Civil Engineering and Architecture 12(5): 3637-3663, 2024 http://www.hrpub.org
DOI: 10.13189/cea.2024.120537

# Comparative Analysis of Thermal Simulation Tools Precision to Predict Thermal Comfort Factors

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*Received May 7, 2024; Revised July 28, 2024; Accepted August 19, 2024*

***Cite This Paper in the Following Citation Styles***

***(a):*** *[1] Giselle Betzabe Sánchez-Salazar, Esteban Felipe Zalamea-León, Mateo Astudillo-Flores , "Comparative Analysis of Thermal Simulation Tools Precision to Predict Thermal Comfort Factors," Civil Engineering and Architecture, Vol. 12, No. 5, pp. 3637 - 3663, 2024. DOI: 10.13189/cea.2024.120537.*

***(b):*** *Giselle Betzabe Sánchez-Salazar, Esteban Felipe Zalamea-León, Mateo Astudillo-Flores (2024). Comparative Analysis of Thermal Simulation Tools Precision to Predict Thermal Comfort Factors. Civil Engineering and Architecture, 12(5), 3637 - 3663. DOI: 10.13189/cea.2024.120537.*



**Abstract** The temperature discrepancy between thermal simulation results and real indoor-real temperature has not been thoroughly studied in Andean climates near the equatorial line. In this region, buildings do not require HVAC systems because of excellent local climate conditions. This research defines an adequate software configuration for providing the most accurate data with reduced error gaps. The three buildings of the Faculty of Architecture of the University of Cuenca were built through the software DesignBuilder and ArchiCAD with the EcoDesigner STAR plug-in, and nine internal classrooms were selected. Both simulation models were configured with equivalent data from a climate file comprising data from on-site weather station measurements. Afterwards, indoor temperature and relative humidity data were collected from nine classrooms via temperature and humidity sensors. The results revealed a 0.81 ℃ and 5% of mean absolute error (MAE) between the temperature and relative humidity simulated in DesignBuilder and a 0.91 ℃ and 6.09% (MAE), with the EcoDesigner STAR simulation demonstrating more accuracy with DesignBuilder which achieved the highest calibrated model benchmark with $\leqslant$1 ℃ and $\leqslant$5% while EcoDesigner achieved the lower standard with $\leqslant$2 ℃ and $\leqslant$10%. The results obtained after infiltration calibration show that for older brick masonry buildings, because of the weak level of airtightness between 20 ACH and 40 ACH, this deficiency means good ventilation rates. Nevertheless, the temperatures are within the comfort zone as long as the areas are fully occupied, and in insulated buildings with better quality windows and lower ventilation infiltration, a rate of 15 ACH was determined, resulting in more stable and comfortable temperatures than those in previous classrooms.

**Keywords** Building Thermal Simulation, Natural Ventilation, Thermal Comfort, Building Simulator Precision

## 1. Introduction

During the architectural design process, the indoor air temperature can be predicted through simulation software, and an accurate simulation can provide decision-making parameters to designers in the early stage of the process. Conducting a design process with these tools can reduce the energy consumption of buildings by approximately 10% and can reduce energy consumption in extremely warm weather by up to 40% [1]. Nevertheless, software predictions due to model uncertainty can differ by up to 26% of the simulated energy consumption [2].

The type of software employed for this study utilizes a simulation engine, DesingBuilder (DB) uses the Energy Plus dynamic simulation engine [3], while Ecodesigner Star (ED) uses the Strusoft dynamic simulation engine “VIP-core” [4]; both of them integrate a climate file to input the specific location weather, allow for a detailed export of air temperature and relative humidity and can calibrate the best energy efficiency capabilities to support a parametric analysis [5]. Sixty per cent of the papers covered by Chong's bibliographic review utilized EnergyPlus [6]. Since the buildings studied in this research are not mechanically climatized, the novelty of this research concerns these aspects and the comparison of the two software programs.

In the equatorial Andean climate, the aim of using thermal simulation software is different from that in extreme climates where internal spaces need to be thermally conditioned through heating, ventilation, and air conditioning (HVAC) to reach habitable comfort levels. Therefore, in extreme climates, the goal is to reduce energy consumption. Nonetheless, at middle-altitude valleys close to the equator, increasing thermal comfort is important since most buildings do not adopt HVAC systems. In this research, we focus on classroom thermal comfort levels, which improve health and performance in the learning process [7].

Several studies have used building energy simulation software to assess the validation, calibration, and correlation of the simulated results [8]. Most of these studies have focused on climate conditions far from the equatorial region. Chong's review indicated that only 4% of these types of studies have been conducted at equatorial latitudes and mainly in warm tropical climates [6].

Since the climate is determined by several factors, such as latitude and altitude [9], the specific climate zone. In this case, the location of Cuenca city, has particular climate characteristics. However, it could be representative of several locations and cities, including capital cities such as Quito or Bogota, which are also located in valleys in the Andean Mountain range.

The average temperature in Cuenca city is 16.3 ℃ throughout the year. Despite that, it fluctuates between 27.2 ℃ and as low as -1.7 ℃, and the relative humidity is between 40% and 85%. Ninety percent of the local population feels thermal comfort between 17.62 ℃ and 22.62 ℃, with a relative humidity between 40% and 65% [10].

In energy simulation software, the correct configuration of the airtightness and thermal transmittance allows a 15% reduction in the discrepancy of the results [11]; therefore, these parameters are considered the most important variables for comparing the two simulation tools.

The thermal transmittance of a material corresponds to heat transmission per time unit through a material or constructive element, also known as the U factor or U value, expressed in ($W/m^2K$) [12]. The air change rate (ACH) between the interior and exterior of a building depends on two variables: airtightness or infiltration and natural ventilation; infiltration means no controlled air interchange between the exterior and interior areas and depends on the permeability of the building's fabric as well as the site's environmental conditions, while natural ventilation can be controlled through openings such as windows and doors and designed intentionally for ventilating internal spaces. For this research, the thermal transmittance is fixed, while the ventilation is estimated by the carpentry conditions.

This research uses previously modelled 3D buildings of the Faculty of Architecture of Cuenca University, created in DB and ArchiCAD, to simulate interior thermal fluctuations using the ED plug-in. In both cases, the results are compared with the measured data of three classrooms, with a 5% error percentage obtained for DB [7] and a 9% error percentage for ED [13]. For this research, nine classrooms located at different buildings and floor levels are compared.

Similar studies employ different metrics and at times more than one metric, amongst others, the most commonly used are the Coefficient of Variation of the Root Mean Square Error (CVRMSE), Normalized Mean Bias Error (NMBE), Error percentage (%error) and the one used in this research, Mean Absolute Error (MAE), the suggested thresholds based on air temperature and relative humidity for the MAE, its specified for a high precision model to be ⩽1 ℃ for temperature and 5% for relative humidity, and for a lower precision model ⩽2 ℃ and ⩽10% [8].

The difference in metrics is important to note since it can seem different while being equivalent values calculated with different equations, therefore when analyzing different articles, the results have been variated while accomplishing the goal to obtaining a calibrated model in different levels depending on the particular objectives, for example Serag et al. [14], obtain a +3.51% error percentage of energy consumption with DB and -9.84% with Ladybug&Honneybee plug in software.

Jain et al. [15] obtain results of -3.7% NMBE of electric consumption and -3.3% NMBE of gas consumption utilizing DB complying with the ≤5% limit stablished by the ASHRAE guideline14 [16] to be considered calibrated.

The Ta and RH discrepancy can also be expressed using the error percentage as expressed by Villalba Lozano & Ortiz Morales [17] obtaining Ta results between 0.62% and 11.23% with DB and between 0.91% and 9.34% in LegacyOpenstudio plug in software in addition RH results between 1.95% and 14.82% with DB and between 1.01% and 13.22% with LegacyOpenstudio, although the use of error percentage for temperature can be questioned for the difference that implies the use of different units as Fahrenheit and Kelvin that cannot be identified by presenting the discrepancy with this metric.

It is expected that comparative charts, in which discrepancies exist between simulator results and real measurements can be identified, and by using a specific configuration, the breach can be reduced by obtaining the correct calibration. In addition, the models will be ready to propose improvements, and an appropriate baseline for understanding the values and configuration for new buildings, especially those that have the same construction system and are located in the same climate zone, will be set.

**Nomenclature**

| | |
|---|---|
| **ED** | EcoDesigner STAR |
| **DB** | DesginBuilder |
| **Ta** | air Temperature |
| **RH** | Relative Humidity |
| **MAE** | Mean Absolute Error |
| **NMBE** | Normalized Mean Bias Error |
| **HVAC** | Heating Ventilation and Air Conditioning |
| **Rsi** | Surface resistance interior |
| **Rse** | Surface resistance exterior |

## 2. Materials and Methods

The applied methodology is empirical and quantitative, virtually building and calibrating the classroom geometry, materiality, location, occupancy, varying ventilation rate and ventilation schedule, by the occupation rate of each thermal block. This aspect is calibrated similarly for the concordant parameters in both software programs to obtain the most concordant input, obtaining results for both software programs and knowing the usual occupancy of these classrooms.

This research follows two previous investigations that independently simulated and compared the results of the internal temperature in the ED [13] and in DB [7] for three classrooms. These works were taken as a baseline to draw from their pre-created models and calibrate them with the same inputs while adding information and correlating their conclusions.

Most of the model calibrations and validations have been performed to prepare uniform models and validate them to formulate improvements to existing buildings [18]. Consequently, an algorithm is designed to explain the steps taken, using both users' manuals toward achieving equivalent results as a basis (Fig. 1).

The accuracy of the simulated results versus real parameters depends on the accuracy of the model development and input data. Many precise parameters are difficult to model, such as real conditions of the exact occupancy rate or real and precise physical parameters of the materials. The ASHRAE guideline 14 establishes that to reduce energy consumption, it is important to understand the existence of two uncertainties, namely, measurement uncertainty and modeling uncertainty [16].

This research focuses on modeling uncertainty by comparing the accuracy of the temperature and relative humidity results by equalizing the geometry in the models in both simulation programs and determining how different from reality the results of the software programs are.

The equipment utilized to obtain the thermal data inside the classrooms was composed of a data processor, a PT100 temperature sensor, a relative humidity sensor and a $CO_2$ sensor [7], this equipment was calibrated in January 2022, and the data was taken on a 10min interval frequency.

