Optimal setpoint operation of the climate control of a church

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Optimal setpoint operation of the climate control of a monumental church

A.W.M. van Schijndel and H.L. Schellen

Eindhoven University of Technology (TUE)

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Abstract

The report presents the characteristics of the Walloon Church in Delft (Netherlands) and a description of constraints for the indoor climate, giving criteria for the indoor air temperature and relative humidity with the focus on the preservation of the monumental organ. The setpoint operation of the HVAC system is evaluated by simulation using MatLab, Comsol and Simulink models. The next main model components are presented and combined in a single integrated Simulink model: 1) a HAMbase Simulink building model for simulating the indoor temperature and relative humidity, 2) a Comsol PDE model for simulating detailed dynamic moisture transport in the monumental wood (organ) and 3) a Simulink controller model. The building model is validated with measurements. The main advantage of the integrated model is that it directly simulates the impact of HVAC control setpoint strategies on the indoor climate and the organ. Two types of control strategies are discussed. The first type is a limited indoor air temperature changing rate. The second type is a limited indoor air relative humidity changing rate. Recommendations from international literature suggest that 1) a changing rate of 2 K/h will preserve the interior of churches and 2) a limited drying rate is important for the conservation of monumental wood. This preliminary study shows that a limitation of indoor air temperature changing rate of 2 K/h can reduce the peak drying rates by a factor 20 and a limitation of the relative humidity changing rate of 2 %/h can reduce the peak drying rates by a factor 50. The second strategy has the disadvantage that the heating time is not constant. ve easy to create EU maps using MatLab
1 INTRODUCTION

1.1 The Walloon church in Delft

In the Walloon Church in Delft a monumental organ is present which has been restored in the spring of 2000. To prevent causing damage to the organ again, the indoor climate has to meet certain requirements. Recent studies (Neilen 2003, Schellen 2002, and Stappers 2000) have been performed for the preservation of the monumental organ. As a result of this research several adjustments have been made to the heating system. Afterwards measurements showed that the indoor climate did meet the requirements for preservation of the organ.

The Walloon Church is not only used for services, but also for several other activities e.g. organ recitals. Since people are sitting in the church without wearing their overcoat, a temperature of 18 to 20°C is desirable. The result of this rather high temperature for monumental churches, is that the Relative Humidity (RH) of the indoor air becomes very low (30%). Since such a low RH can cause damage to the organ, the heating system is restricted. As soon as the RH of the indoor air threatens to drop below 40%, the heating system is shut down. As a result of this restriction it is not possible to reach an indoor temperature of 18°C in winter when it is freezing outside. Humidifying of the indoor air was seen as a possible solution. Due to this measure, the RH of the indoor air remains high enough for preserving the organ and at the same time the indoor air can be heated to the required comfort temperature of 18°C. As a consequence of humidifying during winter conditions there is a risk that condensation and fungal growth develops on cold surfaces. For that reason a request for further research by simulations was received from the church council. With the help of these simulations an assessment can be made of the potential risks.

The main task is to protect the wooden monumental organ from drying induced stresses. In recent studies it is conclude that:
- the increase of drying rate causes a non uniform distribution of the moisture content in dried material and this involves the drying induced stress (Kowalski 1999),
- fracture is more likely if the dried body is thick and/or the drying rate is high (Kowalski 2002).

These studies show that the peak drying rate has to be minimized in order to minimize the risk of drying induced stress and fracture.

1.2 Objectives

The main objectives are:
- Development of a single model for simulating the indoor climate, the detailed moisture distributions of wood and the HVAC system.
- Evaluation of the current setpoint operation strategy of the HVAC system of the Walloon church.
- Development and evaluation of new strategies including RH control

2 MODELING

2.1 The church indoor climate model using HAMBase SimuLink
The indoor climate is simulated using HAMBase. The main objective of HAMBase is the simulation of the thermal and hygric indoor climate and the energy consumption. A brief description of the model here will be given here. A more detailed description can be found in (Wit 2001).

