An Overview of Experimental and Simulation Work on Indoor Climate and Control in Historic Houses and Monumental Buildings

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Introduction

In Eindhoven University of Technology, the Building Physics and Systems Unit is working on topics of building physics and HVAC systems. The group, which has a number of experimental facilities, has been working for over thirty-five years on the computer simulation of the indoor climate of buildings in general and on the thermal comfort of people in particular. The group has a lot of contacts with institutes involved in 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; and the balance among conservation, human comfort, and sustainability. The purpose of their work is threefold: increasing the knowledge of building physics and systems in monumental buildings; improving the indoor climate and durability of the buildings and their collections; and propagating this knowledge to students, engineers, and architects in practice.

Method of Approach

To increase the knowledge of building physics and systems, a lot of experimental work is done. This work includes conducting experimental work in laboratories and climate rooms and taking measurements on indoor and outdoor climate both 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 are then used in comparing variants and in making suggestions for improvements in indoor climate and other targets.

Results

A number of models have been developed to increase the 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 the following projects:

1. The heating of monumental churches and its effects on the preservation of the indoor collection
2. The improvement of the indoor climate of museums and historic buildings
3. Heat and mass transfer through monumental materials, and their dimensional effects
4. The control of heating, cooling, and ventilating systems in monumental buildings
    - 4a. The optimal set point operation of the climate control of a monumental_church
    - 4b. Conservation heating to control relative humidity and create museum indoor conditions in a monumental building
    - 4c. The Modeling of a High-Tech HVAC System for a Museum Storage—Simulation of the Climate System Performance of a Museum in Case of Failure
    - 4d. The application of an integrated indoor climate and HVAC model for the indoor climate performance of a museum

In this paper, a short description of each project and some of the results will be given.

1. The Heating of Monumental Churches and Its Effects on the Preservation of the Indoor Collection (Schellen 2002)

When restoring monumental churches, the heating system and its renewal have to be taken into account. In previous times, different types of heating systems were installed; they varied from warm- or hot-air heating to floor heating, infrared radiant heating, radiator panel and convector heating, and local or pew heating. From the literature, there is evidence that some of these heating systems caused serious damage to church organs and other valuable interior parts of churches. In this section 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 with regard to preservation conditions and 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 (Heat, Air, and Moisture Buildings and Systems Engineering tool) has been used for the modeling of indoor temperature and humidity climate and for the calculation of the energy use and capacitance of a heating system (Wit 2006). The model is part of the HAMLab environment and originated from WAVO, which was adapted for thick walls and for different heating and humidifying systems and controls to describe the temperature and humidity behavior of a monumental church (Wit 2000). The model originates from two early simulation models: the simplified multizone thermal simulation model ELAN (Wit and Driessen 1988) and the second-order model AHUM, for the prediction of indoor air humidity (Wit and Donze 1990). The geometrical complexity, together with the uncertainties regarding material properties, dimensions, construction assemblies, air infiltration, outdoor rain exposure, and so on, make an accurate prediction of the indoor climate an almost 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. These factors constitute an argument to keep the model simple. With the calibrated model, changes of the indoor climate by a heating system can then reasonably be predicted with a model that has essentially the same physics.

FlexPDE

FlexPDE (Backstrom 1994) and Comsol (Comsol Group 2000) were applied to solve the partial differential equations regarding two- and three-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 Künzel (1994) and has been implemented in FlexPDE (2-D and 3-D).

The description and use of the models have been described more elaborately by Schellen (2002).

Applications

Heating versus No Heating

For St. Martin's Church in Weert, the Netherlands, a simulation study was done for the effect of heating, in comparison to no heating. The results are presented in figures 1a and 1b (no heating) and 2a and 2b (stationary heating). The long-term behavior of calculated indoor and outdoor temperatures was compared, as was the indoor vapor and outdoor vapor pressure. In the figures, the mean daily values are correlated. Figures 1a and 2a 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 temperature. In the autumn (IV), however, the indoor air temperature is clearly higher than the outdoor temperature.

In figure 2a, it can be seen clearly that the indoor church temperature is maintained at a stationary level by thermostat during the heating season and was kept close to 15°C. The relation between the indoor and outdoor vapor pressures is less clear (fig. 2b). During the heating season (I, IV), there is a slight increase of the vapor pressure due to desorption of moisture from walls and ceiling.

Heating and Dew Point Difference

Because of the lagging effect of the indoor climate on the outdoor climate, surface condensation and high relative humidity (RH) near cold indoor surfaces may occur—e.g., during spring. An effective way to reduce the condensation risk is by 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 will also increase slightly, because of desorption of moisture at the walls and ceiling. The difference between the surface temperature and the dew point temperature—the dew point difference—is a measure for this condensation risk. For St. Martin's Church, a simulation study was done to show the effects of different primary temperature levels. The results are presented in figures 3 and 4.

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 of 15°C. For those situations, the dew point temperature is calculated too. The effect of heating on the dew point is that it will slightly increase: the absolute humidity will increase because of desorption of moisture from the walls and ceiling.

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

Heating and Relative Humidity Changes

From a literature study, it was known that air heating, for example, might cause severe problems for monumental organs and other monumental objects in the interior of a church (Schellen 2002). High air inlet temperatures 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 RH. Dramatically low RH values and related drying out and shrinkage of the organ 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 in Delft, the Netherlands, a typical Sunday service was extracted. Figures 5a and 5b give air temperature and RH in front of the organ at a height of 15 m, just beneath the vault.

Wood Shrinkage and Swelling Due to Heating

When the ambient RH falls, the equilibrium moisture content (EMC) of wood (and other organic materials) drops, and the wood shrinks and undergoes important resulting deformations. Conversely, the wood will swell with increasing RH. For practical purposes, the relationship between deformation and EMC may be assumed to vary linearly (Camuffo 1998).

The results from wood deformation tests were used to predict the deformation and resulting internal stresses of two wooden organ parts: a wooden organ pipe and a wind drawer (Schellen 2002). For the deformation as a function of EMC, a linear relation was assumed, derived from shrinkage deformation tests of a cubic 50 x 50 x 50 mm^3 beech sample. The relationship is graphed in figure 6.

Heating Damage to Monumental Organs

A damage analysis was done to show that the low RH levels at the Walloon Church resulted in the shrinkage of the wooden parts of the monumental organ and thus led to related cracks in the wooden parts (fig. 7). Schellen describes the results of this damage analysis (Schellen 2002). 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 align with the square pipe wood direction (it was assumed to be perpendicular), and thus the caps blocked the deformation of the surrounding wooden pipe.

Cracks in the wind drawer were the result of shrinkage in one direction and the blockage of it by other wooden parts (fig. 8). Simulations with FlexPDE on the changing moisture content of both examples, due to changing RH, and the related deformation and stresses, demonstrated the dramatic humidity effects on the monumental organ (fig. 9).

The stresses turned out to be in the order of magnitude of maximum allowed stresses parallel to the fibers (=14 N/mm^2) but exceeded those in the direction perpendicular to the fibers (=0.4 N/mm^2) of hardwood. Therefore, cracks in the wooden organ pipes (and also in the wind drawer) parallel to the fibers could be explained by changes in RH. In the model, however, no relaxation was involved. In practice, the situation might be less critical than the upper portion of the 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 varied from –10°C to 20°C. The lengthening of metal organ pipes was calculated, due to thermal deformation, as were the effects of changing temperature on sound velocity in air. The effects of the lengthening of the pipes on the sound frequency were negligible: an inaudible change of 0.01 Hz at 15 Hz and a similarly inaudible 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 changes in temperature. The conclusion is that organs should be tuned at the temperature prevailing when they are used. Furthermore, the organ should be used at air temperatures that 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 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 were varied were: the primary temperature maintained in the church continuously, the comfort temperature desired during the service, the ventilation rate of the church, 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 by Neilen, Schellen, and Aarle (2003).

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 Schellen (2002). For one type of heating system (e.g., warm air heating), these performance requirements can be summarized as in table 1.

Property	Symbol	Unity	Lower value	Upper value
Indoor air comfort temperature	T_i	°C	15	20
Primary temperature	$T_{primary}$	°C	5	10
Relative humidity, mean	RH_{mean}	%	45	75
Yearly change in RH	RH_{year}	%		30
Relative humidity, short term	RH_{short}	%	40^{*}	90
Daily change in RH	RH_{day}	%		10
Heating rate	T/ t	K/h		2
Indoor air velocity comfort area	u	m/s		0.15
Temperature stratification	T/ h T_{max}	K/m K		0.1 2^{**}
Supply air temperature	T_{supply}	°C		$T_i + 25$
Length of throw	l_{max}	m		2/3 l_{object}
Supply air velocity	u_{supply}	m/s	Ar < 0.05	From l_{max}
Number of air inlet grilles	n_{in}		From Schellen 2002	
Number of air extraction grilles	n_{out}		$n_{in}/5$	
Floor surface temperature	T_{floor}	°C		25.28

Table 1

Summary of recommendations for warm air heating from Schellen (2002) for the preservation of monumental churches and interiors (* = 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 RH to be reached.

Thermal comfort depends on conditions related to the visitor (clothing and metabolism) and related to 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 the great heights of the walls and glazing and the 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 low air temperatures. An upper limit of 15°C, therefore, is used for Roman Catholic churches (Schotes 1972) and is based on the wearing of winter coats during services. Other thermal comfort predictions may be based on models for thermal comfort calculations (Loomans 1998).