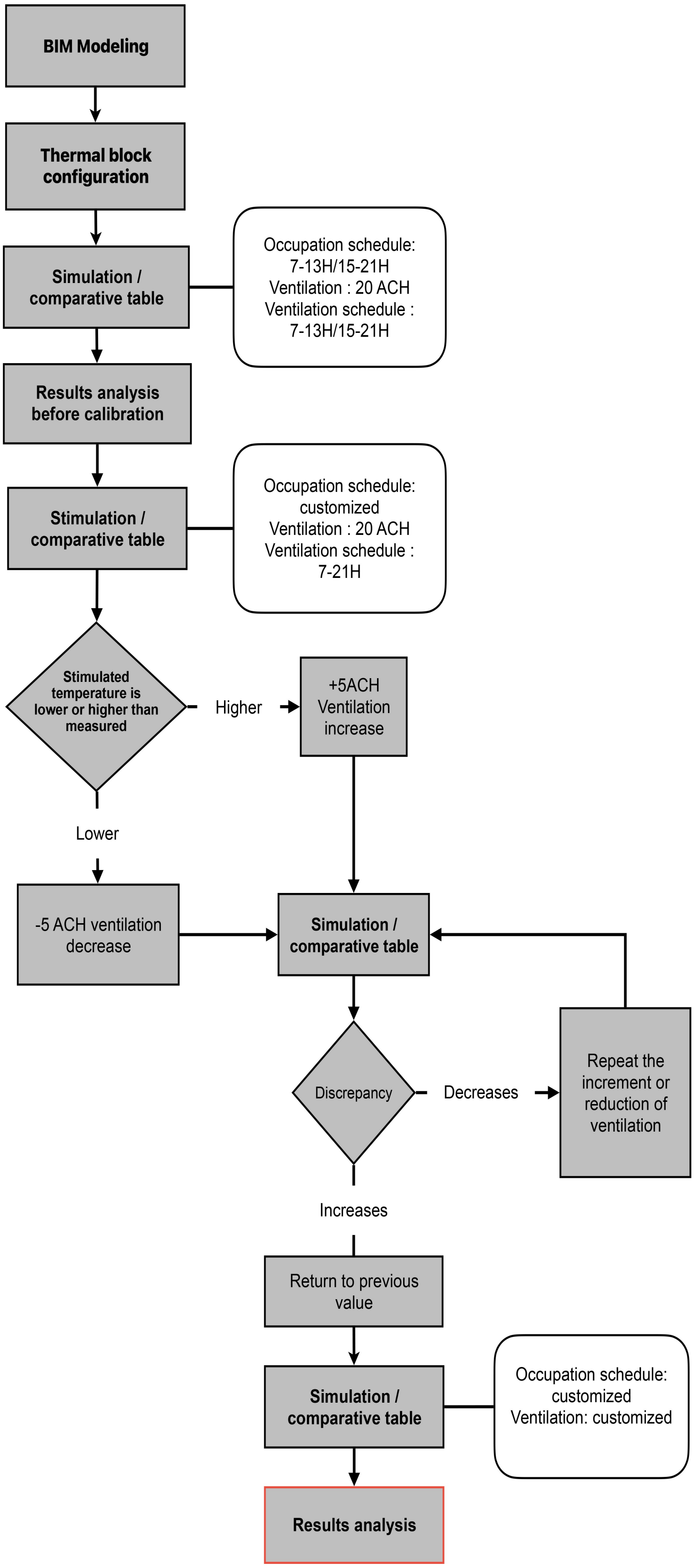



**Figure 1.** Model configuration and calibration algorithm

### 2.1. Modeling

This research starts by modeling the same buildings in DB and ArchiCAD, where classroom physical and occupancy data are calibrated to be as similar as possible.

To assemble a representative sample of classrooms, each of the nine classrooms is on a different floor in each of the three buildings. These buildings are coded as E1, E2, and E3, and the corresponding classrooms are labeled as follows: E1 -105, E1 011, E1 108, E2 003, E2 102, E2 203, E3 -002, E3 101 E3 302 (Tables 1 to 3).

**Table 1.** Geometry of the classrooms in the E1 building

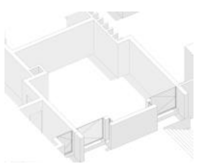
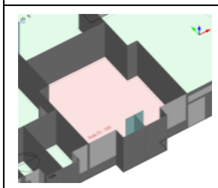
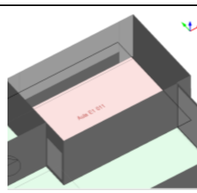
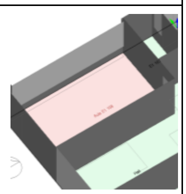
| E1 Building | | |
|---|---|---|
| E1 -105 | E1 011 | E1 108 |
| Subterranean | First floor | Second floor |
|  |  |  |
| ArchiCAD – EcoDesigner STAR 3D models | | |
|  |  |  |
| DesignBuilder 3D models | | |

**Table 2.** Geometry of the classrooms in the E2 building

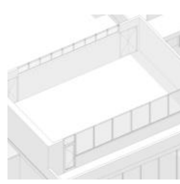
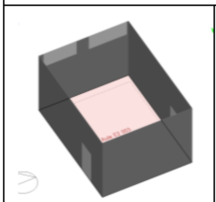
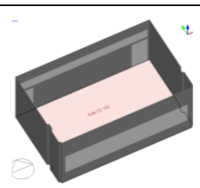
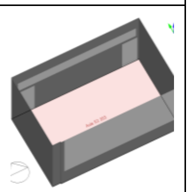
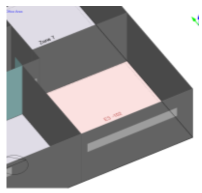
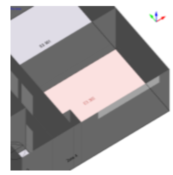
| E2 Building | | |
|---|---|---|
| E2 003 | E2 102 | E2 203 |
| Ground floor | First floor | Second floor |
|  |  |  |
| ArchiCAD – EcoDesigner STAR 3D models | | |
|  |  |  |
| DesignBuilder 3D models | | |

**Table 3.** Geometry of the classrooms in the E3 building

| E3 Building | | |
|---|---|---|
| E3 -102 | E3 101 | E3 302 |
| Subterranean | First floor | Third floor |
|  |  |  |
| ArchiCAD – EcoDesigner STAR 3D models | | |
|  |  |  |
| DesignBuilder 3D models | | |

### 2.2. Thermal Block Configuration

2.2.1. Material and Thickness of the External Walls, Partitions, and Subterranean Areas

The input data in the software include the material thickness and thermal resistance of each layer, but the thermal transmittance or U value of the whole element is calculated by each tool following the recommendation in their user's manual; the data input in each layer is presented in the appendix. Since these internal spaces do not have HVAC systems affecting the internal temperature, this condition is optimal to test the accuracy of each software program, which can thus simulate the internal temperature independent of the performance of the cooling or heating equipment.

For purposes of comparison with the Ecuadorian standard NEC-2018 [12], the thermal parameters of the building ́s external envelope are specified, and their compliance is presented in Tables 4 to10.

**Table 4.** Thermal transmittance of exterior walls above ground level

| Exterior walls above ground level | | | |
|---|---|---|---|
| Type | Description | Thickness (m) | U value (W/m K) |
| 1.1 | Exposed brick | 0.15 | 2.87 |
| 1.2 | Exposed brick | 0.3 | 1.90 |
| 1.3 | Exposed brick | 0.45 | 1.42 |
| 2 | Concrete panel, insulation, concrete block, and mortar | 0.21 | 1.4 |
| 3 | Steel panel, insulation, concrete block and mortar | 0.18 | 1.45 |

**Table 5.** Thermal transmittance of exterior floors above ground level

| Exterior floors above ground level | | | |
|---|---|---|---|
| Type | Description | Thickness (m) | U value (W/$m^2$K) |
| 1 | Reinforced concrete floor over stone with tile finish | 0.3 | 2.51 |

**Table 6.** Thermal transmittance of exterior ceilings above ground level

| Exterior ceilings above ground level | | | |
|---|---|---|---|
| Type | Description | Thickness (m) | U value (W/$m^2$K) |
| 1 | Reinforced concrete slab lightened with pumice block, air chamber, and gypsum | 0.74 | 0.51 |
| 2 | Reinforced concrete slab | 0.3 | 2.84 |
| 3 | Reinforced concrete slab, gravel | 0.45 | 1.14 |

**Table 7.** Thermal transmittance of partitions

| Wall partitions | | | |
|---|---|---|---|
| Type | Description | Thickness (m) | U value (W/$m^2$K) |
| 1.1 | Exposed brick | 0.15 | 2.31 |
| 1.2 | Exposed brick | 0.3 | 1.65 |
| 2 | Mortar, concrete block, mortar | 0.18 | 2.06 |

**Table 8.** Thermal transmittance of the internal floors

| Internal floors | | | |
|---|---|---|---|
| Type | Description | Thickness (m) | U value (W/$m^2$K) |
| 1 | Reinforced concrete slab lightened with pumice block, concrete tile | 0.35 | 1.16 |
| 2 | Reinforced concrete slab lightened with pumice block, concrete tile | 0.45 | 0.94 |
| 3 | Reinforced concrete slab lightened with pumice block, parquet | 0.35 | 1.06 |
| 4 | Reinforced concrete slab lightened with pumice block, parquet | 0.45 | 0.89 |
| 5 | Cement overlay, reinforced concrete slab lightened with pumice block, air chamber and gypsum | 0.74 | 0.46 |

**Table 9.** Thermal transmittance of exterior walls below ground level

| Exterior walls below ground level | | | | |
|---|---|---|---|---|
| Type | Description | Thickness (m) | Depth (m) | U value (W/$m^2$K) |
| 1 | Exposed brick | 0.15 | 0.9 | 1.17 |
| 2 | Mortar, concrete block, mortar | 0.21 | 1.21 | 2.06 |

**Table 10.** Thermal transmittance of exterior floors below ground level

<table>
<tr><td colspan="6">Exterior floors below ground level</td></tr>
<tr><td>Type</td><td>Description</td><td>Thickness (m)</td><td>Depth (m)</td><td colspan="2">U value (W/$m^2$K)</td></tr>
<tr><td>1</td><td>Reinforced concrete slab over stone with parquet finish</td><td>0.30</td><td>0.9</td><td colspan="2">0.51</td></tr>
<tr><td>2</td><td colspan="2">Reinforced concrete slab over stone with cement overlay</td><td>0.3</td><td>1.62</td><td>2.84</td></tr>
</table>

### 2.2.2. Material and Configuration of Openings

The thermal transmittance of the openings according to the Ecuadorian standard-NEC by the construction and materials is as follows:

- Windows: clear glass and aluminum frame, 5.78 W/$m^2$K.
- Doors: hardwood door, 2.56 W/$m^2$K.
- Hollow wooden door, 2.5 W/$m^2$K.

### 2.2.3. Airtightness and Natural Ventilation

In DB, the ACH parameter is configured in the Construction tab, as shown in Fig. 2. The schedule can also be modified with different percentages and halves and quarters of hours since airtightness cannot be controlled, and this parameter has the greatest impact on the results and is equivalent to the natural ventilation parameter in ED. In both cases, simulations start at 20 ACH (Fig. 3) and turn "on" during the general occupation of the faculty. In previous research, this magnitude was also detected by applying DB with the internal temperature as the input [7].

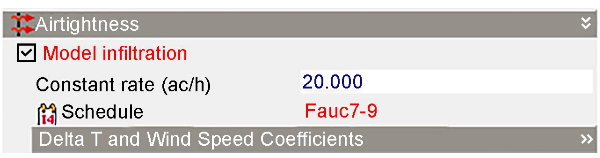



**Figure 2.** Airtightness tab in DesignBuilder

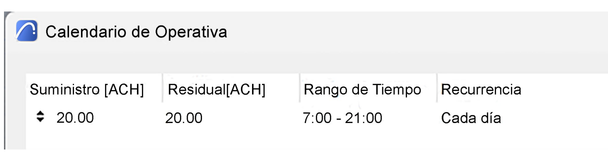



**Figure 3.** The natural ventilation window in ED

In ED, in addition to the parameter of natural ventilation, the permeability of the structures can be modified. The user's manual suggests a range between 0.6 l/s m$^2$ and 1.6 l/s m$^2$; however, the thesis "Modelado y mediciones de las condiciones ambientales interiores en edificaciones FAUC" establishes 20 l/s m$^2$ as a possible value for windows and doors and 100 l/s m$^2$ for air chambers. These values are taken as fixed except for the openings of classroom E2 203, which are set at 40 l/s m$^2$ because during calibration, even with a ventilation of 40 ACH, there was a considerable difference from the measured temperature.

2.2.4. Thermal Block Configurations

The simulation software can set up variables for setting an occupation rate that increases or decreases thermal energy:

Zone type: The classrooms are habitable unconditioned areas.

Occupation: DB was set up at 0.4 p/m$^2$, and ED was set at 2.5 p/m$^2$.

Metabolic: DB is set to 108 W/person for the activity "writing" [19] and a coefficient of 0.9; for ED, this measure is called caloric gain per capita and is provided in the same units.

Clothing: People's clothing is a parameter that is editable in DB only and is not considered in ED; the units used are Clo (clothing parameter). The references considered are between 0.5 Clo and 1.5 Clo [20]. Ninety-eight percent of residences in Cuenca, even at an average temperature of 15 ℃, do not have heating systems. Thus, people tend to wear warmer clothes inside buildings [10]; for this reason, this value is set to 1.5 Clo.