In many simulation models the thermal indoor climate is described with one air temperature only and several radiant temperatures (the indoor surface temperatures). One can wonder how much the detailed calculation of radiation exchange between the surfaces contributes in a realistic way to the accuracy of a model with no thermal stratification and an empty room. Furniture surfaces will 'see' each other very differently. Besides this surface temperatures, with exception of the window temperature, don't differ very much in most buildings. In the HAMBase model an integrated sphere approach is used that reduces the radiant temperature to only one node. This has the advantage that complicated geometry's can easily be modeled too.

In a similar way a model for the air humidity is made. Only vapor transport is modeled, the hygroscopic curve is linearized between RH 20% and 80%, and the vapor permeability is taken as a constant. The main differences are: there is only one room node (the vapor pressure) and the moisture storage in walls and furniture, carpets etc is dependent on the relative humidity. The hygric storage in the furnished room exceeds often the storage in the fabric but is difficult to estimate. Thus the crude treatment of the fabric storage will not be the main cause of inaccuracy.

The HAMBase model has been subjected to the ASHRAE test (Schijndel 2002b) with satisfactory results.

The HAMBase model is also implemented in SimuLink as a hybrid model: A discrete part for calculating hourly based thermal and hygric building construction values and parameters based on the climate data and a continuous part based on ODEs for calculating the indoor climate (Schijndel 2002b). The main advantage of this improvement is that heating, cooling and (de)humidifying can be accurately simulated for small time scales (order ~seconds). This feature is essential for simulating peak drying rates.

Details of the geometry, material properties and boundary conditions of the HAMBase church model can be found in (Schellen 2002) and (Neilen 2003). In SimuLink, the HAMBase model is visualized by a single block with continuous input and output connections. The input signal of the HAMBase SimuLink model is a vector containing for each zone heating/cooling power and moisture sources/sinks. The output signal contains for each zone the comfort temperature, the air temperature and RH. In figure 1 the input/output structure for the church model (containing 2 zones: church and attic) is shown:

Figure 1. The church model in SimuLink. With Q = heating power [W], g = humidifying [kg/s], T comfort = comfort temperature [°C], T air = air temperature [°C], RH air = air relative humidity [-].
2.2 The moisture transport model using Comsol

Comsol (Comsol 2000) is a toolbox written in MatLab. It solves systems of coupled PDEs (up to 32 independent variables). The specified PDEs may be non-linear and time dependent and act on a 1D, 2D or 3D geometry. The PDEs and boundary values can be represented by two forms. The coefficient form is as follows:

\[
\frac{\partial \hat{c}u}{\partial t} + \nabla \cdot (c \nabla u + \alpha u - \gamma) + \beta \nabla u + \alpha u = f \quad (1a)
\]

\[
\hat{g} \cdot (c \nabla u + \alpha u - \gamma) + qu = g - \lambda \quad (1b)
\]

\[hu = r \quad (1c)
\]

The first equation (1a) is satisfied inside the domain \( \Omega \) and the second (1b) (generalized Neumann boundary) and third (1c) (Dirichlet boundary) equations are both satisfied on the boundary of the domain \( \partial \Omega \). \( \hat{n} \) is the outward unit normal and is calculated internally. \( \lambda \) is an unknown vector-valued function called the Lagrange multiplier. This multiplier is also calculated internally and will only be used in the case of mixed boundary conditions. The coefficients \( d_a, c, \alpha, \beta, \gamma, a, f, g, q \) and \( r \) are scalars, vectors, matrices or tensors. Their components can be functions of the space, time and the solution \( u \). For a stationary system in coefficient form \( d_a = 0 \). Often \( c \) is called the diffusion coefficient, \( \alpha \) and \( \beta \) are convection coefficients, \( a \) is the absorption coefficient and \( \gamma \) and \( f \) are source terms.

