Development of a zonal model to assess indoor climate and damage risks to art works in church buildings.

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ABSTRACT

Most of the degradation of works of art in historic buildings is caused by unfavourable indoor climate conditions. The most important works of art receive invasive conservation treatment, called direct action, but this treatment is very expensive. To avoid invasive conservation treatments and ensure that works of art are protected for now and for the future, indirect action to mitigate the deterioration process is necessary. This holds that exposure to unfavourable indoor climate conditions should be avoided, as far as is compatible with its social use.
To assess the preservation conditions and decide upon retrofit or climate control measures properly, it is necessary to take typical conditions in monumental historical buildings into account in indoor climate simulations. The presence of moisture in heavy building walls and the occurrence of hygrothermal gradients (stratification) in the often very large interior volumes due to the limited control by (older) climate installation systems need to be taken into account.
This paper examines to which extent the expansion of a BES tool with a simplified stratification model allows to improve the simulation of the indoor climate in historic buildings. The mathematical background of the chosen airflow model, the temperature-based zonal model by Togari, and the added equations for moisture transport are presented. The coupling of the airflow model with the BES-software TRNSYS is explained and a validation of the model is performed to check the correctness of the coupled zonal-BES model.
Finally the coupled approach is applied to assess the indoor climate problems in an existing case study of a historic church building in which an important panel painting is exhibited. The hygrothermal response of the panel painting exposed to different heating regimes with air heating was studied by coupling the thermal-zonal BES model introduced in this paper with a HAM-model. The moisture buffering of the walls was modelled using an EMPD-model.

KEYWORDS

Preventive conservation, building energy simulation, stratification, humidity control, moisture damage

1 INTRODUCTION

For works of art, different causes of failure exist which are related to inadequate indoor climate conditions. One possible cause is related to the installation of a HVAC system as an answer to the increased thermal comfort demand, not only in new, but also in historical buildings. As a consequence, heating systems have been installed in historical buildings such as churches, which were designed to quickly heat the space during the service. Although the use of the system improves thermal comfort, due to uncontrolled installations of hot air systems in churches, an increase in damage and decay of valuable works of art have been observed (Camuffo et al. 2010).

To assess the preservation conditions and decide upon retrofit or climate control measures properly, it is necessary to take typical conditions in historical buildings into account in indoor climate simulations. The presence of moisture in heavy building walls and the

occurrence of hygrothermal gradients (stratification) in the often very large interior volumes due to the limited control by climate installation systems need to be taken into account.
In order to simulate, assess and compare the influence of multiple retrofitting strategies on preservation conditions, a fast calculating simulation method is necessary that may serve as a design tool. Therefore a BES-tool (Building Energy Simulation) has been expanded with a simplified stratification and moisture buffering model to improve the simulation of the indoor climate in historical buildings, specifically in relation to the typical conditions mentioned above (De Backer et al. 2014, De Backer 2018). The microclimate around works of art may also be studied using computational fluid dynamics (Steeman et al. 2009). However, because of the high computational cost, CFD is not in the scope of this work.

2 MODEL DEVELOPMENT

2.1 Thermal-zonal model

The effect of stratification during intermittent heating of a church building is simulated by coupling a thermal-zonal model with a BES-tool. The coupling builds upon the existing simulation environment TRNSYS (v17). The zonal model adopted was first proposed by Togari et al. in 1993. They intended to develop a simplified model which could be incorporated into an unsteady thermal analysis and which was able to predict the vertical temperatures in an atrium with a glass wall. This model was originally validated using a scale-model of 3mx3mx2.5m.