After the severe winters of the 1960s, many problems with monumental organs were observed. The upper value of 12°C, therefore, originates from these extreme winter conditions—that is, longer frost periods. These days, however, it is technically possible (and relatively easy) to limit the lowest allowable RH due to heating by a hygrostatic device. Therefore, it is better to have limitations in the table on lower RH, guarded in the church by a hygrostatic device.

Primary Temperature

The concept of the primary temperature was introduced for certain reasons: in order to prevent surface temperatures from dropping below dew point temperature, to accelerate heating-up times, and to improve thermal comfort based on higher surface temperatures.

Low surface temperatures may lead to high surface RH values. When the surface temperatures are about 10°C, the difference between surface temperature and dew point temperature is about 4.2 K for surface RH of 75%, and 1.6 K at surface RH of 90%. To prevent long-term higher surface values of above 75% RH, it is therefore recommended to keep the dew point difference larger than 3–4 K. Measurement over an extended period of time (one year) 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 for the prevention of surface condensation problems with this kind of heating is to increase the surface temperatures by some kind of primary heating. It is therefore recommended to keep the primary temperature above about 8°C–10°C.

To prevent church interior wooden parts from being exposed to sudden changes in RH, 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 primary and comfort 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 be maintained at approximately that level, too. This condition 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 Neilen, Schellen, and Aarle (2003) summarizes the yearly extra energy required to maintain a primary temperature level.

Relative Humidity

Indoor air RH conditions for monumental churches should be related to the most critical and valuable interior parts. Most often these are monumental organs and/or interior wooden fixtures, such as monumental pulpits, altars, and pews, which are objects of inestimable value. Where these objects are exposed to indoor conditions, RH should be limited. A lower value of 40%–45% RH is critical when it comes to shrinkage problems. A temporary upper limit of 70%–75% is critical for the avoidance of fungi attack.

To reduce the hygrothermal load of materials and construction, it is suggested that larger fluctuations be allowed during a long period and smaller fluctuations allowed for a short period. From practice, Künzel has suggested 10% RH fluctuation during a day and 30% RH fluctuation during a period of one year, between about 50% and 80% RH (Künzel 1991).

Heading Rate

Of these objects, the monumental organs seem to be most critically susceptible to changes in indoor conditions: they consist of very fragile to more robust wooden and other organic parts, which react to changing indoor conditions, at speeds ranging from very quickly (small and fragile parts) to very slowly (wooden construction parts). 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 1–2 K/h proved to be a safe indoor temperature changing rate (Schotes 1972).

Thermal Stratification

In case of warm air heating systems, thermal stratification should be limited to 1–2 K for the total height of the church. This range will protect monumental organs against temperatures that are too high; a thermostatic device at 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 0.1–0.2 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 0.10–0.15 m/s. The maximum turbulence intensity level at occupation level can then be calculated from the indoor air temperature.

Number of Air Inlet and Extraction Grilles

The behavior of the airflow in a room is fully determined by the situation and the number of air inlet grilles, and it is hardly influenced at all by the number and placement of the air extraction grilles. Schellen discusses the number of air inlet and extraction grilles (Schellen 2002).

Supply Air Temperature

In the work of Schotes, it is recommended that the supply air temperature for warm air heating systems be limited to a temperature difference between supply and indoor air of 25°K, or a temperature of 45°C (Schotes 1972). While it is not mentioned explicitly, this recommendation appears to result from limitations on thermal stratification. In this respect, it seems to be better to limit the Archimedes number (Ar) to a maximum value, 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 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, and it should be much smaller than the distance between the inlet air supply and the 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 two-thirds of the length to an air-reachable object of art, such as a monumental organ (most organs are located at the back end of the church).

Floor Surface Temperature

When the church is heated by floor heating, the maximum floor surface temperature allowed could be based on two assumptions: generated airflows and the thermal comfort of feet.

The difference between floor surface temperature and air temperature leads to considerable airflows. Airflows, in turn, may lead to thermal discomfort and contamination by soot and dust. It is difficult to control heating on airflows and 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 near the feet (to prevent swollen and sweaty feet), the upper floor surface temperatures should be limited to a maximum of 29°C (Loomans 1998). 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°C; for wooden floors, this temperature limit is about 16°C.

Relative Humidity Near Surfaces

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

Conclusion

The first part of this paper showed the application of computer simulation tools for predicting the effect of different heating systems on the indoor climate of monumental churches. The models were compared to experimental work (Schellen 2002), and thus they 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 (Schellen and Leth 2007)

One of the most important buildings in the Netherlands is the monumental building of the Senate in The Hague. People working in the office rooms of this building have complaints regarding thermal comfort during the summer. A number of office rooms are overheated during warm summer days. Furthermore, the rooms are ventilated in a natural way—that is, 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. A paper by Schellen and Leth handles thermal comfort problems in a monumental office building in the summer (Schellen and Leth 2007).

One of the goals of the work is to objectify the complaints. Other intentions are to improve knowledge of the indoor climates of specific rooms in relation to the outdoor climate, to their orientation and specific building physical properties, and to their use and related internal heat loads. Moreover, the aim of the work is to improve the summer indoor climate without affecting the monumental character of the rooms and of 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 that relate to thermal comfort were made. The results were compared with national guidelines regarding excessive temperature, considering 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. The model was calibrated with the indoor climate results from the long-term measurement sessions. A variant study on some propositions for improvement was performed. Comparing the indoor summer climate with the national guidelines indicated that about half of the measured rooms were too warm on warm summer days.

Exemplary results are given in figures 10a and 10b, which show the results of a model validation study (fig. 10a) and its use for design (fig. 10b).

3. Heat and Mass Transfer through Monumental Materials and Their Dimensional Effects: A Hypocaust Hot Air Floor Heating System in the Netherlands (Aarle, Schijndel, and Schellen 2007)

In 2002 a PhD study, "Heating Monumental Churches," was finished at the University of Technology in Eindhoven (Schellen 2002). Most of the heating systems used in the Netherlands were examined. However, at a number of places, unique heating systems are applied. St. Steven's Church in Nijmegen, the Netherlands, is heated by a hypocaust heating system: floor heating by hot air underneath the floor. Hot air is transported through a duct system constructed of bricks. Some 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 h. to raise the temperature 7°C. Second, air is not the most energetic medium for the transport of heat. Third, a part of the capacity is used for heating up the crawl space and the ground.

The purpose of the research by Aarle, Schijndel, and Schellen (2007) is to design a more efficient heating system that considers the preservation of monumental objects (such as church organs), the building itself, and the thermal comfort of those who attend the church. The methodology was: (1) measurement of the current indoor air temperatures, RH values, air inlet flows, air infiltration rate, and external climate; (2) simulation of the current indoor climate; (3) validation by comparing measurements and simulations; and (4) simulation and evaluation of the design options, given the specific criteria for indoor climate for the monumental objects and the thermal comfort of churchgoers.

In the paper, the results of this methodology are extensively discussed. It is concluded that a better heating system for St. Steven's Church would consist of floor heating with warm water underneath the stone flags, with additional hot air heating with floor air supplies.

Exemplary results are given in figure 11, which shows the results of a model validation study.

4. The Control of Heating, Cooling, and Ventilating Systems in Monumental Buildings:

4a. The Optimal Set Point Operation of the Climate Control of a Monumental Church (Schijndel et al. 2003)

This section presents a case study on the optimal operation of the climate control of the Walloon Church in Delft. It provides a description of constraints for the indoor climate, giving criteria for the indoor air temperature and RH, with the focus on the preservation of the monumental organ. The set point operation of the HVAC system is evaluated by simulation through 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 RH, (2) a Comsol PDE (partial differential equation) 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 RH change rate. Recommendations from international literature (Schellen 2002) 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 the indoor air temperature change rate of 2 K/h. can reduce the peak drying rates by a factor of 20, and a limitation of the RH change rate of 2%/h. can reduce the peak drying rates by a factor of 50. The second strategy has the disadvantage that the heating time is not constant.

In the Walloon Church, there is a monumental organ that was restored in the spring of 2000. To prevent damage to the organ again, the indoor climate has to meet certain requirements. Studies have been recently performed for the preservation of the organ (Schellen 2002; Schellen et al. 2003). As a result, several adjustments were made to the heating system. Afterward, measurements showed that the indoor climate did meet the requirements for preservation of the organ.

However, the Walloon Church is used not only for services but also for several other activities—e.g., organ recitals. Since people sit in the church without wearing their overcoats, a temperature of 18°C–20°C is desirable. The result of this rather high temperature for monumental churches is that the 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. Because of 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 of 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 monumental wooden organ from drying-induced stresses. Recent studies concluded that: (1) the increase in drying rate causes a nonuniform distribution of the moisture content in dried material, and this involves drying-induced stress, and (2) 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 are given in figures 12 and 13.

