A Comparison Among Three Whole-Building Dynamic Simulation Software and their Applicability to the Indoor Climate Modelling of Historical Buildings

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Abstract

Building energy simulations are important for assessing the performance of buildings and for designing solutions aimed at reducing energy consumption and carbon emissions. Many software tools perform these simulations, focusing on systems operations and energy losses and gains. When it comes to modelling historical buildings, the simulations could be also used to estimate the risk of damage and decay processes. This paper presents preliminary results based on twelve standardised exercises of increasing complexity for the comparison of microclimate simulations modelled through three whole-building hygrothermal dynamic simulation (BDS) software tools, specifically IDA ICE, WUFI PLUS and ENERGY PLUS. Different to the testing procedures already available, this research focused on the physical variables that are relevant for conservation of historical buildings (i.e., temperature (T) and relative humidity (RH)). Starting from Common Exercise 0 (CE0), seven simulations were customised to capture differences in T values. Then, five building models were specifically conceived to consider some typical features of Historical Buildings (HB0): small window size, heavyweight structures, low insulation of roofs, large volume and free-floating conditions. In the case of CE0, good agreement was found in the simulation of indoor T. In addition, detailed windows reduced the discrepancy in T results compared with the use of simplified windows. In the case of HB0, small windows slightly affected the microclimate simulations regardless of the number of transparent elements and their position. RH variability was driven only by T, as the partial water vapor pressure was affected only by infiltrations through the building. To conclude, the comparison allowed a highlighting of some critical points due to different model implementations, such as weather file timestamp interpretation, window models or irradiation calculations. HB0 models could be used for software and model comparisons, new software testing and training activities.

1. Introduction

Whole-building dynamic simulation (BDS) has been extensively applied over the last decades to study the energy performance of new and existing buildings. BDS can be used as a tool to identify measures aimed at reducing energy consumption and greenhouse gas emissions, as required by the Green Deal to be climate neutral in 2050. In the case of historical buildings, which account for a relevant portion of the total amount of energy consumption (Filippi, 2015) and are part of the cultural heritage, designing efficient and cautious interventions to accomplish the Green Deal goals is a complex matter. In addition, since humidity plays a key role in the different deterioration phenomena affecting materials (making the choice of unique critical thresholds challenging (EN 16893:2018)), simulation can identify the conservation risks of materials triggered by indoor climate conditions (Akkurt et al., 2020; Frasca et al., 2021).

In this context, it was demonstrated that the hygrothermal modeling through BDS can be used advantageously to design solutions for minimizing the energy demand whilst keeping the risk of deterioration low. However, whole set of BDS software needs to accurately model the time behavior of the key hygrothermal variables (e.g., temperature and relative humidity) responsible for degradation on a short and long-term scale. Several commercial BDS software tools are available for hygrothermal modeling. However, since they are based on different numerical methods and parameterizations to solve physical equations, discrepancies may occur in the simulation of indoor climate conditions when the same building is modeled using different BDS software. For this reason, it is worth estimating to what extent the variability among the outputs from different BDS software can affect decision-making on energy (e.g., setup of HVAC systems (Nicolai et al., 2021; Tarantino, 2020)) and conservation issues in real applications (e.g., estimation of climate-induced conservation risks (Frasca et al., 2021; Libralato et al., 2021a)). This evaluation is important, as it offers the chance to provide comparable indoor climate projections regardless of the BDS software in use. This aspect plays a key role when it comes to assessing the impact of the ongoing climate change on material conservation (Campisi & Colajanni, 2021) and the effectiveness of materials for retrofitting/strengthening historical structures. In such a way, the BDS becomes a powerful approach to be applied with the aim of contributing towards meeting global 2030 Sustainable Development Goals (SDGs) in the historical building sector (e.g., definition of adaptation pathways and mitigation strategies against climate change).

