

A strategy for Modelling Typical Indoor Climates in Historic Buildings: moisture buffering of massive walls and stratification by heating

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Abstract

Artworks in historical church buildings degrade due to indoor conditions that are not optimal to preserve artworks. Building Energy Simulation (BES) tools are useful and powerful tools in making decisions of different retrofitting designs to improve the indoor conditions. However, to make a more detailed assessment of the preservation conditions, it is important to take typical conditions in historical church buildings into account in the simulation model. Two of them are the buffering capacity of the heavy thick walls and the stratification during heating. Although BES-tools, based on the well mixed assumption, are adequate for the prediction of an average temperature and relative humidity in small rooms, it cannot predict detailed temperature and airflow distributions within each room. To provide a more realistic representation of thermal and hygric conditions in a church building, in this paper a simplified method is suggested to take into account the stratification during heating in combination with the moisture buffering.

Introduction

Artworks degrade. Most of the degradation to artworks in historic buildings are caused by unfavorable indoor climate conditions (Krus et al, 2007). The process of deterioration of a work of art is unavoidable, however, the degree of deterioration can be reduced by preserving the artworks in an optimal climate.

In case it is desired to improve the existing indoor climate by installing a new HVAC system, it is customary to use a simulation model to analyse the response of the modelled system and then improve, adjust or revise the system (Straube & Burnett, 1999). For this purpose, Building Energy Simulation (BES) tools are useful and powerful tools in making decisions of different retrofitting designs for improving the preventive conservation conditions in buildings (Widström & Mattsson, 2011). Concerning historical buildings, where an insufficient climate could cause the loss of irreplaceable valuable artworks, this makes simulation tools indispensable (Schellen, 2002). The advantage of BES-models is that they allow the detailed calculation of building behaviour under the influence of external inputs such as weather, occupancy and infiltration and for a longer period (Coakley, Raftery, & Keane, 2014). The calculation of a longer period is mandatory to assess the preservation conditions because both short-term fluctuations and long-term variations of the indoor

climate have to be evaluated. A disadvantage in the classical BES-approach, however, is that each zone is represented by one node. The risk on degradation of the object is then estimated using the temperature and relative humidity course of that node and analysing the fluctuations with a method like proposed by ASHRAE (ASHRAE, 2015).

Table 1: ASHRAE conservation classes(ASHRAE, 2015).

Class	Temperature		Relative humidity	
	$\Delta T_{\text{short/space}}$	$\Delta T_{\text{seasonal}}$	$\Delta RH_{\text{short/space}}$	$\Delta RH_{\text{seasonal}}$
AA	$\leq 2^{\circ}\text{C}$	$\leq 5^{\circ}\text{C}$	$\leq 5\%$	No change
As	$\leq 2^{\circ}\text{C}$	$+5^{\circ}\text{C}/-10^{\circ}\text{C}$	$\leq 5\%$	$\leq 10\%$
A	$\leq 2^{\circ}\text{C}$	$+5^{\circ}\text{C}/-10^{\circ}\text{C}$	$\leq 10\%$	No change
B	$\leq 5^{\circ}\text{C}$	$< 30^{\circ}\text{C}$	$\leq 10\%$	$\leq 10\%$
C	$< 25^{\circ}\text{C} (30^{\circ}\text{C})$		-	25 - 75%
D	-		-	$< 75\%$

To make a more correct assessment of the preservation conditions typical conditions in monumental historic buildings have to be taken into account in the simulation model: the presence of moisture in heavy building walls, the occurrence of stratification and hygrothermal gradients in the often very large interior volumes, and the effect of service components (e.g. heating devices and air inlets) on the air flow patterns. Therefore, some questions arise in this classical modelling approach:

- What if the monumental building is quite large?
Some artworks are exhibited in monumental church buildings which have a large interior volume. Furthermore, most church building have a specific heating regime, e.g. intermittent heating during services. In BES-tools the temperature and relative humidity of a room or even of a collection of rooms is assumed to be perfectly mixed. Damage at artworks and objects, however, is not only due to humidity fluctuations in time, but also to humidity variation in space (Table 1). Consequently, stratification should also be taken into account when estimating damage risk of artworks.
- What about the hygric buffering capacity of the building envelope and the hygrothermal behaviour of the building? Historic buildings are characterised by

thick walls made of brick masonry which have a high thermal and hygric capacity (Padfield, 2008). The buffering capacity has the ability to moderate the daily and seasonal temperature and humidity variations of the indoor environment. Because the amplitude of the relative humidity fluctuations (Table 1) is an important parameter for estimating the damage risk for artworks, in some cases it is necessary to include the influence of the hygrothermal behaviour of the walls, as this influences the indoor relative humidity.

To evaluate and optimize the HVAC-design in historical buildings in an integral way, a classical BES-approach is a robust approach in this way that the mentioned two characteristic conditions are not taken into account. To include the stratification and the hygric buffering, the

authors propose two additions to a classical BES-model. (Figure 1).

One addition is the implantation of a simplified airflow model that estimates the stratification in a zone. The research project used an existing model which predicts thermal stratification. To this model, equations to predict also the relative humidity were added.

