Preservation and energy efficiency in historic buildings

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An overview of experimental and simulation work on indoor climate and control in historic houses and monumental buildings

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Topics:
Experimental and simulation work on building physics and (HVAC) systems

Introduction
In Eindhoven University of Technology a unit of Building Physics and Systems (BPS) is working on topics of building physics and (HVAC) systems. The group has a number of experimental facilities and is working for more than 35 years on the computer simulation of the indoor climate in buildings in general and thermal comfort of people in particular. The group has a lot of contacts with institutes on the preservation of monumental buildings and collections. Therefore a special section is working on the topic of building physics and systems in monuments. This group of people is working on topics of heating, cooling and ventilation in historic houses and buildings, effects of humidification and dehumidification, monitoring and controls, pollution and soiling, the balance between conservation and human comfort and sustainability. The purpose of their work is threefold: getting a better knowledge of building physics and systems in monumental buildings, improving the indoor climate and durability for the buildings and their collections and propagation of this knowledge to students, engineers and architects in practice.

Method of approach
To get a better knowledge of building physics and systems a lot of experimental work is done. This work includes experimental work in laboratories and climate rooms and measurements on indoor and outdoor climate on-site in and around (monumental) buildings. To express the understanding of the occurring physical processes the (computer) modeling of the processes is propagated. To prove the correctness of the models the results are validated with measurements. These models then are used to do comparing work on variants and suggestions for improvement on indoor climate and other targets.

Results
A number of models have been developed to get a better knowledge of these physical processes in buildings and systems. These include models on the three dimensional
dynamic heat and mass transfer of buildings and systems. They were used in following projects.
1. The heating of monumental churches and its effects on the preservation of the indoor collection.
2. Improvement of the indoor climate of museums and historic buildings.
3. The heat and mass transfer through (monumental) materials and their dimensional effects.
4. The control of heating, cooling and venting systems in monumental buildings.
4.a. Optimal set point operation of the climate control of a monumental church
4.b. Conservation Heating to Control Relative Humidity and Create Museum Indoor Conditions in a Monumental Building
4.c. The effects of failure of parts of a HVAC system

In this paper a short description and some of the results of these projects will be given.
1. The heating of monumental churches and its effects on the preservation of the indoor collection [8]
When restoring monumental churches (the renewal of) the heating system has to be taken into account. In older times different types of heating systems were installed, varying from warm or hot air heating to floor heating, (infrared) radiant heating, radiator panel and convector heating and local or pew heating. From literature there is evidence that some of these heating systems caused serious damage to church organs and other valuable church interior parts. In this part of the paper performance requirements for church heating systems will be presented with respect to preservation, energy requirements, thermal comfort and aesthetics. Computer simulation models and (measurement) tools have been used to evaluate and design heating systems, including control systems and strategies, for churches.

Introduction
The knowledge of the short and long term thermal and hygric indoor climate of a monumental church is of great interest for preservation conditions and for thermal comfort conditions. Furthermore for thermal comfort and preservation (contamination of surfaces) the indoor airflows are of importance. These conditions can be measured in an existing building with an existing heating system. For the design of a heating system that meets the performance criteria, however, simulation tools that predict the behavior are indispensable.

Simulation tools
HAMBase
The existing computer simulation model HAMBase [11] has been used for the modeling of the indoor temperature and humidity climate and for the calculation of the energy use and capacitance of a heating system. The model originated from WaVo [11], which was adapted for thick walls, different heating and humidifying systems and controls to describe the temperature and humidity behavior of a monumental church. The model originates from two early simulation models: the simplified multizone thermal simulation model ELAN [9] and the second order model AHUM for the prediction of indoor air humidity [10]. The geometrical complexity, together with the uncertainties regarding material properties, dimensions and construction assemblies, air infiltration, outdoor rain exposure etc. make a real prediction of the indoor climate almost an impossible task. A calibration or fine-tuning of the model with measurements in a church is unavoidable. A small number of calibration parameters, the fine-tuning 'knobs', is an advantage and the risk of dependant parameters is smaller. This is an argument to keep the model simple. With the calibrated model changes of the indoor climate by a heating system then can reasonably be predicted with a model that has essentially the same physics.