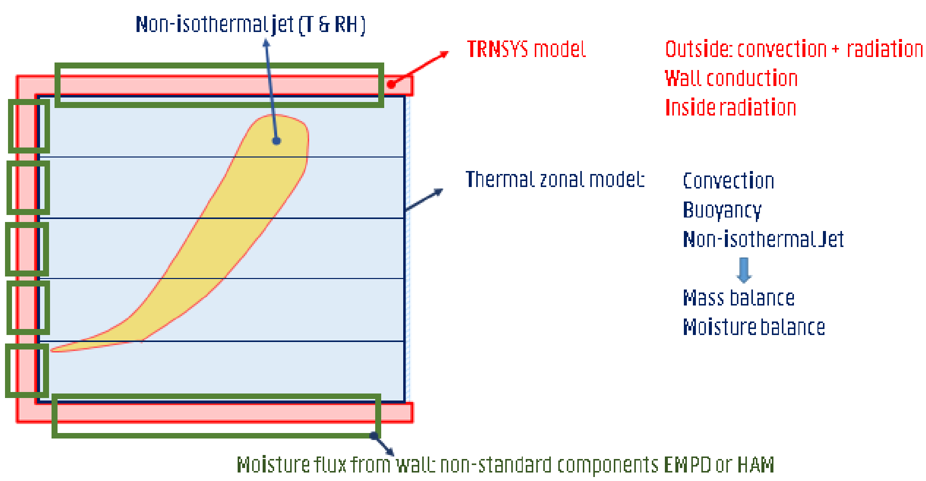

Figure 1: Overview of different submodels within the TRNSYS environment.

The model consisted of three sub-models, applied to a series of horizontal layers subdividing the interior volume (Figure 1):

- a sub-model which provides the interior surface temperature by solving the heat transfer by conduction, convection, and radiation of a building envelope. In the new coupled model the TRNSYS-functionalities are used for this purpose.
- a sub-model for the wall currents which evaluates mass and heat transfer for air along interior surfaces of walls. This model assumes that the convective heat transfer drives a mass flow from the horizontal core layer to the boundary layer of one of the walls adjacent to the horizontal layer. As a consequence the mass flow rate is directly proportional to the convective heat transfer coefficient.

- a sub-model which solves the mass and heat balance for air in the horizontal layers. The calculated wall temperatures are used as boundary conditions for the thermal-zonal model to calculate the vertical temperature distribution in the room air. When a primary airstream, such as a non-isothermal jet, is present, first mass and temperature of the primary stream is calculated using analytical equations for jet trajectory and velocity and temperature profiles, which are subsequently used in the mass and heat balance of the horizontal layers.

To assess the preservation conditions in a space, next to the temperature variation also the humidity variation needs to be predicted. In the original model, there were no equations for moisture transport. Therefore moisture balance equations were added to the thermal-zonal model, as well as equations to define the moisture flux between the wall and the wall current. The model details are documented by De Backer (2018).

2.2 Moisture buffering model

The original EMPD-model (Effective Moisture Penetration Depth) available in the building model of TRNSYS cannot be used for the newly developed thermal-zonal model, because it only calculates one value representing the average moisture storage properties of all room surrounding surfaces. Furthermore, the model is isothermal with constant material properties uncoupled of heat transfer in the wall. In the zonal model, in which one zone is subdivided into a number of horizontal layers, for each separate wall surface a vapour mass flow is necessary to calculate the moisture in the surface air streams. Also in historical buildings non-isothermal effects need to be taken into account in the moisture buffer model (Janssens and De Paepe 2005). To this end, a new TRNSYS type was programmed which consists of a non-isothermal EMPD-model coupled with each wall element, in which moisture transfer and storage properties are updated every time step in relation to the buffering layer temperature and humidity.

2.3 Implementation

Figure 2 shows an overview of all the data streams and which information is needed for the coupled BES- thermal-zonal model.

The first step is providing the input data for the TRNSYS building and the thermal-zonal model. A distinction is made between necessary input data, shown in the first block, and information that is only needed in case a jet flow or in case a moisture flux from the walls is defined. This is shown in block two and three.

- The TRNSYS building model needs geometrical data, properties of the building envelope, outside boundary conditions and the convective heat transfer coefficients.
- For the thermal-zonal model, information of the geometric data is needed. The geometrical model is the same as used for the multi-zone building model (.idf). The thermal-zonal model needs this information to know the positions of all the walls to be able to calculate the wall streams. Furthermore, the same values for the interior convective heat transfer coefficients are needed. The second and third block contains.
- In case a jet flow of moisture flux is present, this data need to be provided only for the thermal-zonal model.

