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Evaluation of the Hygrothermal Conditions of a Typical Residential Building in the Azores Archipelago

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Abstract: This article contributes to the assessment of the hygrothermal conditions of residential buildings in the Azores archipelago and defines strategies that may contribute to the improvement in indoor air quality. These objectives were fulfilled by in situ monitoring of the hygrothermal conditions of a typical building on Terceira Island. Complementary tests to determine the thermal conductivity of exterior walls and ventilation rates were also conducted. The results were used to validate a simulation model, and different ventilation strategies were simulated using the combined heat, air, and moisture transfer model in EnergyPlus. The model took into account the typical construction methods and materials of the archipelago, as well as the reference weather data sets available for the region. The monitoring campaign showed that the percentage of time in which thermal comfort conditions were achieved was very low, varying from 5% to 32%, being the main cause for discomfort in the humidity level in the indoor environment. The simulation results pointed out the sensitivity of the problem, showing that ventilation may not always be, by itself, beneficial to thermal comfort. In particular, ventilation strategies should be established taking into account additional criteria other than the air change rate, namely the periods of the day and year in which ventilation should be performed, as well as the duration of these periods.

Keywords: buildings; EnergyPlus; hygrothermal performance; humidity ratio; numerical simulation; temperature; thermal comfort; ventilation

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Citation: Malça, J.; Almeida, R.M.S.F.; Mendes Silva, J.A.R. Evaluation of the Hygrothermal Conditions of a Typical Residential Building in the Azores Archipelago. *Energies* **2023**, *16*, 5075. https://doi.org/10.3390/en16135075

Academic Editor: Effrosyni Giama

Received: 31 May 2023
Revised: 26 June 2023
Accepted: 28 June 2023
Published: 30 June 2023

1. Introduction

The hygrothermal conditions of the territory, namely the ratio of heat and moisture resources, determine the state and development of terrestrial ecosystems. Several studies in the literature assess these hygrothermal conditions, as well as the importance of air exchange under different aerological risks [1,2]. Several methodologies have been developed for modeling air exchange (ventilation) networks in diverse applications, e.g., excavation sites [1,2], and these methodologies may also apply to the assessment of ventilation in buildings. The importance of ventilation in buildings as a guarantee of indoor comfort and health conditions is widely recognized [3]. Several studies have been carried out to assess air change rates in buildings, mostly in cold climates [4–6], in hot, dry, or humid climates [7,8], and, more recently, in Mediterranean climates [9,10]. Nevertheless, studies are lacking that address the specificities of climates such as that of the Azores archipelago.

The humid temperate climate with oceanic characteristics of the Azores archipelago is characterized by narrow temperature ranges, high precipitation and relative humidity levels, and persistent winds, which influence the hygrothermal environment inside buildings. The quality of the indoor environment is compromised not so much by air temperature but mainly by the humidity levels reached. In the face of these conditions, strategies such as greater thermal inertia or the application of thermal insulation have reduced effectiveness, and interventions must focus on the amount of water vapor in the air and its consequences [11]. On the other hand, the endogenous materials of the archipelago, namely basaltic stone and natural pozzolans of volcanic origin, show a hygrothermal behavior that may be different from that of other materials currently used in building construction. Azores' climatic conditions and the specificity of the materials used in traditional Azorean construction are the main motivations for assessing the hygrothermal performance and indoor conditions of the archipelago's buildings.

Even though the mainstream approach is the adoption of mechanical ventilation and air conditioning systems in buildings [11], this option has important implications at the architectural and economic levels, namely in rehabilitation interventions [12]. The main goal of this article is to evaluate non-invasive strategies with a wide application spectrum to the typical housing stock of the Azores archipelago that allow the mitigation of unfavorable environmental conditions and, simultaneously, the enhancement of health and comfort conditions inside buildings [12].

Through experimental evaluation and numerical simulation, the hygrothermal conditions of a typical residential building in the Azores archipelago are assessed, and strategies are defined that contribute to the improvement in the indoor environment. These objectives include in situ monitoring of the hygrothermal conditions using temperature and humidity sensors (thermo-hygrometers), as well as complementary tests to determine the thermal conductivity of exterior walls and air change rates.

In addition to the experimental setup, a hygrothermal simulation model is used, including specific adjustments for typical building construction solutions and materials of the archipelago and climate data available for the region. Different intervention strategies in the building are simulated with the aim of identifying solutions that mitigate unfavorable environmental conditions and improve health and comfort conditions inside buildings. Modeling moisture transport phenomena is particularly important due to the relevance of humidity in the Azorean context.

2. Materials and Methods

2.1. Hygrothermal Modeling of Buildings

This section presents a description of the computational tools used for the 3D modeling of buildings and the evaluation of their hygrothermal performance. Growing concerns with the hygrothermal performance of buildings aiming for higher indoor air quality have placed hygrothermal modeling as an essential approach. Through robust modeling, a straightforward assessment of how different types of parameters (environmental, construction, use) contribute to the overall performance of a building is possible [13]. Hygrothermal modeling of buildings is a continuously evolving field as a result of the scientific advances in terms of the mathematical models that describe the physical phenomena, as well as the increased computational capacity that technological advances have provided. Several tools for the three-dimensional modeling of buildings are available on the market, with a quite satisfactory degree of complexity and detail.

The approach implemented in this article includes a three-step methodology for the hygrothermal modeling: (i) construction of the 3D model of the building (DesignBuilder software [14]) based on previously conducted dimensional and construction surveys; (ii) integration of the 3D model into a building energy performance assessment software (EnergyPlus); and (iii) processing and visualization of results after numerical simulation (xEsoView software v.0.3.2).

The 3D modeling was performed using the DesignBuilder software [14]. This is an application that combines advanced energy simulation with 3D modeling technology so that engineers, architects, and energy consultants can ultimately assess the sustainability of buildings. Combining a main 3D-modeling module and different optional satellite modules, the software allows a wide range of assessments on buildings, quantified in performance indicators such as energy consumption, carbon emissions, thermal comfort, availability of natural lighting, temperature zoning and air flows, and cost-benefit analysis, among others [14].

For the 3D modeling of the building, the main module of DesignBuilder was used after introducing geometric and construction data (e.g., location and orientation of the building; floors, walls, roof, and windows; and materials used). Practical aspects of the modeling process can be found in Section 3.2.

Of the various programs available on the market for simulating the energy performance of buildings, the EnergyPlus software, developed by the United States Department of Energy, was selected for its capabilities [15,16]. In EnergyPlus, the hygrothermal performance of buildings is assessed through models of relative complexity based on location, climate data, geometry, construction solutions, and usage profiles. A not very user-friendly interface is one of the drawbacks of EnergyPlus, as it is based on reading from (input) and writing to (output) text files. Nevertheless, this difficulty can be overcome by adopting a building modeling tool (e.g., DesignBuilder, as in this article) that also serves as a graphical interface to EnergyPlus.