FlexPDE
‘FlexPDE’ [1] was applied to solve the partial differential equations regarding 2- and 3 dimensional (2-D and 3-D) temperature, moisture and stress and strain calculations in materials. The output of the calculated and/or measured indoor climate, by HAMBase, as a result of outdoor climate, heating system and use of the church has been used as boundary conditions for the more detailed modeling of construction and interior parts. To perform these more detailed calculations on the thermal and hygric behavior of thick walls and monumental interior parts a thermal and hygric
description model has been adapted from [4], and has been implemented in FlexPDE (2- and 3-D). The description and use of the models has been described more elaborately in [8].

Applications

Heating versus no heating
For St. Martins’ Church in Weert a simulation study was done for the effect of heating in comparison to no-heating. The results are presented in figure 1 and figure 2. The long-term behavior of calculated indoor temperatures and outdoor temperatures were compared, as well as the indoor vapor pressure and the outdoor vapor pressure. In the figures the mean daily values are correlated. The left figures show the correlation of the mean daily indoor and outdoor temperatures. The indoor climate lags behind the outdoor climate. During the spring (II) the indoor temperature remains lower than the outdoor climate. In the autumn (IV), however, the indoor air temperature is clearly higher than the outdoor temperature.

![Figure 1: Effects of no heating St. Martins’ Weert](image)

In figure 2 it is clearly to be seen that the indoor church temperature is thermostrated stationary during the heating season and was kept close to 15 °C. The relation between the indoor and outdoor vapor pressures is less clear. During the heating season (I, IV) there is a slight increase of the vapor pressure, due to desorption of moisture from walls and ceiling.
Due to the lagging effect of the indoor climate on the outdoor climate, surface condensation and high relative humidities near cold indoor surfaces may occur, e.g. during spring. An effective way to reduce the condensation risk is heating the church to a primary temperature level, thus raising the surface temperatures to a higher level. During heating, however, the absolute humidity of the church also will increase slightly, due to desorption of moisture at the walls and ceiling. The difference between the surface temperature and the dewpoint temperature, the so-called dewpoint difference, is a measure for this condensation risk. For St. Martins’ in Weert, a simulation study was done to show the effects of different primary temperature levels. The results are presented in the next figures.

Figure 3 shows the calculated (mean) indoor wall surface temperatures of the church when the church would not be heated.

Those temperatures were compared to the situation when the church is floor heated to the actual stationary air temperature level of 15 °C. For those situations the dewpoint
temperature is calculated too. The effect of the heating on the dewpoint is that it will slightly increase: the absolute humidity will increase due to desorption of moisture from walls and ceiling.

![Figure 4: Effect of a primary heating on the dewpoint difference](image)

Figure 4 shows the effects of changing the primary temperature level from no-heating to a primary temperature level of 5, 10 and 15 °C. The results are presented as a dewpoint difference. It is clearly to be seen that increasing the primary temperature level will increase the dewpoint difference too. Condensation risks during spring and winter season therefore will be decreased effectively.

**Heating and relative humidity changes**

From a literature study [8] it was known that air heating e.g. might cause severe problems for monumental organs and other monumental objects in the interior of a church. High air inlet temperatures e.g. cause large thermal stratification and thus lead to high air temperature at elevated levels, where in most cases monumental organs are to be found. A high air temperature involves a low relative humidity. Dramatic low relative humidity values and related drying out and shrinkage of the organic parts may therefore be the result. Cracks and other indications of shrinkage in wooden cabinets of the organs and other wooden interior parts supported this theory.

From the indoor air conditions measured during a year in the Walloon Church a typical Sunday service was extracted. The figure below indicates air temperatures and relative humidities in front of the organ at a height of 15 meters, just beneath the vault.
Wood shrinkage and swelling due to heating

When the ambient relative humidity falls, the equilibrium moisture content (EMC) of wood (and other organic materials) drops and the wood shrinks with important resulting deformations. Vice-versa the wood will swell with increasing relative humidity. For practical purposes, the relationship between deformation and equilibrium moisture content may be assumed to vary linear [2]. The results from wood deformation tests [8] were used to predict the deformation and resulting internal stresses of two wooden organ parts: a wooden organ pipe and a wind drawer. For the deformation as a function of equilibrium moisture content a linear relation was assumed, derived from shrinkage deformation tests of a cubic 50*50*50 mm³ beech sample. The relationship is graphed in figure 6.
Heating damage to monumental organs
A damage analysis was done to show that the low relative humidity levels in Delft resulted in shrinkage of the wooden parts of the monumental organ and thus led to related cracks in the wooden parts. [8] describes the results of this damage analysis. The photographs below show the shrinking damage of a wooden organ pipe and a wind drawer.