This study aimed to compare three commercial whole-BDS software tools (namely EnergyPlus, IDA Indoor Climate and Energy (ICE) and WUFI Plus) frequently validated and commonly used in research activities for the indoor climate modeling of historical buildings (to cite but a few Angelotti et al., 2019; Frasca et al., 2018; Gori et al., 2021; Libralato et al., 2021b). The comparison, based on standardised exercises, was not conceived to identify the most suitable tools for historical buildings modeling, but rather to evaluate the effect on simulations due to the differences in interfaces and modeling approaches. In this contribution, indoor humidity balance considered only the water vapor in/exfiltration through the envelope, to limit the initial uncertainties related to heat and moisture transfer through walls. Further investigations on this topic will be the subject of future studies.

2. Materials and Methods

According to ANSI/ASHRAE 140 Standard, there are three ways to evaluate the accuracy of BDS software tool: empirical validation (comparison with measured data), analytical verification (comparison with a known analytical solution) and comparative testing (the software is compared with itself or to other programs). In this paper, we adopted the comparative testing to estimate the differences among the three BDS software tools. Comparison among BDS software was conceived

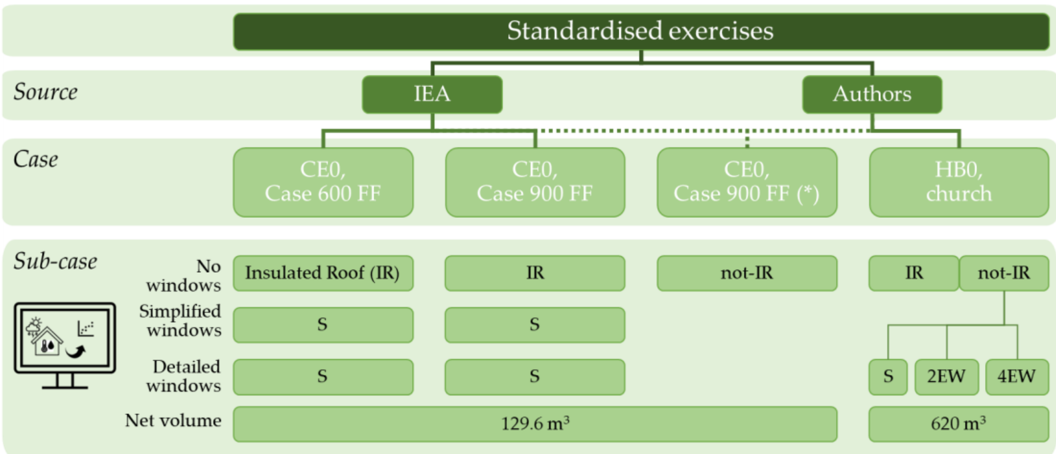

Fig. 1 – Set of simulations based on standardised exercises for the comparative assessment of commercial whole-building dynamic simulation software. CE0: Common Exercise 0; HB0: Historical Building 0; IR: insulated roof; not-IR: not-insulated roof; S: south façade; E: east façade; W: west façade; 2: two windows; 4: four windows

following the schema in Fig. 1. The simulation set consisted of twelve standardised exercises that considered both the BESTEST (Building Energy Simulation TEST) Common Exercise 0 (hereafter called CE0), developed in the framework of the International Energy Agency (IEA), and a historical building (HB0) proposed by the authors. CE0 included seven sub-cases aimed at studying both the influence on simulations of detailed/simplified south-oriented windows as well as the role of a flat insulated/not-insulated roof. HB0, on the other hand, included five sub-cases with a sloping insulated/not-insulated roof and an increasing number of differently oriented windows (South, East-West).

All simulations were run with an initialization period of 31 days and a weather file of data having time steps of 1 hour. All simulations covered one calendar year.

In this study, *.EPW files were used for the weather file. Energy Plus uses the "next hour interpolation scheme", assigning the 1:00 time stamp to the average of the weather file values at hour 0:00 and 1:00. IDA ICE interprets the weather file, assigning the value around the time stamp (average value measured between 30 minutes before and after the time stamp) and the results are reported as the average of the hour preceding the output time stamp. WUFI Plus uses the *.EPW file provided by the user, as it is, starting from hour 01:00 (first observation) and automatically converting radiation and rain (the latter is not included in simulations within this research) in order to consider these loads in accordance with the orientation and the inclination of the individual building component.