4. The Control of Heating, Cooling, and Ventilating Systems in Monumental Buildings:

4b. Conservation Heating to Control Relative Humidity and Create Museum Indoor Conditions in a Monumental Building (Schellen and Neuhaus 2008)

For the conservation of an important museum collection in a historic building, improving control of the indoor climate may be necessary. One of the most important factors is controlling RH. Museum collections are often housed in historic buildings. 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 undesirable indoor air conditions, causing mold and condensation on the cold indoor surfaces or even internal condensation in the building fabric. One way to overcome this problem is to make use of what is called *conservation heating.* A humidistat to limit RH controls the heating system. Conservation heating control was tested in an experimental setup 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 over a long period. The preservation effects of the indoor climate conditions 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, although human comfort may decline. Furthermore, conservation heating is a simple and energy-efficient system that 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 later. 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 the interior and objects (Schellen and Neuhaus 2008). Outside the heating season, high RH often occurs, also causing risk for damage to the interior and objects—for example, by mold growth (Erhardt and Mecklenburg 1994). In most cases the possibility of fully controlling RH in a historic building—such as by installing a full air-conditioning system—is limited. Installing mechanical systems and ducts will always cause damage to the building and its historic authenticity—not to mention the high installation, maintenance, and operating costs. Furthermore, as mentioned above, humidifying devices may lead to high surface humidity and condensation 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 control of the heating system with a humidistat (Staniforth et al. 1994). High RH is prevented by the initiation of heating. Reaching low RH during the cold season is prevented by limiting heating to maintain a certain lower-temperature set point. The use of this control, however, is restricted. In summer it may be necessary to heat, and during wintertime it may be necessary to limit heating, causing thermal discomfort to occupants. In the Netherlands, there is little experience with conservation heating.

Figure 14 shows the simulation results of RH, from 14 January to 14 February 2006, of the humidistatically controlled room in the historic building; the simulation results are validated with measurements. There are minor discrepancies, possibly due to the estimated air exchange rate of 0.8 per hour. It is clear that with the minimum temperature set at 10°C, it is not possible to maintain a minimum of 45% RH, because of the low vapor ratio of the outdoor air, which mostly occurs during winter (in fig. 14, note the period from Jan. 22 to Feb. 4). Over the simulated period, the minimum temperature must be lowered to about 4°C to maintain 45% RH in the Dutch climate.

4. The Control of Heating, Cooling, and Ventilating Systems in Monumental Buildings:

4c. The Modeling of a High-Tech HVAC System for a Museum Depot—Simulation of the Climate System Performance of a Museum in Case of Failure (Schijndel, Schellen, and Timmermans 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 event, the following 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 consisted of the following steps: First, we implemented heat, air, and 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. Timmermans presents the following results in more detail (Schijndel et al. 2006): (1) evaluation of the current HVAC system components and the indoor climate of the museum, (2) evaluation of validation results, (3) evaluation of the simulated performance of the current design in case of failure, and (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 depot is switched off automatically. The construction of the depot creates sufficient thermal inertia to maintain a stable indoor climate for a longer period than if the air supply is maintained; during this time, the fault can be repaired. A further improvement of the design could be to control the climate surrounding the depot instead of controlling the indoor climate of the depot itself. In this case, even if the system did not detect a fault and thus supplied uncontrolled air to the surroundings of the depot, the indoor climate in the depot would remain stable.

Exemplary results are given in figures 15 and 16. Figure 15 shows the HVAC system, including the cooling coil. Figure 16 presents the measured air temperature before the air is cooled by the cooling coil and the measured and simulated air temperature after the air is cooled by the cooling coil.

4. The Control of Heating, Cooling, and Ventilating Systems in Monumental Buildings:

4d. The Application of an Integrated Indoor Climate and HVAC Model for the Indoor Climate Performance of a Museum (Schijndel and Schellen 2006)

In general, the aim of museums is to exhibit artifacts in their original states for as long as possible. The climate performance surrounding preserved artifacts is of great importance. Furthermore, if present, the HVAC system plays a dominant role in the indoor climate. This section presents a case study on the performance-based design of an HVAC system and controller of a museum. A famous museum in the Netherlands has reported possible damage to important preserved wallpaper fragments. This paper provides an evaluation of the current indoor climate through measurements indicating 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 HAM models of the indoor climate, the HVAC system and controller, and a showcase. The presented models are validated by a comparison of simulation and measurement results. An integrated model consisting of all the different models is applied for the evaluation of a new HVAC controller design and the use of a showcase. The results are discussed.

A solution is sought, given that the current HVAC system cannot be replaced (only small modifications are possible), and given that the use of showcases, although not prohibited, is not preferred by the decision makers. This situation leads to the following questions: First, what are the criteria for indoor climate for the preservation of wallpaper? Second, is it possible to improve the indoor climate performance by a new control strategy for the current HVAC system, in such a way that a showcase can be avoided? Third, if not, can the problem be solved by use of a showcase? Due to the preservation of the object, measurement is not an option to answer these key questions, because experimentation with the HVAC system is not allowed. Therefore, simulation is the only option, and an integrated indoor climate, HVAC, and showcase model is needed. There is no such a model available. These circumstances lead to two more key questions: First, can we develop an integrated HAM/HVAC system model capable of predicting the current indoor climate and the climate in a showcase? And second, using this model, can we improve the climate surrounding the object?

The aim of this study was 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, and data, measured by others, have been obtained for validating the showcase model; (3) indoor climate, HVAC, and showcase models were developed and validated; and (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 are given in figures 17a and 17b.

Conclusion

Experimental work and related computer modeling lead 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.

Evaluation

Ongoing Research-Driven Projects

Part 1: The Heating of Monumental Churches and Its Effects on the Preservation of the Indoor Collection

This part shows the results of experimental and simulation work on the indoor climate of churches. It shows the power of simulation tools to predict the effects of heating and no heating on the indoor climate, as well as on the preservation of monumental objects and exterior construction parts. The results of the study led to a performance array for different types of church heating. An example of air heating is shown.

Part 2: Thermal Comfort in the Senate during Summer

The whole building model HAMBase is used for the simulation and evaluation of several design variants. The model is fine-tuned with, and compared to, measurement results. A passive solution strategy leads to an expected solution of the summer overheating problem.

Part 3: The Design of a More Efficient Hypocaust Heating System for a Monumental Church

In this project a rare and complex hypocaust heating system is studied. The simulation environment is used to develop a HAM model for the building and its heating system. This model is used for the simulation and evaluation of several design variants.

Part 4a: A Set Point Operation Strategy Design for the Conservation of a Monumental Church Organ

This part shows a set point operation design for the conservation of an organ. The suggested climate control was realized in 2001. Since that time, no problems have been reported. It should be noted that this is too short a time period to allow the conclusion that the problem has been solved permanently.

Part 4b: The Design of a Hygrostatic Controller

In this case indoor air heating is now hygrostatically controlled. The validation results are quite satisfactory for this controller. Several control strategy designs were evaluated.

Part 4c: Modeling and Simulation of a High-Tech HVAC System for a Museum

The preliminary results of this project indicate that the systems modeling approach can also be applied to high-tech systems with more sophisticated controllers.

Part 4d: An Indoor Climate Controller Design for the Conservation of Monumental Paper Fragments

This part presents an indoor climate controller design for conserving paper fragments. A technically good solution is provided. However, because of aesthetic considerations, the decision makers have not yet determined a course of action.

HAM Modeling and Simulation

Development of an Integrated HAM Modeling and Simulation Environment

The problems caused by the difference in time scales between HVAC and building response are solved by the development of a HAMBase model in Simulink. The hybrid model consists of a continuous part with a variable time step and a discrete part with a time step of 1 h. For the HVAC installation and the room response on indoor climatic variations, a continuous model is used. For the external climate variations, a discrete model is used. The dynamics of the building systems for which small time scales play an important role are accurately simulated. Furthermore, the model becomes time efficient, as the discrete part uses 1 h. time steps (a typical yearly based simulation takes about two minutes on a Pentium III, 500 MHz computer).

Verification and Validation

Verification and validation (V&V) is a continuous process. The models presented here—the building zone model (HAMBase) and the primary systems models—already show a good agreement, respectively, with American Society of Heating, Refrigerating, and Air-

Conditioning Engineers tests (ASHRAE 2001) and with measurements. Preliminary results of ongoing research projects also point in that direction. The V&V of 3-D HAM models of constructions is perhaps a larger problem because of the fact that it is much more difficult to measure the required physical quantities inside capillary-porous materials than it is in air.

Evaluation of the Simulation Environment

Limitations:

- Some specific solvers, such as time-dependent k-ε turbulence solvers, are not available in the Comsol environment yet. The lack of such tools means that, for example, time-dependent 3-D airflow around buildings cannot yet be solved.
- Although it is possible to construct a full 3-D integrated HAM model of the indoor air and all constructions in Comsol, the simulation time would probably be far too long to be of any practical use at this moment.
- A radiation modeling toolbox has just recently become available in Comsol; it is not included in this research.

Drawbacks:

- The software package Matlab and basic knowledge of Matlab are required to use the models.
- At this moment HAMLab is a research tool. Therefore, it lacks facilities for design-oriented users, such as user-friendly interfaces and user guides.
- Although state-of-the-art solvers are present, the simulation of FEM (finite element model) based integrated models can easily become very time-consuming in terms of computation time.

Benefits:

- The simulation environment takes advantage of the facilities of the well-maintained Matlab/Simulink and Comsol simulation environment, such as the state-of-the-art ODE/PDE (ordinary and partial differential equation) solvers, controllers library, graphic capabilities, and so on.