The second step is setting the initial air temperature and relative humidity for every layer in the TRNSYS building model. The model assumes that walls are in equilibrium with the indoor air and therefore the initial interior surface temperatures are the same as the air temperature.

Next, necessary boundary conditions are passed by the TRNSYS building component to the thermal-zonal model. The interior surface temperatures and the temperature and absolute humidity of the air nodes act as boundary conditions for the thermal-zonal model. Once the boundary conditions are passed to the thermal-zonal model, the latter calculates the wall currents and solves the heat, mass and moisture transport for all layers until temperature and absolute humidity reach convergence below a step change of 1E-6 °C and 1E-9 kg/kg . A simple adaptive relaxation technique is used in which is switched between two relaxation parameters, one for under-relaxation and one for over-relaxation.

Once convergence is reached, results are passed to the corresponding air node in the multi-zone building model. To integrate the thermal-zonal model in TRNSYS, a user defined convective heat gain and moisture gain are defined by the thermal-zonal model for every air node. Therefore, the convective gain from the walls to the air node in the building model in TRNSYS is subtracted from the total gain calculated by the thermal-zonal model. In the TRNSYS building model, a new temperature and relative humidity is then calculated for every air node, and the previous steps are repeated every time step.

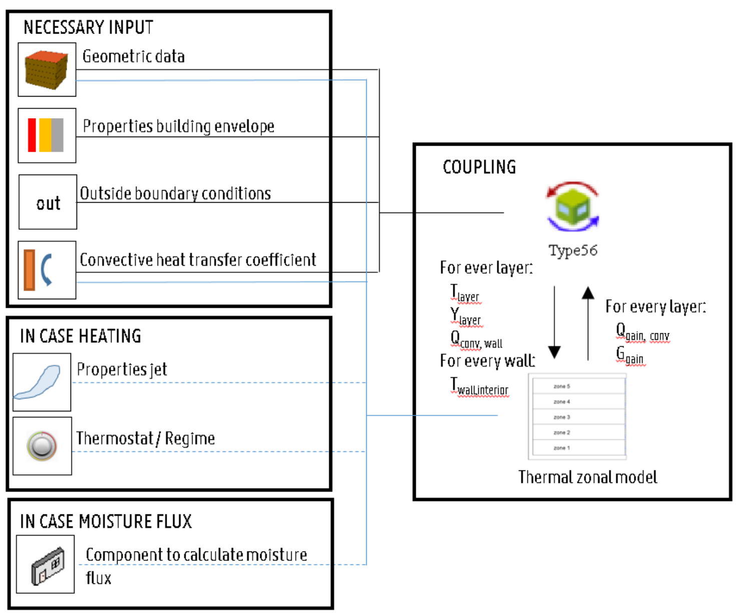

Figure 2: Schematic overview of the coupling between the multi-zone building model in TRNSYS and the developed thermal-zonal model.

3 APPLICATION

3.1 Case study

The investigated church building is based on the Church of Our Lady in Watervliet (Figure 3), dating from the 16th century and located in Belgium. The church is in general not acclimatised. Only during a service or a concert, the church is heated with an air heating system to a setpoint temperature of 16°C. An exception is in wintertime when heating is used to maintain a minimum temperature of 5°C. The heating system is located in a technical room next to the church building. The interior includes woodcarving and panel paintings from the

16th, 17th and 18th century. The most important and valuable painting of the church is the triptych “Nood Gods” (“God’s need” in Dutch). It was painted in the 16th century by an unknown artist and is included on the list of masterpieces of Belgian heritage. Unfortunately, this triptych has been damaged by hanging in an unfavourable climate. A measurement campaign was started in 2011 to gain information about the indoor climate of the church and to detect causes of damage (Maroy et al. 2015). Meanwhile, in the winter season of 2013, an urgent conservation was carried out on the panel painting to fix the paint layers with support of a grant of the Flemish government. Following from this, it was decided to increase the minimum temperature in the church building from 5°C to 11°C (winter of 2013-2014).