Some of the wooden organ pipes were cracked in the corner and showed stretching cracks over the length of the pipe, due to the presence of wooden tuning caps in the pipe.

The caps square wood direction did not strike with the square pipe wood direction (was assumed perpendicular), and thus blocked the deformation of the surrounding wooden pipe. Cracks in the wind drawer were the result of the shrinking in one direction and blockage of it by other wooden parts.
Simulations with FlexPDE on the changing moisture content of both examples, due to changing relative humidity effects and the related deformation and stresses demonstrated the dramatically humidity effects on the monumental organ.

Figure 7: Maximum calculated stresses in the x-direction of a wooden organ pipe, 100*100*5, due to block shape changing of relative humidity ΔRH at the surface [8]

The stresses turned out to be in the order of magnitude of maximum allowed stresses parallel to the fibers (ft;0;rep=14 N/mm²), but exceeded those in the direction perpendicular to the fibers (ft;90;rep = 0.4 N/mm²) of hard wood. Therefore cracks in the wooden organ pipes (and also in the wind drawer) parallel to the fibers could be explained by changes in relative humidity. In the model, however, no relaxation was involved. In practice the situation might be less critical than upper graph suggests.

Mistuning of organs due to heating
The mistuning of church organs in relation to the heating of churches) was examined. In the calculations the air temperature were varied from –10 to 20 °C. The lengthening of metal organ pipes was calculated, due to thermal deformation and the effects of changing temperatures on sound velocity in air. The effects of the lengthening of the pipes on its frequency were negligible: an inaudible change of 0.01 Hz at 15 Hz and a ditto change of 7 Hz at 16 kHz. The temperature effects on the sound velocity, however, turned out to be the cause of the mistuning: audible changes of 0.8 Hz at 15 Hz and 876 Hz at 16 kHz were the result of it. The conclusion is that organs should be tuned at the temperature they are used. Furthermore the organ should be used at air temperatures, which are reasonably constant. Air temperature stratification over the height of the organ pipes should be less than 1 K.

Energy consumption
HAMBase was used for a simulation study to examine the effect of several parameters on the energy consumption and the heating capacity. In order to compare the churches with each other the churches have been simulated on the basis of the same standard input. This standard input was based on the situation in which all churches would be equipped with the same heating system, e.g. a warm air heating system. Each time one input parameter was varied in comparison to the standard input. Parameters that have been varied were: the primary temperature that was maintained in the church continuously, the comfort temperature that was desired during the service, the ventilation rate and the heating rate of the church. The
influence of additional protective glazing and heat insulation of the vaults on the energy consumption of the building was examined. The results were reported in [7].