In addition to data from the 3D modeling of the building, EnergyPlus requires the previous establishment of input variables—e.g., reference climate data, usage profiles with the type of activity, occupancy rates, lighting and equipment densities, HVAC systems, and definitions of intended output parameters (e.g., ambient temperature, relative humidity, surface temperature, heat flows, etc.) and the temporal frequency of these parameters.

The mathematical algorithm for the quantification of energy and mass balances must also be selected and may be more or less complex depending on the objective of the simulation. From the geometric data of the building, the EnergyPlus software creates interior zones that have equal thermal conditions, representing each zone by a node. The energy and mass fluxes between each zone and the respective surroundings, including internal gains, are determined through an iterative prediction-correction process. The mathematical formulation of the energy and mass balances in each zone, as well as the solution algorithms, can be found in [15].

In addition to DesignBuilder and EnergyPlus, auxiliary software was used to facilitate the acquisition, processing, and visualization of information, namely climate datasets for the reference year of the intended location (CLIMAS-SCE v1.0), creation of data files for simulation using a spreadsheet-like tool (IDF-Editor), management of input and output files (EP-Launch) and graphical representation of results (xEsoView file viewer v.0.3.2).

2.2. Theoretical Models for Combined Heat and Moisture Transfer

Several mathematical models are available in the literature for simulating the transfer of heat and moisture in buildings, e.g., (i) the most used but simplified CTF model (Conduction Transfer Function), which does not consider the storage or diffusion of moisture in building elements; (ii) the EMPD model (Effective Moisture Penetration Depth), which quantifies, even though in a simplified way, the simultaneous transfer of heat, air, and moisture by considering a thin surface layer in hygroscopic materials that interacts with ambient air; and (iii) the HAMT model (Combined Heat and Moisture Transfer), which also quantifies the simultaneous transfer of heat, air, and humidity, but in a more comprehensive way than in the EMPD model, thus requiring more detailed knowledge of materials properties and implying a higher computational time [15].

These models have been integrated into several building energy simulation tools, such as Energy Plus, Wufi Plus, or TRANSYS. Yang et al. [17] published a comparison of the accuracy and applicability of the three thermal models in EnergyPlus for calculating moisture effects on building energy consumption in different climate conditions. Another approach to evaluate and predict indoor moisture variations was recently proposed by Zu et al. [18], which uses the theory of moisture buffer value (MBV). Zhao et al. [19] tested a heat, moisture, and airflow coupled model (HAM-CFD) to predict and evaluate the thermal and humid environment of a complex historical building. Within the topic of heritage preservation, Frasca et al. [20] proposed a multi-step methodology to investigate the capability of a BES software coupled with a HAM model (BES + HAM) as a technique for diagnostics and conservation in complex settings such as the 17th-century church of Santa Rosalia (Corleone, Italy).

In addition to air temperature, relative humidity is also a determining factor in the occupants' perception of comfort and the degree of indoor air quality and health in buildings. The hygroscopicity of building materials plays an important role in this aspect. Several studies have addressed this issue, e.g., Balocco and Petrone [21], who numerically simulated the ability of porous and hygroscopic building materials to attenuate indoor humidity variations due to external and internal sources. These authors highlight the importance of correct values for thermophysical properties, porosity, and hygroscopicity of materials and respective adsorption/desorption curves, in order to obtain a rigorous numerical model for the hygrothermal behavior of buildings.

The complexity of the numerical models developed for energy and mass transfer in buildings was also investigated by Goffart et al. [7], who similarly emphasize the importance of considering humidity and the accuracy of the mathematical models that depend on it for an accurate simulation of the building performance. Although the correct simulation of building performance requires consideration of the simultaneous transfer of heat and moisture, only a few computational applications consider both in their codes [16,22].

The CTF model is the most used model when it comes to evaluating the heat flux through the opaque envelope of a building. CTF has the advantage of a simple mathematical formulation, with linear equations of constant coefficients, and is not dependent on the knowledge of temperatures or heat fluxes inside walls. It is, therefore, not very demanding in computational terms. However, the CTF method has several disadvantages as follows: (i) its simplified formulation does not consider the variation of properties with temperature; (ii) the model shows instabilities and possible divergence for smaller simulation time steps; and (iii) the storage and diffusion of moisture in the building elements are not considered, so the hygroscopicity of the surrounding materials and latent heat fluxes are not accounted for [15].

Comparing the EMPD and HAMT models for simultaneous heat and moisture transfer, HAMT is the most complex model, as it simulates the interaction between hygroscopic materials and indoor air in each zone of the building from detailed information on heat and moisture transfer in the building and not just from the interaction with a thin surface layer of materials as occurs in the EMPD model. The EMPD model, therefore, disregards the diffusion of water vapor between the interior and exterior of the building, being limited to the bidirectional adsorption/desorption exchanges between each thin interior surface layer and the respective compartment when exposed to variations of humidity in the air [15].

The HAMT model is a one-dimensional model of the transfer and storage of heat and moisture through surfaces to and from the interior and exterior environments of a building. The HAMT model proposes equations for heat and mass transfer through materials, quantifying generation, transport, and storage terms. Each building element is decomposed into its constituent materials and, along with the thickness of each material, additional cells are created to refine the calculation of gradients for the various properties. It is thus possible to determine different variables, such as temperature, relative humidity, or moisture content in each material layer of a composite wall, as well as to identify surfaces with high surface humidity. A detailed description of the heat and moisture balance equations used in the HAMT algorithm can be found in chapter 3.3 of USDoE [15].

To evaluate the importance of quantifying moisture in building simulation models, an issue of utmost relevance in the archipelagic context, the HAMT model was used. The greatest refinement of the HAMT model implies, however, the previous knowledge of seven additional material properties in relation to the other models, namely porosity, initial moisture content, moisture retention curve, liquid water transport coefficients for suction and redistribution, water vapor diffusion resistance factor, and thermal conductivity [15].

3. Methodology

3.1. Monitoring Campaign and Building Characterization

The monitoring campaign was carried out in a typical building on Terceira Island, an island in the central group of the Azores archipelago. According to the Köppen–Geiger climate classification [23], the climate of Terceira island is a humid temperate climate with temperate summer (Cfb climate, heating degree days of 664 °C for a base temperature of 18 °C).

Two thermo-hygrometers were placed inside the building (one in the living room and another in one bedroom) and one outside. In particular, care was taken to protect the sensors from unwanted disturbances (drafts, heat fluxes, etc.) so that the recorded temperatures could be used to assess the level of thermal comfort of the occupants of the space, in line with the requirements of the ISO 7726 standard [24]. The air temperature and relative humidity sensors have an accuracy of ±0.3 °C and ±2% RH and a resolution of 0.01 for both parameters.

In the climatic context of the Azores, humidity has a strong preponderance in the comfort sensation. In this sense, it was decided to evaluate thermal comfort using the graphical method proposed by ASHRAE 55 [25], which uses operative temperature and humidity ratio (absolute humidity) as inputs, marking a comfort zone on top of a psychrometric diagram.

