SBE21
Sustainable Built Heritage

14-16 April 2021,
Online conference

DRAFT PAPER

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Assessing the role of simulation tool selection for the evaluation of heat and moisture balance in historic buildings

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Abstract. A dramatic improvement of the efficiency of existing dwellings is essential to tackle the climate emergency. About 30% of the European domestic building stock is classified as heritage, with generally poor thermal performance. While retrofitting of historic buildings is therefore essential, it presents increased challenges and risks compared to more modern ones. This is due to preservation requirements, the wider range of pre-retrofit conditions, the limited availability of reliable information on the building fabric and its complex hygrothermal behaviour. These challenges are reflected in the limited ability of current simulation tools to provide representative energy performance estimations for historic buildings, where large discrepancies with in-situ measurements are often unacceptable. This research compared three common dynamic simulation tools (EnergyPlus, IESVE, and WUFI Plus) to explore their relative strengths and weaknesses within the context of historic buildings. A 18th century barn was used as case study. Energy demand, indoor temperature and relative humidity outputs were assessed and compared using descriptive and inferential statistics. Results showed the importance of tool selection depending on the aim of the analysis. While IESVE and EnergyPlus showed similar results for energy performance and heating loads; WUFI Plus and IESVE were more consistent for indoor conditions and thermal comfort evaluation.

Keywords – Historic buildings; Heat and Moisture balance; Dynamic simulation; Retrofit; Energy efficiency.

1. Introduction

Over the past decades, researchers have raised concerns over the impact of the rapid climate change on societies across the world [1]. In an effort to address this overgrowing issue, Governments around the world have introduced policies aiming at reducing greenhouse gas emissions of the building stock, which accounts for 40% of global emissions worldwide [2]. Therefore, tackling the issue will require the retrofit of the existing housing stock including historic buildings [3].

With historic buildings (as defined in [4]) being part of every country's cultural heritage values, building experts should consider holistic approaches to retrofit strategies. Careful design through software simulations is of utmost importance to provide solutions that will ensure the efficient improvement of the heat and moisture performance of the building envelope and overcome technical concerns. However, current dynamic simulation tools are mainly designed for modern buildings, with possible lack of representative hygrothermal input data for various traditional material components and some intrinsic limitations in the simulation models (e.g., to represent features peculiar in historic buildings) [4].

Among the over 200 building energy simulation tools listed on the International Building Performance Simulation Association (IBPSA) webpage [5], the most used for the assessment of hygrothermal performance of historic buildings are EnergyPlus (26%), TRNSYS (15%), WUFI Plus (12%), and IESVE (4%) [4]. To present, several studies have investigated the differences between various software tools to evaluate the energy performance of modern buildings [6,7]. Best practices have also been provided when it comes to the retrofit of historic buildings through software modelling[4]. However, little information exists in the literature on the differences in heat and moisture balance estimates from different dynamic simulation software for historic buildings and the effects that default values may have on the final results.

This study investigated a case-study historic building by means of EnergyPlus, WUFI Plus and IESVE to assess the capabilities of each software with respect to energy demand and hygrothermal balance calculations, and examined the interrelationships between indoor environmental quality (i.e. temperature and relative humidity) and energy performance. The incorporation of moisture buffering related calculations is also discussed.

2. Methodology

An education centre located in Berkshire (UK) and surveyed by the authors was used as case study in this project (figure 1). The building was constructed in the 1700s and was originally a barn. However, in 2011 it was converted into an education centre considering a low-energy, low-carbon retrofit strategy. As a result, the building envelope as well as its energy performance improved significantly.

Figure 1. External view of the education centre.

The building was modelled in EnergyPlus (using the standard Conduction Transfer Function algorithm), WUFI Plus and IESVE to reflect the most common building energy simulation tools used in industry in the UK. Input data (e.g., weather files, geometry, material properties) whose values were available from the survey or architectural drawings were replicated across the three tools, while default values were left unchanged otherwise. Heating loads and indoor environmental quality (e.g., indoor temperature and relative humidity) estimates were assessed and compared to test the variability and limitations of the different dynamic simulation tools.