Performance array for church heating

The computer simulation models can be used to check for the performance of church heating during design. These performance recommendations for the preservation of monumental churches and interior can be taken from [8]. For one type of heating systems, e.g. warm air heating, these performance requirements can be summarized as follows.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unity</th>
<th>Lower value</th>
<th>Upper value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor air comfort temperature</td>
<td>$\theta_i$</td>
<td>°C</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Primary temperature</td>
<td>$\theta_{\text{primary}}$</td>
<td>°C</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Relative humidity mean</td>
<td>RH$_{\text{mean}}$</td>
<td>%</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>Yearly change RH</td>
<td>$\Delta$RH$_{\text{year}}$</td>
<td>%</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Relative humidity short term</td>
<td>RH$_{\text{short}}$</td>
<td>%</td>
<td>40$^*$</td>
<td>90</td>
</tr>
<tr>
<td>Daily change RH</td>
<td>$\Delta$RH$_{\text{day}}$</td>
<td>%</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Heating rate</td>
<td>$\Delta \theta / \Delta t$</td>
<td>K/h</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Indoor air velocity comfort area</td>
<td>$u$</td>
<td>m/s</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Temperature stratification</td>
<td>$\Delta \theta / \Delta h$</td>
<td>K/m</td>
<td></td>
<td>0.1$^*$</td>
</tr>
<tr>
<td>Supply air temperature</td>
<td>$\theta_{\text{supply}}$</td>
<td>°C</td>
<td></td>
<td>$\theta_i + 25$</td>
</tr>
<tr>
<td>Length of throw</td>
<td>$l_{\text{max}}$</td>
<td>m</td>
<td>2/3 $l_{\text{object}}$</td>
<td></td>
</tr>
<tr>
<td>Supply air velocity</td>
<td>$u_{\text{supply}}$</td>
<td>m/s</td>
<td>Ar &lt; 0.05</td>
<td>From $l_{\text{max}}$</td>
</tr>
<tr>
<td>Number of air inlet grilles</td>
<td>$n_{\text{in}}$</td>
<td></td>
<td>From [8]</td>
<td></td>
</tr>
<tr>
<td>Number of air extraction grilles</td>
<td>$n_{\text{out}}$</td>
<td></td>
<td>$n_{\text{in}}/5$</td>
<td></td>
</tr>
<tr>
<td>Floor surface temperature</td>
<td>$\theta_{\text{floor}}$</td>
<td>°C</td>
<td>25..28</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Summarized recommendations for warm air heating from [8] for the preservation of monumental churches and interior

* Limited by a hygrostatic device

** Over height of the church
Indoor air temperature
The values in table 1 for the acceptable indoor air temperature are based on different assumptions: the lower values are based on assumptions on thermal comfort and the upper values are based on allowable low relative humidities to be reached. Thermal comfort depends on conditions related to the visitor (clothing and metabolism) and indoor conditions (air temperature, mean radiant temperature, temperature asymmetry, air humidity, air velocity and air turbulence). In monumental churches optimal thermal comfort is rare: due to great heights of walls and glazing and relative low surface temperatures turbulent airflows in churches cannot be prevented. Winter clothing or thermal radiation (by floor or other higher temperature sources) may compensate for a lack of thermal comfort due to lower air temperatures. An upper limit of 15 °C therefore is used for Roman Catholic churches [6] and is based on the wearing of winter coats during services. Other thermal comfort predictions may be based on models for thermal comfort calculations [5].

After the severe winters of the 1960-ties a lot of problems with monumental organs were observed. The upper value of 12 °C therefore originates from these extreme winter conditions, i.e. longer frost periods. Nowadays, however, it is technically possible (and relatively easy) to limit the allowable lowest relative humidity due to heating by a hygrostatic device. In this (hygric) respect it is better to have limitations in the table on lower relative humidities, guarded in the church by a hygrostatic device.

Primary temperature
The concept of the primary temperature was introduced for some reasons: to prevent surface temperatures to drop below dew point temperature, to accelerate heating up times and to improve thermal comfort due to higher surface temperatures. Low surface temperatures may lead to high surface relative humidities. When the surface temperatures are about 10 °C, the difference between surface temperature and dew point temperature is about 4.2 K for surface relative humidities of 75 % and 1.6 K at RHsurf = 90 %. To prevent long term higher surface humidities of above 75 % RH it is therefore recommended to keep the dew point difference larger than 3 to 4 K. Long time (one year) measurements in a particular church thus may give an indication of the absolute humidity and dew point in that church. For the churches in the case studies a primary temperature based on this criterion has been calculated and is given in table 1.

Measurements in infrared gas heated churches showed that one essential condition to prevent surface condensation problems with this kind of heating is to heat up the surface temperatures by some kind of primary heating. It is therefore recommended to keep the primary temperature above about 8 to 10 °C. To prevent church interior wooden parts to be exposed to sudden changes in relative humidity it is recommended to limit heating rates to 1 or 2 K/h. Heating up times therefore will be very long, when the difference between comfort and primary temperatures is too large.

Thermal comfort also depends on mean radiant and thermal asymmetry temperatures. If the indoor air temperature is maintained at the primary temperature, indoor wall surfaces will approximately be maintained at that level too. This will have a positive effect on mean radiant and thermal asymmetry temperatures.