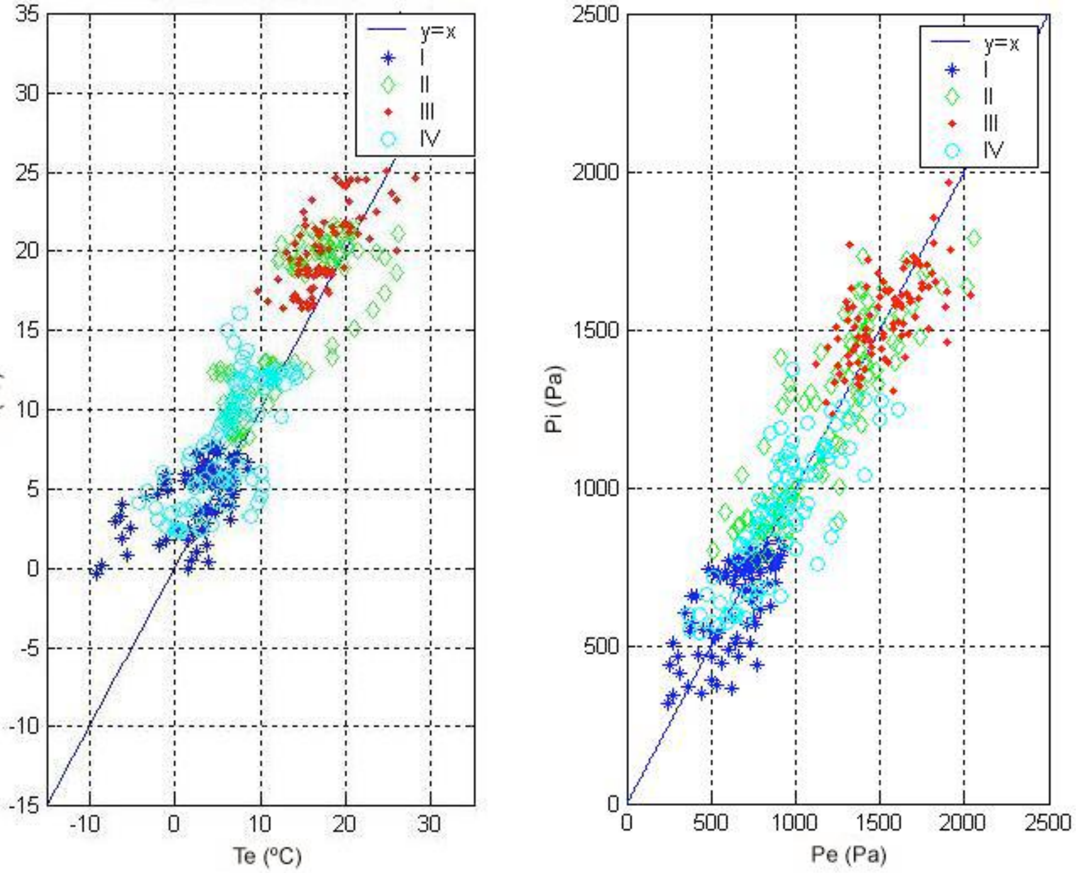
- All presented HAMLab models are public domain.
- Although not explicitly shown, compared to other HAM models, it is relatively easy to integrate new models that are based on ODEs and/or PDEs.
- The simulation environment facilitates open-source modeling, and if desired, models can be compiled into stand-alone applications.

Author Biographies

Dr. Ir. Henk L. Schellen is an engineer in building physics. In 1983 he started working for the Eindhoven University of Technology, the Netherlands, where he became an associate professor of building physics of monumental buildings in 2004. His main expertise is on building physical measurements and simulation, with a special interest in building physical heat and moisture problems in monumental buildings. His PhD dissertation was entitled "Heating Monumental Churches: Indoor Climate and Preservation of Cultural Heritage" (Schellen 2002). Schellen contributed to the European project on the development, measurement, and simulation of a new bench heating system for churches.

Dr. Ir. Ing Jos A. W. M. van Schijndel has a degree in physics engineering from Fontys Polytechnical School, Eindhoven, the Netherlands (1987), and a degree in physics from Eindhoven University of Technology (1998). He joined this university as a Research Engineer in 1991, and he has been Assistant Professor for the Building Physics and Systems Unit since 1999. His PhD dissertation is entitled "Integrated Heat, Air, and Moisture Modeling and Simulation" (2007).

Figures

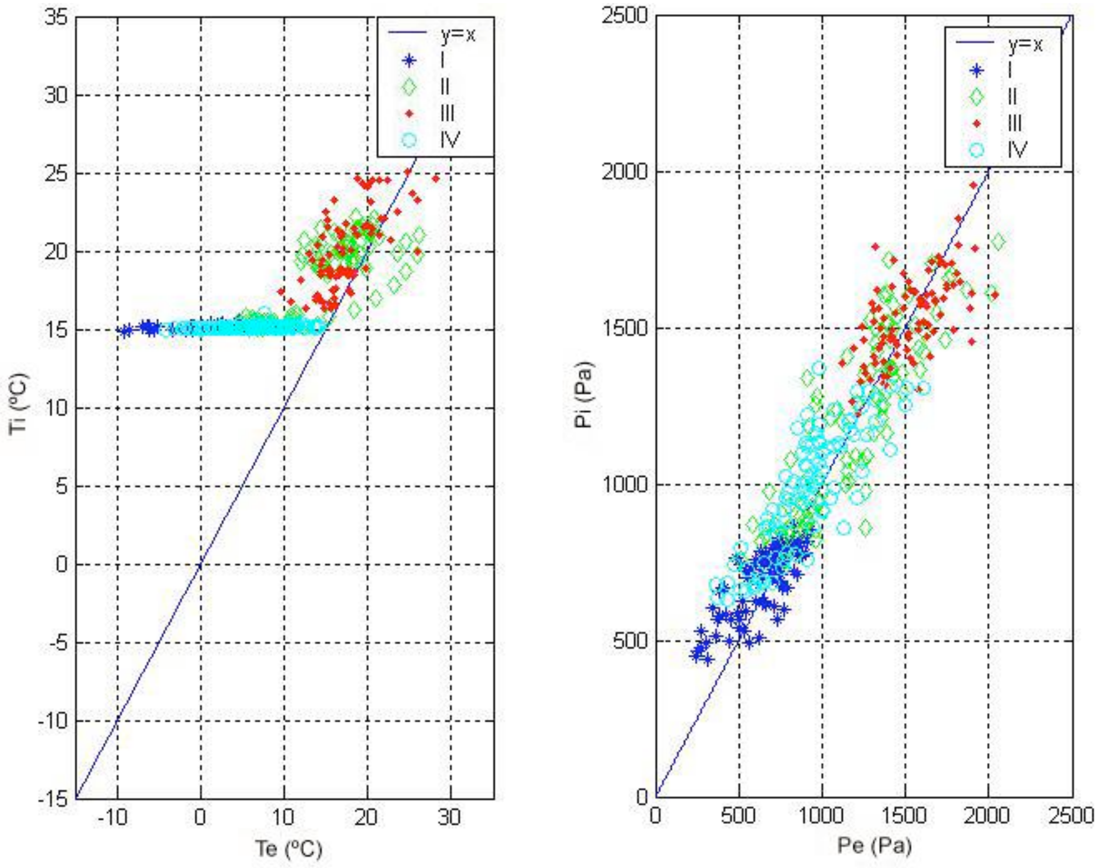


a

b

Figures 1a and 1b

Effects of no heating at St. Martin's Church in Weert. The mean daily indoor and outdoor temperatures are correlated (a), as are mean daily indoor and outdoor vapor pressures (b). (I = winter, II = spring, III = summer, IV = autumn; T_i = indoor temperature, T_e = outdoor temperature, P_i = indoor vapor pressure, and P_e = outdoor vapor pressure.)



a

b

Figures 2a and 2b

Effects of stationary heating at St. Martin's Church. The mean daily indoor and outdoor temperatures are correlated (a), as are mean daily indoor and outdoor vapor pressures (b). (I = winter, II = spring, III = summer, IV = autumn; T_i = indoor temperature, T_e = outdoor temperature, P_i = indoor vapor pressure, and P_e = outdoor vapor pressure.)