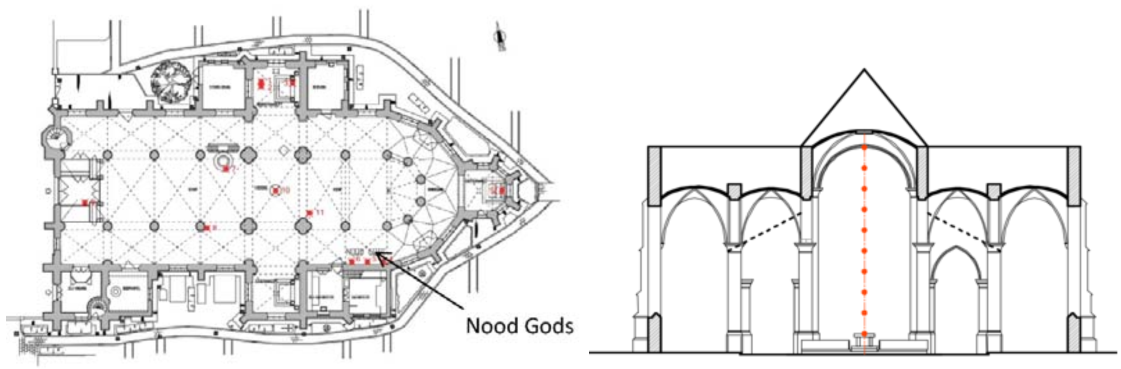

Figure 3: Floor plan and section of the Church of Our Lady with the location of the panel painting “Nood Gods”, and the position of Hobo-loggers (red points).

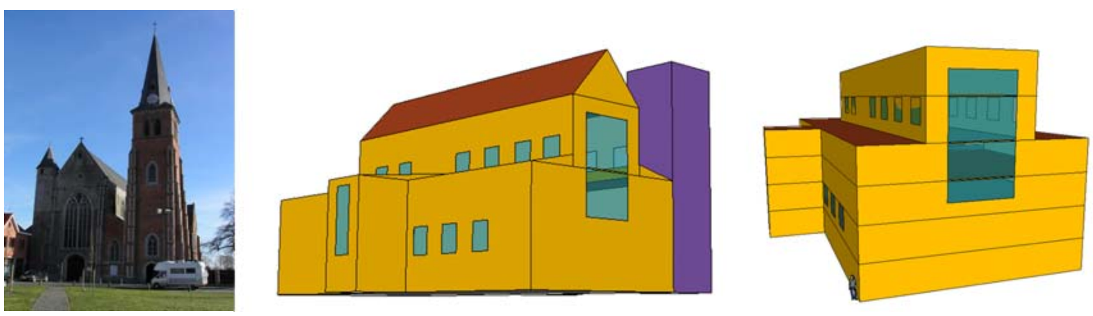

Figure 4: Geometry of the multi-zone model of the church building.

3.2 Simulation methodology

A whole building simulation model was set-up of the church building in which the coupling of a BES-model with the thermal-zonal model was applied. The first step was to design a model of the actual situation, which was calibrated using the measurement data. Using the calibrated model, three types of adjustments to the heating system were tested. Firstly, the temporary situation in which the minimum temperature was raised from 5 to 11°C was simulated to get an idea of the impact of this adjustment on the preservation conditions. Secondly, other adjustments were tested to verify if other, perhaps better solutions were possible. In this paper only the first adjustment is presented. The others are discussed by De Backer (2018).

Figure shows the geometric model developed in Sketch Up. This 3D-model is converted in TNRBuild to a geometric model with necessary boundary conditions so it can be used in the simulation environment TRNSYS 17. The model of the church building is a multi-zone model consisting of three zones: the church volume and two attics. Furthermore, also the tower adjacent to the church building was drawn. This tower is not a part of the geometric model and thus the conditions in the adjacent tower are not simulated. The tower geometry only serves to take into account the shadow related to solar radiative gains. The church building (zone 1) was further refined into six horizontal layers to estimate the stratification in this part based on the thermal-zonal model. Layer one, at the bottom, corresponded to the occupied area. For the other layers the position of the windows was taken into account. This resulted in four layers of 2.5m and two layers of 3m. In TRNSYS a detailed model for radiative heat transfer was applied using view factors.