The maintenance of a primary temperature involves the use of energy. A table in [7] summarizes the yearly extra energy to maintain a primary temperature level.
Relative humidity
The indoor air relative humidity conditions for monumental churches should be related to the most critical and valuable interior parts. Most often these are monumental organs and/or wooden interior parts like monumental pulpits, altars and pews, which are objects of inestimable value. Where these objects are exposed to indoor conditions, relative humidity should be limited. A lower value of 40 to 45 % RH is critical when it comes to shrinkage problems. A temporary upper limit of 70 to 75 is critical for fungi attack.

To reduce the hygrothermal load of materials and construction it is suggested to allow larger fluctuations during a long period and smaller for a short period. From practice Künzel [3] suggested 10 % RH fluctuations during a day and 30 % RH fluctuations during a period of a year, between about 50 and 80 % RH.

Heating rate
Of these objects the monumental organs seem to be most critical for changing indoor conditions: they consist of very fragile to more robust wooden and other organic parts, which react from very fast (small and fragile parts) to very slowly (wooden construction parts) to changing indoor conditions. To protect these objects from internal stress, changing conditions should lead to equally changing conditions in both types of objects. Therefore the largest time constant determines the rate of changing conditions. Furthermore during instationary heating airflows will be generated, which may lead to contamination of surfaces. A heating (and cooling) rate of 1 to 2 K/h proved to be a safe indoor temperature changing rate [6].

Thermal stratification
In case of warm air heating systems thermal stratification should be limited to 1 to 2 K for the total height of the church. This will protect the monumental organs against too high temperatures; a thermostatic device on occupation height mostly controls indoor air temperature. Furthermore the temperature difference over the length of an organ pipe should not exceed 1 K. For most churches the thermal stratification should therefore be limited to 0.1 to 0.2 K/m, measured over the height of the church.

Indoor air velocity and turbulence
For thermal comfort reasons the indoor air velocity should be limited to 0.1 to 0.15 m/s. The maximum turbulence intensity level at occupation level then can be calculated from the indoor air temperature.

Number of air inlet and extraction grilles
Where the behavior of the airflow in a room is considered, this is fully determined by the situation and number of the air inlet grilles and is hardly influenced by the number and place of the air extraction grilles. [8] gives an indication of the number of air inlet and extraction grilles.

Supply air temperature
In the work of [6] the supply air temperature for warm air heating systems is recommended to be limited to a temperature difference between supply and indoor air of 25 K or a temperature of 45 °C. It is not mentioned explicitly, but it is expected that this recommendation resulted from limitations on thermal stratification. In this respect it seems to be better to limit the Archimedes Number Ar to a maximum number, because thermal stratification not only depends on the temperature difference between
supply and indoor air, but is also determined by the air supply velocity. If the Archimedes Number Ar is limited to approximately 0.05 it is possible to limit the thermal stratification to about 0.1 K/m. Furthermore the supply air should not directly reach the monumental organ. A limitation on the length of throw should be given, much smaller than the distance between inlet air supply and object.

**Supply air velocity**
The maximum of supply air velocity depends on the length of throw and the minimum depends on the maximum Archimedes number. The length of throw should be limited to a maximum of about 2/3 times the length to an air reachable object of art, like a monumental organ, mostly being at the back end of the church.

**Floor surface temperature**
When the church is heated by floor heating, the floor surface temperature maximum allowed could be based on two assumptions: generated airflows and thermal feet comfort.
The difference between floor surface temperature and air temperature leads to considerable airflows. This may lead to thermal discomfort and contamination by soot and dust. In this respect it is difficult to control heating on airflows or air velocities. A control based on the above mentioned temperature differences, or a maximum air temperature allowed under winter conditions should be considered. For thermal comfort reasons near the feet (to prevent swollen and sweaty feet) the upper floor surface temperatures should be limited to a maximum of 29 °C [5]. The allowable lower floor surface temperatures depend on the thermal feet contact temperature and may be improved by the contact floor material. For stone floors the lower floor temperature is about 24, for wooden floors this temperature limit is about 16 °C.