The original project of the building was consulted, and a detailed inspection of the building was carried out in order to characterize its elements. The most relevant results can be summarized as follows:

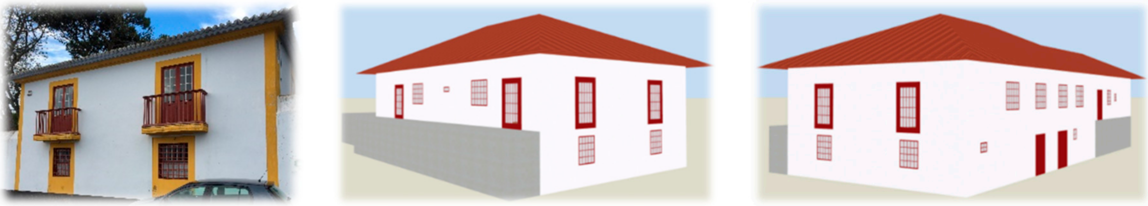
- 60 cm thick external opaque walls, consisting of interior and exterior lime-based mortar coatings and two layers of basaltic stone (28 cm each, approximately);
- recently renovated interior walls consisting of a simple layer of brick masonry (hollow brick of 11 cm thickness) coated on both sides with lime-based mortar;
- ground floor with basaltic stone slabs (40 cm thick, approximately);
- first floor with oak wood flooring supported by beams of the same material;
- first-floor ceiling consisting of an oak wood structure (4.8 cm thick) beneath expanded polystyrene (EPS) boards for thermal insulation (4 cm thick);
- sloping roof with a non-accessible unvented attic consisting of ceramic tile (2.5 cm thick) on a wooden structure;
- glazed windows made up of painted oak wood frames, with grid and simple light-colored glass (0.4 cm thick). The windows are single-glazed (U-value of 5.81 $W.m^{-2}.K^{-1}$ and total solar transmission of 0.85) and have a painted wooden frame (thermal conductivity of 0.190 $W.m^{-1}.K^{-1}$), with horizontal and vertical dividers (width of 2 cm).

The Simple Hot Box—Heat Flow Meter Method (SHB-HFM), based on the procedure described in ISO 9869 standard [26], was applied in the case study to evaluate the thermal resistance of the exterior wall. A detailed description of the apparatus and procedure can be found in Roque et al. [27]. Throughout the test, the temperature gradient between the two sides of the wall was 12 °C, approximately. The measured thermal resistance was 0.45 $m^2.K.W^{-1}$, which corresponds to a U-value of 1.63 $W.m^{-2}.K^{-1}$.

The building characterization also included the in situ measurement of the ventilation rate using the tracer gas method and the decay technique. The measurements were carried out inside the living room. The tracer gas used was carbon dioxide, and two sampling points were defined. The test duration was 2 h, approximately. The air change rate was 0.28 h^{-1} and 0.31 h^{-1} in the two sampling points.

3.2. Building Simulation Model

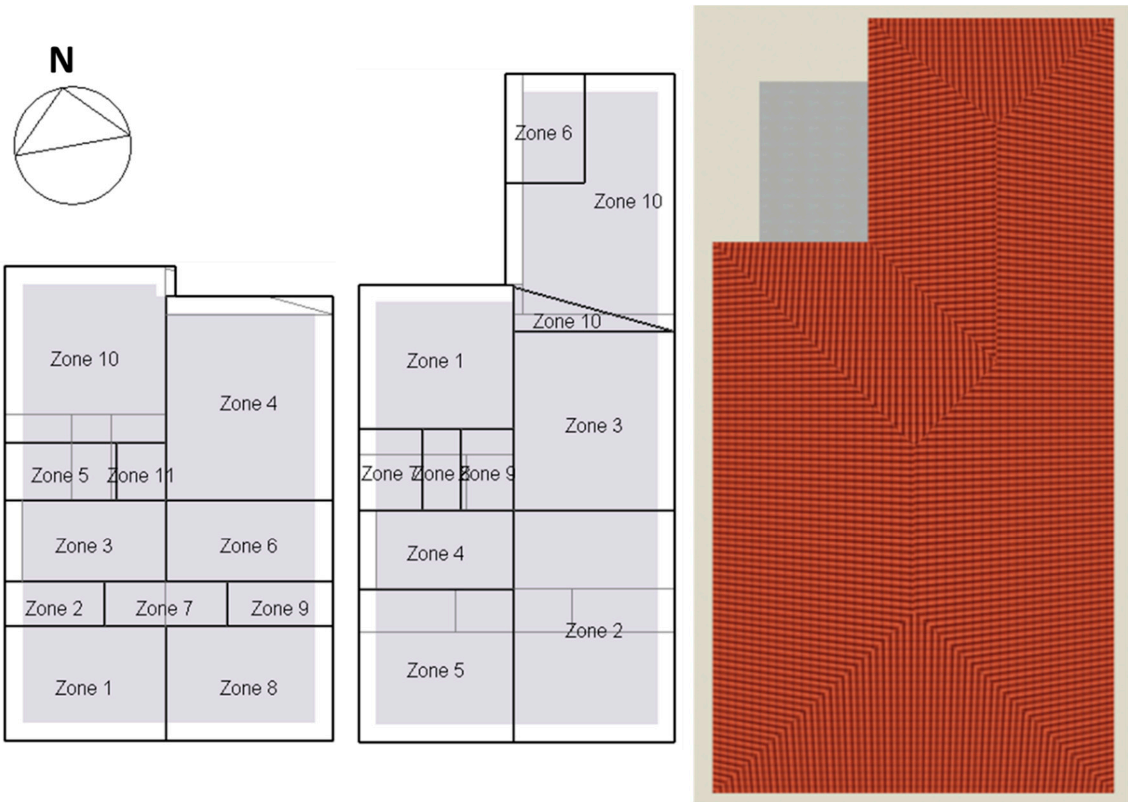
The software DesignBuilder was used to build the 3D model of the selected building [14]. Several aspects were taken into account, namely location, orientation, geometry, construction solutions, and materials used. Figure 1 shows the selected building as well as two perspectives of the 3D model, illustrating the geometry of the main body of the building, its multi-pitch roof, and some details of the glazed windows. The outer envelope marked in gray represents buried walls.



(**a**) (**b**) (**c**)

Figure 1. Selected building (**a**) and 3D model as seen from southwest (**b**) and southeast (**c**).

The floor plans of the building and orientation are shown in Figure 2. Each floor is divided into several zones, as detailed in Table 1. The model followed the actual compartmentation of the building, thus defining a thermal zone for each compartment. Floors 0 (ground floor) and 1 have a ceiling height of 2.35 m and 2.85 m, respectively. Depending on the surface under assessment (floor, wall, ceiling, etc.), the appropriate boundary conditions were defined for each zone, e.g., ground, outside air, or adjacent compartment.



(**a**) (**b**) (**c**)

Figure 2. Floor plans of the modeled building, including geographic orientation and room layout: (**a**) floor 0 (ground); (**b**) floor 1; (**c**) roof. The main façade of the building is oriented toward SSE (170°).

Table 1. Room geometric characteristics of the modeled building.

