Development of a three-dimensional hygrothermal model of a historic building in WUFI®Plus vs EnergyPlus

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Abstract. Historic artefacts are crucial to transmit history to future generations. Depending on the characteristics of their components these objects can be prone to biological attacks, chemical decay or even mechanical degradation. These three types of decay are induced by the indoor relative humidity and temperature, which are largely dependent on the characteristics of the building envelope, the outdoor climate and the number of occupants. In order to attain a proper indoor climate for the conservation of the artefacts it may be necessary to implement some types of changes. However, and due to the high heritage value of most of the buildings that house these artefacts, any type of changes has to be thoroughly studied prior to its implementation. These studies are usually carried out using a hygrothermal model of the building validated by the measured indoor conditions. The development of these models is entirely based on non-destructive procedures, which is a key factor when studying historic buildings. The yearly indoor climate of a 13th century church in Lisbon was measured and then used to develop a hygrothermal model of the church in two of the most used software in cultural heritage: EnergyPlus and WUFI®Plus. The obtained results for each model were compared against the measured indoor temperature and water vapour pressure to determine which are the advantages of the two software.

1 Introduction

Historic buildings are an important instrument for conveying history throughout time since they are a representation of our past. Nowadays, many of these buildings are used to house artefacts, which means that certain requirements must be ensured so that these objects can be preserved, mainly in terms of relative humidity and temperature [1].

However, guarantying these requirements can be quite difficult, especially in historic buildings, since they were not initially built for that purpose and, therefore, may lack the necessary characteristics to ensure such requirements. Hence, it may be necessary to perform some changes in the use of the building, e.g. reducing the number of occupants, or in some cases to implement retrofit measures. However, and due to their high heritage

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value, any type of intervention has to be thoroughly studied prior to its application to avoid jeopardizing the building [2].

This can be done by developing a validated hygrothermal model of the building and then assess the selected interventions (such as, the application of a thermal insulation system in the walls or replacing the windows [3,4]) by quantifying their effects and determining if those measures improve the quality of the indoor climate in terms of artefact's conservation without jeopardizing the building. These models are based on long-term and non-destructive monitoring campaigns, which are an important aspect for historic buildings, and can be used for several types of analysis [5].

The development of these models has several phases, namely: a) monitoring the indoor and outdoor climate, b) constructing the model and c) calibrating the model against the measured conditions. This last phase is a key part of the development of these models, since the more robust the model is, the more accurate the models' outputs will be. Normally, these models are validated against the yearly indoor temperature and relative humidity. Alternatively, it is possible to validate the building's moisture behaviour using water-vapour pressure in order to avoid replicating errors, since relative humidity depends on both variables [5].

Several software have been used to develop computational models of historic buildings [6]. This paper assesses two of these software (WUFI®Plus [7] and EnergyPlus [8]) by constructing a model of the same case-study (Saint Christopher church) in each software and then comparing each model outputs against the measured indoor conditions using four statistic indices: the *coefficient of determination* (R^2), the *coefficient of variation of the root mean square error* (CV(RMSE)), the *normalized mean bias error* (NMBE) and the *goodness of fit* (fit). These indices were selected in accordance to what is used in literature in terms of validating hygrothermal models [5].

2 Methodology

2.1 Case-study

Saint Christopher church, whose construction dates from 13th century is located in the slope of São Jorge Castle in Lisbon, has approximately 5250 m³ and is constituted by several compartments, namely a nave, a sacristy and a mortuary (Fig. 1). The church has thick mortared limestone walls, limestone floor slabs, double wood layer ceilings (with an air space in the middle of the layers), ceramic tiles roof and single-glazed windows. The properties of each material simulated can be seen elsewhere [5].

In terms of internal gains, it was considered that each occupant generates heat (126 W – transmitting 60% by radiation and 40 % by convection), moisture (54 g/h) and CO₂ (39.8 g/h) and has a metabolic rate of 1.3 met. The adopted lighting power density was 11.7 W/m². A more detailed description of these parameters can be found in Ref. [5]. The church is open between Tuesday-Saturday from 17:00-19:30 and from 11:00 to 13:30 at Sunday.

Fig. 1 – Saint Christopher's Church (a) and SketchUp model of the church (b).

2.2 Indoor and Outdoor climate

In order to accurately characterize the indoor climate of Saint Christopher's church an extensive monitoring campaign was installed in the building for more than a year with a recording frequency of 10 minutes [9]. The length and recording frequency were chosen so that the variability of the indoor climate was recorded with the lowest number of observations [10]. The outdoor conditions were also monitored during this time period [9].

The accuracy of the sensors was in accordance with EN 15758 [11] for temperature and EN 16242 [12] for relative humidity. All sensors were placed in specific locations in order to characterize the church indoor climate accurately, but their location were chosen carefully so that the obtained measures were not influenced by unwanted sources [10], such as the solar radiation, the artificial lighting system, the air flow through openings and the heat loss through the envelope. A more detailed description can be seen in [10].