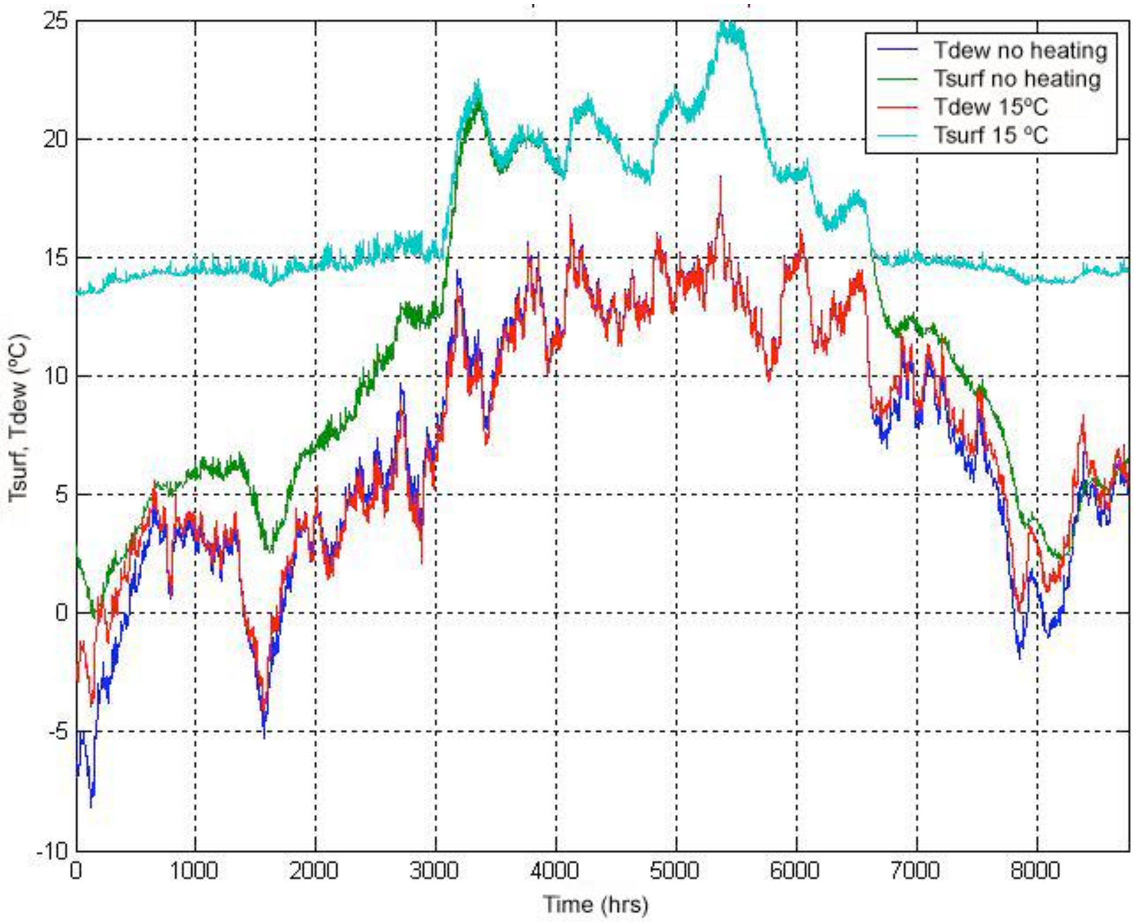


Figure 3

Comparison of surface temperature (T_{surf}) and dew point temperature (T_{dew}) for no heating at St. Martin's Church and for heating the church to a primary level of 15°C.

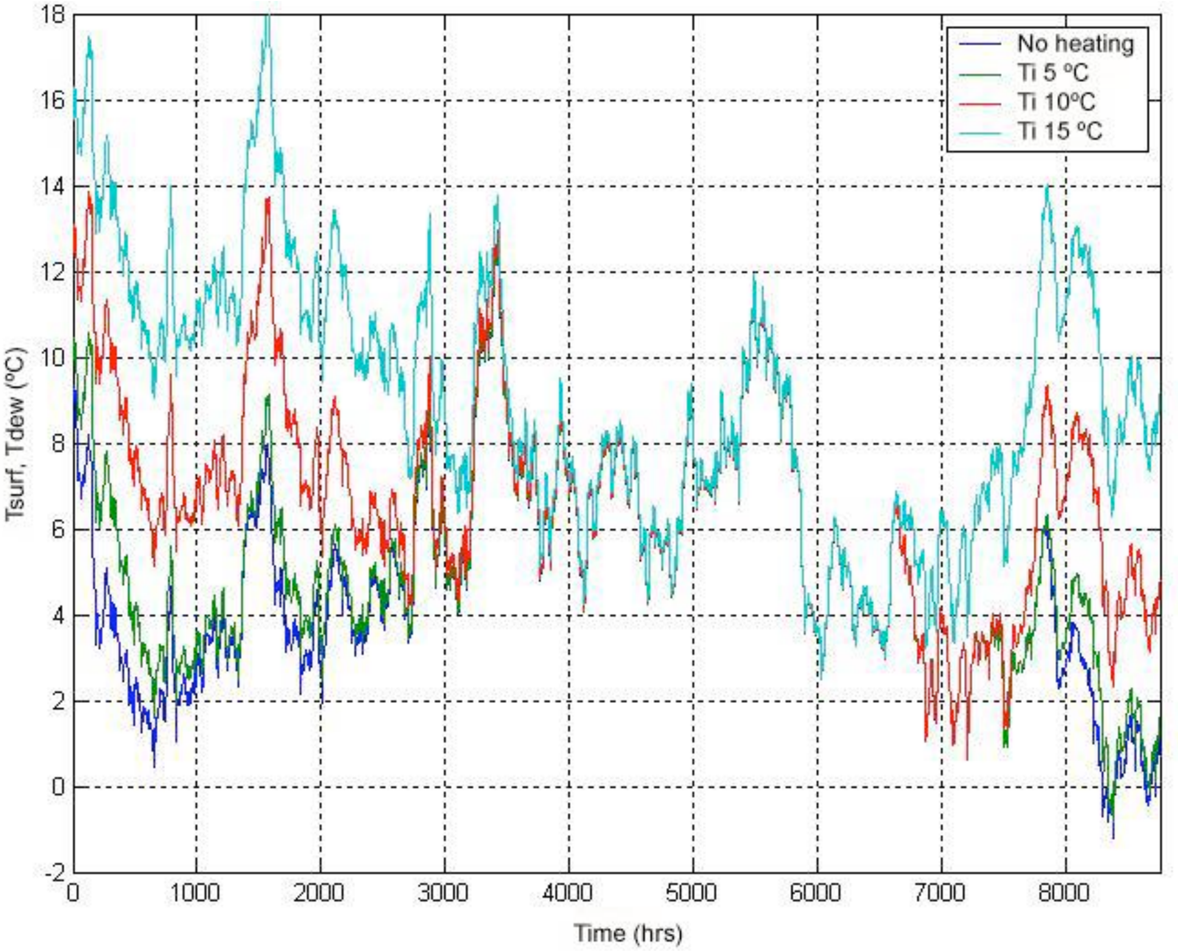
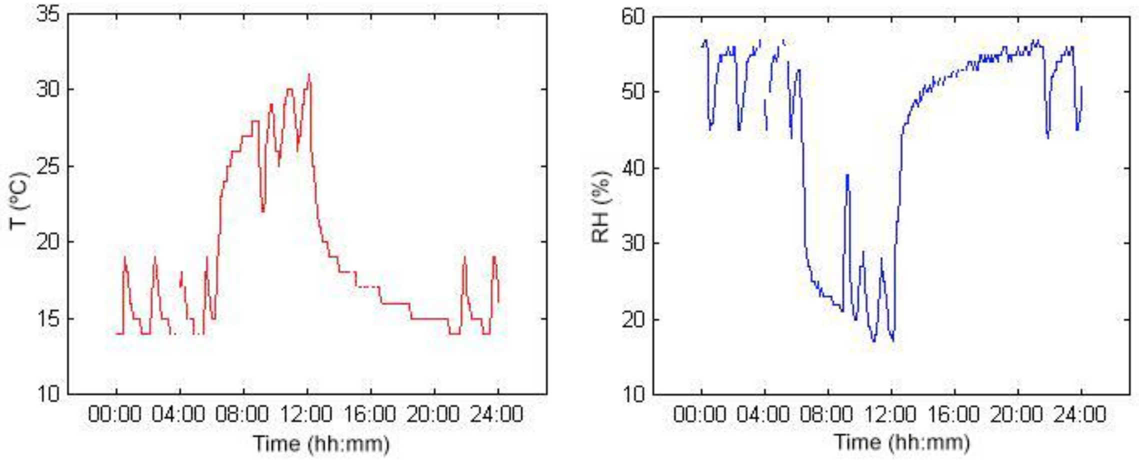


Figure 4

Effect of primary heating on the dew point difference at St. Martin's Church (T_{surf} = surface temperature; T_{dew} = dew point temperature, T_i = indoor temperature).



a

b

Figures 5a and 5b

Air temperature (a) and RH (b) measured in front of the organ in the Walloon Church in Delft at a height of 15 m (T = temperature).

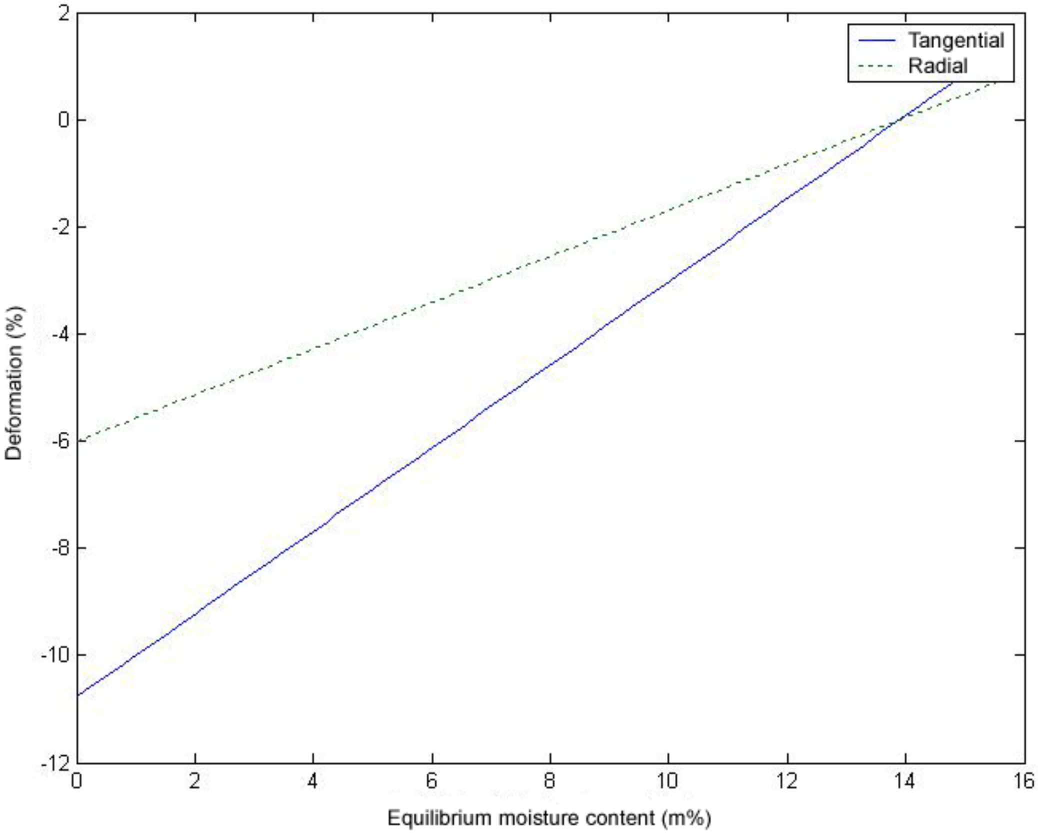


Figure 6

Contraction of wood as a function of equilibrium moisture content.