**Relative humidity near surfaces**
In principle relative humidity near surfaces should not exceed the limits, which are mentioned for indoor air relative humidity. Due to the lower surface temperature of cold walls and glazing the relative humidity near these surfaces increases. For short periods, e.g. less than an hour, higher values up to 90 %RH may be accepted.

**Conclusion**
This first part of the paper showed the application of computer simulation tools to predict the effect of different heating systems on the indoor climate of (monumental) churches. The models were compared to experimental work [8] and thus can be used for checking the predicted indoor climate with the performance array for the preservation of the monumental church and its interior.
2. The improvement of the indoor climate of museums and historic buildings: Thermal comfort problems in a monumental office building in summer [13]

One of the most important buildings in The Netherlands is the monumental building of the Senate. People working in the office rooms of this building have complaints on thermal comfort during summer time. A number of office rooms is overheated during warm summer days. Furthermore the rooms are ventilated in a natural way, i.e. by opening the windows. The installation of split air conditioning units or a HVAC system would have an unacceptable effect on the monumental interior and exterior. Paper [13] handles thermal comfort problems in a monumental office building in summer. One of the objectives of the work is to objectify the complaints. Furthermore it is the intention to have a better knowledge of the indoor climate of specific rooms in relation to the outdoor climate, their orientation and specific building physical properties and the use and related internal heat loads of the room. Moreover the aim of the work is to improve the summer indoor climate without affecting the monumental character of the rooms and the building itself. The method of approach is to objectify the complaints by measurements of the indoor climate in relation to the outdoor climate. Typical physical measurements considering thermal comfort were made. The results were compared with national guidelines regarding temperature exceeding limits, weighing hours and adaptive temperature limits. To improve the summer indoor conditions a simulation study on the indoor climate of a number of rooms was performed in HAMBASE (Heat, Air and Moisture, Buildings And Systems Engineering tool). The model was calibrated with the indoor climate results of the long term measurement sessions. A variant study on some improvement propositions was performed. Checking the indoor summer climate with the national guidelines indicated that about half of the measured rooms were too warm during warm summer days.

Exemplary results
Figure 8 shows the results of a model validation study and the use for design

Figure 8 Left: Measured and simulated indoor climate of a warm office room Right: Simulated indoor air temperature for suggested (passive) measures
3. The heat and mass transfer through (monumental) materials and their dimensional effects: A hypocaust hot air floor heating system in the Netherlands [14]

In 2002 a PhD study was finished on Heating Monumental Churches at the University of Technology in Eindhoven [8]. Most of the used heating systems in the Netherlands were examined. However, at a number of places which were not accounted for in the previous mentioned study, unique heating systems are applied. The Stevens’ Church is heated by a hypocaust heating system: floor heating by hot air underneath the floor. Hot air is transported through a constructional duct system of bricks. A part of the hot air enters the church via a wall and floor air supplies, the rest is recirculated. The system is not very energy efficient: First, through the massive floor the heating system is very slow. It takes a very long time to heat up the church, almost 40 hours to heat up 7 °C. Second, air is not the most energetic medium for transport of heat. Third, a part of the capacity is used for heating up the crawl space and the ground. The purpose of research [14] is to design a more efficient heating system considering the preservation of monumental objects (such as church organs), the building itself and thermal comfort of the church attendance. The methodology was: (1) Measurement of the current indoor air temperatures, relative humidities, air inlet flows, air infiltration rate and external climate; (2) Simulation of the current indoor climate; (3) Validation by comparing measurements and simulations; (4) Simulation and evaluation of the design options given the specific criteria for indoor climate for the monumental objects and thermal comfort of the churchgoers. In the paper the results of previous mentioned methodology will be extensively discussed. It is concluded that a more optimal heating system for the Stevens Church would be a floor heating with warm water underneath the flags (stone) with additional hot air heating with floor air supplies.

**Exemplary results**
Figure 9 shows the results of a model validation study.

![Figure 9](image-url)

Figure 9 Measured and simulated of the current indoor climate of the church
4. The control of heating, cooling and venting systems in monumental buildings: 
4.a. Optimal set point operation of the climate control of a monumental church [15]

This part of the paper presents a case study on the optimal operation of the climate control of the Walloon Church in Delft (Netherlands). It provides 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 set point 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 in a detailed way the 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 set point strategies on the indoor climate and the organ. Two types of control strategies are discussed. The first type is a limited indoor air temperature change rate. The second type is a limited indoor air relative humidity change rate. Recommendations from international literature [8] suggest that 1) a change 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 change rate of 2 K/h can reduce the peak drying rates by a factor 20 and a limitation of the relative humidity change 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.