Schedule: The class schedule can help determine the expected occupancy in each classroom and thus the internal heat gain due to occupancy. This parameter must be calibrated because the listed schedules are not strictly followed.

To compare the accuracy of using a generic versus a specific schedule, the first simulation is executed with a maximum capacity of 7 h to 13 h and of 15 h to 21 h. After calibration, guided by the thermal results as well as the $CO_2$ measured inside the classrooms, the final simulation provides a final error percentage of the simulated temperature and humidity.

Heat gains due to office equipment: In DB, this parameter is set at 1.83 w/m$^2$, and the radiant fraction is set at 0.2, as recommended by the user's manual. The occupation profile in ED is also set at 1.83 w/m$^2$, and the illumination is 0.5 w/m$^2$.

Humidity load: This parameter is editable in ED only and is set to 0 by default since there are no hot water sources.

Warm water consumption: This parameter is set at 0 for both simulators since there is no internal hot water use, as stated previously.

2.2.5. Climate Data

The climate file format used by the simulation programs is an .epw file (energy plus weather file), which can be edited with Microsoft Excel by converting it beforehand to a .cvs file using the software program DeEPWaCVS (Fig. 4). After the information is modified, it is converted back to the original format, and then the Weather software from EnergyPlus files .stat and. audit are generated.

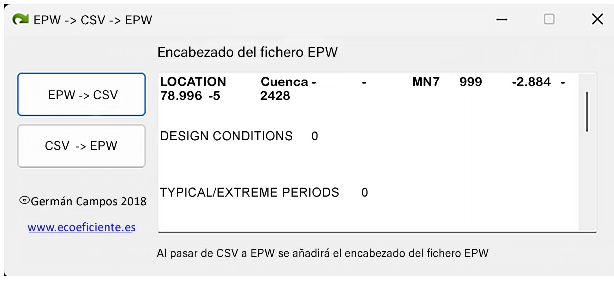



**Figure 4.** Weather software is utilized to convert the .epw files

The faculty buildings have deployed a weather station on the rooftop of the E3 Building WS-GP2 Advanced Automatic Weather Station System model, which includes sensors to measure rain, solar radiation, air temperature, relative humidity, and wind speed and direction [21] However, the required information is relative humidity (%), air temperature ( ℃), wind speed (m/s), and wind direction (deg) only. These data are extracted from March 19 to July 28, 2022, when the classroom internal temperature is also measured. However, since the weather station captures measurements for each 10 min time step, the six values per hour are averaged to import them into the climate file to coincide with the EnergyPlus climate file requirement.

2.2.6. Site Configuration

In the ED in the Environmental Definitions tab, the climate data are set by importing the .epw file. Additionally, climate information, location and altitude above the sea level data are needed.

Considering the climate classification of Cuenca, another site requirement is set, i.e., "humid environment". In the soil and ground type, "gravel" is used, and in the immediate surroundings, "garden" is set, given the building's surroundings. The ground reflectance is considered to be 20% since there is no reflective material in the surroundings and snow is not expected.

Wind protection is set to the north and south and is partially protected because of blockage from nearby buildings.

In DB, the site template is also configured by importing the climate file where the location and elevation are automatically determined.

### 2.3. Simulation Date Selection

To compare the simulations with reality for an unfavourable day, the coldest day among the measurements is identified based on information from the weather station that corresponds to the range of temperatures measured inside the classrooms.

Of the nine classrooms, eight had the same range of time from March 19 to May 17; therefore, for this group, the coldest day was April 20, with an average external temperature of 13.54 ℃, and for the ninth classroom (E3 203), the coldest day coincided with the coldest day of the entire year, with an average temperature of 11.4 ℃ on June 26; thus, for this classroom, the simulation is performed for this day.

### 2.4. Data Export

Once the energy models are ready for use, the simulations are performed, and the results are exported as a Microsoft Excel .xls format. For ED, it is important to have the ED plug-in instead of the energy evaluation built into ArchiCAD. Additionally, when exporting the file, the "Project Results-Hourly" box must be checked to obtain quantitative numerical results.

In the initial simulation, the data obtained are used to assess the empirical calibration and alter the occupancy schedule and natural ventilation values. Each software program allows for the modification of the exportation parameters. For the simulation, the temperature units are set to degrees Celsius (℃), and the relative humidity is set as a percentage. For this study, the air humidity indicator is considered supporting data for verification since it is dependent on the temperature. The simulation data are compared with the information measured internally in the classrooms, where the information recorded includes temperature, relative humidity, $CO_2$, and solar radiation. The data are collected in the geometrical centre of each classroom at a height of approximately 1.7 m.

### 2.5. Calibration

The initial simulation is set up with a 20 ACH infiltration rate during the occupation from 7 h to 13 h and 15 h to 21 h. This occupancy is set to the same schedule and density to ensure equal standards of regular classroom occupancy.

To obtain the discrepancy of both software with measured data it is important to consider the parameter (Ta, RH), the data frequency (hourly), and the metric to be used (MAE), this is selected for the present study for the unit of the result is dependent of the data, Celsius for the air temperature and % for the relative humidity, hence it can be accurately interpreted, the result is calculated by using Equation (1), which takes the absolute value of the difference between the measured and the simulated data hourly and computes the average of this difference for the day [8].

$$MAE = \frac{\sum_{i=1}^{n}|m_i - s_i|}{\text{n}} \tag{1}$$

$m_i$= Measured value
$s_i$= Simulated value
n= number of entries

This value in the calculation tables and graphs allows for this research to start the calibration process by changing the natural ventilation and occupation parameters and obtaining the most accurate results.

After calibrating the occupancy from the schedule provided by the faculty staff and modifying it to increase or decrease the temperature according to the graphs, the natural ventilation-infiltration calibration starts, following the algorithm previously presented. Then, the ventilation schedule is altered to further close gaps that are still noticeable in the graphs.

Tables 11 and 12 synthesize the results and present an average that will be understood as the model's general result or status to compare with the benchmark values, at this point the model complies with the MAE allowed for a lower precision model ≤2°C and ≤10% [8] except for the Ta in ED since this presents an opportunity for improvement these are specified as results before calibration.

**Table 11.** Temperature error percentage results before calibration

| Temperature difference | | |
|---|---|---|
| Classroom | DesignBuilder | EcoDesigner |
| E1 -105 | 1.45 | 1.60 |
| E1 011 | 3.44 | 2.51 |
| E1 108 | 1.29 | 1.22 |
| E2 003 | 1.22 | 2.45 |
| E2 102 | 0.72 | 2.23 |
| E2 203 | 1.54 | 5.93 |
| E3 -102 | 1.01 | 0.87 |
| E3 101 | 2.40 | 1.37 |
| E3 302 | 0.54 | 1.07 |
| Average | 1.51 | 2.14 |

**Table 12.** Relative humidity error percentage results before calibration

| Relative humidity error percentage | | |
|---|---|---|
| Classroom | DesignBuilder | EcoDesigner |
| E1 -105 | 5.22% | 7.40% |
| E1 011 | 10.14% | 7.91% |
| E1 108 | 3.90% | 6.89% |
| E2 003 | 4.91% | 6.72% |
| E2 102 | 4.50% | 7.48% |
| E2 203 | 4.59% | 15.29% |
| E3 -102 | 4.21% | 5.66% |
| E3 101 | 7.38% | 6.05% |
| E3 302 | 5.48% | 8.56% |
| Average | 5.59% | 8.00% |

# 3. Results and Discussion

## 3.1. Standard Verification

The Ecuadorian standard NEC defines a city in climate zone 3 as having continental rainy conditions with an altitude of 2500 m.a.s.l. By this regulation, the U value of the building fabric for the building envelope was defined, with and without mechanical internal conditioning. Since the classrooms are not equipped with HVAC systems, in Tables 13 and 14 the comparison is made as a non-climatized section. Thus, it is possible to evaluate only the internal temperature, independent of heating and cooling equipment calibration or its specific performance. Importantly, for walls below ground level, the value is presented as the C-factor (thermal conductance), which expresses the temporary rate of heat transfer between a material or assembly of two surfaces [12]; it uses the same units as the thermal transmittance, with the only difference being that the c-factor does not consider the air barriers on the assembly surfaces.

The maximum assembly is the assembly with the maximum thermal transmittance allowed because the assembly consists of thermally homogenous layers [22].

In the subsequent tables, the compliancy between the previously described structures (tables 4-10) is reviewed and underlined the non-compliant ones.

**Table 13.** Comparison of the maximum assembly allowed and the actual U–value of the elements

| Fabric | Type | Maximum assembly U value | Actual U Value |
|---|---|---|---|
| Walls | 1.1 | 2.35 | <u>2.92</u> |
| | 1.2 | | 1.94 |
| | 1.3 | | 1.45 |
| | 2 | | 1.4 |
| | 3 | | 1.45 |
| Windows | 1 | 5.78 | <u>5.87</u> |
| Doors | 1 | 2.6 | 2.56 |
| | 2 | | 2.5 |
| Roofs | 1 | 2.9 | 0.51 |
| | 2 | | 2.84 |
| | 3 | | 1.14 |

**Table 14.** Comparison of the maximum assembly allowed and the actual U values of the elements below ground level

| Fabric below ground level | Type | Maximum assembly U value | Actual U Value |
|---|---|---|---|
| Walls | 1 | 6.47 | 1.17 |
| | 2 | | 2.06 |

From these comparison tables, it is evident that one type of wall and all of the windows do not comply with the current Ecuadorian standard, which indicates a low thermal capability in the classrooms to keep the indoor areas at a comfortable temperature. The construction deficiencies are especially evident in the E1 and E2 buildings since the carpentry is designed with partial louvre windows and there are some missing pieces. Thus, a very high infiltration rate is expected.

While obtaining the inside air temperature hourly by the sensors and the outside air temperature by the weather station, those values are shown in Tables 15 and 16 since the average for the day can provide a general understanding of how the classroom performs in terms of thermal comfort

**Table 15.** Daily average air temperature comparison

| Classroom | Outside air temperature | Inside air temperature | Range |
|---|---|---|---|
| E1 -105 | 13.53 | 18.39 | ≥17.62 ℃ ≤22.62 ℃ |
| E1 011 | | <u>15.51</u> | ≤17.62 ℃ |
| E1 108 | | 17.90 | ≥17.62 ℃ ≤22.62 ℃ |
| E2 003 | | <u>15.30</u> | ≤17.62 ℃ |
| E2 102 | | <u>15.63</u> | ≤17.62 ℃ |
| E2 203 | 11.44 | <u>12.28</u> | ≤17.62 ℃ |
| E3 -102 | 13.53 | 17.77 | ≥17.62 ℃ ≤22.62 ℃ |
| E3 101 | | 17.53 | ≥17.62 ℃ ≤22.62 ℃ |
| E3 302 | | 18.52 | ≥17.62 ℃ ≤22.62 ℃ |

**Table 16.** Daily average Relative Humidity comparison

| Classroom | Outside RH | Inside RH | Range |
|---|---|---|---|
| E1 -105 | 82 | 62.12 | ≥40% ≤65% |
| E1 011 | | <u>71.50</u> | ≥65% |
| E1 108 | | 61.13 | ≥40% ≤65% |
| E2 003 | | <u>67.90</u> | ≥65% |
| E2 102 | | <u>69.20</u> | ≥65% |
| E2 203 | 72.29 | 64.20 | ≥40% ≤65% |
| E3 -102 | 82 | 62.76 | ≥40% ≤65% |
| E3 101 | | 62.62 | ≥40% ≤65% |
| E3 302 | | 56.45 | ≥40% ≤65% |

## 3.2. Simulation Results

After calibration, the final comparison tables are drafted to determine the final error percentage for the internal air temperature and relative humidity, at this point the classroom occupation (Table 17) and ventilation schedule

(Table18) play a key component since increasing the ventilation rate the temperature drops and by increasing the occupation it rises, both parameters in different impact levels help closing the gap between measured and simulated data.

