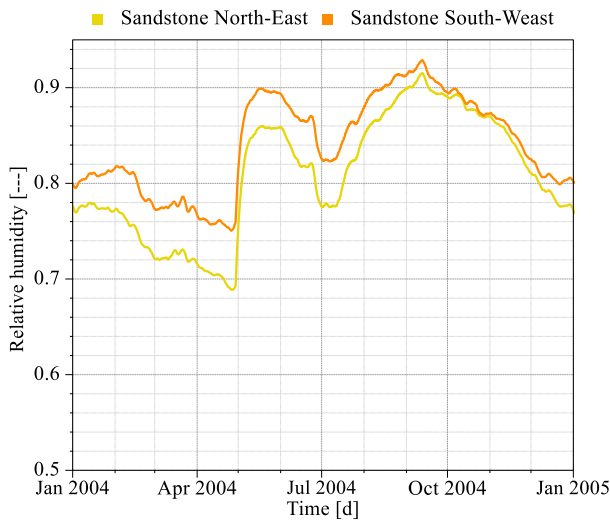
**Figure 10.** WTA wood degradation model applied at the wooden beam head (point B) for simulations with and without mortar joints.

same simulation, with the only difference that in one the historical wall is represented simply by a one-dimensional stone layer (completely neglecting the mortar joints), while in the other the more complex model of Figure 2 is used, which includes also the mortar joints. Figure 11 and Figure 12 show the results for the simulations using sandstone instead of limestone for the orientation which can potentially be the most critical ones: North-East and South-West.

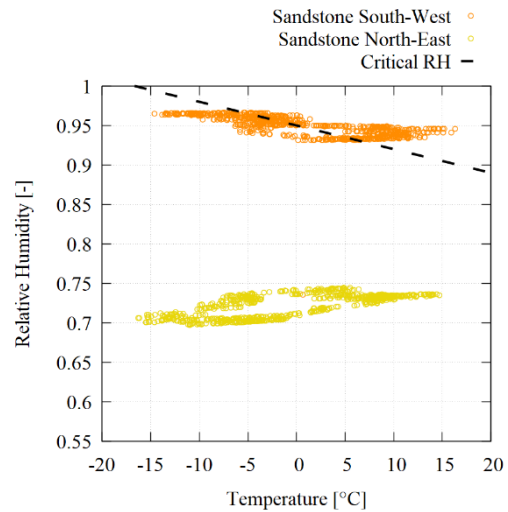
## 5. Discussion

Figure 7 and Figure 8 indicate that the analysed retrofit solution is always verified, looking both at the interface between the existing wall and the insulation layer and at the wooden beam head. In Figure 7 it can be observed that the relative humidity behind the insulation has a similar behaviour for all the orientations. It raises considerably starting with May when the hut opens, and the exterior climate is still





**Figure 11.** Relative humidity at the interface between insulation and existing wall (point A) using sandstone.



**Figure 12.** WTA wood degradation model applied at the wooden beam head (point B) using sandstone.

relatively cold. Then it rises again with the beginning of the touristic peak season, when the interior moisture loads are higher, reaching a maximum at the middle of September. Then the low touristic season starts and later, at the end of October, the hut closes, allowing the construction to dry in the winter months. The orientations that exhibit the highest relative humidities in the critical point A are the two facing North, with North-East being the highest. The same consideration holds true also looking at Figure 8, indicating that the low water uptake coefficient of the stone limits the negative impact of the driving rain. In fact, South-West, the orientation with the highest amount of driving rain (see Figure 4) is the one with the lowest relative humidity levels. Another important consideration is that the driving rain has no influence in winter time since the rain is substituted by snow.

In order to evaluate the influence of mortar joints on the simulation results, an additional simulation is carried out for the South-West orientation since the difference between the two models is supposed to depend mostly on the driving rain. Figure 9 and Figure 10 show that the difference between the model with mortar joints and the simplified model. It can be observed that for this specific case and for the selected outputs the influence of the mortar joints is limited. In fact, the relative humidity increases by less than 1% in point A and by 2-3% in point B. Similar results are reported in [6,7].

Furthermore, the influence on the choice of existing materials is investigated. The drawn conclusion about the worst orientation and about the safety of the proposed solutions totally depend on the characteristic of the existing stone. Indeed, looking at Figure 11 and Figure 12 for the sandstone the worst orientation is South-West. For this orientation there is also a relevant wood degradation risk, that would mean that this retrofit solution should not be recommended. The sandstone has a higher water absorption value and this leads to driving rain penetration in the construction. Therefore, it is important to observe the crucial role played by laboratory measurements on the existing material, to select the suitable material and obtain correct simulation results. Even if a full material characterization is not possible, one can still identify and measure the parameters that mostly influence the final simulation results – in this case the water absorption coefficient – and use the output of these measurements to support the identification of the most similar material within a database.

## 6. Conclusion

This paper presents the detailed hygrothermal analysis performed to design the internal insulation of a mountain hut located in Trentino-Alto Adige, “Rifugio Boè”. It is showed that the proposed retrofit intervention does not give rise to moisture related damages through the analysis of two critical points of the construction: the interface between the insulation layer and the existing historical wall and the wooden beam head of the intermediate floor slab. Additional simulations give the first preliminary

results on two research questions: the role played by the mortar joints on the hygrothermal behaviour of the wall and the importance of selecting the correct material in a hygrothermal simulation. As regards the first question, a first simulation shows a limited impact of the detailed representation of the mortar joints on the hygrothermal behaviour of the two critical points of the construction that are analysed. Conversely, the selection of the correct material for the stone layer turns out to be crucial to obtain the correct behaviour of the simulation. In fact, in the analysed case study, selecting a stone with the wrong water uptake coefficient leads to completely different results especially for the hygrothermal behaviour of the beam head.

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