2.1. Space modelling

The teaching area of the education centre was modelled for the purpose of this study. The geometry along with a 3D representation of the building used for the simulations are showed in figure 2. The geometrical models of the building implemented in the three tools varied in dimensions to ensure that the thermal envelope of the space remained the same. According to [8], the dimensions of the model in EnergyPlus should correspond to the outside ones to make sure that the simulated thermal envelope conforms with the architectural plans. Conversely, WUFI Plus and IESVE manuals [9,10] recommend that the centreline dimensions are used to model the exterior constructions. The internal floor area of the simulated space was ensured to be 93 m^2 for all three software.

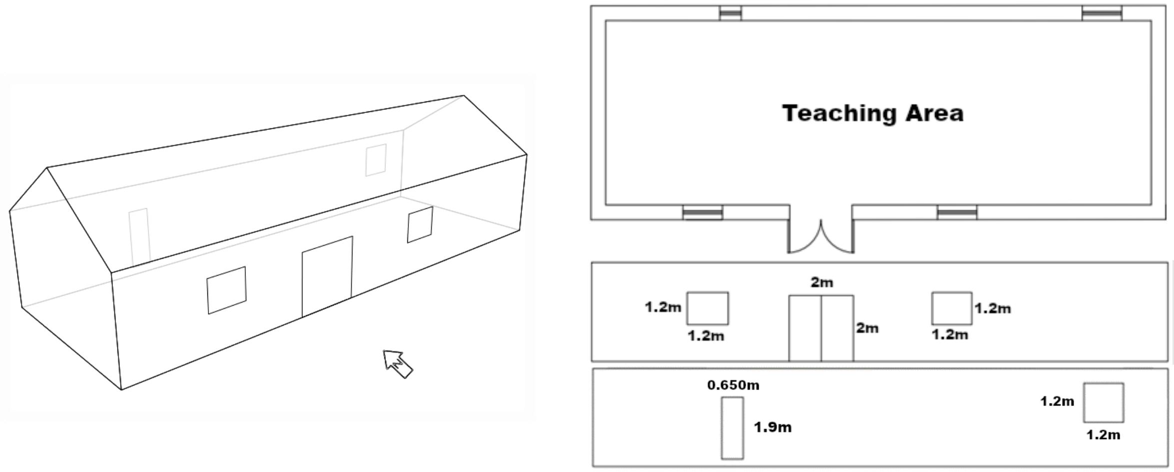

Figure 2. 3D model (left), floor plan and side views (right) of the teaching area.

2.2. Construction properties

The cross-sections of the building envelope components were kept the same in the three tools to ensure that the comparison of results between tools is not undermined by differences in materials characteristics. Their hygrothermal properties, namely the thermal conductivity, density, specific heat capacity, and water vapour resistance were either extracted from from manufacturer's data sheets or the literature (when limited knowledge was available). The hygrothermal properties of the building components are summarized in table 1.

Table 1. Hygrothermal properties of the materials in the building envelope components.

Component	Material	Thickness [mm]	Thermal conductivity λ [W/(mK)]	Density ρ [kg/m^3]	Specific heat capacity c_p [J/(kg K)]	Water vapour resistance factor μ [-]	Ref
Exterior wall	Brick	330	0.84	1700	800	9.0	[11]
	Sand plaster	6	0.80	1600	840	9.0	[11]
	Lime plaster	8	0.80	1600	840	9.0	[11]
	Wood fibre insulation board	100	0.043	175	2100	9.5	[12]
	Lime plaster	8	0.80	1600	840	9.0	[11]
Floor	Recycled Foamed Glass	300	0.078	120	850		[13]
	Limecrete slab	100	0.070	400	840	4.0	[14]
Roof	Wood fibre insulation board	20	0.047	240	2100	5.0	[15]
	Wood fibre insulation batt	100	0.038	50	2100	2.0	[16]
	Composite wood fibre insulation board	100	0.041	55/270	2100	5.0	[17]
Door	Plywood	37	0.13	500	-	-	[18]
Glazing	Outer pane	6	1.06				[18]
	Air	12	-				[18]
	Inner pane	6	1.06				[18]
	Note: 20% Metal Frame percentage Emissivity 0.837 for both panes Total U-value 2.25 W/m^{2}K						