In the Walloon Church in Delft a monumental organ is present which has been restored in the spring of 2000. To prevent damage to the organ again, the indoor climate has to meet certain requirements. Recent studies [8, 19] have been performed for the preservation of the monumental organ. As a result 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. However, 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 may become 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. Humidification 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 humidification during winter there is a risk for condensation and fungal growth 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 concluded that:
- the increase of drying rate causes a non uniform distribution of the moisture content in dried material and this involves drying induced stress,
- fracture is more likely if the dried body is thick and/or the drying rate is high. These studies show that the peak drying rate has to be minimized in order to minimize the risk of drying induced stress and fracture.

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

Exemplary results

Figure 10 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)

Figure 11 The peak drying rate during a period of 1 day (starting Saturday 0.00 o'clock)
For the conservation of an important museum collection in a historic building a better controlled indoor climate may be necessary. One of the most important factors is controlling relative humidity. Museum collections often are part of the interior of a historic building. In most cases the installation of an expensive air-conditioning system may cause damage to the building and its historic authenticity. Furthermore humidifying may lead to dramatic indoor air conditions with mould and condensation effects on the cold indoor surfaces or even internal condensation in the construction. One way to overcome this problem is to make use of so-called ‘conservation heating’. A humidistat to limit relative humidity controls the heating system. Conservation heating control was tested in an experimental set-up in the laboratory and experience was gained in a historic building in the Netherlands. Control strategies and regimes were tested both by experiment and by simulation. The simulation model is validated by measurements. In the historic building the indoor climate was monitored during a long period. The preservation conditions of the indoor climate on the collection and the monumental building were evaluated. The indoor climate for preservation of a monumental building and its monumental interior may be improved by conservation heating. The human comfort however may decline. Furthermore it is a simple and energy efficient system which requires low maintenance.

Originally, historic buildings did not have any other heating system than open fire or some kind of local heating system. Sometimes a central heating system was installed afterwards. Measurements in one of the most valuable historic buildings prove again that heating during the cold period leads to low indoor RH, causing damage to interior and objects [16]. Outside the heating season high RH often occurs, also causing risk for damage to interior and objects e.g. by mould growth (Erhardt et al. 1994). In most cases the possibilities to fully control relative humidity in a historic building, e.g. by installing a full air-conditioning system, is limited. Installing mechanical systems and ducts always will cause damage to the building and its historic authenticity. The high installation, maintenance and running costs are not even mentioned. Furthermore humidifying devices may lead to dramatic indoor air conditions with high surface humidity and condensation effects on the cold indoor surfaces of the exterior walls, single glazing and roofs, or even condensation in the inner parts of the construction (Schellen 2002).

The principle of conservation heating is controlling the heating system using a humidistat device (Staniforth et al. 1994). High relative humidity is prevented by starting heating. Reaching low relative humidity during the cold season is prevented by limiting heating to maintain a certain lower temperature setpoint. The use of this control however is restricted. In summer it may be necessary to start heating and during wintertime it may be necessary to limit heating, causing thermal discomfort of occupants. In the Netherlands there is little experience with conservation heating.

Figure 12 shows simulation results of relative humidity from January 14th to February 14th 2006 of the humidistatically controlled room in the historic building. Simulation results are validated with measurements. Minor discrepancies occur possibly due to the estimated air exchange rate of 0.8. Visible is that with a Tmin set to 10˚C it is not
possible to maintain a minimum of 45% RH due to the low vapor ratio of the outdoor air, which mostly occurs during wintertime (Figure 22/01–04/02). Over the simulated period T_min has to be lowered to about 4°C to maintain 45% RH in the Dutch climate.