The other addition is the incorporation of a model which estimates the moisture exchange between the air and porous materials in a simplified way or in a more detailed way.

These two additions will be combined in one model, so that for every subzone a moisture flux coming or going to the wall can be incorporated.

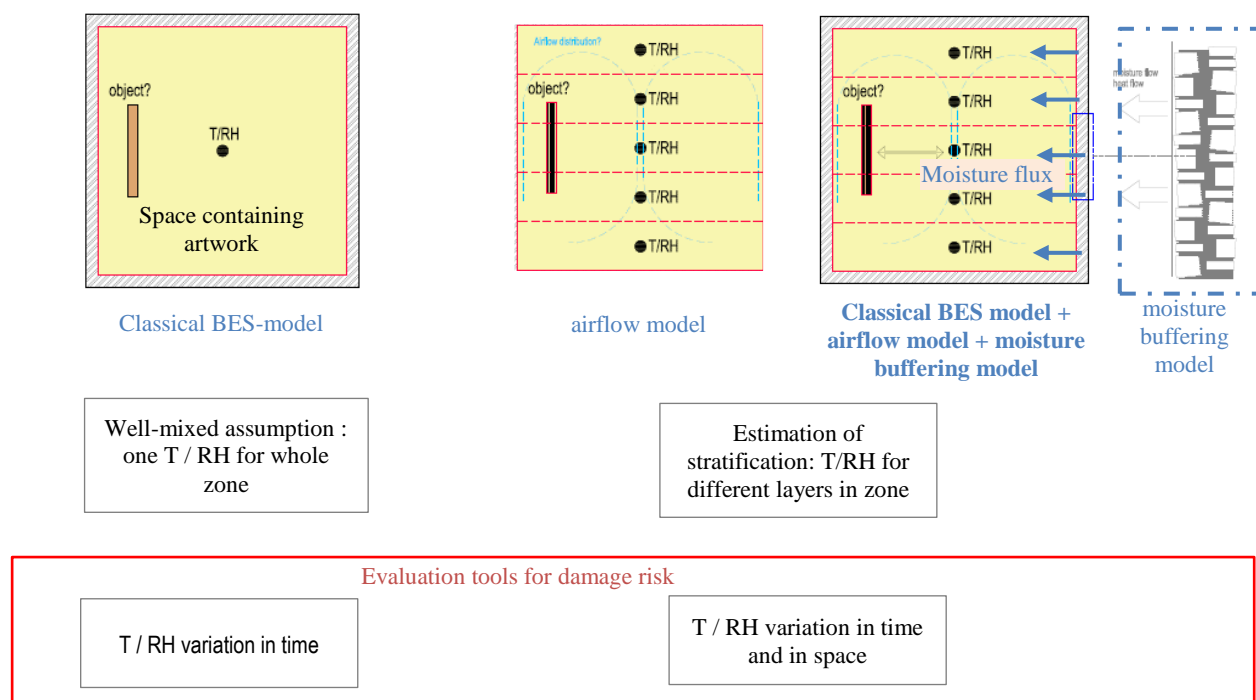


Figure 1: Extensions to classical BES-model, TRNSYS v17. (Left) airflow model. (Right) moisture exchange between the air and porous materials.

Practical: BES-software TRNSYS 17

The computer simulation program TRNSYS, version 17, will be used to model the thermal and hygric behavior of the building. TRNSYS simulates the behavior of transient systems with a modular structure. In other words, one complex problem is subdivided into smaller sub problems. TRNSYS is made up of two parts. The first is the kernel that reads and processes input files, iteratively solves the system, The second part, essential for this purpose, is a library of components each of which models the performance of one part of the simulated system (Robert et al, 2014). Next to its own library of components, the software also allows for implementing an own written component. The model to estimate the stratification and the model to add the hygric buffering were programmed as own components for TRNSYS v17.

The airflow model to predict stratification was a new component based on a theory found in literature. To model the hygric buffering behaviour, a former model was adapted (detailed model) and a new model (simplified model) was programmed.

Addition 1: hygro-thermal-zonal model

Literature review: Predicting Stratification in High Buildings

To predict the temperature, relative humidity and air flow in buildings, the range of complexity of airflow models is between the coarse fully mixed models and the very detailed Computational Fluid Dynamics (CFD) (Figure 2).

The first category, one-zone and multi-zone models, are the coarsest type of models. This category includes the BES-models. The models in this category allow the prediction of an average temperature and relative humidity in small rooms, but they cannot predict detailed temperature and airflow distributions within one zone. To estimate the airflow within one zone, an airflow model and a BES-model can be coupled¹. At the other end of the spectrum is the so-called CFD-approach. In this approach, models predict accurately the temperature, velocity and other flow parameters by solving the complete set of the Navier-Stokes equations. The use of CFD seems attracting to predict the airflow pattern. However, coupled simulation of BES and CFD cannot be used to perform controls evaluation (Zuo et al., 2016) and simplified airflow predicting models still have benefits over complex models: user friendliness, straight forward, and fast calculation (Wang & Chen, 2001).