2.3. Modelling assumptions

Common assumptions and simplifications were made based on the information available from technical drawings and in-situ survey, to minimize the effect of confounding variables on the results of the simulations. According to best-practice recommendations, air infiltration rate was assumed to be 3 m^3/h-m^2 at 50 Pa [19], corresponding to 0.2322 h^{-1} at ambient pressure.

A single thermal zone approach was implemented. The space was allowed to be heated between 20-26 °C during occupied hours, which were assumed to be between 09:00 and 17:00. No setpoints were set for the remaining time. No cooling schedule and mechanical ventilation systems were implemented in the model to replicate the actual configuration of the case study building.

Due to the limited data available, assumptions on internal heat gains and losses were made. The primary source of lighting was considered to be daylight, although artificial LED lighting was also assumed to be used during operational hours. Occupancy was not taken into account.

2.4. Comparative analysis

Annual estimates of indoor temperature and relative humidity (RH) as well as the heating loads from the three tools were assessed and compared. All tools yielded hourly timeseries, leading to 8760 points for each of the variable assessed. The data were analysed through descriptive and inferential statistics, and the analysis was complemented by an assessment of the building's performance during the coldest day of the year.

3. Results

3.1. Descriptive statistics

A summary of the descriptive statistics for each output timeseries assessed (i.e. indoor temperature, RH and heating loads) is reported in table 2. The mean values of the data points extracted averaged between 17.6-18.1 °C for the internal temperature, 52.2-55.7% for RH and 0.6-0.7 kW for heating loads. While the standard deviation (SD) of indoor temperature data across tools ranged between 3.2-3.9 °C, a relatively large difference was observed between the SD of the indoor RH points obtained from WUFI Plus (6.8 °C), EnergyPlus (12.7 °C) and IESVE (13.6 °C).

The skewness and kurtosis values with regards to indoor temperature and RH lied between -0.8 and 0, which are compatible with an assumption of normally distributed data [20,21]. Conversely, there is no indication of such characteristic for the heating loads timeseries, based on these statistics.

Table 2. Summary of descriptive statistics for the indoor temperature, RH and heating load outputs.

	Indoor temperature [°C]			Indoor relative humidity [%]			Heating loads [kW]		
	WUFI	E+	IESVE	WUFI	E+	IESVE	WUFI	E+	IESVE
Mean	17.6	18.1	17.7	55.7	52.2	53.8	0.7	0.7	0.6
Median	18.7	19.5	19.0	55.6	52.7	54.5	0.0	0.0	0.0
SD	3.2	3.9	3.5	6.8	12.7	13.6	1.5	2.6	1.5
Range	17.8	26.0	19.7	45.2	73.6	77.6	11.6	76.6	12.7
Skewness	-0.8	-0.4	-0.6	-0.3	0.0	-0.1	3.2	8.7	4.0
Kurtosis	-0.2	-0.3	-0.2	-0.3	-0.2	-0.3	12.3	128.3	19.3
Min	7.0	2.6	6.6	31.0	17.0	16.9	0.0	0.0	-0.2
Max	24.8	28.6	26.4	76.3	90.6	94.6	11.6	76.6	12.5

3.2. Inferential statistics

Potential correlation between the meteorological data, the indoor temperature and RH, and the heating loads of the teaching space was investigated using the Pearson's correlation coefficient (table 3). The analysis shows that the indoor temperature and RH are highly correlated with the outdoor dry-bulb temperature and outdoor moisture content respectively in almost all cases, except the outdoor moisture content and the indoor relative humidity datasets calculated in EnergyPlus.