3.3 Model calibration and verification

Simulations were initialized using climatic data of the four months preceding a detailed indoor climate monitoring campaign (6th-29th of march 2012). This monitoring data was used to calibrate and verify the model. After the manually iterative calibration, a maximum root mean square error of 1.0 °C was found over this time span. For the absolute humidity the maximum root mean square error was 0.3 g/kg.

Figure 5 shows the measured and simulated vertical profile for indoor temperature and relative humidity of a day during the measurement campaign on which heating occurred during a short period of time, namely 11/3/2012. The coupled BES-thermal-zonal model shows a reasonable level of agreement between the measured and simulated values. The part during the warming up, at 9:45 and 9:30, has the largest inaccuracy. This is due to the steep slope in the beginning, which is sensitive to parameters related to the jet flow model; the throw constant of the jet, the spread angle of the velocity profile and the chosen mathematical representation for the jet-model.

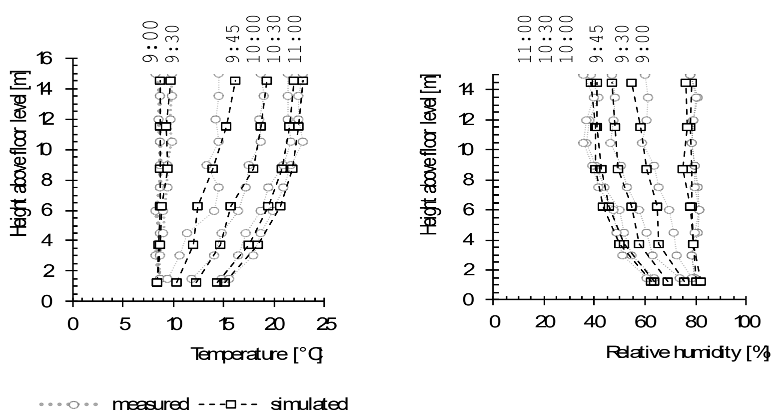

Figure 5: Measured and simulated vertical temperature and humidity profile on a day with intermittent heating.

3.4 Simulated influence of increase in set-point

Using the calibrated model the same period as above was simulated to study the effect of this proposal, but instead of using the actual setpoint of 5°C, the setpoint was raised to 11°C as advised by the national heritage guidelines on church heating in 2002. It was studied which outcome this has on the gradient in time and in space.

Figure 6 shows the temperature and relative humidity course for the two cases. In the base case in which the minimum temperature was 5°C, the intermittent heating causes in the lowest layer a temperature increase of 7°C and a relative humidity drop of 21%RH. In the highest layer, a temperature increase of 12°C and a relative humidity drop of 36%RH is noticed. By raising the setpoint, the gradient in time decreased to 5°C and -17%RH and to 9°C and -28%RH. So the spatial temperature and humidity gradient is still occurring in case the setpoint is raised. This confirms that stratification is almost inevitable unless air distribution is very carefully considered. Furthermore, the heating switches more frequent on and off in case the setpoint is raised. On the 11th of march, indoor temperature was 8°C without heating. In the base case, the heating device only switched on during service, while in case the minimum temperature was raised to 11°C, the heating was permanently in operation. This resulted in an increase of the frequency of daily temperature and relative humidity fluctuations which may also affect preservation conditions (De Backer et al. 2018).