Floor	Zone	Room	Area [m^2]	Volume [m^3]
0	1	Bedroom	14.8	34.8
	2	Bathroom	3.9	9.2
	3	Stairway	12.7	29.8
	4	Reception	30.0	70.6
	5	Bathroom	5.9	13.8
	6	Hall	13.2	31.1
	7	Circulation	5.8	13.6
	8	Bedroom	15.4	36.3
	9	Bathroom	4.2	9.9
	10	Laundry room	24.3	57.1
	11	Circulation	3.0	7.1
1	1	Bedroom	20.3	58.1
	2	Living room	35.8	102.0
	3	Dining room	29.9	85.3
	4	Stairway	-	-
	5	Office	21.6	61.7
	6	Pantry	6.5	18.7
	7	Bathroom	4.5	12.8
	8	Bathroom	3.6	10.4
	9	Circulation	5.0	14.4
	10	Kitchen	31.7	90.4

The 3D model of the building was imported into EnergyPlus for numerical simulation [15]. Several input parameters have to be defined, not only related to the mathematical simulation algorithms but also to the specific characteristics of the building, namely local climate data, hygrothermal properties of materials, and usage profiles.

The application of hygrothermal models involves detailed knowledge of several properties of building materials. The list of materials considered in the building under study includes basaltic stone, lime plaster, oak wood, hollow ceramic brick, and EPS insulation, as described in Section 3.1. In addition to thermal properties, the HAMT model also requires humidity-related properties. However, the absence of directly available hygrothermal properties for some materials required a search in different databases.

Table 2 lists the thermal conductivity, density, and specific heat of the building materials, as required by the CTF and HAMT models. Table 2 also shows porosity and initial moisture content, which are required solely by the HAMT model, having no effect on the CTF model. To determine the initial moisture content of each material, the moisture retention curve of the material and its density are used, according to Equation (1):

$$W_{initial} = \frac{W_{RH=60\%}}{\rho} \quad (1)$$

where $W_{initial}$ (kg.kg^{-1}) represents the initial moisture content of the material, $W_{RH=60\%}$ (kg.m^{-3}) indicates the moisture content of the material for a relative humidity of 60% (calculated from the moisture retention curve of the material), and ρ represents the density of the material (kg.m^{-3}).

Additional properties are required for the application of the HAMT model, namely liquid water transport coefficients for suction and redistribution and water vapor diffusion resistance factor. The variation curve of these and other properties with the moisture content of the material or with the relative humidity of the environment is also required by the HAMT model. For each material, a detailed description of all the properties, including variation curves, can be found in Kumaran [28], Freitas and Pinto [29], and the WUFI database [30].

Table 2. λ, ρ, c_P, porosity, and initial moisture content of the building materials [28–30].

Material	λ ($W.m^{-1}.K^{-1}$)	ρ ($kg.m^{-3}$)	c_P ($J.kg^{-1}.K^{-1}$)	Porosity ($m^3.m^{-3}$)	Initial Moisture Content ($kg.kg^{-1}$)
Basaltic stone	1.66	2850	1000	0.095	0.00224
Lime mortar	0.70	1600	850	0.30	0.01375
Oakwood	0.152	700	1600	0.35	0.11430
Hollow brick (11 cm)	0.13	650	850	0.74	0.00914
EPS	0.04	15	1500	0.95	0

The occupancy profile of each building zone, as well as the activity performed in each space, have direct implications on the hygrothermal balance of the building due to the internal heat loads (sensible and latent) that emerge from indoor activities. Determining these loads involves the accounting of people, the nature of the activity, the type of lighting and equipment in the space, and its utilization rates.

The occupants of the building develop a sedentary activity, corresponding to a metabolic rate of 70 $W.m^{-2}$ [31]. Assuming an average adult body surface area of 1.8 m^2, a total heat load of 126 W/person is calculated. EnergyPlus discriminates this load into sensible and latent components. The heat load corresponding to the water vapor generated in other activities (cooking, showers, laundry) is calculated using Equation (2)

$$\dot{Q} = \dot{m} \ast \Delta h \tag{2}$$

where $\dot{Q}$ indicates the heat load (W); $\dot{m}$ represents the generation rate of water vapor (kg/s); and Δh represents the enthalpy of water vapor ($J.kg^{-1}$). Water vapor generation rates were obtained from Kalamees et al. [32]: 2.4 kg/day for cooking, 0.3 kg/shower, and 1 kg/day for laundry. Internal gains associated with other equipment and lighting were considered through a global power of 4 W per unit of floor area, with continuous operation.

The hygrothermal behavior of buildings also depends on the existing ventilation conditions. In the base scenario, an air change rate of 0.3 h^{-1} is considered, in line with the in situ measurements. If other ventilation regimes are intended, e.g., variable ventilation throughout the day, the procedure is similar, simply defining the desired air change rate zone by zone and the corresponding temporal periods.

The simulation ran for the period of one year, from 1 January to 31 December, with weather data for a reference year. The climate file for the geographical location of interest (city of Angra do Heroísmo, in the Azores) was obtained through the CLIMAS-SCE application, provided by the Portuguese National Laboratory of Energy and Geology within the scope of the National Building Certification System [33]. This file compiles hourly values of ambient temperature, global, direct and diffuse solar radiation, relative humidity, wind magnitude and direction, and precipitation, among other properties, to characterize the typical meteorological year. It is based on meteorological data provided by the Portuguese Institute for Sea and Atmosphere for the period 1971–2000, adjusted to take into account climate models compatible with the most recent emission scenarios [34].

After a complete definition of the building and weather data, further information is required to run the simulation, namely the choice of the calculation algorithm for energy and moisture balances. The option included the CTF (energy only) and HAMT (energy and moisture) models, with the aim of comparing the models' outcomes.

The selection of the appropriate time increment for simulation (timestep) is also important: high increments can lead to instabilities in the calculation, whereas small increments can drastically increase the time required for simulation. A timestep of 20 (i.e., 20 time increments in each hour) is chosen, being the minimum suggested value when using the HAMT algorithm [15].

The output variables considered in EnergyPlus include air temperature and absolute humidity in previously selected zones: zone 8 (bedroom) and zone 10 (laundry room), on the ground floor (floor 0); and zone 1 (bedroom) and zone 2 (living room), on the first floor. These zones, aside from covering the two floors of the house, are located in opposite areas of the building (northwest and southeast quadrants). The laundry room, in addition, is a space with its own specificities in terms of water vapor production.

4. Numerical Simulation Results

4.1. CTF Versus HAMT Models

The simplified heat transfer CTF model is compared with the more complex simultaneous heat and moisture transfer HAMT model. As an example of the outputs, Figure 3 shows annual air temperature profiles calculated by both models for zone 1 (bedroom) of the 1st floor. There is good agreement between the two temperature profiles, with fluctuations of similar magnitude and differences between mean values (T_{HAMT}–T_{CTF}) that do not exceed −0.33 °C in January and +0.67 °C in August.