IDA ICE climate calculations were based on the "BDFwall" thermal model using a finite differences algorithm of a multi-layer component including wind-dependent bidirectional heat and moisture transport through leaks.

WUFI Plus performed thermal calculations including methods for wind-dependent heat transfer on external surfaces and moisture balance due to in/exfiltration.

In Energy Plus, the heat balance algorithm used is the "Conduction Finite Difference" algorithm, based on the finite difference method. The surface convection algorithm for the external surfaces is the "DOE-2" algorithm, wind-dependent and based on measurements, while for the internal surfaces, constant convection coefficients are used.

In all simulations, a constant air infiltration was set, meaning that no wind-driven air and vapor infiltrations were considered.

2.1 BESTEST Developed in the Framework Of IEA Annex

The CE0 exercise was used to investigate differences in free-floating (FF) simulations among the three BDS software for both lightweight (Case 600) and heavyweight (Case 900) buildings, using the weather at the site of Denver-Stapleton. The FF cases were chosen, as in most historical buildings, active climate control systems are not used. The common exercise adopted was slightly modified to study the features of the BDS software in the simulation of indoor temperature through cases at increasing complexity. All features were retrieved from the Publications and Work Reports available online for the IEA Annex 41 (Rode & Woloszyn, 2007). The influence of solar radiation incident on opaque and transparent surfaces was evaluated modeling the building firstly without windows and, then with windows on the southern façade (U-value = 3.0 $W \cdot m^{-2} \cdot K^{-1}$; hemispherical SHGC = 0.686). Specifically, windows were modeled using both simplified and detailed models available in the BDS software to estimate the influence of the input parameters on the indoor temperature. Windows models differ from the number of input parameters that users can set. In addition, we decided to modify Case 900 FF by replacing the original roof with a not-insulated roof. This case, renamed Case 900 FF (*), was conceived to understand the influence on indoor temperature simulations of not-insulated roof in heavyweight structures (i.e., typical features in historical buildings).

2.2 Standardised Exercise for Historical Building (HB0)

A new standardised exercise for historical buildings (HB0) was proposed by the authors, starting from the average features extracted from the literature on the topic (Akkurt et al., 2020) and from the Italian technical report UNI/TR 11552:2014. All the cases are considered in free-floating conditions, without internal gains (occupants and other devices) in accordance with CE0.

Fig. 2 shows the 3D geometry of the HB0 model used in the tested sub-cases. Table 1 summarizes some features of the opaque elements in HB0. The simulations are performed using the IWEC weather file for Rome.

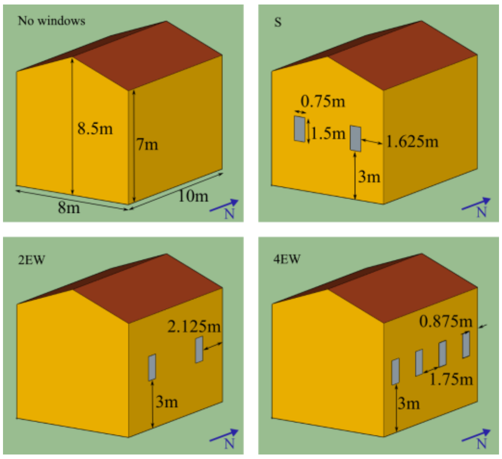

Fig. 2 – 3D sketch of the standardised exercise HB0 used to compare commercial whole-building dynamic simulation software in case of a historical building. Net floor area = 80 m^2; net volume = 620 m^3

U-value of the floor is extremely low in accordance with the BESTest and to avoid the effect of ground modeling on the indoor climate simulation. Windows were modeled as single pane glass with a total transparent area of 0.75×1.5 m^2 without frame and a U-value of 5.5 W·m^{-2}·K^{-1}. Five sub-cases were modeled (Fig. 2):

- no transparent elements and insulated roof (hereafter called IR);
- no transparent elements and not-insulated roof (not-IR);
- two windows on south façade (2S);
- two windows on both east and west façades (2EW);
- four windows on both east and west façades (4EW).