**Table 17.** Classroom occupation schedule

| Occupation schedule | |
|---|---|
| Classroom | schedule |
| E1-105 | 8 h to 12 h; 13 h to 21 h. |
| E1 011 | 16 h to 18 h |
| E1 108 | 7 h to 13 h; 15 h to 18 h, 19 h to 21 h |
| E2 003 | N/A |
| E2 102 | 7 h to 11 h; 15 h to 20 h |
| E2 203 | N/A |
| E3-102 | 7 h to 10 h; 17 h to 20 h |
| E3 101 | 7 h to 9 h; 17 h to 21 h |
| E3 302 | 7 h t 9 h; 15 h to 21 h |

With a 0.82 ℃ discrepancy for DB, and a 0.75 ℃ discrepancy for ED, the E1 -105 classroom has higher temperature oscillations toward the late night, and the lowest temperature of the day is near the lower limit of thermal comfort (≥17.62 °C ≤22.62 C°), with 17.32 ℃, being at 2 pm. Consequently, there is no solar gain during the morning since the classrooms avoid direct solar incidence. Importantly, even when the simulators did not emulate the steadiness of the temperature without any further specification that exceeded the aim of this study, the input data yielded very similar results (Fig. 5), the RH value had a 62.12% on average at the measured day and the MAE with DB was 6.67% and with ED 5.35% (Fig. 6).

**Table 18.** Classroom ventilation schedule and value

| Ventilation schedule | | |
|---|---|---|
| Classroom | schedule | |
| E1 -105 | 8 h to 17 h | 20 ACH |
| | 17 h to 8 h | 2 ACH |
| E1 011 | 9 h to 19 h | 30 ACH |
| | 19 h to 9 h | 6 ACH |
| E1 108 | 7 h to 17 h | 20 ACH |
| | 19 h to 21 h | 20 ACH |
| E2 003 | 9 h to 17 h | 40 ACH |
| | 17 h to 9 h | 12 ACH |
| E2 102 | 7 h to 21 h | 30 ACH |
| E2 203 | 24 h | 40 ACH |
| E3 -102 | 7 h to 20 h | 15 ACH |
| E3 101 | 7 h to 21 h | 15 ACH |
| E3 302 | 7 h to 21 h | 15 ACH |

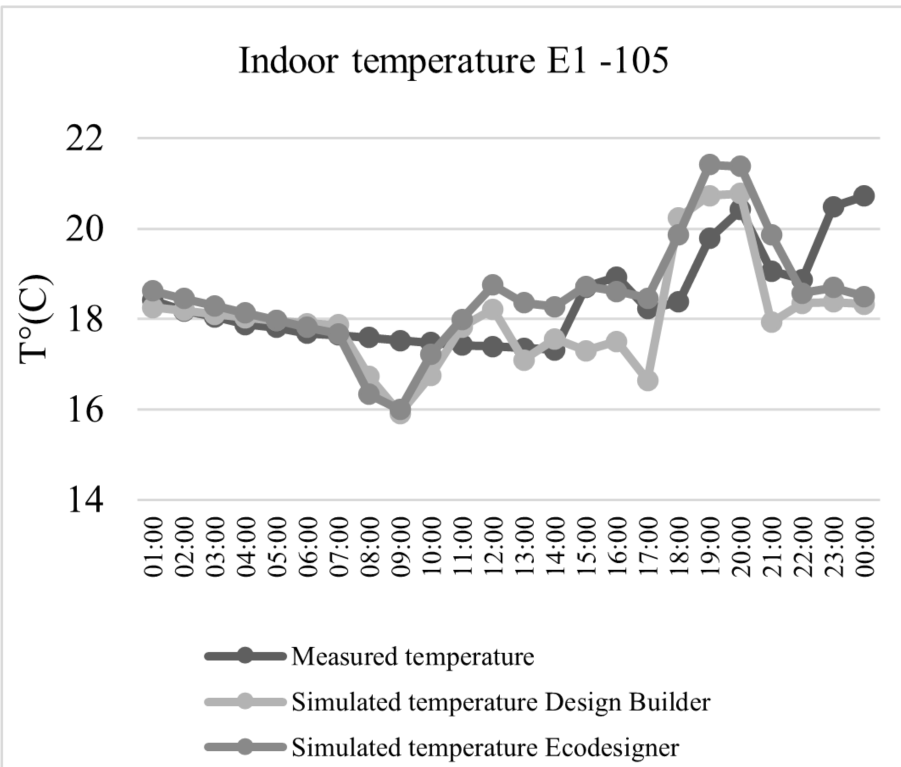



**Figure 5.** E1 -105 Temperature comparative graph

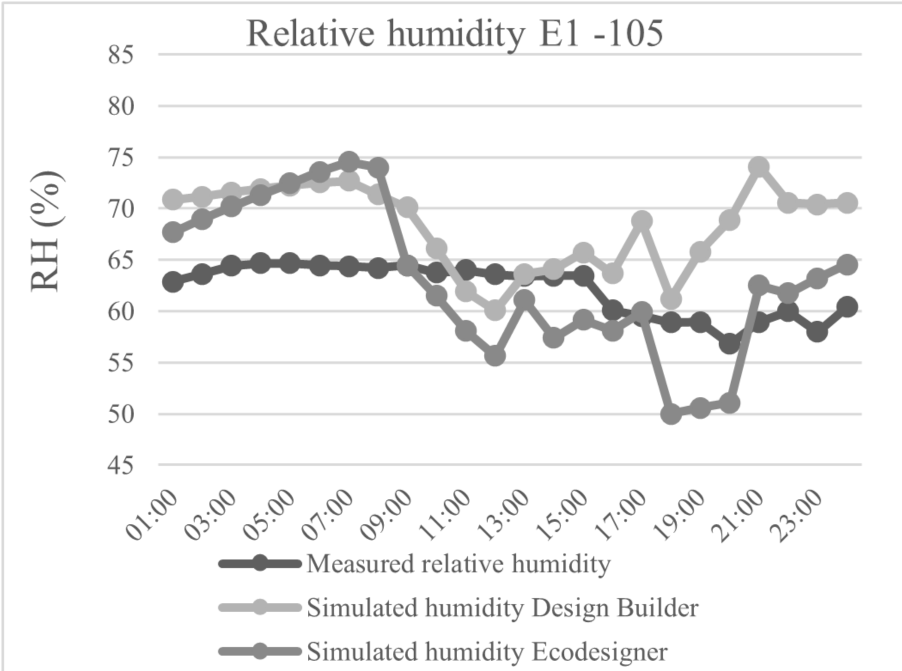



**Figure 6.** E1 -105 Relative humidity comparative graph

For the E1 011 classroom, the temperature was relatively stable throughout the day. Still, the measured temperature showed a lack of thermal gain midday in both simulations (Fig. 7). Even when ventilated and unoccupied, the temperature, in general, remains below thermal comfort, except for the increase in the measured temperature at midnight. Since this study was conducted while the classrooms were in use, occupancy at that hour was not considered, but the similarity between both simulation curves indicates that the main discrepancy is due to a lack of information about the internal events and not a software error. This explains the reason for having one of the lowest precisions of the research with 1.16 ℃ in DB and 1.14 ℃ in ED.

The relative humidity graph (Fig. 8) shows that this classroom does not present comfortable humidity conditions (≥40% ≥65%) with 71.50% on average and has a lower discrepancy than in the case of the temperature though it is concordant.

For the E1 108 classroom, both the temperature (Fig. 9) and humidity (Fig. 10) graphs present similar behaviour and minimal discrepancy closer to the lower temperatures of the comfort range with 17.9 ℃ on average. This result implies that with a minimal increase in hermeticity, the classroom can be comfortable throughout occupancy hours.

The E2 003 classroom, which is situated in the E2 building on the ground floor, does not receive much direct sunlight, and the temperature graph (Fig. 11) shows that it stays below a comfortable level of 15.3 ℃. For this particular day, it was not occupied; therefore, the simulations showed its performance under unused scenarios with 0.82 ℃ and 1.07 ℃ of discrepancy for the temperature simulated in DB and ED respectively. The humidity levels are in the comfort zone, and the graph (Fig. 12) shows that the values are closer between simulators than to the measured data.

The E2 102 classroom has a lower ventilation rate and higher temperature than the other classrooms in the same building, as shown in Fig. 13. Nevertheless, the ventilation rate, and temperature remain lower than the comfort range with 15.63 ℃ (≤17.62 °C) on average. The humidity measurements and simulation (Fig. 14) show that the humidity was above comfortable levels on average and similar discrepancy between software with 5.16% in DesingBuilder and 5.21% in ED.