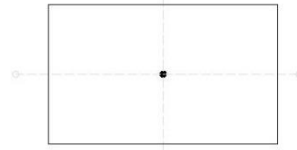
The third category is an intermediate approach between a fully mixed model and a detailed flow model and is a suitable method to predict the airflow in a large space in a simplified way. Because HVAC designers and architects often have no access to a powerful computer to perform calculations, these models are more appropriate. These models, which predict the airflow in a room, can be linked to a BES-software in which one zone is assumed to be perfectly mixed. By doing so, the influence of the airflow on the temperature distribution and vice versa can be calculated, in order to judge the thermal comfort and preservation conditions in one zone.

A wide variety of model for the intermediate approach exist. Griffith (2002) makes a distinction between so-called zonal and nodal models. The nodal models consist off flow paths between defined nodes in the room. Contrary to the nodal models, which only calculates the temperature in the defined nodes, in a zonal model the room is subdivided into volumes or cells and no assumptions are needed for airflow direction (Megri & Haghighat, 2007). The air flow between the grid surfaces of the cells are calculated based on the corresponding conservations equations. The difference with a CFD model is that the cells are much coarser and the solution of the conservation equations are simplified. Based on the simplifications made, the zonal models can be further subdivided into the pressure-zonal, the temperature-zonal and the momentum-zonal models (Griffith, 2002).

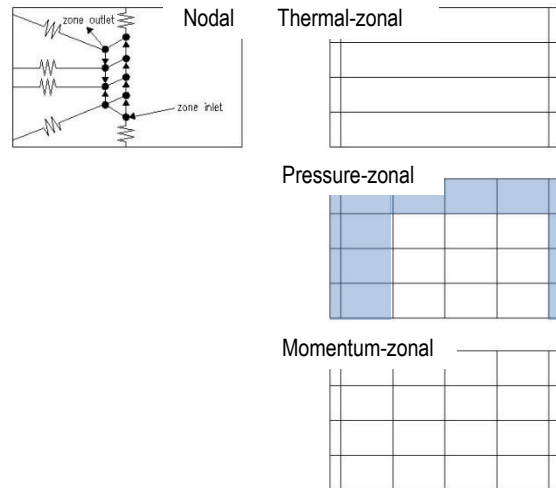
The goal of this study was to develop a user-friendly model which can be used to predict the conservation conditions in a building, while taking into account the stratification. The selected model was the thermal zonal model. In this model, the airflows along the vertical wall surfaces and supply airstreams are assumed to be the main components of the air movement in a large space. This assumption is reasonable for church buildings, where draught from cold surfaces, such as tall windows

and almost any tall masonry surface are present (Bordass & Bemrose, 1996).

Fully mixed: One-zone approach



Intermediate: Nodal and Zonal approach



Detailed: CFD approach

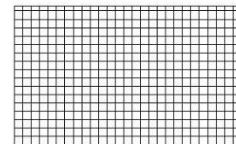


Figure 2: Schematic representation of airflow modelling techniques: (a) one-zone (b) zonal and (c) CFD approach (based on (Griffith, 2002)). The zonal models are further subdivided into thermal-zonal, pressure-zonal and momentum-zonal models. [Blue = distinction made in grid cells, based on expected flow path]

The thermal-zonal model

The thermal-based zonal model was first proposed in 1993 by Togari, Arai and Miura. 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. The model consisted of three sub-models:

- a sub-model which solves the mass and heat balance in vertical zones,
- a sub-model which evaluates mass and heat transfer along interior surfaces of walls,
- a sub-model which provides the interior surface temperature by solving the heat transfer by

¹ This coupling may not be confused with the coupling of a BES-model with a multi-zone airflow model in which the airflow between different zones of the building or between a zone and a plant, crack,... is modelled

as a network of nodes. A well-known example is TRNFLOW (Weber, 2002), which is the integration of the airflow model COMIS (Feustel, 1999) in the BES-software TRNSYS.

conduction, convection, and radiation of a building envelope. The airflows along the vertical wall surfaces and supply airstreams are assumed to be the main components of the air movement in a large space.

In this work, the thermal-model as described by Togari et al. (1993) was used to implement in the BES-software TRNSYS v17. This includes the sub-model which solves the mass and heat balance in vertical zones and the sub-model which evaluates mass and heat transfer along interior surfaces of walls. All boundary conditions necessary for these two sub-models are provided by the TRNSYS. The coupling holds that:

- the sub-model which provides the interior surface temperature is the one programmed in the TRNSYS. To calculate the convective heat transfer, convective coefficients are provided by an own-written equation written. The radiative heat transfer will be calculated by the Gebhart method.
- the sub-model for natural ventilation is a model available in the TRNSYS library.
- a sub-model for primary air stream is added. Because the description of jet model implemented by previous authors was very concise and because no model was already available in TRNSYS, a sub-model to include the mass and heat flow added by a non-isothermal free jet was implemented together with the thermal zonal model. This is described further.

However, to estimate the preservation conditions, next to temperature variation in space also the relative humidity in the space have to be known. In the original thermal-zonal model, there were no equations of the moisture transport. Therefore, to be able to estimate the humidity stratification following transport equations were added to the original model:

1. Addition of moisture transport in the air. Hereby the air was assumed as a mixture of dry air and water vapour, each component (vapour and dry air) obeying the ideal gas equation. A detailed description of the integrated zonal model, the equations and the validation has been given in a previous paper by De Backer, De Paepe and Janssens (2014).
2. Addition of moisture flux coming from a wall. This is described in the next chapter.