Table 3. Summary of Pearson’s correlation coefficients between indoor and outdoor data.

Indoor variables/ meteorological data	Outdoor dry-bulb temperature [°C]	Wind speed [m/s]	Outdoor relative humidity [%]	Outdoor moisture content [kg/kg]
Temperature WUFI	0.72	0.15	-0.46	0.57
Temperature E+	0.69	0.10	-0.43	0.54
Temperature IESVE	0.72	0.12	-0.47	0.56
RH WUFI	0.57	-0.07	0.07	0.70
RH E+	0.16	-0.12	0.20	0.31
RH IESVE	0.41	-0.07	0.38	0.68
Heating loads WUFI	-0.19	0.13	-0.05	-0.24
Heating loads E+	-0.17	0.05	0.08	-0.15
Heating loads IESVE	-0.22	0.09	0.04	-0.22

A Pearson’s correlation coefficient matrix was produced to assess the relationship between the indoor temperature, RH and the heating loads across tools (table 4). A strong positive correlation was found between all three indoor temperature datasets. The RH values calculated by all tools were also positively correlated. The strongest relationship was identified between the data extracted from IESVE and WUFI Plus, while weaker correlation characterized the RH values from EnergyPlus and the other two tools. A possible explanation might be the weaker relationship between the outdoor moisture content and the relative humidity identified in table 3. The heating loads calculated in IESVE and Energy Plus were found to strongly correlate, while weaker correlation was observed for all other pairs of heating load datasets.

Table 4. Pearson’s correlation coefficients between indoor results.

	Temp WUFI	Temp E+	Temp IESVE	RH WUFI	RH E+	RH IESVE	Heating loads WUFI	Heating loads E+	Heating loads IESVE
Temperature WUFI	1.00								
Temperature E+	0.82	1.00							
Temperature IESVE	0.91	0.90	1.00						
RH WUFI	0.18	0.29	0.20	1.00					
RH E+	-0.14	-0.16	-0.21	0.57	1.00				
RH IESVE	-0.06	-0.10	-0.15	0.70	0.58	1.00			
Heating loads WUFI	0.34	0.21	0.29	-0.56	-0.47	-0.52	1.00		
Heating loads E+	-0.17	0.10	0.12	-0.16	-0.33	-0.28	0.19	1.00	
Heating loads IESVE	-0.06	0.19	0.27	-0.32	-0.44	-0.48	0.45	0.79	1.00

The indoor temperature and RH datasets were examined by means of ANOVA [22] and Tukey-Kramer honest significance test [22] for equal-sized samples (tables 5 and 6). The results indicate that there is a significant difference between the indoor temperature values extracted from EnergyPlus and the other two tools; no significant difference was identified for WUFI Plus and IESVE instead. All pairs of indoor RH datasets were found to be significantly different. Although the temperature values between tools were found to correlate well with each other and no significant difference was identified between the results from IESVE and WUFI Plus, the significant difference with regards to the RH datasets indicates that moisture-related calculations may differ across tools. Similar analysis could not be performed on the heating loads from any of the three tools, as the descriptive statistics analysis indicated that these timeseries are not normally distributed.

Table 5. Summary of the ANOVA and Tukey-Kramer honest significance test for indoor temperature.