The air infiltrations were set to a constant air change of 0.7 h^{-1}, i.e., an average infiltration rate in historical churches (Akkurt et al., 2020). In addition, solar emissivity and absorption of internal/external opaque surfaces were set equal to 0.9 and 0.6, respectively.

2.3 Statistical Analysis

The average of the maximum semi-dispersion (Δ_{max}, i.e., the mean half spread between the smallest and largest number over the simulation period) was used as a synthetic index to compare the variability of hourly microclimate values (i.e., temperature and relative humidity) resulting from the annual simulations modeled by the three BDS software tools. As no reference has been defined so far to estimate agreement between simulations run by different BDS software tools, we decided to use the threshold suggested in (Frasca et al., 2021; Rajčić et al., 2018) for the accuracy assessment of the hygrothermal simulations with respect to microclimate observations: high agreement, if data are within ± 1 °C for T and ± 5 % for RH, good agreement, if data are within ± 3 °C for T and ± 10 % for RH, and poor agreement, if data are beyond ± 3 °C for T and ± 10 % for RH.

Table 1 – Summary of thermo-physical properties of opaque elements in HB0

Building component	**Area**	**U-value**	**Thermal mass**
Unit	[m^2]	[W·m^{-2}·K^{-1}]	[kJ·m^{-2}·K^{-1}]
External walls	264	0.67	1184
Roof	88	2.48	255
Floor	80	0.04	112

In the case of CE0, the daily evolution of indoor and outdoor temperatures was plotted to assess agreement at a short-term time scale among the three BDS software tools on the coldest and the hottest days of the year of the weather file, respectively.

In the case of HB0, a 3-by-3 matrix of plots was used to analyse the differences in the microclimate outcomes (temperature and partial water vapor pressure). The scatter plots in the matrix allowed a comparison of the outputs between pairs of BDS software (*inter-comparison*). Along the matrix diagonal, stair plots were displayed to study the influence of different HB0 configurations on the microclimate variables within the same BDS software (*intra-comparison*).

3. Results

3.1 BESTEST in IEA Annex (CE0)

Table 2 shows that:

- in the case without windows, temperature simulations were in good agreement both in light- and heavyweight structures;
- the highest variability is associated with the simulations of Case 600 FF with simplified windows;
- the use of detailed windows allowed a reduction in dispersion among simulated indoor T values from 1.4-2.2 °C to 0.9-1.8 °C.

Table 2 – Summary of the maximum semi-dispersion (Δ_{max}) of the hourly temperature values modeled by the three BDS software tools in case of CE0 in free-floating conditions

Case	No windows	Simplified windows	Detailed windows
Case 600 FF	1.0	2.2	1.8
Case 900 FF	0.7	1.4	0.9
Case 900 FF (*)	1.1	-	-

In addition, for both Case 600 FF and Case 900 FF with detailed windows, the modeled minimum annual temperature values (i.e., when the impact of solar radiation is limited) were in accordance with the reference ranges reported in (Rode & Woloszyn, 2007).

On the other hand, lower agreement was observed with the reference ranges in terms of the average and maximum annual temperature values, due to differences in the calculation of solar gains through windows. The first source of discrepancy in the time series of the results is different interpretation of the weather file (WF) due to the different conversion of the time stamp to specific points in time used by the BDS software.

As an example, Figs. 3 and 4 show that the weather file temperatures considered by each software (WF series) have a time shift of at least one hour.

The discrepancy in the WF series influences the simulation of indoor temperatures. Indeed, although highly correlated, T peaks modeled by WUFI Plus and Energy Plus models showed a one-hour delay compared with IDA ICE. This behavior is also affected by differences in the calculation of the wind-driven coefficients of convection and radiation heat transfer, as described in Section 2.