Mathematical Description of the Hygrothermal-Zonal Model

Principles of the original model

The space is divided into a finite number of horizontal layers. Each layer consists of a core cell and several wall cells (Figure 3). The core cell represents a horizontal layer. Where the layer is bounded by a wall, a wall cell is defined which accounts for the mass flow along the wall. The wall cell is fictive and has no volume.

- The horizontal temperature of each layer is assumed to be uniform, except for the regions affected by supply air jet ventilation.

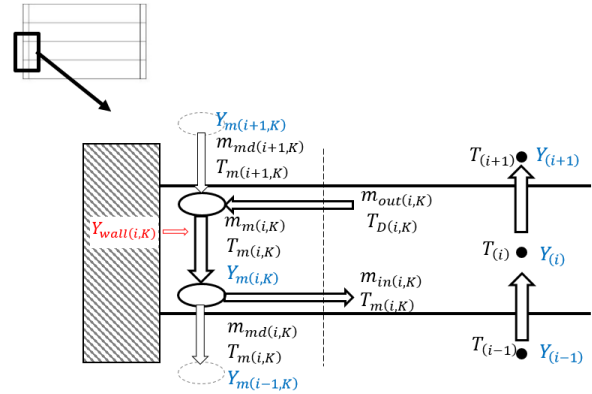


Figure 3: Schematic representation of the wall currents and air mass flows in one layer. (blue: addition of moisture conservation equations) (red: addition of moisture flux coming or going to the wall).

Adding equations to model non-isothermal free turbulent jet

A free jet is principally a jet that flows in an infinitely large space (Heiselberg, Murakami, & Rulet, 1998) and this type is representative for heating a large space like a church building. For this reason, equations to model this type of jet were implemented in the zonal model. To do so, the air flow rate and the heat flow rate of the jet entering each layer are necessary (Figure 4).

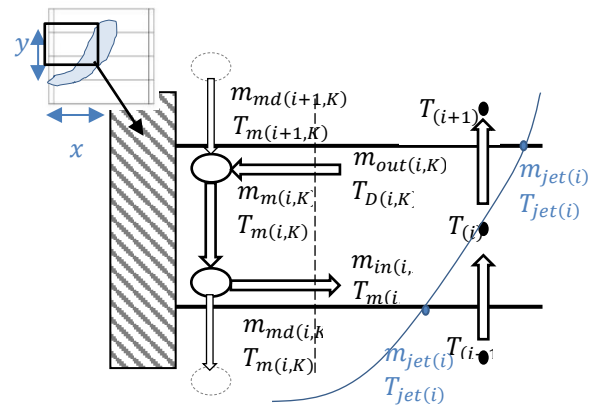


Figure 4: Schematic representation of jet model.

To calculate the air flow rate, the velocity profile and velocity decay of the jet have to be known. These are dependent on the opening discharging air into the large enclosure. The following diffuser types are integrated in the zonal model (Goodfellow & Tahti, 2001):

- Compact air jet: The jet is formed by square or rectangular openings with a small aspect ratio ($1 < b/h < 40$). Compact air jets are three-dimensional and axisymmetric.
- Linear air jet: The jet is formed by rectangular slots with a large aspect ratio ($b/h > 40$). The jet flows

approximately two-dimensional. Air jets are symmetric in the plane. At some distance from the diffuser, linear air jets tend to transform into compact jets.

The free jet has four zones (Table 2) depending on the development of the jet and each zone is characterized by the centreline velocity decay (ASHRAE, 2005; Awbi, 2003; Zhang, 2004). In the first three zones, room air is entrained into the jet and mixed with supply air. In the fourth zone, the jet collapses inward from the boundaries and the supply air is distributed to the room air as the jet disintegrates (Rajaratnam, 1976). In the code of the TRNSYS component, dependent on the provided characteristics of the jet (Table 5), the jet trajectory and velocity is calculated. In case the temperature of the jet is different than the surrounding air temperature, the diffusion of the jet will be influenced both by the buoyancy forces as well as by inertia forces due to jet momentum (Awbi, 2003). For different types of supply openings, the equation of Fren and Billington (1955) was used to calculate the jet trajectory.

$$\frac{y}{\sqrt{A_0}} = 0.226 \left(\frac{x}{\sqrt{A_0}} \right)^{2.61} Ar \quad (1)$$

The 3rd zone is the most important, from engineering point of view, as the jet enters the occupied area within this zone (ASHRAE, 2005). In this region, the velocity profile is usually expressed as a Gaussian distribution (Reichardt, Rajaratnam, 1976):

$$v(x, r) = v_{x,max} \exp \left(- \left(\frac{r(x)}{\delta(x)} \right)^2 \right) \quad (2)$$

Where $v_{x,max}$ is the maximum velocity at the centreline, $r(x)$ the radial coordinate and $\delta(x)$ the distance to the jet boundary which is related to the spread of the profile across the centreline.