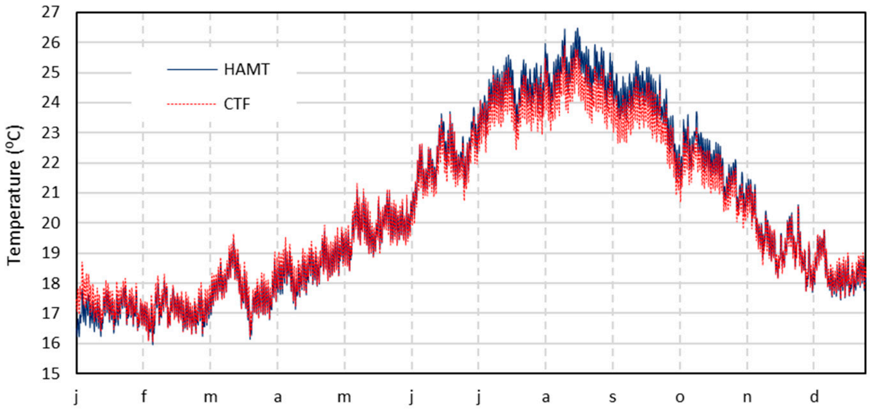


Figure 3. Annual indoor air temperature profiles were calculated with the CTF and HAMT simulation models (zone 1 of floor 1).

Nevertheless, the differences between the two models become high when absolute humidity or relative humidity of indoor air is calculated (Figure 4a,b). Moisture fluctuations in the CTF model are of greater magnitude, as this model does not take into account the contribution of surrounding materials to moisture transport and storage. Simulation results show a mean relative humidity of μ_{RH} = 67.6% (standard deviation σ_{RH} = 2.3%) with the HAMT model and μ_{RH} = 69.7% (σ_{RH} = 7.8%) with the CTF model. Although the average value is not very different, the variability found is substantially greater in the CTF model. Moreover, the calculation of the percent mean absolute relative error (PMARE), as proposed by Ali and Abustan [35], shows PMARE = 1.36 for indoor air temperature and PMARE = 7.23 and 7.55 for the humidity ratio and relative humidity, respectively, which indicates a better agreement between the models for indoor air temperature. Given the importance of humidity in the perception of thermal comfort and indoor air quality, namely in the context of the Azores archipelago, the HAMT model is used in the remaining simulations, despite its greater computational demand and the need for a more detailed characterization of the materials' properties.

Goffart et al. [7] also emphasize the importance of considering humidity and the rigor of the mathematical models for a correct simulation of building performance. These authors simulated the hygrothermal behavior of a brick masonry building in a hot and humid climate and concluded that the HAMT model generated the most satisfactory results, despite the greater computational demand. Qin and Yang [16] also analyzed the mathematical models available in the EnergyPlus software. The analysis was carried out for three distinct climates—hot and humid, temperate, and hot and dry—and it was concluded that the HAMT model produces the most satisfactory results. For hot and dry climates, the

CTF model could also be used with relative confidence, but this is not the type of climate prevailing in the Azores archipelago.

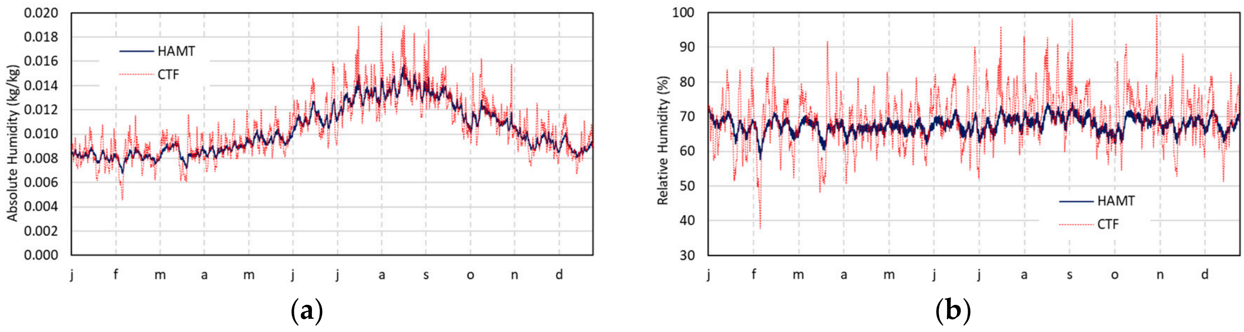


Figure 4. Annual indoor air profiles of (**a**) absolute humidity and (**b**) relative humidity, calculated with the CTF and HAMT simulation models (zone 1 of floor 1).

4.2. Scenario Analysis

The reference scenario for numerical simulation considers a permanent ventilation regime with an air change rate of 0.3 h^{-1}, as measured in the experimental tests. Figure 5 compares numerical results for the baseline scenario with measured values from the two monitored compartments in the building (zones 1 and 2, floor 1): a good agreement between experimental values in situ and numerical results for air temperature and absolute humidity is shown, with similar patterns either for values or dispersion. Comfort conditions are approximate in both cases: 11% and 15% for zone 1 and 28% and 38% for zone 2. It is important to stress that the differences in terms of discomfort are mainly due to the time periods considered, from September to January for in situ data monitoring and a full calendar year for numerical simulation.

