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Calibrated hygrothermal simulation models for historical buildings

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ABSTRACT

Historic buildings are a living representation of our past and it is our duty to ensure that future generations have access to their heritage. In order to accomplish this, it is necessary to determine the conditions that the buildings are in and, if needs be, to make the necessary changes. In this latter stage, it is helpful to have a validated whole-building hygrothermal model since it takes into consideration most of the processes that affect their hygrothermal performance, thus allowing us to choose the most appropriate interventions.

This paper aims to establish a validation process for historic buildings based on annual indoor conditions using simulation software. Hence, the indoor conditions is a 13th century church in Lisbon were monitored over a year. The model accuracy was assessed by comparing the simulated and measured temperature and water-vapour pressure, and quantified using the coefficient of determination, coefficient of variation of the root mean square error, normalized mean bias error and goodness of fit. The hygrothermal model was then validated by comparison against other models in literature and existing standards/guidelines.

Four outdoor weather files were simulated to show the importance of monitoring the outdoor climate as closely as possible to the case-study. The soil/slab interface temperature was obtained using six different models. A sensitivity analysis was developed to optimize some of the inputs. Ultimately, the church hygrothermal model was validated. However, in hygrothermal models the simulation time can be long, therefore, a simplified model was developed using two of the four tested simplifications.

1. Introduction

Historic buildings are a living representation of our past and it is our duty to ensure that future generations have access to their heritage. Nowadays a substantial number of historic buildings house collections. Consequently, certain levels of temperature and relative humidity must be guaranteed in these buildings so that the artefacts are kept safe and at the same time to ensure human comfort. However, it is important to bear in mind that most of these buildings were not designed for this purpose, therefore it can be difficult to guarantee such indoor conditions.

In order to guarantee such indoor conditions, powerful mechanical systems have traditionally been used. However, nowadays these systems are continually questioned owing to their high energy expenditure and consequent high financial and environmental costs. This change of approach has opened the way to other solutions (such as the passive rehabilitation techniques [1]) that can lead to energy reduction. However, the potential of the passive system is largely dependent on the outdoor conditions as well as the building's characteristics (e.g. wall assemblies) [1]. In addition, hygrothermal improvements of heritage buildings are not always possible without sacrificing authenticity [2]. At the same time it is also important to study strategies for climate control, which are based on energy savings but also take the local climate, collections or comfort needs into account [3].

The first step to promote the safety of the housed artefacts is to conduct a thorough monitoring of the building's indoor conditions, over a sufficient period of time, in order to assess if the present conditions are suitable or not for the preservation of the objects [4,5]. Should the conditions not be adequate for the preservation of the artefacts, the necessary changes will have to be implemented to ensure a more suitable environment.

However, one of the downsides of using the monitored climate, which usually does not cover more than one year, is the fact that it cannot take into account years with different climates, to evaluate future scenarios of climate changes and the impact of hygrothermal improvement measures. The use of simulation models is an important tool for the microclimatic analysis of cultural heritage, since it allows us to test possible retrofits and/or different climate control strategies with a high level of confidence, as in Ref. [6], for example. Additionally, computer simulations are non-intrusive for occupants and building [7], which is important for historic buildings.

However, the models must be validated against the building's indoor

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conditions so that they can reliably simulate its hygrothermal behaviour [8–11]. The combined use of several statistical parameters and the use of more than one compared variable (e.g. temperature and water-vapour pressure) should lead to a more reliable model [12,13]. Poorly calibrated or uncalibrated models assume an even greater importance for historic buildings since any measurement based on such models may lead to irreparable damage to the building [9]. The more robust the hygrothermal model, the closer simulation outputs will be to reality.

The thermal and hygrothermal models of historic buildings found in literature are used for several different types of analysis, which shows how valuable this type of research tool is. For example, Huijbregts et al. [14] modelled and validated rooms in two museums in order to assess how the climate change would affect the artefacts' welfare. Wang et al. [15] developed a thermal model of the National Gallery of Edinburgh to study several low energy solutions for its renovation project. Kramer et al. [16] analysed the potential for energy saving of several setpoints strategies using a validated hygrothermal model of a museum, damage functions and an adaptive temperature guideline. Ferdyn-Grygierek et al. [17] modelled a Polish museum to evaluate the impact of several ventilation systems in its energy consumption. Sciurpi et al. [18] developed a thermal model of the "La Specola" museum to evaluate the strategies of replacing windows and the use of different solar shadings. Kramer et al. [19] developed a setpoint calculation algorithm that takes into account both the collection's and the visitors' requirements and used the algorithm to analyse the energy demand in museums.