Dependent on the type of opening the spread and the maximum velocity at the centreline of isothermal jets can be described by the equations in Table 3 (Awbi, 2003; Goodfellow & Tahti, 2001). Based on these equations, the flow rate for unit length at any section of the jet is calculated by:

$$m_{jet,i}(x_i) = \rho v_{max}(x_i) \int_0^\infty \exp \left(- \left(\frac{r(x_i)}{\delta(x_i)} \right)^2 \right) r dr \quad (3)$$

Where $r(x)$ is the radial coordinate [m] and $\delta(x)$ the spread of the profile across the centerline (Table 3).

Table 2: Boundaries adopted for the four zones of a free jet with their characteristic velocity decay

Zone	Range	Velocity
Core zone	$x \leq 4D$	$\frac{v_{centerline}}{v_0} = 1$
Transient zone	$4D < x < 8D$	
Characteristic decay region	$4D < x < b*4(b/h)$ (linear)	$\frac{v_{centerline}}{v_0} \sim \frac{1}{x^n}$ $n = 0.33 - 1$

Turbulent zone Axisymmetric decay region	$x \leq 25D$ - 100D	$\frac{v_{centerline}}{v_0} \sim \frac{1}{x}$
Degradation zone Terminal zone	$x > 100D$	$\frac{v_{centerline}}{v_0} \sim \frac{1}{x^n}$

Table 3: Spread and velocity decay used in the model for a compact and linear jet (Awbi, 2003; Goodfellow & Tahti, 2001).

Type of jet	Spread $\delta(x)$	Velocity
Compact: Circular jet	0.151x	$\frac{v_{x,max}}{v_0} = \frac{K_1}{x/d_0}$
Compact 3D-Jet		$\frac{v_{x,max}}{v_0} = \frac{K_1}{x/\sqrt{A_0}}$
Plane Jet (2D)	0.272x	$\frac{v_{x,max}}{v_0} = \frac{K_1}{\sqrt{x/h}}$

Where v_0 is the average velocity at the supply and $v_{x,max}$ the velocity at the centreline. K_1 is a constant usually referred to as the throw constant. Theoretical values of the characteristic K_1 depend upon the type of velocity profile equation and supply conditions assumed (Goodfellow & Tahti, 2001). Values for K_1 can be derived from the table presented in ASHRAE (ASHRAE, 2005). d_0 is the effective diameter of the supply opening, h is the height.

To calculate the heat flow, the temperature profile and the temperature decay have to be known. The temperature profile of a jet is similar, but flatter than the velocity profile. In general, the two profiles are related by the following equation:

$$\frac{v(x, r)}{v_{x,max}} = \frac{(T(x, r) - T_i)^{1/Pr}}{(T_{x,max} - T_i)} \quad (4)$$

The temperature decay in the centerline of the jet was calculated with the following equation.

$$\frac{T_{x,max} - T_i}{T_0 - T_i} = \frac{K_2 \sqrt{A_0}}{x} \quad (5)$$

Where $T_{max}(x)$ is the temperature at the centreline, T_i the temperature of the room and T_0 is the supply temperature. Pr is the Prandtl number [-]. In equation 5, the value for K_2 was calculated by the formula of Shepelev (sec (Goodfellow & Tahti, 2001)):

$$K_2 = \frac{1}{K_1} \frac{(1 + Pr)}{2\pi 0.082^2} \quad (6)$$

Validation of the jet model

The case described in the report of Togari et al. (1993) was used to validate the model. They performed a scale-model test using a test room. The geometrically simple test room has a ground plane of 3m x 3m and measures 2,5m in height. The room consist of insulated boards (three vertical walls, ceiling and floor) and one glass wall. In the wall opposite to the glass wall, two openings were made in the symmetry plane: a supply inlet at 0,625m

above the floor and a return outlet at 0,250m above the floor. The room described above was fully modelled in TRNSYS. The space was vertically divided into 5 layers (Figure 5). In the model described by Togari the calculations of the stratification started based on measured wall surface temperatures, while in the model in TRNSYS there was started from outdoor conditions and wall temperatures were calculated.

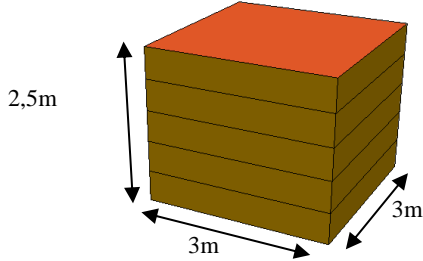


Figure 5: The simulation model of TRNSYS, where the room was vertically divided into 5 layers.

In this case study, the outside temperature of the test room was kept between 11°C and 12°C. Hot air was supplied to the test room. The temperature of the supplied air was 40,7°C and the supply air volume was 150m³/h. Figure 6 shows the comparison between the measured and simulated results presented in the paper of Togari, and the results calculated by the thermal-zonal model. Table 4 tabulates the root mean square error. Good agreement was found between the measured and calculated results.