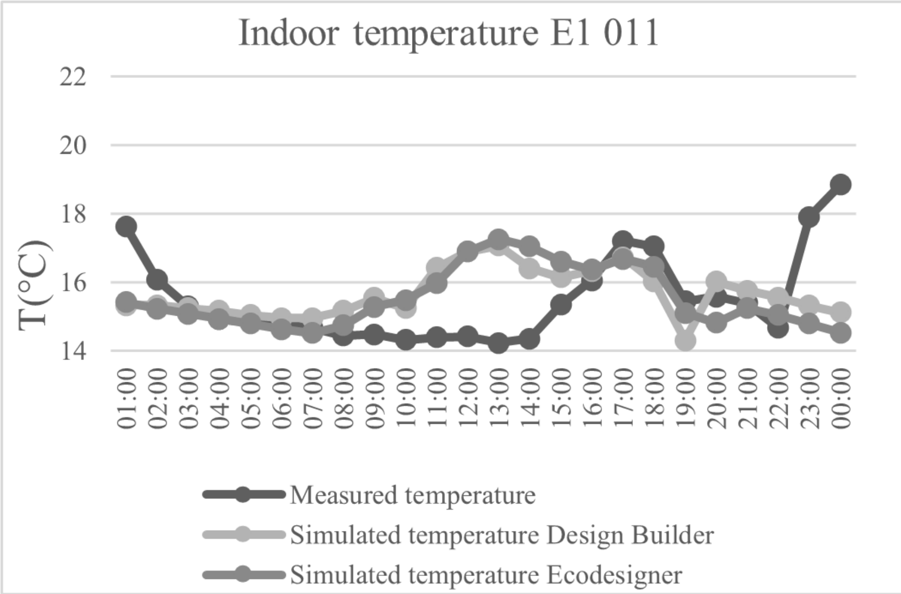



**Figure 7.** E1 011 Temperature comparative graph

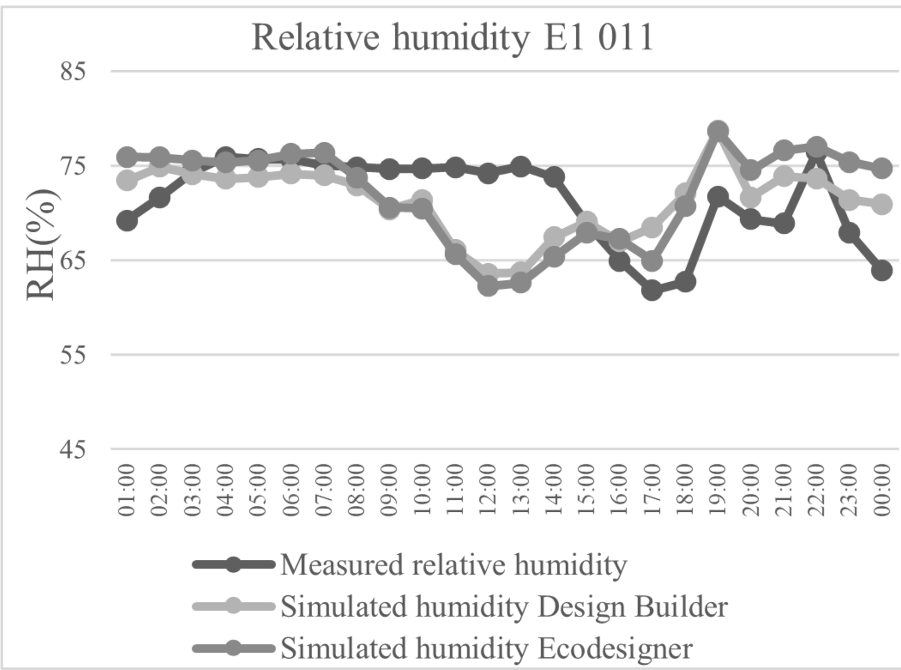



**Figure 8.** E1 011 Relative humidity comparative graph

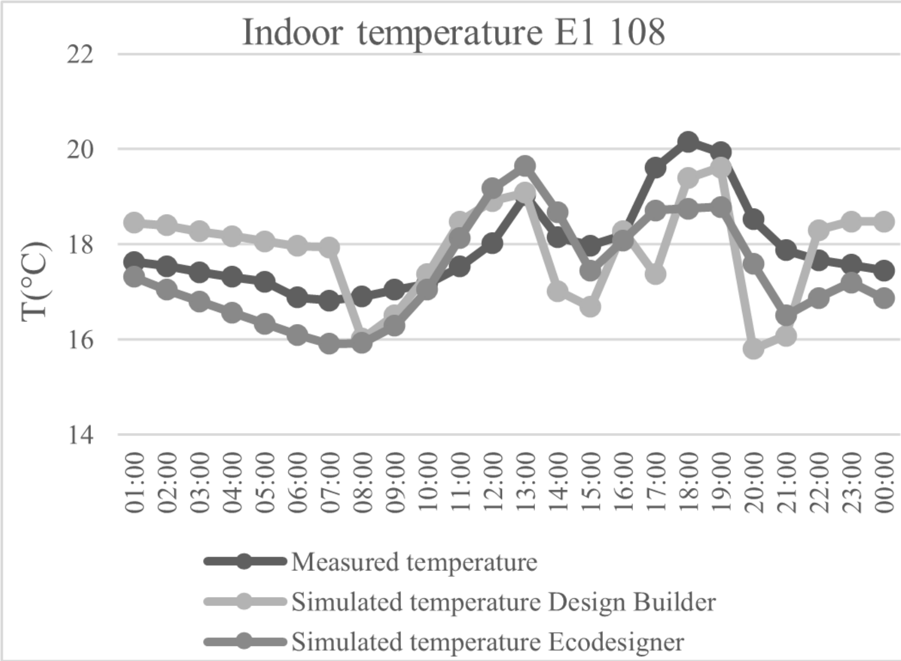



**Figure 9.** E1 108 Temperature comparative graph

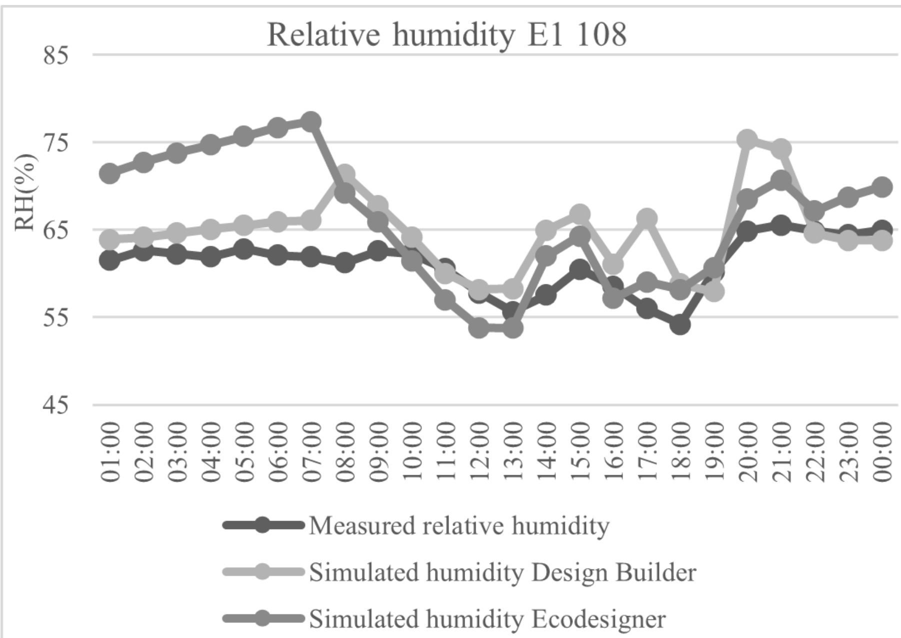



**Figure 10.** E1 108 Relative humidity comparative graph

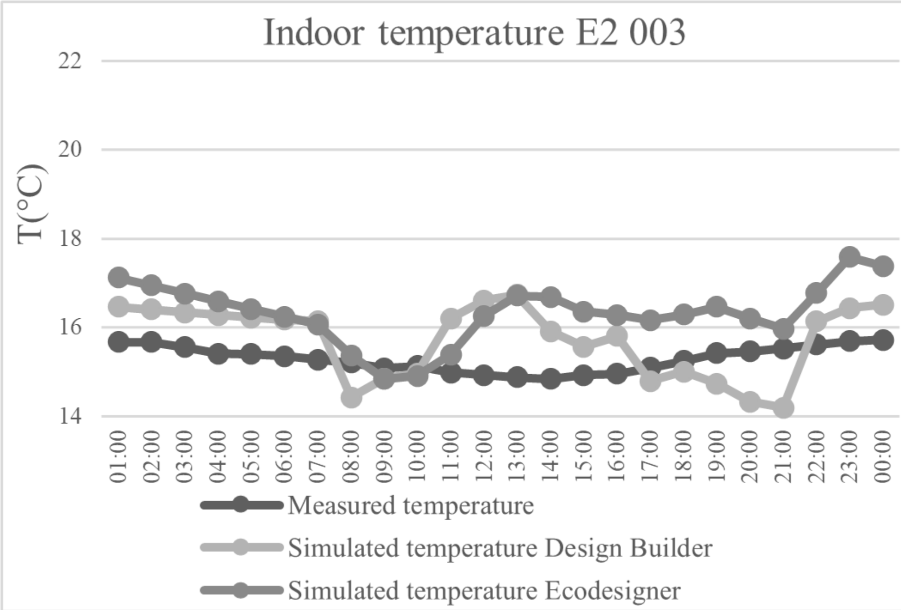



**Figure 11.** E2 003 Temperature comparative graph

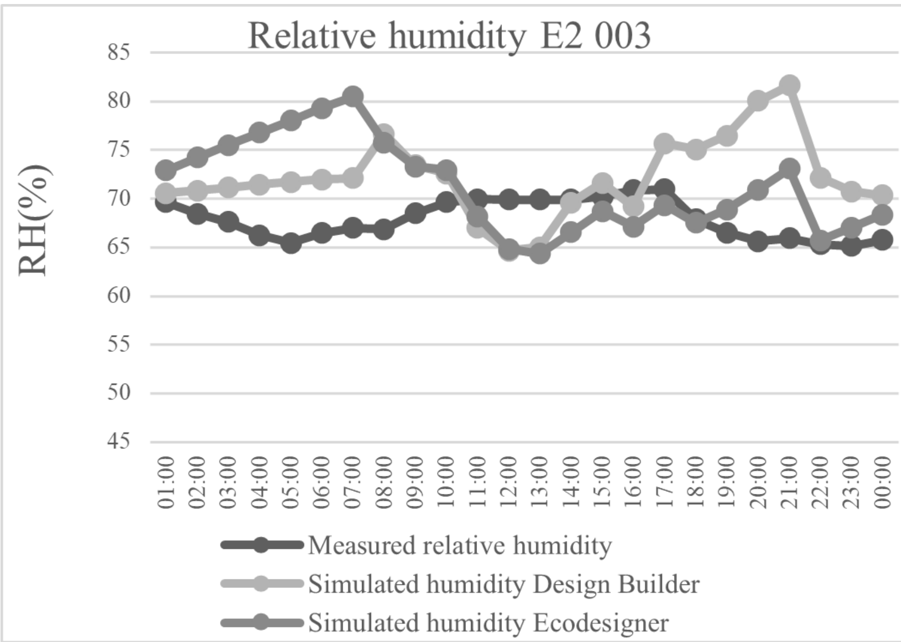



**Figure 12.** E2 003 Relative humidity comparative graph

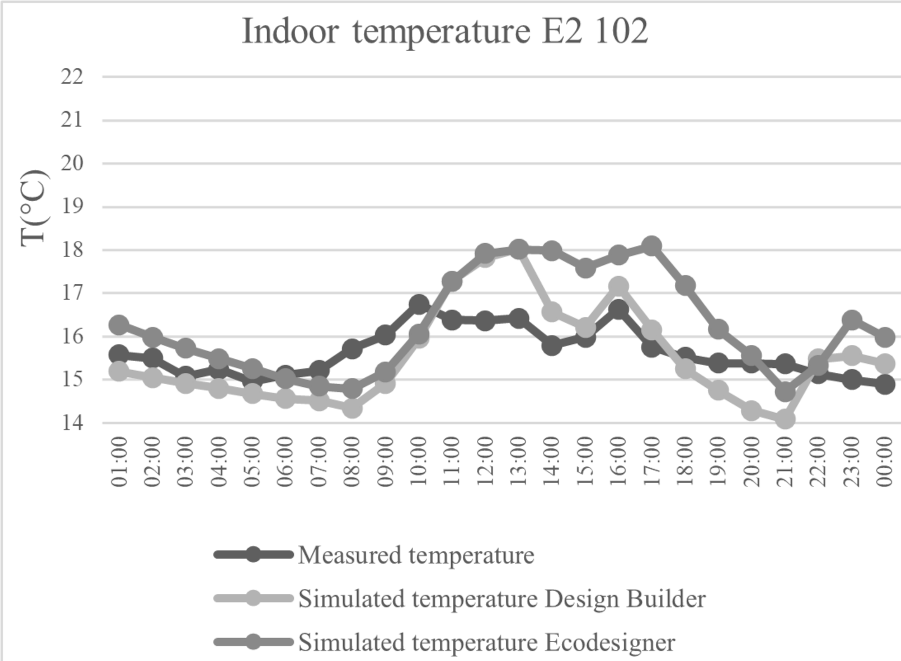



**Figure 13.** E2 102 Temperature comparative graph

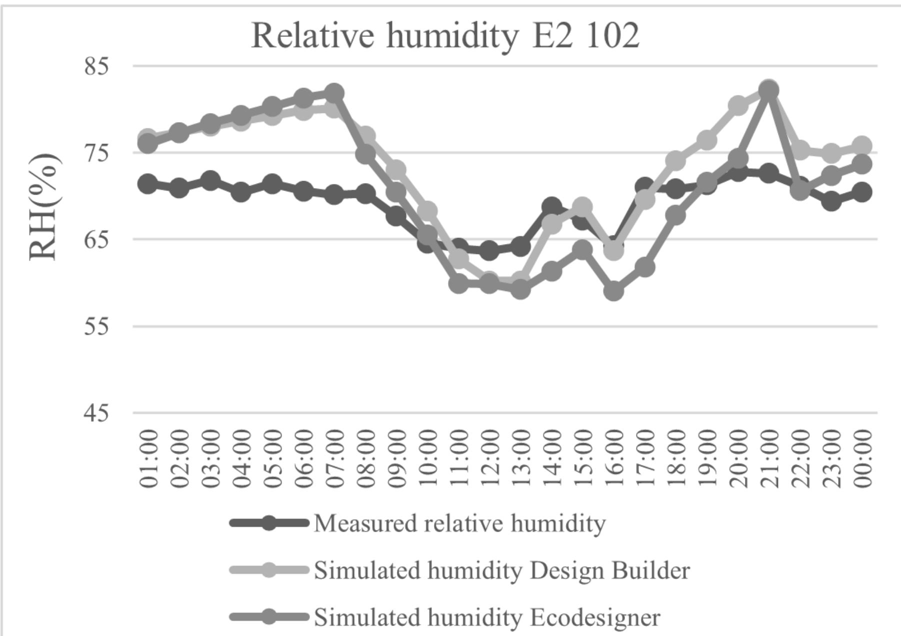



**Figure 14.** E2 102 Relative humidity comparative graph

During calibration in ED, the infiltration in windows and doors was increased from 20 l/s m ²to 40 l/s m ²only for classroom E2 203 to reduce the discrepancy without affecting the results in DB, where the closest values were obtained at 30 ACH. Moreover, since it is not a parameter that can be edited in DB to render comparable results, this exception is applied to this classroom only.