Figure 7

Shrinking damage of a wooden organ pipe from the monumental organ of the Walloon Church. Photo: Sanders/Mensink, Reinwardt Academy, 2000.

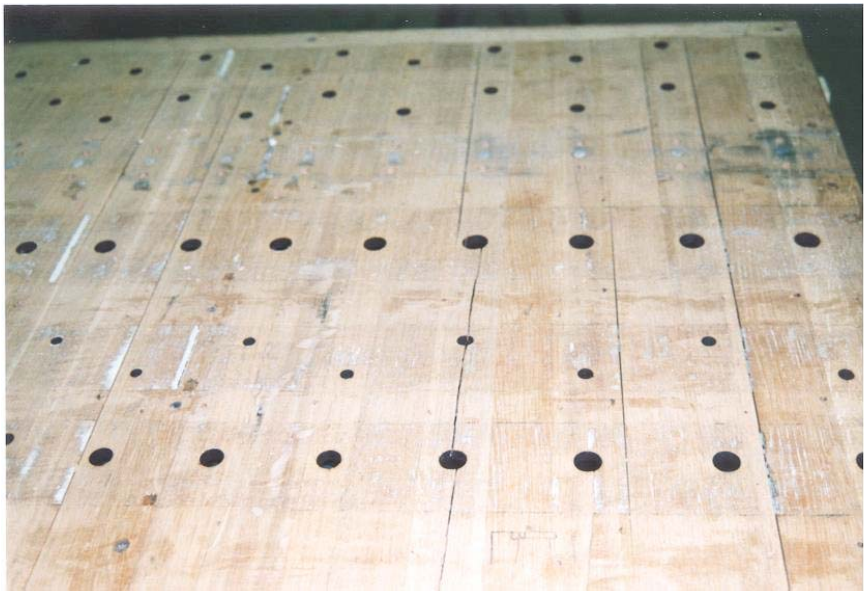


Figure 8

Shrinking damage of a wind drawer from the monumental organ of the Walloon Church. Photo: Sanders/Mensink, Reinwardt Academy, 2000.

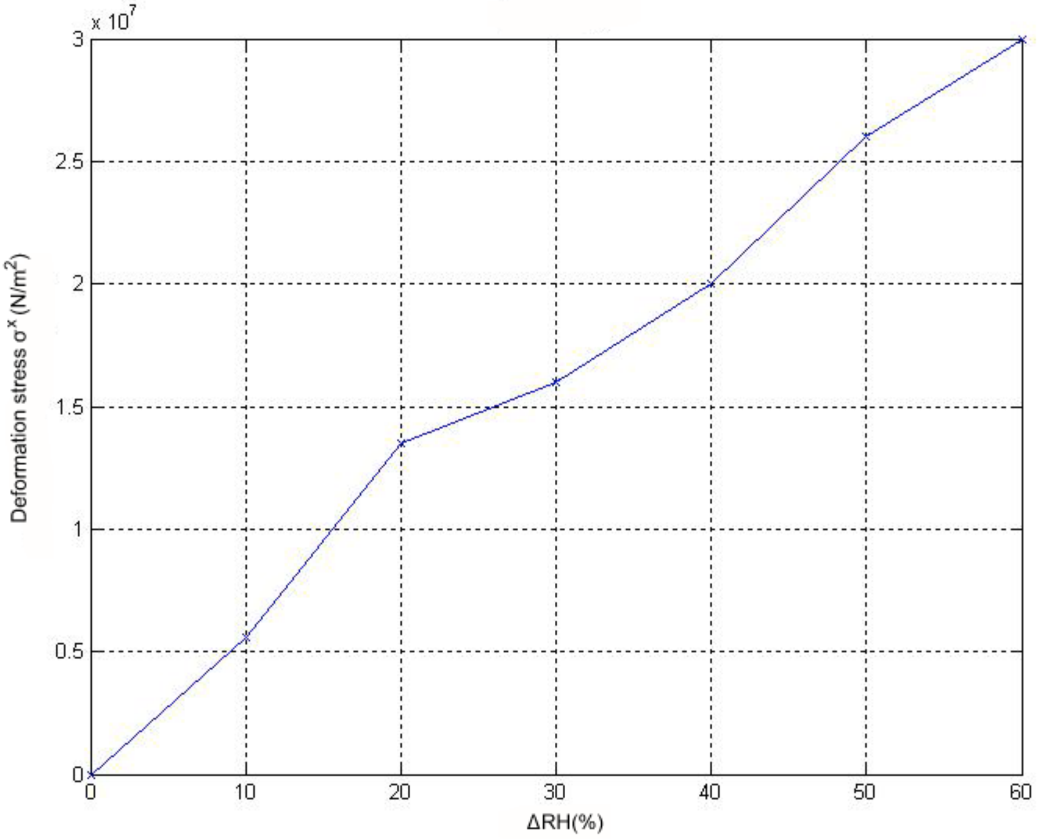
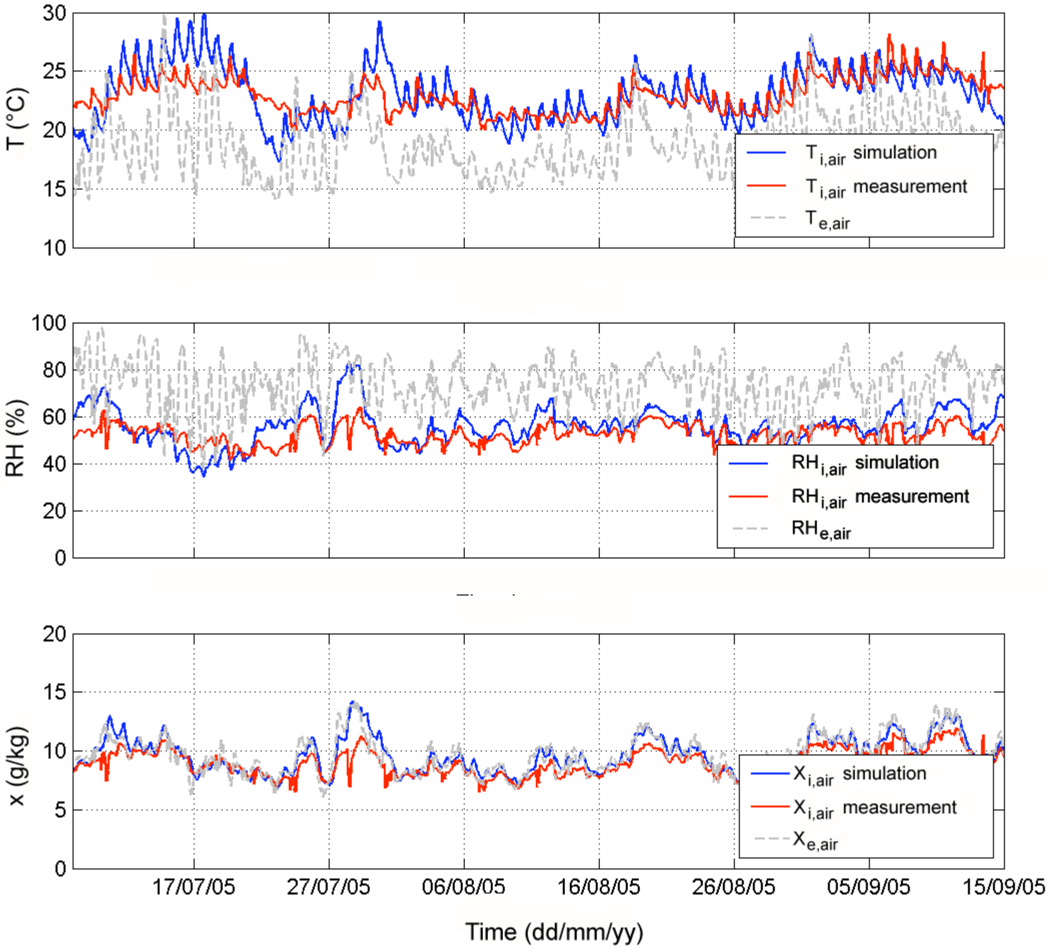