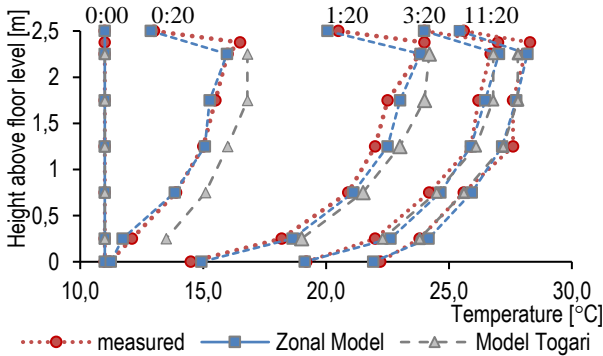


Figure 6: The progress of the temperature in case of hot air supply condition (jet).

Table 4: Root Mean Square of the temperature.

	0:00	0:20	1:20	3:20	11:20
RMSE	0.26	0.63	0.73	0.54	0.55

Addition 2: Hygrothermal Wall Behaviour

In monumental historic buildings, heavy walls release and adsorb moisture. Because the amplitude of the relative humidity fluctuations is an important parameter for estimating the damage risk for artworks, the possibility is integrated into the thermal-zonal model to include the influence of the hygrothermal behavior of the walls. In the zonal model, an input is defined for each wall to account for the moisture flux, $m_{wall(i,K)}$ (Figure 3). The mass

$m_{wall(i,K)}$ is added in the equation used to determine the humidity ratio of the wall current $Y_{m(i,K)}$, yielding:

$$Y_{m(i,K)} = \frac{Y_{i(i,K)}^{p-1} m_{out(i,K)} - Y_{i(i,K)}^{p-1} m_{in(i,K)}}{m_{m(i,K)}} + \frac{Y_{m(i-1,K)}^{p-1} m_{md(i-1,K)}}{m_{m(i,K)}} + \frac{Y_{m(i+1,K)}^{p-1} m_{md(i+1,K)}}{m_{m(i,K)}} + \frac{m_{wall(i,K)}}{m_{m(i,K)}} \quad (7)$$

Can the EMPD-model in TRNSYS be used?

In TRNSYS itself, an effective moisture penetration depth (EMPD)-model is available. This model, however, cannot be used for the newly developed thermal-zonal model, because it calculates one value representing the average moisture storage properties of all room (thermal zone) surrounding surfaces (Figure 8). Though, in the zonal model, one thermal zone is subdivided into different horizontal layers with separate wall elements, a vapor mass flow $m_{wall(i,K)}$ has to be provided for each wall element. Therefore, when using the coupled zonal-TRNSYS model, the EMPD-model in TRNBuild is not usable. In the next paragraphs, two moisture models which estimates the moisture exchange between the air and porous materials in a simplified way or in a more detailed way are proposed.

Simplified modelling of moisture buffering: EMPD-model

In the EMPD approach, the assumption is that only a thin part of the interior surface of the moisture absorbent material, with a fictitious thickness d_{EMPD} , contributes to the moisture buffering process (Janssen & Roels, 2009). The thickness d_{EMPD} is related to the period of the moisture variation cycle and the moisture storage and sorption properties of the material. Because the EMPD model used in TRNSYS has some limitations, there was chosen to program another type of EMPD model.

The EMPD-model in TRNSYS is an isothermal moisture model with constant material properties and is not coupled with heat transfer in the wall. In insulated buildings these model assumptions are accepted because the thin buffering layer has a constant temperature (Janssens & De Paepe, 2005). As shown by Janssens and De Paepe (2005), in cases where a temperature gradient is present, the EMPD-model is not able to predict the initial fast response of indoor humidity to changes in moisture production. Because this study deals with historical buildings, where the temperature gradient in the buffering layer could be important, the chosen model was an EMPD model, coupled with heat transfer in the material and in which material properties are updated every time step (Janssens et al., 2008).

The effective penetration depth d_{EMPD} is calculated by equation 8, in which t_p is the period of cyclic variation (s).

$$d_{EMPD} = \sqrt{\frac{\delta(\varphi)P_{v,sat}(T)t_p}{\rho\xi(\varphi)\pi}} \quad (8)$$

Where $\delta(\varphi)$ is vapour permeability [s], $\rho\xi(\varphi)$ is the moisture capacity in terms of humidity derived from the material sorption isotherm [kg/m³] and $P_{v,sat}(T)$ represents the saturation water vapour pressure [Pa] at temperature T [°C].

As in TRNSYS, the EMPD-model consists of two buffering layers; one for short-term and one for long-term moisture buffering. The following equations are then solved together with the moisture balance equation for indoor air within a space under the non-steady-state.

$$A\rho_{buf}d_{buf}[\xi(\varphi)]_{buf} \frac{d\varphi_{buf}}{dt} = \frac{A(P_{v,i} - P_{v,buf})}{Z_{buf}} - \frac{A(P_{v,buf} - P_{v,deep})}{Z_{deep}} \quad (9)$$

$$A\rho_{deep}d_{deep}[\xi(\varphi)]_{deep} \frac{d\varphi_{deep}}{dt} = \frac{A(P_{v,buf} - P_{v,deep})}{Z_{deep}} \quad (10)$$

$$A\rho_{buf}C_{p,buf} \frac{dT_{buf}}{dt} = \frac{A(T_{surf,i} - T_{buf})}{R_{buf}} - \frac{A(T_{buf} - T_{deep})}{R_{deep}} \quad (11)$$

$$A\rho_{deep}C_{p,deep} \frac{dT_{deep}}{dt} = \frac{A(T_{buf} - T_{deep})}{R_{deep}} \quad (12)$$

Where the buffer and deep layer are described by the following characteristics: $A\rho d$ the mass of the layer [kg], $\xi(\varphi)$ moisture capacity [kg/kg], Z moisture transfer resistance for diffusion [Pa.m²s/kg], C_p de heat capacity [J/kg.K] and R the heat transfer resistance [m²K/W].