This classroom is simulated on the coldest day of the year, and since there were no occupants on Sunday, this classroom has the lowest temperatures (Fig. 15) with 12.28 ℃ the discrepancy with DB is 0.72 ℃ and 1.47 ℃ with ED. Since it is on the 3rd floor facing north, the wind seems to provide the most ventilation during the 24 hours of the day, and the greatest discrepancy for the ED simulation. This result implies that, upon reaching these levels of ventilation and low temperatures, the accuracy of this software program may start to decrease, although the relative humidity discrepancy is equal to that of the other classrooms (Fig. 16) being Ecodesigner the lesser discrepancy.

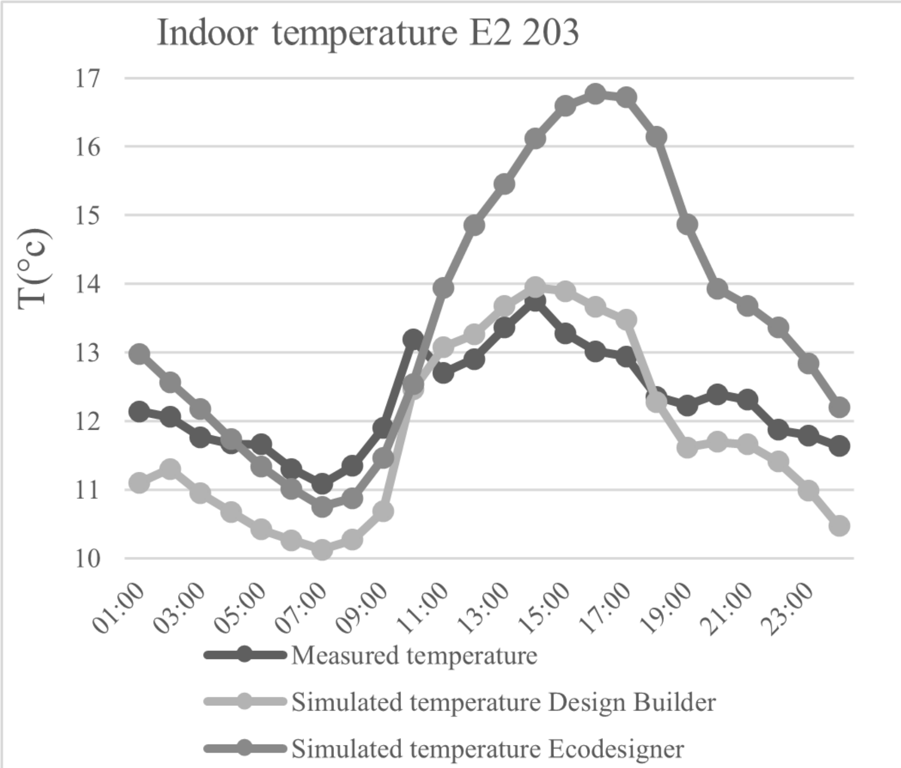



**Figure 15.** E2 203 Temperature comparative graph

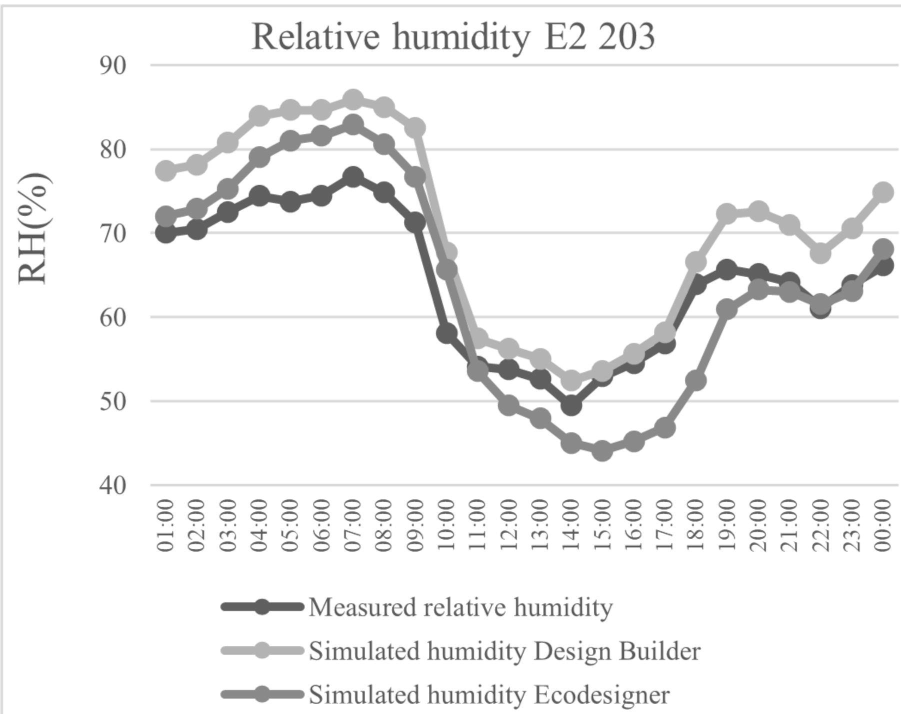



**Figure 16.** E2 203 Relative humidity comparative graph

E3 -102 is an underground classroom and a computer lab. Therefore, there was extra heat gain from computer usage and lower ventilation, resulting in a stable comfortable temperature during the whole day (Fig. 17). The humidity also remained stable and within the comfort range, with low discrepancies between the measured data and the simulation results (Fig. 18).

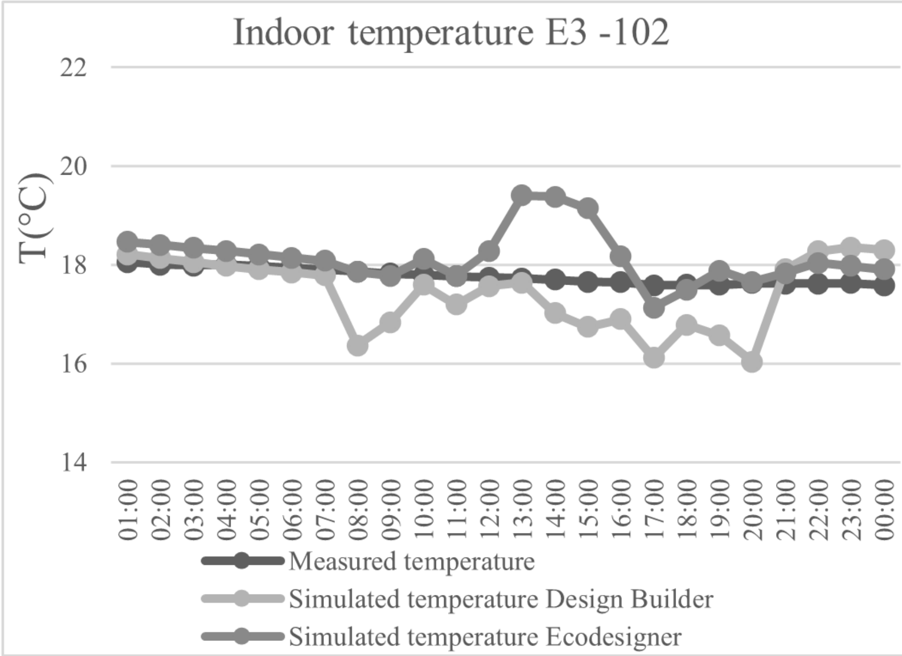



**Figure 17.** E3 -102 Temperature comparative graph

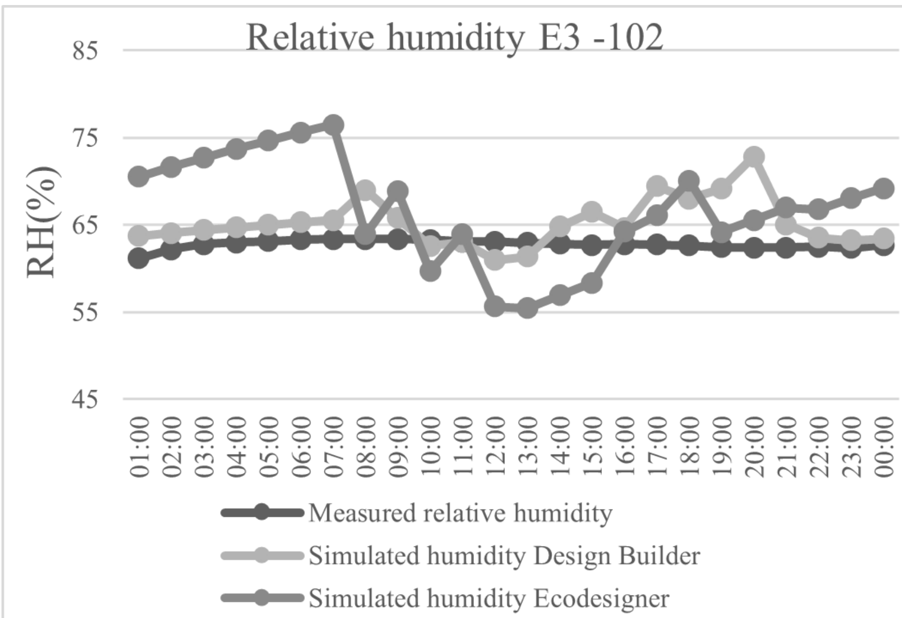



**Figure 18.** E3 -102 Relative humidity comparative graph

In ED, the E3 101 classroom scenario presented the best results for predicting temperatures during the day (Fig. 19). This scenario had temperatures near the lower values of the comfort range with small variations, but for the humidity, it exhibited a much greater discrepancy (Fig. 20). In the DB scenario, it had an average difference of approximately 5.5% for both temperature and humidity.

The E3 302 classroom is located on the highest level on the 4th floor and has a comfortable and stable temperature during the day (Fig. 21). Both simulation software programs presented a low discrepancy for the temperature but a much higher MAE for the relative humidity results (Fig. 22).