Figure 9

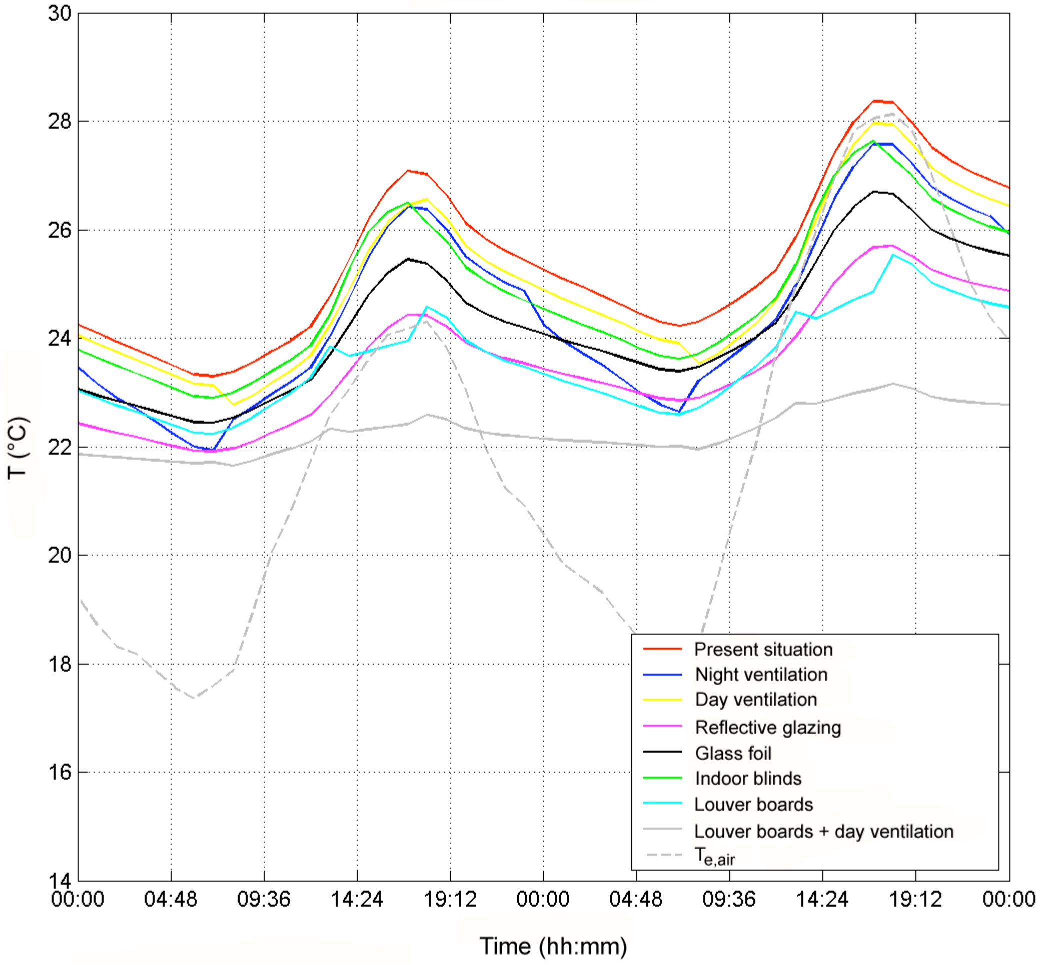
Maximum calculated stresses in the x-direction of a wooden organ pipe measuring 100 x 100 x 5 mm, from the monumental organ of the Walloon Church. Stresses are due to sudden changes in RH at the surface (Schellen 2002).



a

Figure 10a

Measured and simulated indoor climate of a warm office room in the Senate of the Netherlands in The Hague, for the period from 30–31 August 2005. (T = temperature, T_i = indoor temperature, T_e = outdoor temperature, RH_i = indoor RH, RH_e = outdoor RH, x = water vapor content, x_i = indoor water vapor content, and x_e = outdoor water vapor content).



b

Figure 10b

Measured and simulated indoor air temperature of a warm office room in the Senate of the Netherlands in The Hague for suggested passive measures, for the period from 30–31 August 2005. (T = temperature, T_i = indoor temperature, T_e = outdoor temperature, RH_i = indoor RH, RH_e = outdoor RH, x = water vapor content, x_i = indoor water vapor content, and x_e = outdoor water vapor content).

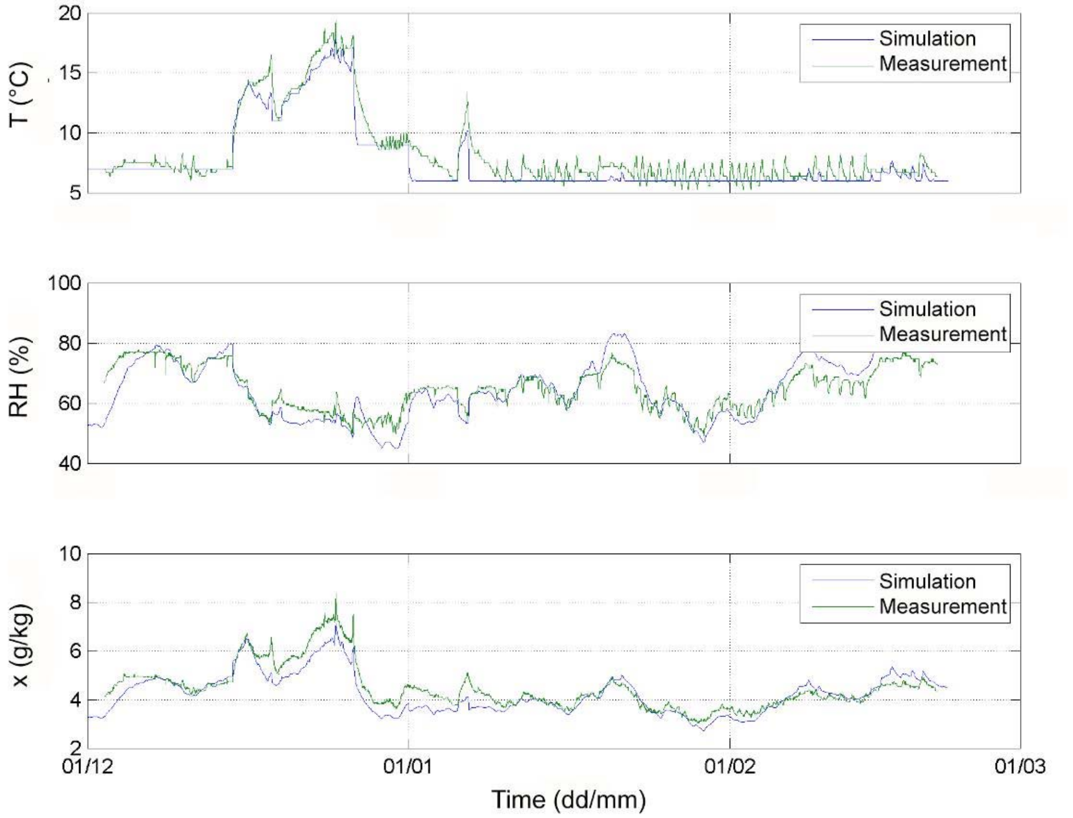


Figure 11

Measured and simulated current indoor climate of St. Steven's Church in Nijmegen, the Netherlands (T = temperature; x = water vapor content).

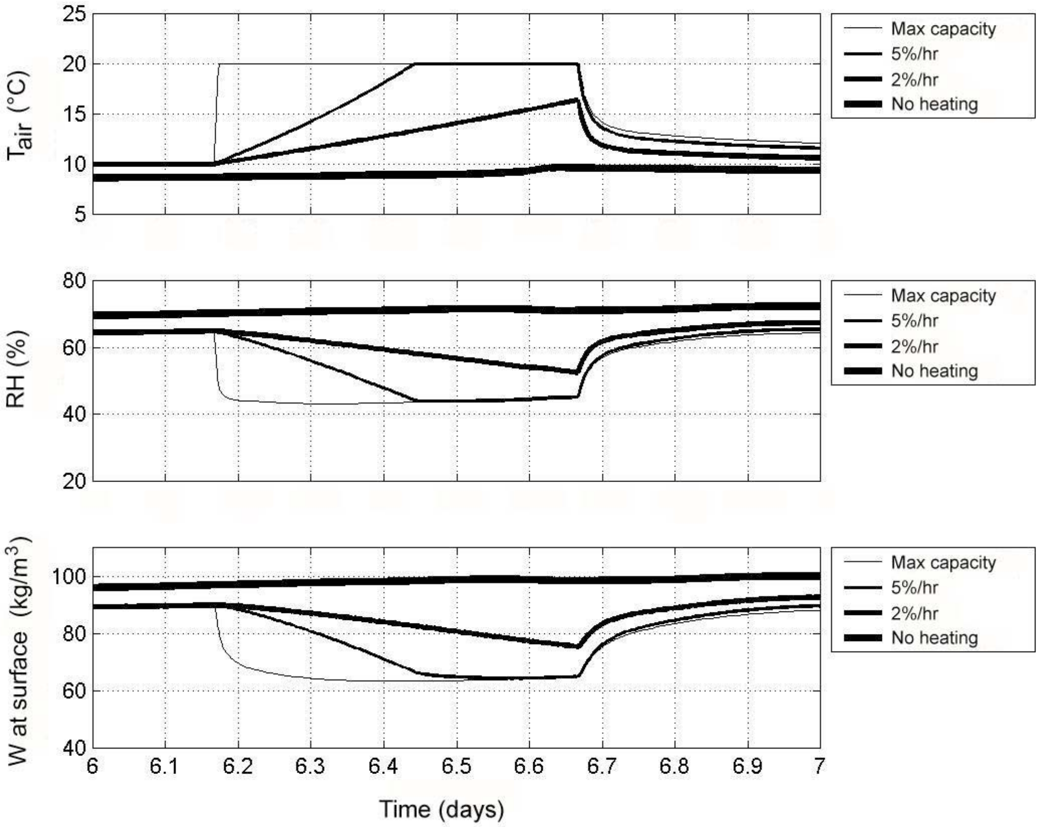


Figure 12

Indoor air temperature (T_{air}) and RH near the surface of the monumental organ of the Walloon Church and moisture content of the wood (w) over a period of 1 day (starting Saturday at 00:00).