Detailed modelling of moisture buffering: HAM-model

For historic buildings with a high hygroscopic content, a detailed modelling of the hygrothermal behavior may be important as neglecting non-isothermal moisture buffering may lead to a misjudgment of the indoor climate (Steeman, 2010). To this end, Steeman et al. (2010) developed a HAM-component for TRNSYS. Detailed information about the model and validation can be found in Steeman (2010). In case a more detailed hygro-thermal behavior is desired, this component will be coupled to the zonal-BES model. Following adaptations were made to the original component:

- Translation from FORTRAN to C++. This was a personal choice because the author has experience with C++ and knows in that language how to solve memory issues. In this context, the original model was improved by lower computational time (convergence scheme, dealing with storage, ...).

- The code of the component is not programmed in one file anymore, but it instead into multiple files (.cpp). By separating the code of the HAM-equations and the code which reads the TRNSYS-inputs, the HAM-code could also easily be used for interfacing with other software, such as MATLAB (flexibility).
- Different mathematical formulations of the moisture sorption curve, instead of only the empirical equation given by Hansen (Freiesleben Hansen, 1985) (flexibility).
- The water vapour resistance Z_{PE} between two nodes is now calculated as following:

$$Z_{PE} = \frac{\Delta x_{PE}}{\delta_{g,e}} = \frac{\Delta x_{PE}\delta_{g,E} + \Delta x_{eE}\delta_{g,P}}{\delta_{g,E}\delta_{g,P}} \quad (10)$$

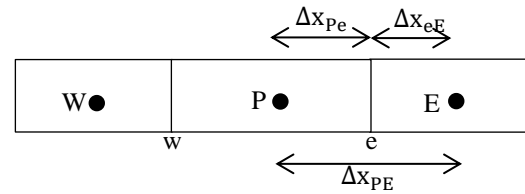


Figure 7: Spatial discretization scheme for heat and mass transfer.

TRNSYS: coupling of the hygrothermal zonal model and moisture buffering model

In the release of TRNSYS v17, the multi-zone building model (Type 56) has been extended with some new features. A thermal zone, in the former release existing of one zone node with perfectly mixed assumption, can be now subdivided into one or more air nodes defining the convective zones. The heat exchange between building surfaces and the air node is based on convection only whereas the shortwave radiation distribution and the longwave radiation exchange is performed over the whole radiative zone (Figure 8). This new feature simplifies the simulation of stratification effects (Aschaber, Hiller, & Weber, 2009; SEL, 2012).

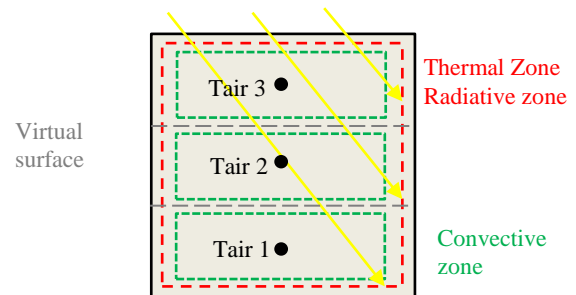


Figure 8: One radiative zone subdivided into different air nodes, each with their own convective gain (based on Aschaber, 2009).

Another new interesting feature in TRNSYS v17, necessary for the stratification estimation, is the detailed calculation of the diffuse radiation distribution and longwave radiation exchange within a zone based on view factors. Namely, because the airflow in the thermal-zonal

model is partially driven by difference between surface temperature and indoor air temperature, a more detailed result of the surface temperature will also influence the resulting stratification in the thermal zone.

To integrate the thermal zonal model in TRNSYS it looks obvious to make use of the possibility to provide a value for the mass flow between the different layers (The new option available for TRNSYS v17). However, instead a heat gain and a moisture gain were defined for every air node in TRNSYS. The reason was to avoid that the convective heat gain will be calculated twice: once by the thermal-zonal model and once by the multi-zone building model in TRNSYS. Therefore, the convective heat gain from the building model in TRNSYS will be subtracted from the total heat gain calculated by the thermal-zonal model. The residual heat flux will be implemented in TRNSYS as a heat gain. The moisture gain in every air node will also be looked at the difference in absolute humidity between the values for the air node in the building model of TRNSYS and the absolute humidity for the air node in the thermal-zonal model. The difference in

moisture will be added in TRNSYS by defining a moisture gain for every model.