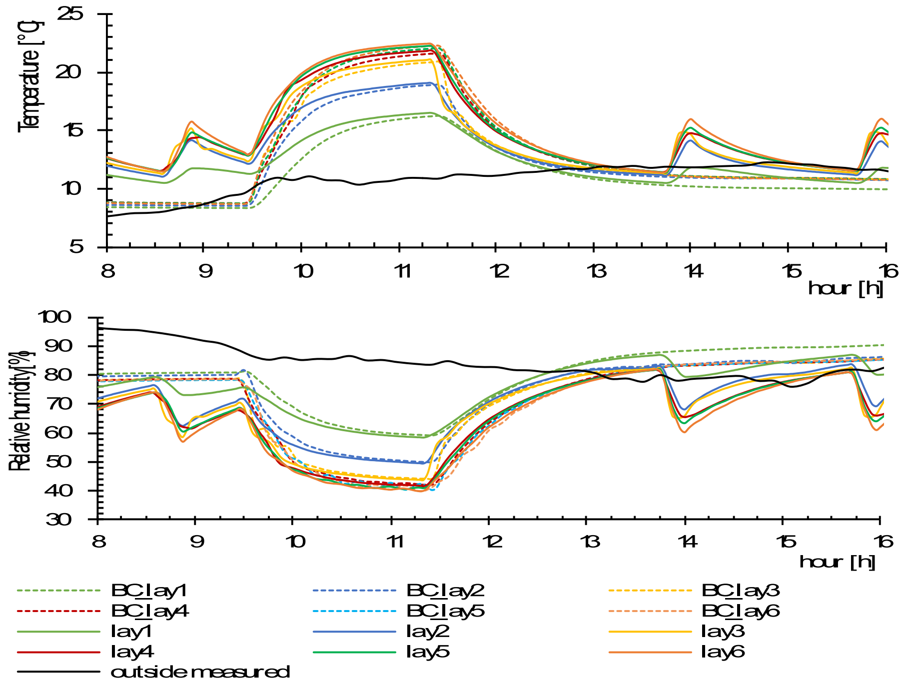

Figure 3: Temperature and relative humidity course for the base case (BC) and the adjusted case.

4 CONCLUSIONS

This paper examined to which extent the expansion of a BES tool with a simplified stratification model allows to improve the simulation of the indoor climate in historic buildings. The chosen airflow model, the temperature-based zonal model by Togari, and the added moisture transport model are presented. The coupling of the airflow model with the BES-software TRNSYS is explained and a verification of the model is performed to check the correctness of the coupled zonal-BES model.

The coupled approach is applied to assess the indoor climate problems in an existing case study of a historic church building in which an important panel painting is exhibited. The simulation study compared the base case (minimum temperature of 5° and 16°C during service) to the solution chosen as an temporary measure - increasing the minimum temperature to 11°C. The simulation demonstrates the practical use of the newly developed coupling to predict thermal and humidity stratification in large spaces with air heating, to assess preservation conditions.

5 REFERENCES

Camuffo, D., E. Pagan, S. Rissanen, L. Bratasz, R. Kozlowski et al. (2010). An advanced church heating system favourable to artworks: a contribution to Europen standardisation. *Journal of Cultural Heritage*, 11: 205-19.

De Backer L., J. Laverge, A. Janssens and M. De Paepe (2014). The use of a zonal model to calculate the stratification in a large building. *35th AIVC Conference Proceedings*, 522-531

De Backer L. (2018), *Preventive conservation of works of art in historic buildings: assessment and modelling*. Doctoral dissertation (supervisors A. Janssens & M. De Paepe), Faculty of Engineering and Architecture, Ghent University.

De Backer L., Janssens, A., M. Steeman and M. De Paepe (2018). Evaluation of display conditions of the Ghent altarpiece at St. Bavo Cathedral. *Journal of Cultural Heritage*, 29: 168-172.

Janssens, A. and M. De Paepe (2005). Effect of moisture inertia models on the predicted indoor humidity in a room. *26th AIVC Conference Proceedings*, 287-294.

Maroy K., M. Steeman, L. De Backer, A. Janssens, M. De Paepe (2015). Conservation Climate Analysis of a Church Containing Valuable Artworks. *Energy Procedia*, 78:1269–74

Steeman, H.J., M. Van Belleghem, A. Janssens and M. De Paepe (2009). Coupled simulation of heat and moisture transport in air and porous materials for the assessment of moisture related damage. *Building and Environment*, 44: 2176-84.

Togari S., Y. Arai, K. Milura (1993). A simplified model for predicting vertical temperature distribution in a large space. ASHRAE Transactions 99: 84-90.