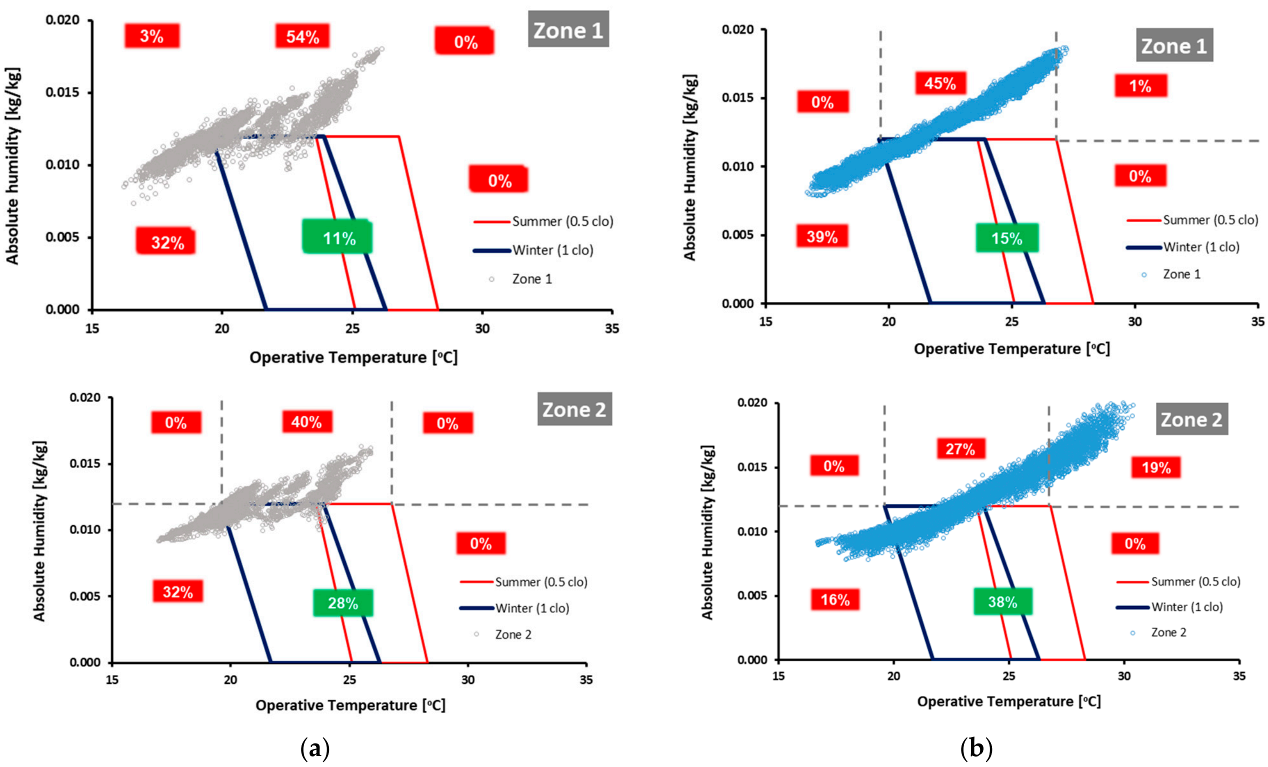


Figure 5. Hygrothermal conditions in two compartments of floor 1 (zones 1 and 2) for the base scenario (compared to the ASHRAE 55:2013 comfort zone): (**a**) measured in situ (September to January) and (**b**) from numerical simulation (full calendar year).

As previously described, in order to cover different spaces throughout the building in the numerical model, two areas on the ground floor—zones 10 and 8, respectively, laundry room and bedroom—are also considered in the assessment of thermal comfort (Figure 6). The laundry room, in particular, (i) has two buried walls; (ii) is oriented northwest; and (iii) its main activity of washing clothes and bedding is a specific water vapor source.

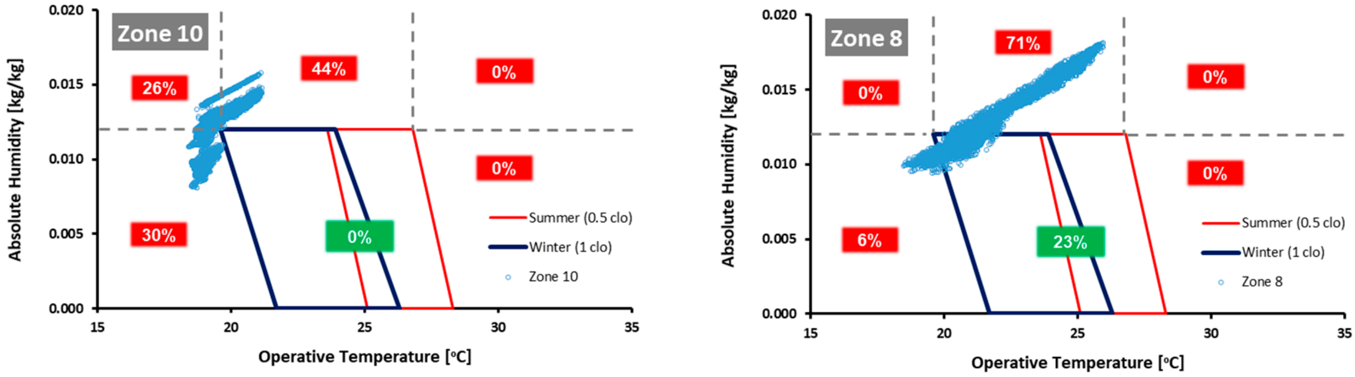


Figure 6. Hygrothermal conditions in two compartments of floor 0 (zones 10 and 8) were calculated from numerical simulation for the base scenario (compared to the ASHRAE 55:2013 comfort zone) (full calendar year).

To evaluate the potential for reducing indoor absolute humidity through increased air change rates, two alternative scenarios were defined to simulate different ventilation strategies. In the first scenario, the base ventilation regime is maintained with an air change rate of 0.3 h^{-1}, intermittently increased to 1 h^{-1} overnight. A variable ventilation regime was considered between 10 pm and 6 am, with half-hour periods in which the air change rate alternates between 0.3 h^{-1} and 1 h^{-1} (Figure 7). With this approach, an increased ventilation regime is guaranteed in comparison to the base scenario, although not compromising indoor air temperature at night. A second, less conservative scenario considers a continuous regime of 1 h^{-1} air change rate.

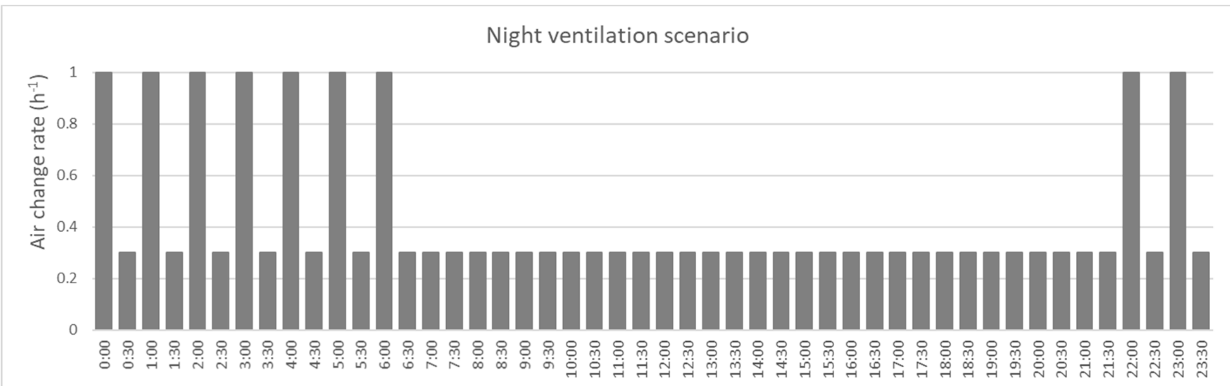


Figure 7. Night ventilation scenario.

Simulation results of the alternative ventilation scenarios are presented in Figures 8 and 9 for the four different zones of the building. Comparing the night ventilation scenario with the baseline scenario, although point clouds present similar spatial dispersion, the point density—i.e., the number of readings taken in each of the six regions into which the comfort diagram was divided—moved towards reduced indoor air temperature and absolute humidity. It is interesting to distinguish between floors 1 and 0 of the building.