Practical use of the hygro-thermal zonal model

The thermal zonal model is implemented in the Simulation Studio as Type 223. TRNSYS uses a so-called proforma file to define parameters, inputs and output values to the model. Parameter values are assigned a constant value during the whole simulation, like the number of air nodes and the number of walls. Depending on the number of layers and number of walls defined in the building model of TRNSYS, the volume of each layer, the wall temperature and other input values can be set. Contrary, input values can be coupled to other models in the simulation. For instance, the zone temperature, relative humidity, convective heat gain and wall temperature are calculated by the multi-zone building model and then transferred to the thermal zonal model as a boundary condition. Required parameters, input and output values are listed in Table 5.

Table 5: Parameters, input and output values for Type 223. (Green = modelling of jet, Blue = hygrothermal model).

Parameter Values		
layers	Number of layers in the thermal zonal model (= number of air nodes in the building model)	-
walls	Number of walls in the thermal model and building model	-
height layer [layers]	Height of each layer	m
Area between layers[layers-1]	Area between two horizontal layers	m ²
iterations	Maximum number of iterations	-
time step	Time step of the zonal model	s
volume [layers]	Volume of each air nodes	m ³
area opening	Area of the supply outlet	m ²
hydraulic area	Hydraulic area of the supply outlet (linear jet = h; compact jet = sqrt(area))	m
type jet	Diffuser types. [1] =Linear; [2] = compact	-
K1	Throw constant. Values for K1 can be derived from the table presented in ASHRAE (ASHRAE, 2005)	-
layer Outlet	Layer in which the supply outlet is located	-
layer Inlet	Layer in which the return air inlet is located	-
layer Infiltration		
layer Exfiltration		
Input Values		
T _{zone} [layers]	Temperature of the zone	°C
AH _{zone} [layers]	Absolute humidity of the zone	kg/kg
T _{wall} [walls]	Temperature of the wall	°C
h _{wall} [walls]	Convective heat transfer coefficient	W/m ² K
Q _{conv} [layers]	Convective heat gain for every layer, calculated by TRNSYS	kJ/h
m _{walls} [walls]	Moist flux from or to the wall	kg
C _{p,air}	Heat capacity air	J/kgK
C _{p,vap}	Heat capacity vapour	J/kgK
h _{ev}	Latent heat vapour	J/kg
Q _{jet}	Jet flow rate	kg/h
T _{jet}	Temperature of the jet at the supply	°C
AH _{jet}	Absolute humidity of the jet at the supply	kg/kg
Q _{inf}	Infiltration rate	kg/h
T _{inf}	Temperature of the infiltration	°C
AH _{inf}	Absolute humidity of the infiltration	kg/kg

Output Values		
m_{vap}	Moisture gain	kg/h
Q_{cur}	Convective heat gain related to the thermal-zonal model	kJ/h

Conclusion

Artworks deteriorate, that is unavoidable. The degree of natural deterioration, however, can be reduced. Within the framework of preventive conservation, BES-tools are useful and powerful tools in making decisions of different retrofitting designs for improving the preventive conservation conditions in buildings. To estimate the ‘quality’ of the preservation conditions, the average value and the amplitude of the temperature and relative humidity are used. To make a correct assessment of the them, it is important to take typical conditions in historical church buildings into account in the simulation model which has an effect on the average value and the amplitude of the temperature and relative humidity. Two of them are the buffering capacity of the heavy thick walls and the stratification during heating. In Building Energy Simulation programs, the airflow in one zone is treaded as ‘fully mixed’ and the moisture buffering is calculated in a simplified way.

TRNSYS v17 was used as BES-software. Next to its own library of components, used to model the building and its systems, the software also allows for implementing own written components. To model the stratification, a thermal-zonal model was programmed which can be implemented in TRNSYS as a component in the modular structure. Equations to model non-isothermal free turbulent jet, which is representative for heating a large space like a church building is added. To include the moisture buffering of the surrounding walls, two models were suggested. The first model is a simplified model EMPD-model. This model was a newly developed component. The second model was a more detailed D-HAM-model, originally developed by Steeman et al. (2010).

Preliminary results and Future Work

These types will be used to evaluate preservation conditions, related to the temperature and relative fluctuations in time and in space, in a typical historic Catholic church building (Figure 9).

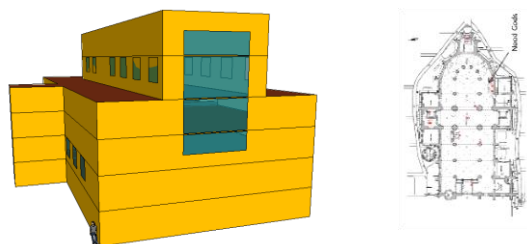


Figure 9: The geometrical model of the TRNBuild-model (left). This model was based on a typical historic Catholic church (right).

The effect of the different modelling options (one-zonal, thermal-zonal and thermal-zonal coupled with buffering) on the preservation conditions will be compared. Besides the simulation study of a real case study, the thermal-zonal model will be also refined. And a sensitivity analysis on a simple case (box) will be performed to study how the model is sensitive to boundary conditions (e.g. surface temperature, time step, simplification of convection coefficient, simplification of modelling of radiation).

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