Although Comsol is well equipped for solving complex building physics problems (Schijndel 2003), the Comsol model in this paper is quite simple. The emphasis of this study lies not on the complexity of the individual models but on the complexity of the combination of models. The moisture transport is assumed to be 1D and dominated by vapor transport. This means for the PDE coefficients of (1a – 1c):

\[
u = w \quad (2a)
\]
\[
d_a = 1 \quad (2b)
\]
\[
c = D_w \quad (2c)
\]
\[
g = \beta_{RH} \cdot (RH_{air} - RH_{surface}(w)) \quad (2d)
\]
\[
\alpha = \beta = \gamma = a = f = q = h = r = 0 \quad (2e)
\]

where \( w \) = moisture content [kg/m\(^3\)], \( D_w \) = moisture diffusivity [m\(^2\)/s], \( \beta_{RH} \) = moisture surface transfer coefficient [kg/m\(^2\)/s], \( RH_{air} \) = indoor air relative humidity, \( RH_{surface}(w) \) = relative humidity at surface calculated from the hygroscopic curve. Furthermore it is assumed that the diffusion coefficient is constant and the moisture retention curve is linear in the range of 20% < RH < 90%. The thickness of the wood is 1 cm.

The Comsol model is exported to SimuLink. In figure 2 the SimuLink model and its input/output structure is shown:
The implementation of a more accurate model for the moisture transport and moisture induced stresses is left over for future research.

2.3 The controller (Proportional) using SimuLink

In figure 3 the controller model is shown:

The set point of the air temperature is generated by a pulse block with properties: Period: 1 week, start time 04.00 o'clock Sunday, duration: 12 hours, lower value: 10 °C higher value 20 °C. The input of the PID controller consists of the set point minus the actual air temperature. The settings of the PID controller are: $P = 10^2$, $I=D=0$, so in this case it acts like a proportional controller. The output of the controller is limited between 0 en 90 kW.

2.4 The complete model in SimuLink

The complete model consists of the models of the church, wood and controller. In figure 4 the complete model is shown:
There are two closed circuits:

a) an output of the church, the air temperature, is connected to input of the controller and the output of the controller, heating power, is connected to an input (heating/cooling) of the church.

b) another output of the church, relative humidity, is connected to the input of the wood and an output of the wood, moisture exchange rate is connected to an input (humidifying) of the church.

In this case, the amount of wood compared with other hygroscopic material (walls) is small. So the influence of the moisture exchange rate of wood on the indoor climate is also small. The connection between the output of the wood and input of the church therefore may be omitted.

3 RESULTS

3.1 Validation of the HAMBase model

The HAMBase model has been subjected to a validation study by (Neilen 2003). The measured and simulated air temperature and relative humidity of one month (December 2000) are compared. In figure 5 the results are shown:
Figure 5. Validation of the HAMBase model. The measured and simulated air temperature and relative humidity of one month (December 2000) are compared (Neilen 2003).

Figure 5 shows that simulation and measurement are in good agreement.

3.2 Validation of the Comsol model

In (Schijndel 2003) a 1D-moisture transport model in Comsol is validated and shows a good agreement between measurement and simulation. The same model is used, but with other material properties (wood) in (Schellen 2002). In this thesis it is shown that simulation and measurement are in good agreement in case of drying and wetting of wood by a fluctuating air relative humidity (35% < RH < 85%). In figure 6 the drying result is shown:
Figure 6. Simulation and measurement of moisture profiles in case of drying of a cylinder of wood (diameter 25 mm) by a step in relative humidity from 85% to 35% (Schellen 2002).

Figure 6 shows that simulation and measurement are in good agreement.

3.3 Drying rates

The moisture content near the surface and the drying rate (= rate of change of moisture content near the surface) is studied, by using the model of figure 4, for 2 cases: a) no heating and b) full heating capacity, i.e. no limitations in air temperature or relative humidity changing rate. The simulation period is again one month (December 2000). For all following case studies, the setpoint operation of figure 3 is used. This means that the church is heated 4 times a month. In figure 7, the indoor air temperature, the relative humidity and the moisture content of the wood near the surface is shown for the 2 cases, no heating and maximum capacity:
Figure 7. The indoor air temperature, the relative humidity and the moisture content of the wood near the surface. The simulation period is December 2000.

In figure 8, the drying rate is shown during a period of 1 day (starting Saturday 0.00 o'clock) for the 2 cases, no heating and maximum capacity:
Figure 8. The drying rate during a period of 1 day (starting Saturday 0.00 o'clock).