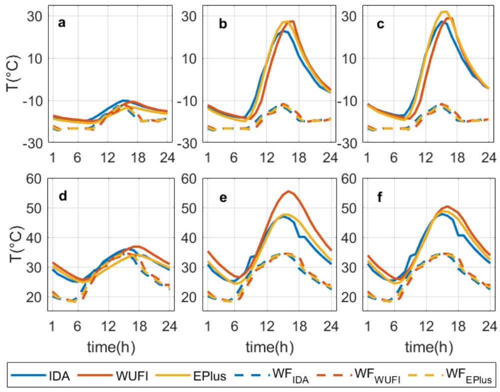

Fig. 3 – Time evolution of temperature on the coldest day (upper panels) and the warmest day (lower panels) in Case 600 FF without windows (a, d), with simplified windows (b, e) and with detailed windows (c, f). The WF series indicates the weather file temperature considered by the software

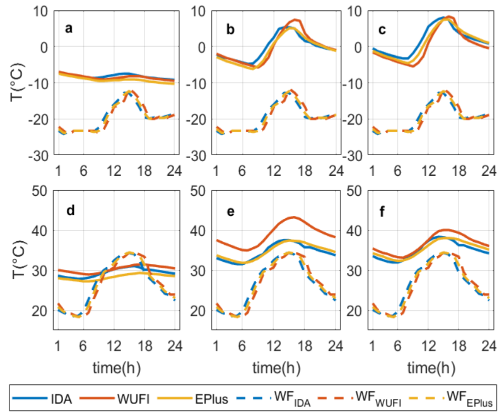

Fig. 4 – Time evolution of temperature on the coldest day (upper panels) and the warmest day (lower panels) in Case 900 FF without windows (a, d), with simplified windows (b, e) and with detailed windows (c, f). The WF series indicate the weather file temperature considered by the software

Moreover, the three BDS software tools calculate the resulting solar radiation incident on surfaces differently, leading to a different indoor heat balance due to the solar net radiative balance. For example, Energy Plus and IDA ICE use the Perez model, but with a different set of coefficients. This effect was evident when comparing the intensity of T peaks in the case of simplified windows models, which seem to be differently reproducing the transparent surface behavior in both Case 600 FF (Fig. 3) and Case 900 FF (Fig. 4).

3.2 Standardised Exercise for Historical Building (HB0)

In the case of HB0, simulations were run using detailed windows.

The values of total annual incident solar radiation on opaque surfaces (walls and roof) were compared to better interpret whether some of the differences in T simulations were ascribable to this contribution (Fig. 5). The smallest differences can be seen for the east side of the roof, as well as for east and west façades. However, specific implementations of the combination of direct and diffuse solar radiation result in different solar gains at each opaque surface. For example, in WUFI Plus, the total annual incident solar radiation is higher on north and lower on south façades than those of the other two BDS software tools. In addition, in IDA ICE, the total annual incident solar radiation on the west side roof is higher not only than that of the other two BDS software but also than that of the east side roof.

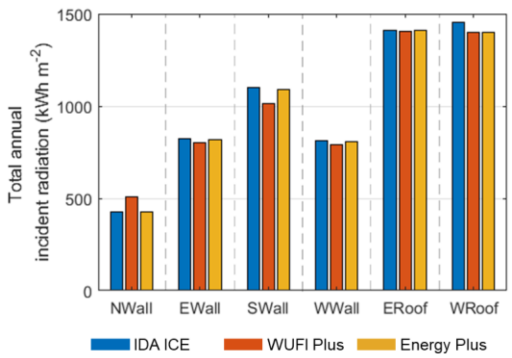

Fig. 5 – Total irradiance incident on opaque elements modeled by the three BDS software for each HB0 case

It was found that T and RH simulations resulting from the three BDS software tools showed good agreement with Δ_{max} ranging between 0.9-1.5 °C for T and 4.9-6.1 % for RH (Table 3).

T simulations modeled by WUFI Plus were on average higher (up to 2 °C) than those modeled by IDA ICE and Energy Plus. For the sake of brevity, only the minimum values were plotted in Fig. 6 as differences in Δ_{max}, for average and maximum values are negligible.