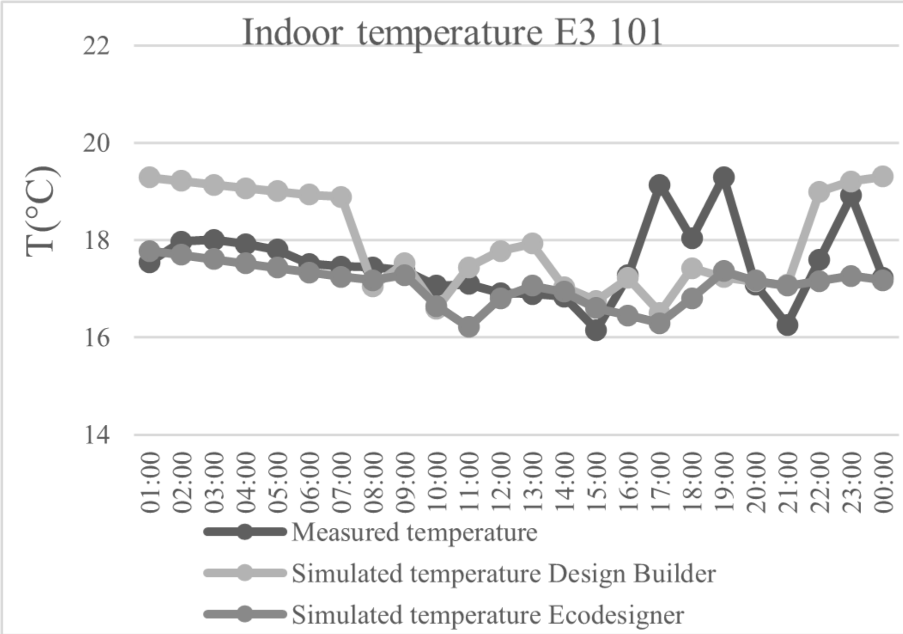



**Figure 19.** E3 101 Temperature comparative graph

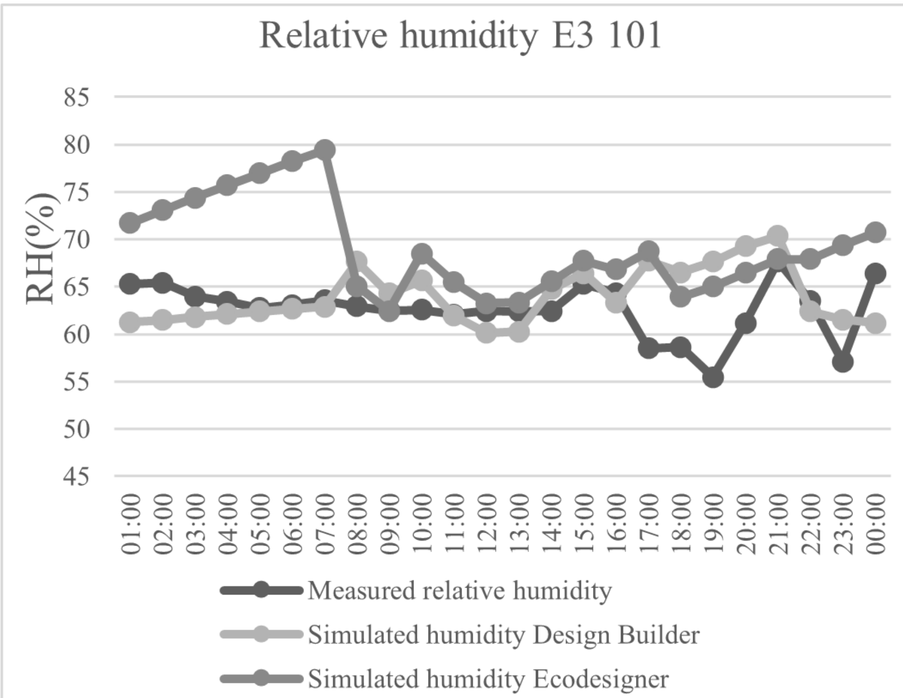



**Figure 20.** E3 101 Relative humidity comparative graph

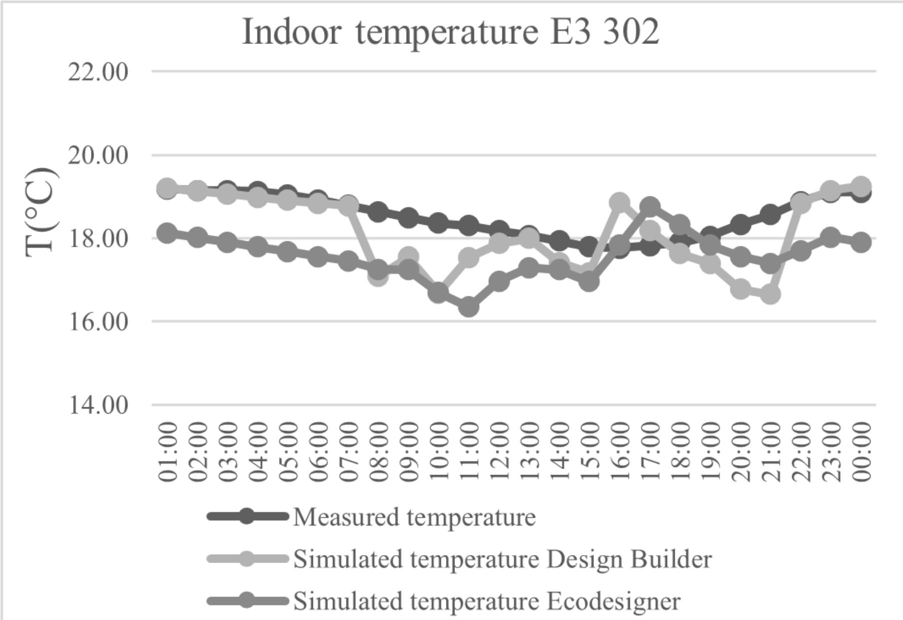



**Figure 21.** E3 302 Temperature comparative graph

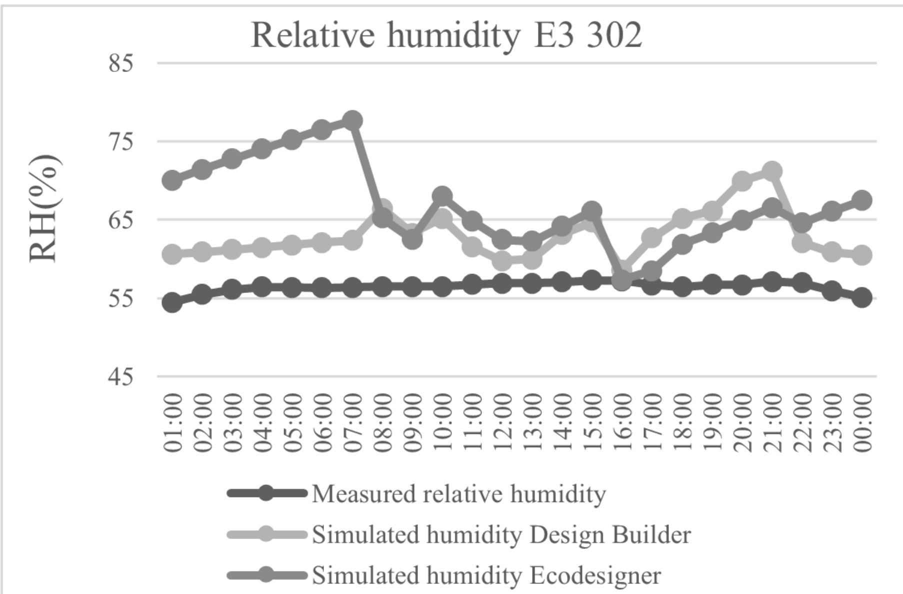



**Figure 22.** E3 302 Relative humidity comparative graph

The results indicate that after calibration, the comparison between the simulation and the measured temperature discrepancy decreased from 1.57 ℃ to 0.81 ℃ in DB and from 1.59 ℃ to 0.91 ℃ in ED (Table 19). For relative humidity, the MAE decreased from 5.59% to 5.00% in DB and from 8.00% to 6.09% in ED (Table 20).

**Table 19.** The temperature difference of the classrooms after calibration

| Temperature difference | | |
|---|---|---|
| Classroom | DesignBuilder | EcoDesigner |
| E1 -105 | 0.82 | 0.75 |
| E1 011 | 1.16 | 1.14 |
| E1 108 | 0.95 | 0.73 |
| E2 003 | 0.83 | 1.07 |
| E2 102 | 0.70 | 0.94 |
| E2 203 | 0.72 | 1.47 |
| E3 -102 | 0.57 | 0.44 |
| E3 101 | 0.97 | 0.60 |
| E3 302 | 0.54 | 1.07 |
| Average | 0.81 | 0.91 |

**Table 20.** The relative humidity error percentage of the classrooms after calibration

| Relative humidity error percentage | | |
|---|---|---|
| Classroom | DesignBuilder | EcoDesigner |
| E1 -105 | 6.67% | 5.35% |
| E1 011 | 4.45% | 4.97% |
| E1 108 | 3.98% | 6.10% |
| E2 003 | 5.51% | 5.25% |
| E2 102 | 5.16% | 5.21% |
| E2 203 | 6.41% | 4.81% |
| E3 -102 | 2.82% | 6.25% |
| E3 101 | 3.43% | 6.45% |
| E3 302 | 3.53% | 10.38% |
| Average | 5.00% | 6.09% |

The simulations and real internal measurements show a high ACH rate and ventilation in the classrooms; E1 and E2 have the most variations between 20 ACH, 30 ACH, and 40 ACH. These classrooms are mostly active during general occupation hours from 7 h to 21 h; and in the classroom, E2 203 infiltration remains on during all hours, which reveals a hermeticity deficiency due to construction design or location since no barriers are protecting it from south winds. The E3 building has a ventilation of 15 ACH during general faculty use.

Natural ventilation has been proven to be relatively controlled since outside of occupation hours, ventilation rates drop drastically for most classrooms, and the temperature becomes more stable.

For this study, the findings suggest that the models are calibrated and can be utilized to simulate changes and optimize areas to reach comfort levels for longer periods via both software programs.

# 4. Discussion and Conclusions

## 4.1. Discussion

This work builds on previous investigations by taking virtual thermal simulation models and calibrating them to compare them between different simulation engines. It confirmed the results of a temperature simulation comparison with an average of 0.81 ℃, which, compared with previous studies, equals a relative 5% average discrepancy for Design Builder's simulation and was found to decrease from 9% in previous studies to approximately 6% for ED with a 0.91 ℃ temperature difference. These results are based on the average measurements for nine classrooms, resulting in three times the amount of data used in previous studies. This study also goes beyond previous research to simulate the relative humidity and obtain its average precision for each software program.

For this research the calibration parameters have been restricted to only ventilation rate and occupation, in other published studies the models have been calibrated in several thermal block parameters [17], and this can be beneficial to a specific model which intends to present only modifications to said model, however for this research purposes the comparison of both software under equally predictable and common scenarios presented a challenge that must be prioritized.

## 4.2. Conclusions

The obtained data can be used as a basis for new classroom designs locally because of the possible discrepancy in the software programs even without calibration, the precision is less than 1.58 ℃ ta MAE, and less than a 10% RH MAE. Moreover, the data can even be considered to pose restrictions on building occupancy to maintain comfort. Though, these tools are alternatives for comparing similar scenarios, and in reality, thermal conditions are affected by several factors that are difficult to consider together.

The studied classrooms are proven to have great potential for meeting thermal comfort levels without energy consumption since their main problem is staying near the lower end of the comfort temperature range with very high infiltration-ventilation levels. Consequently, increasing ACH control by improving hermeticity would probably result in reaching comfort levels, especially when occupancy adds internal gains. Adding insulation to specific constructive elements such as windows can prevent heat loss.

The parameters that altered the simulated temperature the most were infiltration in DB and natural ventilation in ED. These parameter values conditioned the temperature results comparably. Importantly, in DB, the natural ventilation parameter does not impact the results equally, whereas the infiltration parameter in ED does, as mentioned. This value is expressed for each constructive element and in different units; therefore, since this study focuses on comparing the two software programs, this value is mostly fixed, as previous research has indicated.

The older brick buildings E1 and E2 have a higher ACH, i.e., 20, 30, and 40 ACH, than the newer building with only 15 ACH, which consequently produces more comfortable temperatures.

The precision of the obtained data can be improved by simulating and comparing the simulated results on several days at different times of the year and taking measures throughout the year.

Both simulation software reached a calibrated status with ED achieving lesser results with ≤2°C and ≤10% for the model, although it runs two infiltration-ventilation parameters therefore it can be an indication that there is room for lowering the discrepancy obtained in a non-comparison research.

DesignBuilder which achieved the highest calibrated model benchmark with ≤1 ℃ and ≤5% can be understood as the one that can get to the calibration status easier due to the fewer parameters available, but with less room for specification.