A negative drying rate means that water is transported from the material to the surroundings i.e. drying. In figure 9, the peak-drying rate defined as the absolute value of the drying rate for that same period is shown on a log scale.
Figure 9. The peak drying rate during a period of 1 day (starting Saturday 0.00 o'clock).

From figure 9 the difference in peak drying rate for the case of no heating and the case of full heating capacity is very clear: The peak drying rate, in the case of full heating, is of order $\sim 100$ times bigger than in case of no heating. These peaks can cause drying induced stresses (Kowalski 1999) and have to be minimized to prevent possible damaging of the wood. In the next section some alternative setpoint operations will be discussed.

4 SETPOINT OPERATION STUDY

In Section 3 the results of the control strategies: No heating and full heating capacity are already evaluated. In this section two alternative setpoint operations will be discussed.

4.1 Limitation of the air temperature changing rate

Recommendations from international literature (Schellen 2002) suggest that an air temperature changing rate of 2 K/h will preserve the interior of churches. The limitation of the air temperature changing rate is modeled by a 'Rate Limiter' block of SimuLink. The complete model including the setpoint temperature Rate Limiter is shown in figure 10:
The output of the air temperature setpoint is connected to a 'Rate Limiter' block of SimuLink. This block has two parameters: the Rising slew rate (R) and the falling slew rate (F). This block is modeled by:

\[
rate = \frac{u(i) - y(i-1)}{t(i) - t(i-1)}, \quad (3a)
\]

if \(rate > R\) : \(y(i) = \Delta t \cdot R + y(i-1)\) \((3b)\)

if \(rate < F\) : \(y(i) = \Delta t \cdot F + y(i-1)\) \((3c)\)

else : \(y(i) = u(i)\) \((3d)\)

where \(u = \) input of the block, \(y = \) output of the block, \(t = \) time, \(\Delta t = t(i) - t(i-1)\), (i) = actual time step, (i-1) = previous time step.

In figure 11, the indoor air temperature, the relative humidity and the moisture content of the wood near the surface during a period of 1 day (starting Saturday 0.00 o'clock) is shown, for different cases including limitation of the air temperature heating change rate of 1.5 K/h and 2.5 K/h. (This means for the parameters of the rate limiter that the rising slew rate R equals 1.5/3600 resp. 2.5/3600 and the falling slew rate F equals -\(\infty\) in both cases).
Figure 11. The indoor air temperature, the relative humidity and the moisture content of the wood near the surface during a period of 1 day (starting Saturday 0.00 o'clock).

In figure 12 the peak-drying rate is shown for these cases:
Figure 12. The peak drying rate during a period of 1 day (starting Saturday 0.00 o'clock).

From figure 12 it follows that a limitation of the temperature changing rate of 2 K/h reduces the peak drying rates by an order of ~10 compared with no limited temperature heating change. However, the peak factor is still an order of ~10 higher compared with no heating.

4.2 Limitation of the relative humidity changing rate

A more challenging task is to model the heating of the church with a limitation of the relative humidity. In figure 13 the complete model including the relative humidity changing limiter is shown.
The output of the air temperature setpoint block is connected to a new developed 'Variable Rate Limiter' block. This block has 3 inputs 1) the air temperature setpoint, 2) the (variable) rising slew rate (Rvar) and the (variable) falling slew rate (Fvar). The output of this block is analog to the 'Rate Limiter'. It can now also handle variable rising and falling slew rates. The slew rates Rvar and Fvar are calculated by the block 'calcTrate'. The inputs of this block are the air temperature and the relative humidity. The output consists of the slew rate of the air temperature. The output is calculated from standard psychometrics functions, already programmed in MatLab and the only parameter of this block, dRh, the relative humidity changing rate in %/h:

\[
Trate = \left| Tair - tdew \left( \frac{Rh \cdot psat(Tair)}{Rh-dRh} \right) \right| / 3600 \quad (4)
\]

where \( Trate \) = computed temperature changing rate [°C/sec], \( Tair \) = air temperature [°C], \( tdew \) = dewpoint function [°C], \( Rh \) = relative humidity [%], \( psat \) = saturation pressure function [Pa], \( dRh \) = maximum relative humidity changing rate [%/h].