Table 3 – Summary of the maximum semi-dispersion (Δ_{max}) of the hourly temperature (T) and relative humidity (RH) values modelled by the three BDS software in case of HB0 in free-floating conditions

Sub-case	Code	T (°C)	RH (%)
no windows			
insulated roof	HB0_0	0.9	4.1
not-insulated roof	HB0_1	1.5	6.1
two S-windows	HB0_2S	1.4	5.6
two E-W- windows	HB0_2EW	1.4	5.6
four E-W- windows	HB0_4EW	1.4	5.3

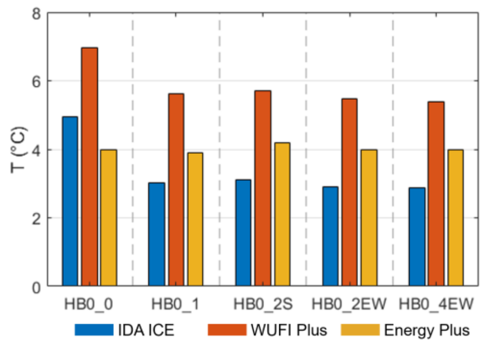

Fig. 6 – Annual minimum temperature values (T) modeled by the three BDS software for each HB0 case

As HB0 differed from Case 900 FF (*) only for the building net volume (Fig. 1), we can assume that differences among the three software tools can be mainly ascribable to the amount of air mass in the calculation. Fig. 7 shows a matrix plot that allows a comprehensive assessment of the differences among HB0 sub-cases (BDS *intra-comparison*, i.e., stair plots along diagonal matrix with the frequency distribution) and among BDS software (*inter-comparison*, scatter plots of paired BDS software).

Looking at the stair plots, transparent elements did not strongly affect T distributions within the same BDS software. In addition, simulations performed by Energy Plus were not sensitive to the insulation on the roof (HB0_0 and HB0_1), as no significant difference in annual T values and distributions was detected (on the contrary, IDA ICE and WUFI Plus simulated lower T values in HB0_0 than those in HB0_1 due to the lower heat transmittance of the roof). Looking at the scatter plots, T simulations resulting from IDA ICE and Energy Plus are scattered around the bisectrix (dashed grey line in Fig. 6), whereas T values simulated by WUFI Plus were usually above the bisectrix in all the sub-cases. If we compare T simulations of WUFI Plus and Energy Plus, it is evident that they were more in agreement in HB0_0 than in the other sub-cases, where T by WUFI Plus were higher than those by Energy Plus. This might be due to differences in the convective heat transfer coefficient in vertical upward flow.

Regarding RH simulations (Table 3), Δ_{max} ranged from between 4.1 % (HB0_0) and 6.1 % (HB0_1), showing good agreement among BDS software. To study the indoor humidity conditions without dependence on T, the partial water vapor pressure (e_v) values were compared in the matrix plot (Fig. 6). Since e_v did not change from one sub-case to another, the differences in RH values were driven only by the difference in T, meaning that moisture exchanges occurred only by infiltration. Although BDS software were able to similarly simulate water vapor saturated conditions, IDA ICE and Energy Plus modeled a higher frequency of saturation conditions (for the sake of brevity, RH plots are not shown).

4. Conclusion

In this paper, a new set of benchmarks for historical building models was presented and used with three BDS software tools with the aim of evaluating the effect on indoor climate simulations related to the differences in their modeling approaches. The benchmarks are designed to represent the characteristics of historical buildings and consist of twelve standardised models, seven of them being a variation of the BESTEST Common Exercise 0 (CE0), while the others are a variation of a single zone historical building (HB0), proposed by the authors. All the buildings are considered in the free-floating condition, without internal gains (occupants and other devices). The results of the comparison of IDA ICE, WUFI Plus and Energy Plus were presented, showing how the benchmark could be used to identify the differences between software.

The variables considered for the comparison are the ones of interest for the conservation of historical buildings, such as indoor air temperature and relative humidity. Incident solar irradiation is also considered for its relevance in the calculations. The maximum semi-dispersion between the time series is used to evaluate the differences between the simulations. Because of their relevance, the time