ANOVA								
Sources	SS	df	MS	F	p-value	F crit	RMSSE	Omega Sq
Between groups	1351	2.000	675.626	**54.039**	<0.001	**2.996**	0.079	0.004
Within groups	328533	26277	12.503					
Total	329884	26279	12.553					

TUKEY HDS/KRAMER									
Group	mean	n	ss	df	q-crit				
WUFI	17.593	8760	90869						
E+	18.101	8760	129635						
IESVE	17.653	8760	108029						
Total		26280	328533	26277	**3.314**				
Q TEST									
Group 1	Group 2	mean	Std err	q-stat	lower	upper	p-value	mean-crit	Cohen d
WUFI	E+	0.508	0.038	**13.455**	0.383	0.633	<0.001	0.125	0.144
WUFI	IESVE	0.060	0.038	**1.595**	-0.065	0.185	0.497	0.125	0.017
E+	IESVE	0.448	0.038	**11.860**	0.323	0.573	<0.001	0.125	0.127

Table 6. Summary of the ANOVA and Tukey-Kramer honest significance tests for indoor RH.

ANOVA									
Sources	SS	df	MS	F	p-value	F crit	RMSSE	Omega Sq	
Between groups	54636	2.000	27318	**208.603**	<0.001	**2.996**	0.154	0.016	
Within groups	3441177	26277	130.96						
Total	3495814	26279	133.03						
TUKEY HDS/KRAMER									
Group	mean	n	ss	df	q-crit				
WUFI	55.773	8760	403340						
E+	52.205	8760	1414833						
IESVE	53.819	8760	1623004						
Total		26280	3441177	26277	**3.314**				
Q TEST									
Group 1	Group 2	mean	Std err	q-stat	lower	upper	p-value	mean-crit	Cohen d
WUFI	E+	3.528	0.122	**28.852**	3.122	3.933	<0.001	0.405	0.308
WUFI	IESVE	1.913	0.122	**15.649**	1.508	2.319	<0.001	0.405	0.167
E+	IESVE	1.614	0.122	**13.203**	1.209	2.019	<0.001	0.405	0.141

3.3. Worst case scenario analysis

An example of indoor temperature, RH, and heating loads obtained from the three simulation tools for the coldest day of the year (27th February according to the weather file used) is shown in figure 3. From visual inspection, no obvious differences were observed between the results obtained from the three tools for indoor temperatures as they exhibit a similar trend (figure 3, left). A cooling curve is observed in all cases between 17:00-09:00 (when the heating system is turned off), with IESVE showing the most rapid decrease.

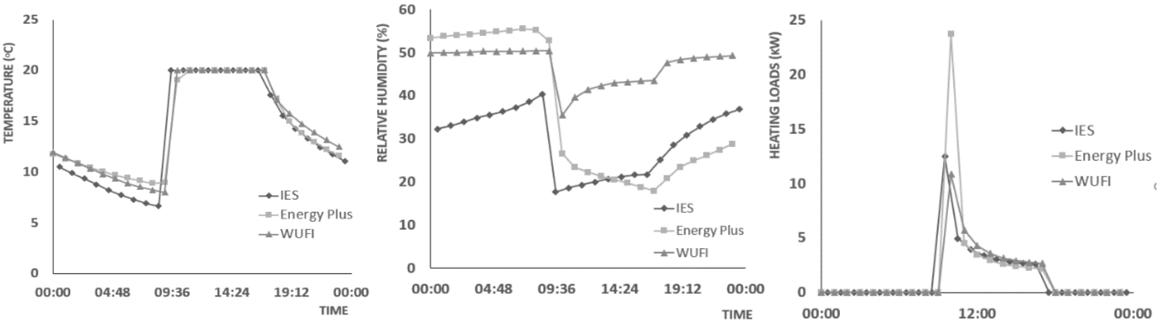

Figure 3. Indoor temperature (left), RH (middle) and heating loads (right) for the coldest day of the year.

Similar trends among the three tools were also generally obtained for heating loads (figure 3, right). The main difference was represented by a high energy demand at 9:00 in EnergyPlus (not observed in IESVE and WUFI Plus). However, the values rapidly decreased as soon as the set point temperature was reached. This behaviour suggests that EnergyPlus assumes that the temperature setpoint is instantly met as the heating schedule kicks in.