However, there are also models that are not validated against the indoor conditions, or their accuracy is only assessed by visual comparison between the simulated and measured values for each of the hygrothermal variables. The use of statistical parameters gives the model's developers a quantitative notion of how well the model simulates the behaviour of the real building. Some authors use statistical parameters to assist the validation process of whole-building models. For example, Ferreira et al. [20] used the annual average, the standard deviation and the minimum and maximum of the difference between the measured and simulated values to validate a hygrothermal model of a museum at Oporto in addition to the visual comparison. Pisello et al. [21] and Pernetti et al. [22] used the statistical parameters proposed by ASHRAE guideline 14:2002 for the validation process of thermal models [23], with the coefficient of determination also being used in the latter paper. Mustafaraj et al. [13] used simultaneously the goodness of fit, mean absolute error, mean squared error and coefficient of determination to validate thermal models of an office in London. Kramer et al. [12] also used the mean square error, mean absolute error and goodness of fit to validate several hygrothermal models of historic buildings.

Although whole-building hygrothermal models are valuable as a research tool, it is quite difficult to develop them for historic buildings due to the lack of information about the building materials, as well as the techniques that were used in the building, the ventilation rates, occupancy schedules and soil/slab interface temperature. Most often, only the building's architecture and surface materials are known, and due to their heritage value it is difficult to conduct the necessary characterization tests.

In this paper, a simulation model is a 13th century church in Lisbon – Saint Christopher's Church, was developed using the software WUFI® Plus [24] with the aim of establishing a methodology for the calibration and validation process of hygrothermal models, specifically for historic buildings, based on annual indoor conditions. Hence, the whole-year indoor conditions monitored in the church [4,25] were used to validate the model against the measured data. The hygrothermal accuracy of the simulations was assessed by comparing the measured and simulated temperature and water-vapour pressure using four statistic indices, namely the coefficient of determination R^2, the coefficient of variation of the root mean square error CVRMSE, the normalized mean bias error NMBE, and the goodness of fit.

To overcome the usual difficulties in simulation studies, the authors studied the influence of the outdoor climate by testing four different weather files for Lisbon; and the temperature of the interface between the soil and slab by testing six different methodologies for determining such temperature. To calibrate the model, a sensitivity analysis was carried out for three parameters – air change rate, solar heat gain coefficient of windows and short-wave radiation absorption coefficient, performing a total of 48 simulations. Finally, four simplifications of the validated Saint Christopher's Church model were tested to reduce the simulation time while guaranteeing the accuracy of the model.

2. Methodology

2.1. Case study

For the purposes of the current study, a hygrothermal model of Saint Christopher's Church in Lisbon was developed. The church is a 13th century building classified as a national monument and is located on the slopes of St George's Castle in Lisbon. The church is approximately 5250 m^3 in volume and it is made up of a nave (ca. 286 m^2), a funeral home to the south (ca. 93 m^2), a sacristy to the north (ca. 71 m^2), two towers (ca. 9 m^2 each) and an annex at the end of the nave (ca. 11 m^2). A photo of the southern façade and the horizontal plan of the church can be seen in Fig. 1. The church is naturally ventilated and does not have a climate control system.

The building has been widely studied by Silva and Henriques [4,25], who conducted a microclimatic monitoring of the church from November 2011 to August 2013 in which the temperature and relative

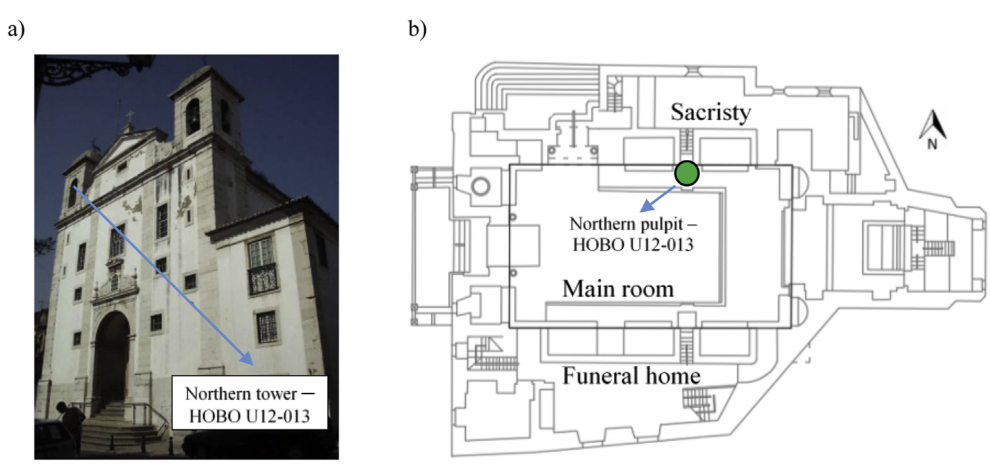

Fig. 1. Southern façade of St Christopher's Church (a) and the horizontal plan with the reference sensor (b).