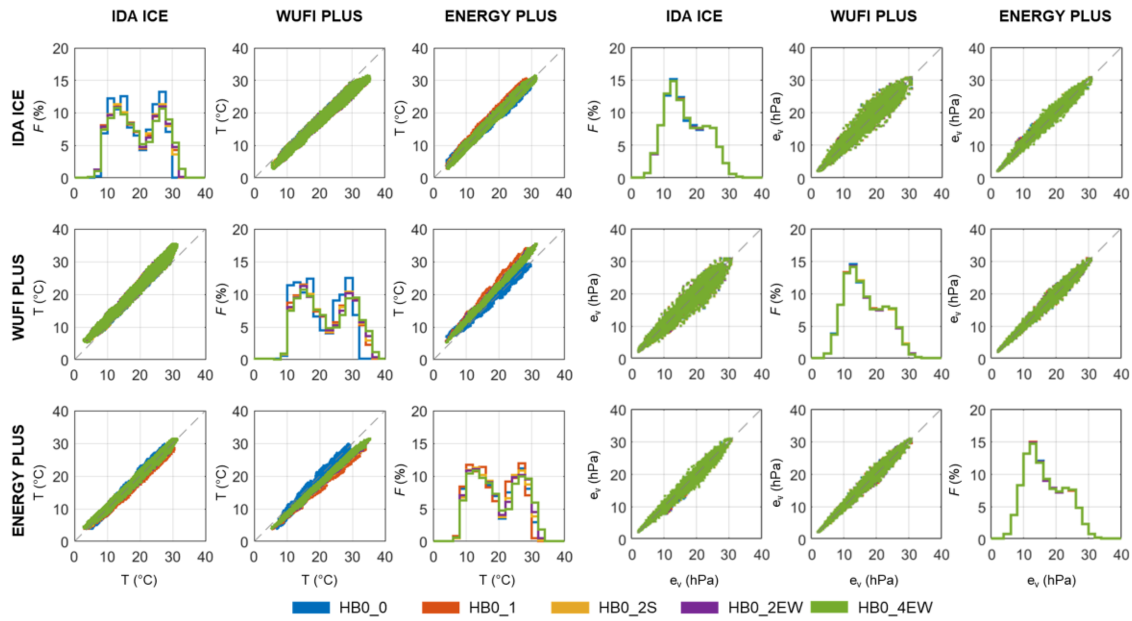

Fig. 7 – Matrix plots of temperature (T) and partial water vapor pressure (e_v) modeled by the BDS software for each HB0 case. Stair plots along the diagonal show the frequency distribution (F)

series of the temperatures of the coldest and the hottest day of the year are compared.

When the benchmark comparison is performed on the three software tools, the results highlighted the differences in the software models and implementations:

- the comparison among the temperature simulations in the case of CE0 showed good agreement in the sub-case without windows both in light- (Case 600 FF) and heavyweight structures (Case 900 FF);
- the addition of the windows increased the variability among the results, with the highest dispersion associated with the Case 600 FF with simplified windows and the lowest with the Case 900 FF with detailed windows;
- in the case of HB0, the annual minimum values of temperature simulated by the BDS software showed low agreement. In general, T simulations modelled by WUFI Plus were on average higher than those modelled by IDA ICE and Energy Plus. These differences are probably ascribable to the amount of air mass considered in the calculation.
- some discrepancies found in the modeled incident solar radiation might have been caused by the different implementations in the BDS software of the combination of direct and diffuse solar radiation resulting in different solar gains at each opaque surface.

These preliminary results provided a basis for two potential future research lines:

- a more detailed comparison of the BDS software, including models of simultaneous heat and moisture transfer through walls, would require an in-depth study of the hygrothermal properties of historical building materials, including also simplified models (Zu et al., 2020);
- a software-independent procedure for the calibration of a hygrothermal model of a historical building should be defined using indoor temperature and relative humidity observations collected in a real context.

Both these research lines could lead to a better interpretation of the energy and indoor climate scenarios through hygrothermal simulation and an increased awareness of the confidence of calibration in the case of historical buildings (Frasca et al., 2019).

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Nomenclature

Acronyms

BDS	Building Dynamic Simulation
CE0	Common Exercise 0
E	East
e_v	Partial water vapor pressure
HB0	Historical Building 0
IEA	International Energy Agency
IR	Insulated Roof
N	North
S	South
SHGC	Solar Heat Gain Coefficient
U-value	Thermal transmittance
W	West

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