For a punctual study of one classroom, it is also possible to capture more data on the occupation, such as how many students were in the classroom and, if any, how many computers were in use as well as the carpentry openings, to determine what changed during occupation and at what time.

This research can be reproduced and altered for different climate zones, construction systems and times of year to start generating a database for new buildings that are to be constructed under the same climate conditions, thus preventing increased error when the software tools are not calibrated.

It can be interpreted as follows: due to the reduction from general occupation to a more exact occupation schedule and natural ventilation to reduce the temperature difference, the relative humidity difference is also reduced.

This reduction in the error is not that important, still, it creates an opportunity for new studies that can specifically research this phenomenon and identify parameters that affect it in a more significant way, especially for detecting infiltration in local carpentry.

## Acknowledgements

This research was funded by the Vice Rector for Research of the University of Cuenca (VIUC), for which we are grateful, and is part of the Project “Planificación energética territorial: Situación actual y metodología para integración de generación y redes eléctricas en el territorio y PDOTs”.

# Appendix

**Table 21.** Façade walls U-value Calculation

| Walls | Material | λ (W/mK) | Thickness (m) | Thermal resistance ($m^2$*K/w) | Thermal transmittance (W/m K) |
|---|---|---|---|---|---|
| | | | | R= thickness/Coef. | U=1/Rt |
| type 1.1 | | | Rsi | 0.13 | |
| | Brick | 0.84 | 0.15 | 0.178571429 | |
| | | | Rse | 0.04 | |
| | | | ∑R+Rsi+Rse | 0.348571429 | 2.87 |
| type 1.2 | | | Rsi | 0.13 | |
| | Brick | 0.84 | 0.15 | 0.178571429 | |
| | Brick | 0.84 | 0.15 | 0.178571429 | |
| | | | Rse | 0.04 | |
| | | | ∑R+Rsi+Rse | 0.527142857 | 1.90 |
| type 1.3 | | | Rsi | 0.13 | |
| | Brick | 0.84 | 0.15 | 0.178571429 | |
| | Brick | 0.84 | 0.15 | 0.178571429 | |
| | Brick | 0.84 | 0.15 | 0.178571429 | |
| | | | Rse | 0.04 | |
| | | | ∑R+Rsi+Rse | 0.705714286 | 1.42 |
| type 2 | | | Rsi | 0.13 | |
| | Concrete facade panel | 2 | 0.05 | 0.025 | |
| | Isolation | 0.15 | 0.05 | 0.333333333 | |
| | Concrete block | 0.62 | 0.09 | 0.14516129 | |
| | Mortar | 0.5 | 0.02 | 0.04 | |
| | | | Rse | 0.04 | |
| | | | ∑R+Rsi+Rse | 0.713494624 | 1.40 |
| type 3 | | | Rsi | 0.13 | |
| | Steel facade panel | 50.2 | 0.0025 | 4.98008E-05 | |
| | Isolation | 0.15 | 0.05 | 0.333333333 | |
| | Concrete block | 0.62 | 0.09 | 0.14516129 | |
| | Mortar | 0.5 | 0.02 | 0.04 | |
| | | | Rse | 0.04 | |
| | | | ∑R+Rsi+Rse | 0.688544424 | 1.45 |

**Table 22.** Envelope floors U-value Calculation

| Floors | Material | λ (W/mK) | Thickness (m) | Thermal resistance ($m^2$*K/w) | Thermal transmittance (W/m Ꝁ) |
|---|---|---|---|---|---|
| | | | | R=thickness/λ | U=1/Rt |
| type 1 | | | Rsi | 0.17 | |
| | Concrete tile | 1.3 | 0.02 | 0.015384615 | |
| | Mortar | 0.5 | 0.01 | 0.02 | |
| | Concrete | 1.63 | 0.07 | 0.042944785 | |
| | Stone | 1.83 | 0.2 | 0.109289617 | |
| | | | Rse | 0.04 | |
| | | | ∑R+Rsi+Rse | 0.397619018 | 2.51 |

**Table 23.** Envelope ceilings U-value Calculation

| Ceilings | Material | λ (W/mK) | Thickness (m) | Thermal resistance ($m^2$*K/w) | Thermal transmittance (W/m Ꝁ) |
|---|---|---|---|---|---|
| | | | | R=thickness/λ | U=1/Rt |
| type 1 | | | Rsi | 0.1 | |
| | Mortar | 0.5 | 0.02 | 0.04 | |
| | Concrete | 1.63 | 0.07 | 0.042944785 | |
| | Lightweight concrete block | 0.56 | 0.2 | 0.357142857 | |
| | Air chamber lightly ventilated | 0.32 | 0.43 | 1.34375 | |
| | Gypsum | 0.25 | 0.01 | 0.04 | |
| | | | Rse | 0.04 | |
| | | | ∑R+Rsi+Rse | 1.963837642 | 0.509207064 |
| type 2 | | | Rsi | 0.1 | |
| | Mortar | 0.5 | 0.02 | 0.04 | |
| | Concrete | 1.63 | 0.28 | 0.171779141 | |
| | | | | 0.04 | |
| | | | ∑R+Rsi+Rse | 0.351779141 | 2.84269271 |
| type 3 | | | Rsi | 0.1 | |
| | Gravel | 0.36 | 0.01 | 0.027777778 | |
| | Mortar | 0.5 | 0.01 | 0.02 | |
| | Concrete | 1.63 | 0.07 | 0.042944785 | |
| | Lightweight concrete block | 0.56 | 0.35 | 0.625 | |
| | Mortar | 0.5 | 0.01 | 0.02 | |
| | | | Rse | 0.04 | |
| | | | ∑R+Rsi+Rse | 0.875722563 | 1.141914166 |

**Table 24.** Partition walls U-value Calculation

| Walls | Material | λ (W/mK) | Thickness (m) | Thermal resistance ($m^2$*K/w) | Thermal transmittance (W/m K) |
|---|---|---|---|---|---|
| | | | | R=thickness/λ | U=1/Rt |
| type 1.1 | | | Rsi | 0.13 | |
| | Brick | 0.84 | 0.145 | 0.17261905 | |
| | | | Rse | 0.13 | |
| | | | ∑R+Rsi+Rse | 0.43261905 | 2.31 |
| type 1.2 | | | Rsi | 0.13 | |
| | Brick | 0.84 | 0.145 | 0.17261905 | |
| | Brick | 0.84 | 0.145 | 0.17261905 | |
| | | | Rse | 0.13 | |
| | | | ∑R+Rsi+Rse | 0.6052381 | 1.65 |
| type 2 | | | Rsi | 0.13 | |
| | Mortar | 0.5 | 0.02 | 0.04 | |
| | Concrete block | 0.62 | 0.09 | 0.14516129 | |
| | Mortar | 0.5 | 0.02 | 0.04 | |
| | | | Rse | 0.13 | |
| | | | ∑R+Rsi+Rse | 0.48516129 | 2.06 |

**Table 25.** Partition floors U-value Calculation

| Floors | Material | λ (W/mK) | Thickness (m) | Thermal resistance ($m^2$*K/w) | Thermal transmittance (W/m K) |
|---|---|---|---|---|---|
| | | | | R=thickness/λ | U=1/Rt |
| type 1 | | | Rsi | 0.17 | |
| | Concrete tile | 1.3 | 0.02 | 0.01538462 | |
| | Mortar | 0.5 | 0.01 | 0.02 | |
| | Concrete | 1.63 | 0.07 | 0.04294479 | |
| | Lightweight concrete block | 0.56 | 0.25 | 0.44642857 | |
| | | | Rse | 0.17 | |
| | | | ∑R+Rsi+Rse | 0.86475797 | 1.15639292 |
| type 2 | | | Rsi | 0.17 | |
| | Concrete tile | 1.3 | 0.015 | 0.01153846 | |
| | Concrete | 1.63 | 0.07 | 0.04294479 | |
| | Lightweight concrete block | 0.56 | 0.35 | 0.04294479 | |
| | Mortar | 0.5 | 0.015 | 0.625 | |
| | | | Rse | 0.17 | |
| | | | ∑R+Rsi+Rse | 1.06242803 | 0.94124023 |

Table 25 continued

| | | | | | |
|---|---|---|---|---|---|
| type 3 | | | Rsi | 0.17 | |
| | Parquet | 0.17 | 0.015 | 0.08823529 | |
| | Mortar | 0.5 | 0.015 | 0.03 | |
| | Concrete | 1.63 | 0.07 | 0.04294479 | |
| | Lightweight concrete block | 0.56 | 0.25 | 0.44642857 | |
| | | | Rse | 0.17 | |
| | | | ∑R+Rsi+Rse | 0.94760865 | 1.05528796 |
| type 4 | | | Rsi | 0.17 | |
| | Parquet | 0.17 | 0.015 | 0.08823529 | |
| | Concrete | 1.63 | 0.07 | 0.04294479 | |
| | Lightweight concrete block | 0.56 | 0.35 | 0.625 | |
| | Mortar | 0.5 | 0.015 | 0.03 | |
| | | | Rse | 0.17 | |
| | | | ∑R+Rsi+Rse | 1.12618008 | 0.88795746 |
| type 5 | | | Rsi | 0.17 | |
| | Cement overlay | 0.46 | 0.015 | 0.0326087 | |
| | Mortar | 0.5 | 0.015 | 0.03 | |
| | Concrete | 1.63 | 0.07 | 0.04294479 | |
| | Lightweight concrete block | 0.56 | 0.2 | 0.35714286 | |
| | Air chamber lightly ventilated | 0.32 | 0.43 | 1.34375 | |
| | Gypsum | 0.25 | 0.01 | 0.04 | |
| | | | Rse | 0.17 | |
| | | | ∑R+Rsi+Rse | 2.18644634 | 0.45736316 |

**Table 26.** Subterrain envelope walls U-value Calculation

| **Walls** | **Material** | **λ (W/mK)** | **thickness (m)** | **Thermal resistance ($m^2$*K/w)** | **Thermal transmittance (W/m Ʉ)** |
|---|---|---|---|---|---|
| | | | | R=thickness/λ | U=1/Rt |
| Type 1 | Brick | 0.84 | 0.145 | 0.172619048 | |
| | Brick | 0.84 | 0.145 | 0.172619048 | |
| | | | ∑R | 0.345238095 | 1.17 |
| Type 2 | Concrete block | 0.62 | 0.09 | 0.14516129 | |
| | Mortar | 0.5 | 0.02 | 0.04 | |
| | | | ∑R | 0.18516129 | 1.22 |

**Table 27.** Subterrain floors U-value Calculation

| Floors | Material | λ (W/mK) | Thickness (m) | Thermal resistance ($m^2$*K/w) | Perimeter | Area | B´ | Depth | Thermal transmittance (W/$m^2$K) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | R=thickness/λ | | | B´=A/(0.5*P) | | Table 4 |
| Type 1 | Parquet | 0.17 | 0.015 | 0.088235294 | 9.86 | 71.2 | 14.44421907 | 0.9 | |
| | Mortar | 0.5 | 0.015 | 0.03 | | | | | |
| | Concrete | 1.63 | 0.07 | 0.042944785 | | | | | |
| | Concrete | 1.83 | 0.2 | 0.109289617 | | | | | |
| | | | ∑R | 0.270469697 | | | | | 0.30 |
| Type 2 | Cement overlay | 0.46 | 0.015 | 0.032608696 | 8.17 | 64.2 | 15.72582619 | 1.62 | |
| | Concrete | 1.63 | 0.07 | 0.042944785 | | | | | |
| | Concrete | 1.83 | 0.2 | 0.109289617 | | | | | |
| | | | ∑R | 0.184843098 | | | | | 0.25 |

The thermal transmittance of subterrain elements is obtain using tables 4 and 5 of the document "Calculo de parametros caracter ísiticos de la envolvente" [22].

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