In figure 14, the indoor air temperature, the relative humidity and the moisture content of the wood near the surface during a period of 1 day (starting Saturday 0.00 o'clock), is shown for different cases including limitation of the relative humidity changing rate of 2%/h and 5%/h:
Figure 14. The indoor air temperature, the relative humidity and the moisture content of the wood near the surface during a period of 1 day (starting Saturday 0.00 o'clock)

In figure 15 the peak-drying rate is shown for these cases:
From figure 15 it follows that a limitation of the relative humidity changing rate of 2% /h reduces the peak drying rates by an order of ~50 compared with no limited temperature heating change. However, the peak factor is still an order of ~5 higher compared with no heating. Notice that in this case, the maximum occurring indoor air temperature is 16 °C. This far below the setpoint temperature of 20 °C.

5 DISCUSSION

5.1 Comparing the control strategies

The control strategies of limiting the temperature or relative humidity changing rates look rather familiar for the peak drying rates (see figure 12 and 15). However, they are not the same. The difference in the controlling strategy is shown in figure 16. In this figure the air temperatures of figures 11 and 14 are combined and shown for 2 different days.
Figure 16. The air temperature for the controlling strategies. The upper part shows the air temperature at 6 December, the lower part shows the air temperature at 27 December.

From figure 16 it follows that the 5%/h relative humidity rate limitation approaches the 2.5 K/h temperature rate at 6 December, but it approaches the 1.5 K/h temperature rate at 27 December. Also from figure 16 it can be seen that the time needed for heating the church to 20 ºC in case of the 5%/h relative humidity rate limitation varies from 0.25 days (= 6 hours) on 6 December to 0.15 days (=3.6 hours) on 27 December. These differences show that the 2 strategies, temperature and relative humidity change rate limitation are quite different. This is also shown in figure 17, where the air temperature (variable) Rising slew rate (Rvar) is plotted against time for the relative humidity change rate limitations.
From figure 17 it follows that the air temperature Rising slew rate (Rvar) can change by a factor ~3 during the time period in case of relative humidity change rate limitation.

5.2 Optimal setpoint operation

All heating strategies presented in this paper are now evaluated:
- The best solution to prevent high peak drying rates is no heating. Due to thermal discomfort, this is not an acceptable solution.
- The worst solution to prevent high peak drying rates is full heating capacity. From figure 9 it follows that the peak drying rate is of order ~100 times bigger than in case of no heating. This is seen as the main cause of the damaging of the previous organ of the Walloon church (Schellen 2002, Neilen 2003) and is therefore not acceptable.
- Two possibilities to limit the peak drying rates are studied: Limitation of the changing rate of the air temperature and the relative humidity. Both are rather familiar in case of the limitation of the peak drying rates. The disadvantages of a limitation of the relative humidity changing rate compared to a limitation of the air temperature changing rate are:
The time to heat the church is not constant.
A more complex controller is needed (compare figure 10 with 13).
Therefore a limitation of the air temperature changing rate is preferred.

The studied parameters of the limitation of the air temperature changing rates of 1.5 and 2.5 K/h are based on a recent study of (Schellen 2002). In this study it is suggested that a limitation of the indoor air temperature changing rate of 2 K/h will preserve the interior of churches. A more detailed study based on drying induced stresses in wood is needed to further this parameter and is left over for future research.

6 CONCLUSIONS

The setpoint operation of the HVAC system is evaluated by simulation using MatLab, Comsol and Simulink models. The next main model components are presented and combined in a single integrated Simulink model: 1) a HAMBase Simulink building model for simulating the indoor temperature and relative humidity, 2) a Comsol PDE model for simulating detailed dynamic moisture transport in the monumental wood (organ) and 3) a Simulink controller model. The main advantage of the integrated model is that it directly simulates the impact of HVAC control setpoint strategies on the indoor climate and the organ in terms of peak drying rates. Two types of control strategies are discussed. The first type is a limited indoor air temperature changing rate. The second type is a limited indoor air relative humidity changing rate. A limitation of the air temperature changing rate of 1.5 to 2.5 K/h is preferred. A more detailed study based on drying induced stress in wood is needed to further refine the temperature changing rate.

7 LITERATURE

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