Figure 12  Simulation results of temperature and relative humidity in the humidistatically heated room over the period from January 14th to February 14th 2006

Measured versus Simulated, 14-Jan-2006 to 14-Feb-2006
The study concerns the HVAC system of the National Naval Depot, which should have a very high reliability. However, during the year a seemingly harmless HVAC fault almost caused a serious problem for the preservation of the artifacts. As a result of this, the next research questions are investigated in this project. What is the performance of this high tech installation in case of a major failure? Is it possible to improve the climate control in such a case? The methodology of research was: First, we implemented heat, air & moisture (HAM) models of the building and installation components in SimuLink. Second, we validated the models by measurements. Third, we evaluated the current and new designs by simulation. In [Timmermans 2006], the following results are presented in more detail: (1) Evaluation of the current HVAC system components and indoor climate of the museum; (2) Evaluation of validation results; (3) Evaluation of the simulated performance of the current design in case of failure; (4) The performance of improved designs in case of a failure. It is concluded that the current design performs well if in case of a fault, the air supply to the depots is switched off automatically. The construction of the depots contains sufficient thermal inertia to maintain a stable indoor climate for a longer period in which the fault can be repaired. A further improvement of the design could be to control the climate surrounding the depots instead of controlling the indoor climate in the depots itself. In this case, even if the system would not detect a fault and thus supplies uncontrolled air at the surroundings of the depot, the indoor climate in the depot would remain stable.

**Exemplary results**

Figure 13 shows the HVAC system including the cooling coil. Figure 14 presents the measured air temperature before the cooling coil and the measured and simulated air temperature after the cooling coil.

This part presents a case study on the performance based design of a HVAC system and controller of a museum. A famous museum in the Netherlands has reported possible damage to important preserved wallpaper fragments. The paper provides an evaluation of the current indoor climate by measurements, showing that the indoor climate performance does not satisfy the requirements for the preservation of old paper. To solve this problem, possible solutions are evaluated by simulations using integrated heat air & moisture (HAM) models of respectively: the indoor climate, the HVAC system & controller and a showcase. The presented models are validated by a comparison of simulation and measurement results. An integrated model consisting of all different models is applied for the evaluation of a new HVAC controller design and the use of a showcase. The results are discussed.

In general, the aim of museums is to exhibit artefacts in its original state as long as possible. The climate performance surrounding the preserved artefact is of great importance. Furthermore, if present, the heating, ventilation and air-conditioning (HVAC) system plays a dominant role on the indoor climate. A famous museum in the Netherlands has reported possible damage to important preserved wallpaper fragments. Preliminary measurements indicate that the indoor climate performance does not meet the criteria for preservation of wall paper. A solution is sought-after, given that the current HVAC system cannot be replaced (only small modifications are possible) and that the use of showcases, although not prohibited, is not preferred by the decision makers. This leads to the next questions: First, what are criteria of the indoor climate for preservation of wall paper? Second, is it possible to improve the indoor climate performance, by a new control strategy of the current HVAC system, in such a way, that a showcase can be avoided? Third, if not, can the problem be solved by using a showcase? Due to the preservation of the object, measurement is not an option to answer these key questions because it is not allowed to experiment with the HVAC system. Therefore simulation is the only option and an integrated indoor climate, HVAC and showcase model is needed. There is no such a model available. This leads to two more key questions: First, can we develop an integrated heat air & moisture (HAM)/HVAC system model capable of predicting the current indoor climate and the climate in a showcase? Second, can we improve the climate surrounding the object, using this model?

The aim of this chapter is to answer the key questions. The following methodology was used: (1) Reviews on the indoor climate criteria for preservation of wallpaper and on integrated indoor climate, HVAC and showcase models have been carried out. (2) The current indoor climate and HVAC performances were extensively measured. Data, measured by others, have been obtained for validating the showcase model. (3) Indoor climate, HVAC and showcase models were developed and validated. (4) An integrated model has been developed for the simulation of climate conditions near the object in case of a new HVAC controller design, with and without the use of a showcase.
Exemplary results

Figure 15 Top: The moisture related model equations. Middle: The measured and simulated air temperature in the showcase. Bottom: Schematic view of the modeled quantities ($\varphi = \text{RH}$)

Conclusions
Experimental work and related computer modeling leads to a better understanding of the physical processes in monumental buildings and their (HVAC) systems. This insight is used to improve the conditions for the preservation of the buildings and their collections.
References


Related work