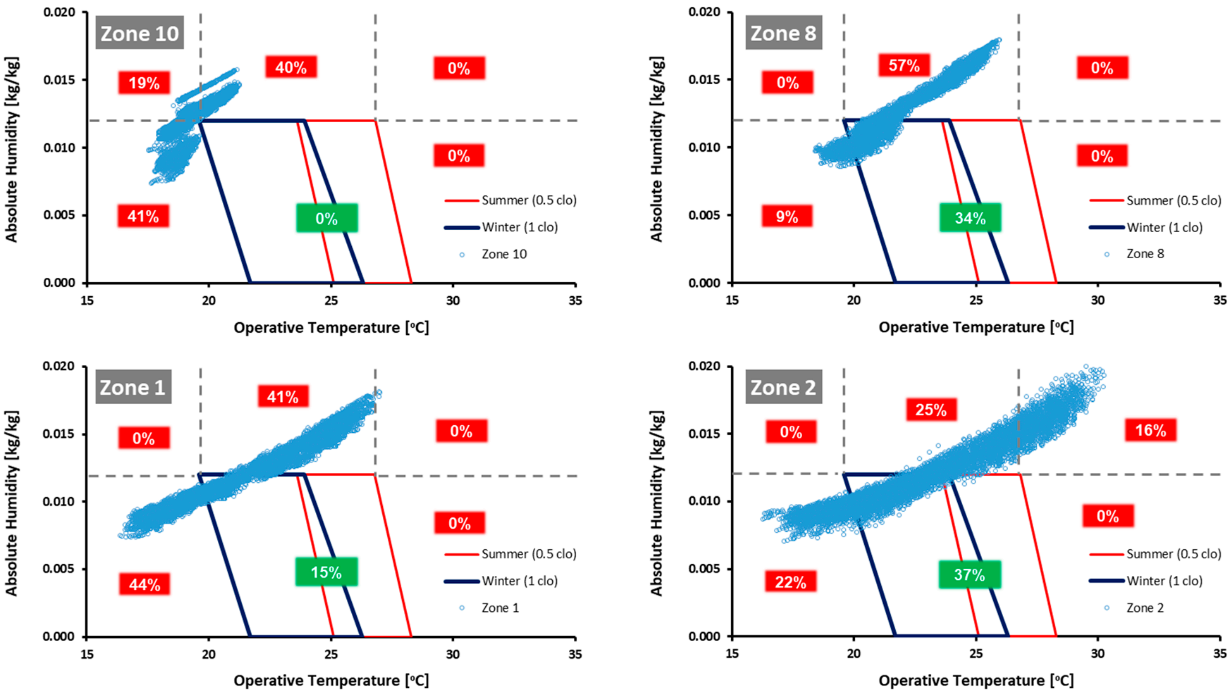


Figure 8. Representation in the ASHRAE 55:2013 comfort diagram of the hygrothermal conditions in four compartments (zones 10 and 8 of floor 0 and zones 1 and 2 of floor 1), as calculated from numerical simulation for the night ventilation scenario (full calendar year).

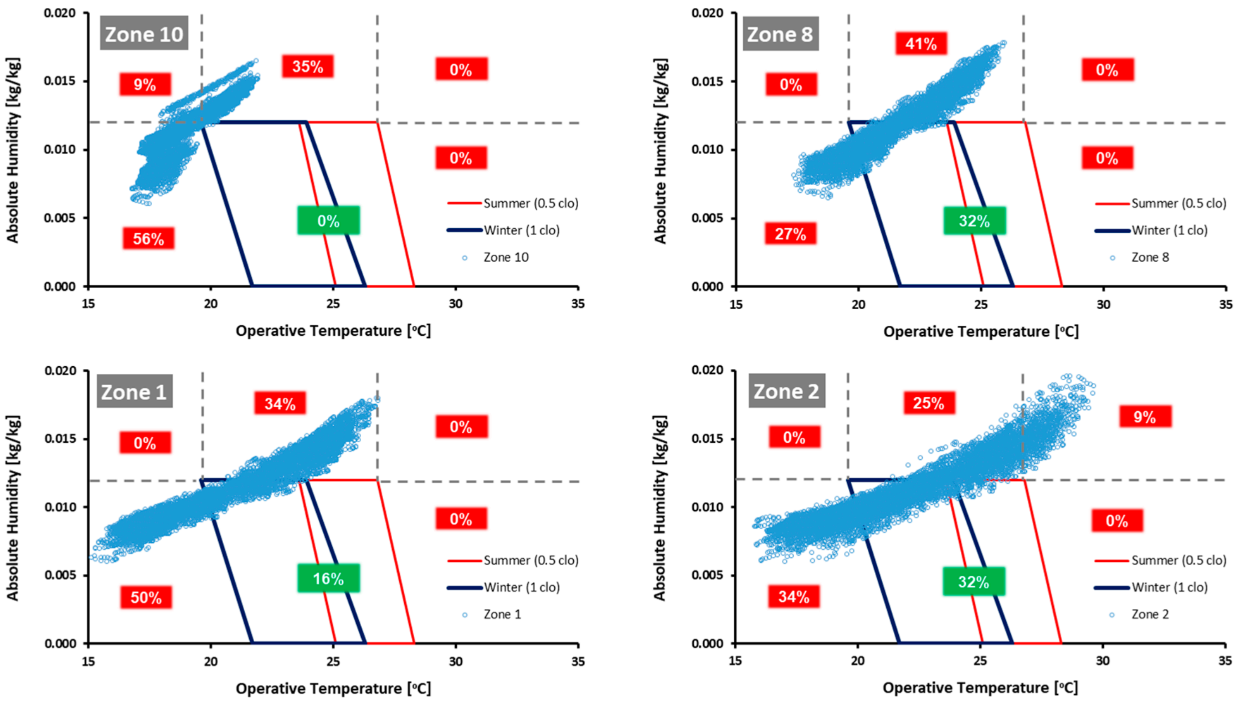


Figure 9. Representation in the ASHRAE 55:2013 comfort diagram of the hygrothermal conditions in four compartments (zones 10 and 8 of floor 0 and zones 1 and 2 of floor 1), as calculated from numerical simulation for the scenario of 1 h^{-1} constant air change rate (full calendar year).

Analyzing the two rooms on floor 1, there are changes in the periods of discomfort due to excess humidity (reduction from 45 + 1 = 46% to 41% in the bedroom and from 27 + 19 = 46% to 25 + 16 = 41% in the living room) and due to low temperature (increase from 39% to 44% in the bedroom and from 16% to 22% in the living room), without a significant change, however, in the calculated comfort period. Therefore, the migration of points towards decreasing temperature and humidity means that some points leave the discomfort zone due to excess humidity to enter the comfort zone, whereas other points leave the comfort zone to enter the zone of discomfort due to temperature deficit. In any case, it becomes evident that the night ventilation strategy contributes to the effective reduction in indoor absolute humidity.

In the bedroom of floor 0, although the migration of points between the base scenario and the night ventilation scenario is equivalent to that of floor 1, the temperature drop is not as significant, leading to an increase in the period in which thermal comfort conditions are in effect for the occupants (from 23% to 34%). The temperature drop may not be as significant due to the greater temperature constancy associated with the ground floor. The laundry room is a particular example, but here too, the overall period of discomfort due to excess humidity has decreased from 44 + 26 = 70% to 40 + 19 = 59%.