As expected Fig. 2 shows that the indoor climate is much less variable than the outdoor climate, especially in terms of temperature. This is mainly due to the high thermal inertia of the church walls and thermal properties of the floor slabs. The water-vapour pressure was obtained using the equation presented in EN 16242 [12] and resorting to the measured temperature and relative humidity. Further information on the monitoring campaign can be found in Ref. [9].

Fig. 2 – Indoor and outdoor measured temperature (a) and water-vapour pressure (b).

2.3 Model calibration

Both Saint Christopher models was calibrated using four statistic indices: *coefficient of determination* (R^2), *coefficient of variation of the root mean square error* (CV(RMSE)), *normalized mean bias error* (NMBE) and *goodness of fit* (fit), simultaneously for temperature and water-vapour pressure, thus leading to a more robust model [5]. These indices were chosen because they are used in literature to validate hygrothermal models

(e.g. [13]), but also because they allow to compare the performance of the thermal mode against the performance of the moisture mode, since they are either presented in percentage (CV(RMSE)), NMBE and fit) or are unitless (R^2).

The *good of fit*, which assesses the fluctuation of the simulated and measured data and is the most robust of the four selected indices [5], is obtained using equation (1) [14]:

$$fit = \left(1 - \frac{\sqrt{\sum_{i=1}^n (X_{i,meas} - X_{i,sim})^2}}{\sqrt{\sum_{i=1}^n (X_{i,sim} - \bar{X}_{meas})^2}} \right) \cdot 100 \quad (1)$$

where $X_{i,meas}$ is the measured value of the parameter at i , $X_{i,sim}$ the simulated value of the parameter at i , n the total number of points for the studied period and $\bar{X}_{meas}$ the average of the measured values during the studied time period.

The model was considered validated if the average fit was higher than 80% (i.e. average between the fit (T) and fit (P_v)) [5]. According to IPMVP [15], the CV(RMSE) has to be lower than 20 % and the NMBE has to be lower than 5 % for the hourly thermal model to be validate. The model is more accurate the lower the CV(RMSE) and NMBE, and the higher the R^2 and Fit.

3 Results

The obtained values show that both software appropriately model the hygrothermal behaviour of Saint Christopher church. Table 1 summarizes the obtained values of the four selected indices concerning temperature and water-vapour pressure. In terms of goodness of fit the WUFI®Plus model attains a significantly higher temperature fit as well as a higher water-vapour pressure fit when compared to the EnergyPlus model. Although the EnergyPlus model does not surpass the imposed limit, the obtained value is very close to the limit, which makes it acceptable. WUFI®Plus higher accuracy might be due to the fact that a sensitivity analysis to determine some of the inputs is carried out, something that is not done in EnergyPlus since the aim of this paper is to test the same model in both software, the same inputs were used in both models.

The obtained CV(RMSE) and NMBE for both models are lower than the demand values by IPMVP [15] for the model to be validated (especially, CV(RMSE) which is ca. 4 times lower than the imposed limit). On the other hand, it is visible that the R^2 is not an appropriate index to compare both software, since the obtained values are very high. Furthermore, R^2 is not the most suitable index to perform a robust calibration of hygrothermal models [5].

Fig. 3 displays the annual variation of the indoor temperature and water-vapour pressure of the monitoring campaign data and the simulated values for both models. Although the models' outputs do not perfectly overlay the recorded data it is visible that they have a very similar variability, thus showing that the obtained values from both models are acceptable.

The model of Saint Christopher church was developed in the hygrothermal mode of WUFI®Plus and using the Combine Heat and Moisture Transfer (HAMT) in EnergyPlus. It is noteworthy that both the hygrothermal mode and the HAMT mode are based on Künnel's [16] governing equations for the simultaneous calculations of heat and moisture transfer in building materials [17].

Table 1 – R^2 , CV(RMSE), NMBE and goodness of fit for temperature (T) and water-vapour pressure (P_v) of the models developed in WUFI®Plus and EnergyPlus.

Software	R ² [-]		CV(RMSE) [%]		NMBE [%]		Fit [%]		
	T	P _v	T	P _v	T	P _v	T	P _v	Avg.
WUFI®Plus [5]	0.99	0.97	3.2	4.4	2.7	3.4	84.8	81.7	83.2
EnergyPlus	0.99	0.96	4.1	5.5	3.5	4.1	80.4	76.5	78.5

Fig. 3 – Simulated WUFI®Plus and EnergyPlus and measured indoor temperature (a) and water-vapour pressure (b) of Saint Christopher’s church.

4 Conclusions

Computational models are a powerful tool to study the hygrothermal behaviour of historic buildings since they allow to make a thorough analysis of several aspects that influence their behaviour, such as the study of the effects of any retrofit measures prior to implementation, the effects of different climate control strategies and the effects of the building occupation rate, among other types of analysis. However, for these models to replicate the reality they have to be thoroughly validated against the indoor conditions.

A substantial number of software is used in literature to develop computational models. Hence, the model of the same historic building (Saint Christopher church) was built in WUFI®Plus and EnergyPlus. Although the WUFI®Plus model attained overall better results than the EnergyPlus, both software are appropriate to develop hygrothermal models of historic buildings due to the high values of accuracy attained by both models.

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