Conversely, distinct trends are observed for indoor RH (figure 3, middle). Similar trends were observed during the hours when the heating system is turned off (although with distinct initial values). However, during the occupied period (when the space is heated), the RH from EnergyPlus followed a different trend than the other two tools. Highest RH values were reached when indoor temperature was lower.

4. Discussion

The results from the annual simulations showed a strong correlation between outdoor dry-bulb temperature and indoor temperature for all three dynamic simulation tools. A strong correlation was also identified between the three indoor temperature timeseries.

There was some discrepancy in the estimation of annual heating loads, with a strong correlation between EnergyPlus and IESVE but significant differences with WUFI Plus. This may have an influence on the evaluation of the energy performance of the building and the sizing of building services.

A different picture is given in the evaluation of thermal comfort. The annual indoor relative humidity was strongly correlated with outdoor moisture content for IESVE and WUFI Plus, which also showed similar indoor RH timeseries. Poor correlation instead was exhibited for EnergyPlus results.

Since no indoor moisture generation was incorporated in the simulations, indoor environmental conditions are only governed by indoor-to-outdoor heat and moisture transfer both through building envelope components and air infiltration. As air infiltration rates were replicated across the three tools, possible differences in the indoor RH trends are likely to be generated by the implementation and consideration of air infiltration in the three tools. The differences observed may be also due to the hygric properties of the building envelope components, although to a lower extent. Indoor RH ranges and standard deviation obtained for the three tools (table 2) showed noticeably smaller values for WUFI Plus than IESVE and EnergyPlus. This may be because IESVE and WUFI Plus allow the setting of the vapour resistivity and incorporate moisture calculation and the effect of moisture buffering, whereas this is not included in EnergyPlus.

5. Conclusions

Dynamic simulations are of great importance during the retrofit process of historic buildings to carefully identify solutions that ensure indoor thermal comfort for the occupants, an efficient improvement of the heat and moisture performance of the building envelope, and overcome technical concerns. Common simulation tools available have been mainly developed for modern constructions, with known limitations (e.g., lack of representative hygrothermal input data for traditional building materials, limited ability to represent peculiar historic features) to provide representative heat and moisture performance estimations for historic buildings.

This study investigated the relative performance of three commonly used dynamic simulation tools (i.e. EnergyPlus, IESVE, and WUFI Plus) to evaluate the hygrothermal balance and energy demand of a 1700s barn recently refurbished to host an education centre in Berkshire (UK), used here as case study. Descriptive and inferential statistics analysis of indoor temperature, indoor relative humidity and heating loads obtained from the three software tools highlighted the importance of tool selection depending on the aim of the analysis. While IESVE and EnergyPlus showed similar results for energy performance and thermal loads, WUFI Plus and IESVE were more consistent for indoor conditions and thermal comfort, with WUFI Plus suggesting the influence of hygrothermal buffering of materials in dampening fluctuations of indoor relative humidity.

Although the results obtained relate well with the building physics of the case study, this work highlights some key areas that need to be further investigated, including the suitability of dynamic models for the analysis of indoor environmental quality in historic buildings. Future work will aim at expanding the analysis undertaken in this study by means of less commonly used and more advanced heat and moisture transfer algorithms for EnergyPlus (e.g., the combined Heat And Moisture Transfer model) to investigate whether it may help explaining some of the discrepancies observed in indoor RH predictions. Additionally, the simulation results will be compared with in-situ measurements to test the robustness and repeatability of the outputs (due to the Covid-19 pandemic outbreak, the data collection had to be unfortunately paused).

Acknowledgements

This research was made possible by support from the UCL Bartlett Synergy Grant and the EPSRC UCL Doctoral Prize Fellowship [grant number: EP/N509577/1]. The authors are also grateful to Richard Oxley for providing information about the case study and making this work possible.

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