The night ventilation scenario is conservative in the sense that it was intended to limit the overnight reduction in indoor air temperature associated with increased air change rates. In the second alternative scenario, however, a continuous air change rate of 1 h^{-1} is used. Comparing Figures 8 and 9, it can be concluded that the higher ventilation rate of 1 h^{-1}, in addition to not bringing benefits concerning thermal comfort (comfort periods are only maintained or even reduced), leads to a significant increase in the periods of discomfort due to low temperature (from 41%, 9%, 44%, and 22% to 56%, 27%, 50%, and 34%, respectively for the laundry room, bedroom of floor 0, bedroom of floor 1, and living room). It should be noted, however, that the analysis does not consider the use of space heating systems that could partially offset the cooling effect associated with the higher ventilation rate. The provision of sensible heat from the space heating system combined with dehumidification by increased ventilation would certainly lead to an increase in comfort periods.

The ventilation rate increment discussed in this section can be achieved by using, e.g., self-regulating ventilation grilles strategically placed and correctly sized to obtain the desired effect. There are examples in the literature that evaluate the effectiveness of such measures. Mijakowski and Sowa [36], for example, monitored indoor air temperature, relative humidity, and CO_2 concentration in a kindergarten for a month and proposed the installation of natural ventilation grilles activated by relative humidity levels in the room as a way to improve indoor air quality. The building was monitored again for a month after the measure had been implemented. Despite improving the conditions of the indoor environment, with reductions in relative humidity and CO_2 concentration, the strategy proved, however, to be insufficient to comply with the regulatory framework for new buildings.

Almeida and Freitas [37] also evaluated the effectiveness of indoor air quality by installing a ventilation system in a school building. These authors monitored for two months the indoor environment in four classrooms, two of which had been subject to intervention. The authors opted for an active ventilation system, with extraction by mechanical fans placed above doors and self-regulating grilles for air supply in blind boxes. Through a centralized technical management system, it was possible to define a conditional operating regime for the variable speed fans, whose start, stop, and actual flow varied according to outside air temperature and indoor CO_2 concentration. Results demonstrated the effectiveness of the solution, with lower CO_2 concentrations in the intervened rooms and an air temperature only marginally lower (although within the comfort zone) than that registered in non-intervened rooms.

Results show that the single action of ventilating may not be, by itself, beneficial for the comfort of building occupants. It is important that ventilation regimes be established, taking into account criteria other than the simple air change rate. In addition to the daily period in which ventilation would be more interesting, an important aspect concerns the periods of the year when this strategy can be more advantageous. Given the limited monitoring period in the tests by Mijakowski and Sowa [36] (December and March) and

Almeida and Freitas [37] (March to May), it is not possible to establish whether there would be some seasonality effect on the conclusions drawn in each of these studies.

5. Conclusions

This article assesses the hygrothermal conditions of residential buildings in the Azores archipelago and defines ventilation strategies that contribute to the improvement in the indoor environment. These objectives involved in situ monitoring of the hygrothermal conditions of a typical residential building in the Azores using temperature and humidity sensors and complementary tests to determine the thermal conductivity of building exterior walls and air change rates.

It is observed that the periods in which thermal comfort conditions are in effect for building occupants are quite low, ranging from 5% to 32% of the time. The main cause for discomfort is the absolute humidity in the indoor environment: even with acceptable air temperature values, occupant discomfort varies between 39% and 69% due to high levels of absolute humidity in the air. Moreover, absolute humidity indoors is higher than absolute humidity outdoors, which allows the potential reduction in indoor humidity levels through ventilation (calculated between 1.63 and 2.65 g $H_2O.kg^{-1}$ dry air, on average). Monitored values show that the absolute humidity reduction potential is at its maximum in the early morning, so a judicious ventilation process (e.g., periods of intermittent ventilation in the early hours of the morning) may reduce absolute humidity without compromising indoor air temperature.

A thermal resistance of 0.45 $m^2.K.W^{-1}$ and a U-value of 1.63 $W.m^{-2}.K^{-1}$ are calculated using an experimental setup for heat transfer estimation through walls, which is consistent with previous studies on the thermal performance of stone masonry walls with the thickness under test. Moreover, using the tracer gas method and the decay technique, an air change rate of approximately 0.3 h^{-1} is also obtained from in situ tests. These values were used as inputs in the hygrothermal modeling of the building.

The hygrothermal simulation model using DesignBuilder and EnergyPlus is based on construction solutions and materials typical of the Azores archipelago, as well as climate data for the region and building usage profiles. A comparison is made between a CTF (Conduction Transfer Function) mathematical heat transfer algorithm and a HAMT (Combined Heat and Moisture Transfer) simultaneous heat and moisture transfer algorithm. Modeling the phenomena of generation, transport, and storage of moisture assumes special relevance due to the importance of humidity in the Azorean context; thus, the HAMT model is applied in the simulations, despite its greater computational demand.

Different ventilation strategies are addressed using the numerical simulation model. A permanent ventilation regime with an air change rate of 0.3 h^{-1}, as calculated experimentally in situ, constitutes the baseline scenario. Numerical results from this baseline scenario are compared with two alternative scenarios in order to quantify the potential for reducing the absolute humidity inside buildings. The first alternative scenario, with a base ventilation regime of 0.3 h^{-1} intermittently increased to 1 h^{-1} overnight, shows changes in the prevalence of different discomfort zones, although the calculated comfort period remains nearly unchanged. Nevertheless, results also show that increased night ventilation contributes to the effective reduction in indoor absolute humidity. The increased ventilation rate of the second alternative scenario (constant air change rate of 1 h^{-1}) does not bring benefits in terms of thermal comfort (comfort periods are merely maintained or even reduced) and leads to significant increases in the periods of discomfort due to reduced temperature. The provision of a space heating system combined with dehumidification by increased ventilation may, however, lead to an increase in the comfort periods inside the building.

Increasing ventilation rates can be achieved using such things as self-regulating ventilation grilles strategically placed and correctly sized to obtain the desired effect. Nevertheless, results show that the single action of ventilating may not, by itself, be beneficial for improved comfort. It is therefore important that ventilation regimes be established, taking into account additional criteria other than just the air change rate, namely the periods of the day and year in which ventilation is applied and the duration of these periods.

To deepen the knowledge of the ability of different finishing materials for moisture buffering inside buildings and their contribution to improving an indoor environment, further works should focus on additional case studies with alternative finishing layers. Moreover, parametric and sensitivity analyses from additional case studies may enable the establishment of generalized mathematical relationships between the data gathered and the output indicators calculated.

Author Contributions: Conceptualization: J.M., R.M.S.F.A. and J.A.R.M.S.; methodology: J.M., R.M.S.F.A. and J.A.R.M.S.; experimental tests: J.M. and R.M.S.F.A.; writing: J.M. and R.M.S.F.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data available on request.

Acknowledgments: The authors gratefully acknowledge the Azorean Regional Laboratory of Civil Engineering, the Azorean Regional Direction of Culture, the Hydrometeorological Automated Azores Network, and Maduro Dias, the owner of the selected building.

Conflicts of Interest: The authors declare no conflict of interest.

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