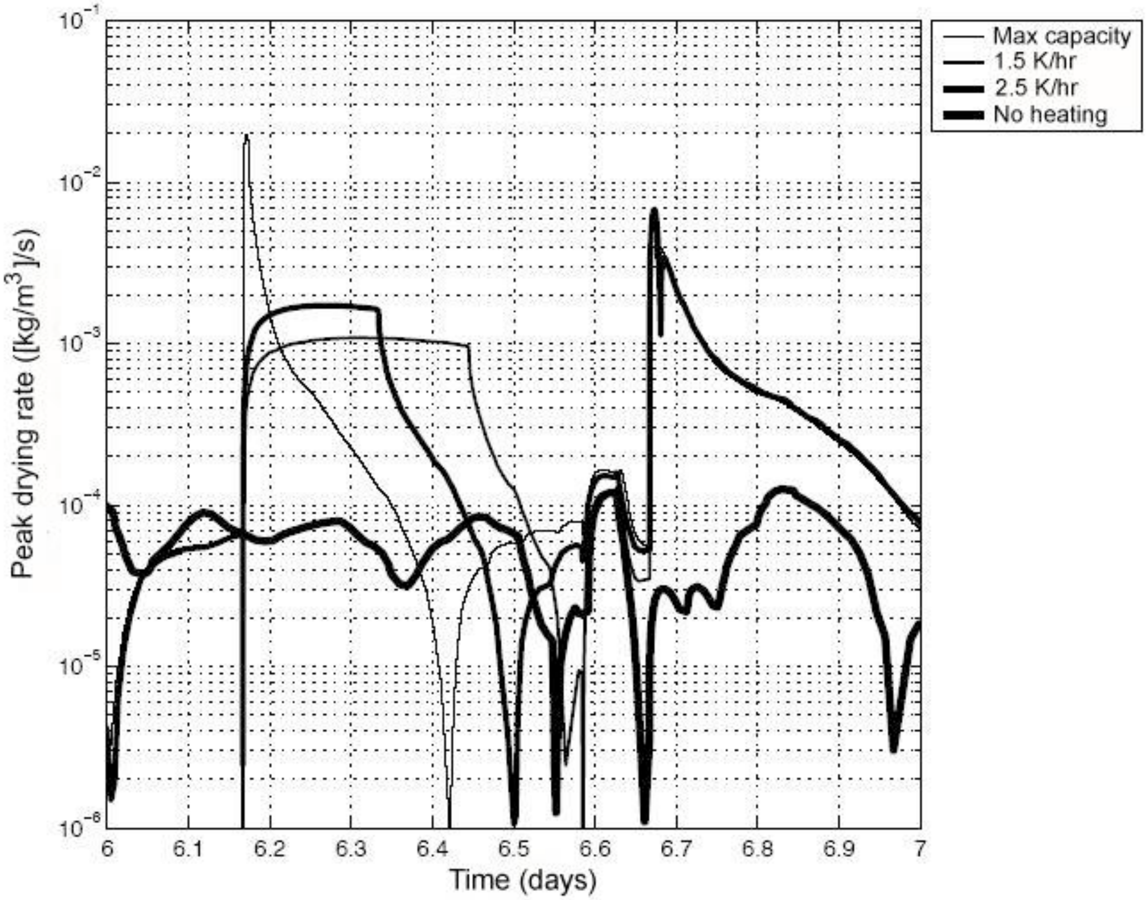


Figure 13

Peak drying rate of the monumental organ of the Walloon Church over a period of 1 day (starting Saturday at 00.00).

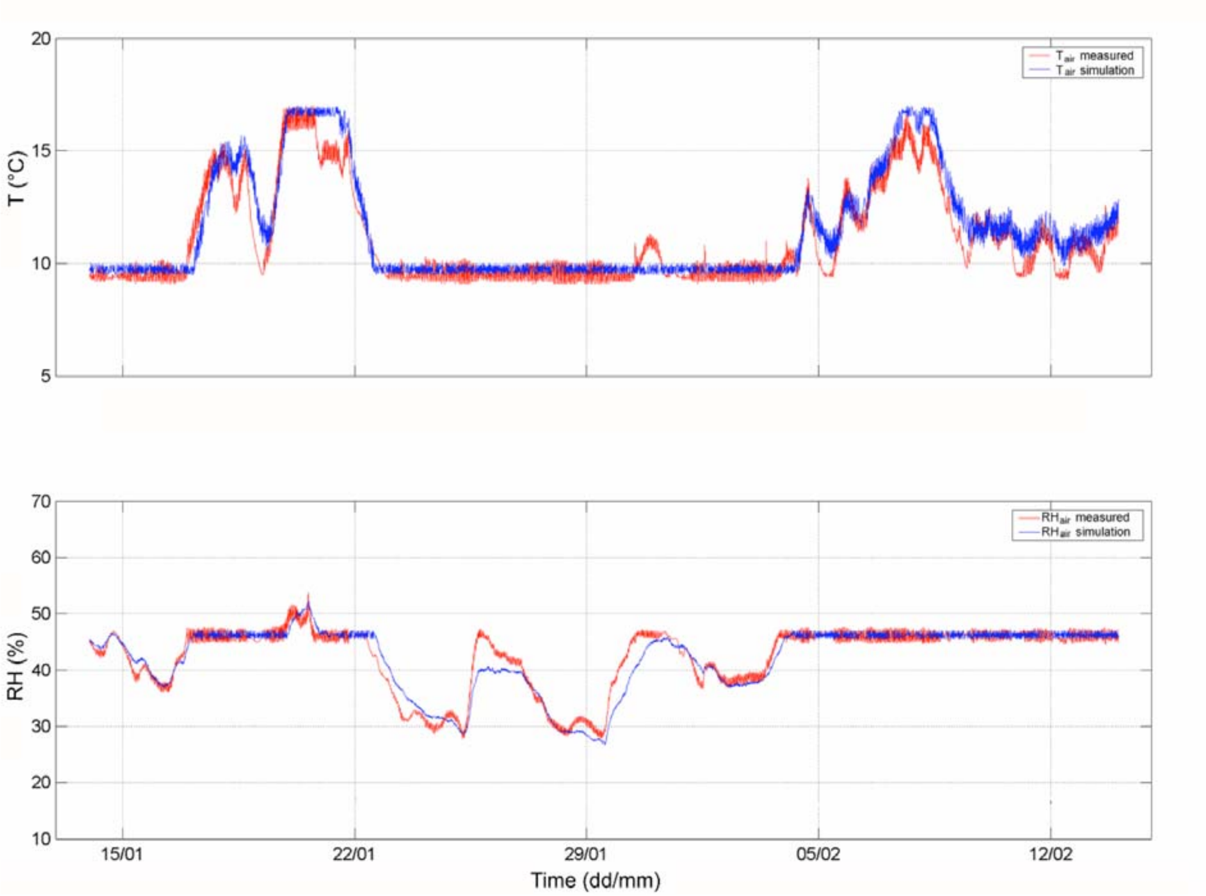


Figure 14

Measured and simulated temperature (T) and RH in a humidistatically heated room, over the period from 14 January to 14 February 2006, in a historic building in the Netherlands.

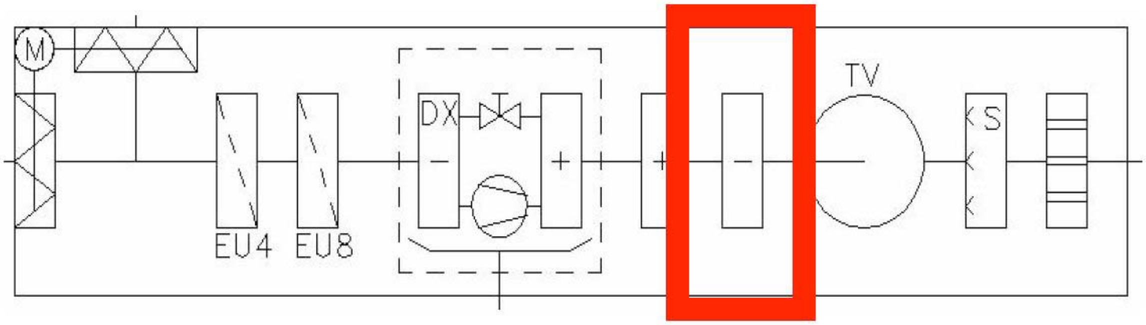


Figure 15

The HVAC system and cooling coil (indicated by the red rectangle) of the National Maritime Museum's storage facilities, the Netherlands. (M = dampers; EU = filter quality indication; DX = direct expansion; + = heating; - = cooling; T = valve; TV = fan; S = steam humidification).

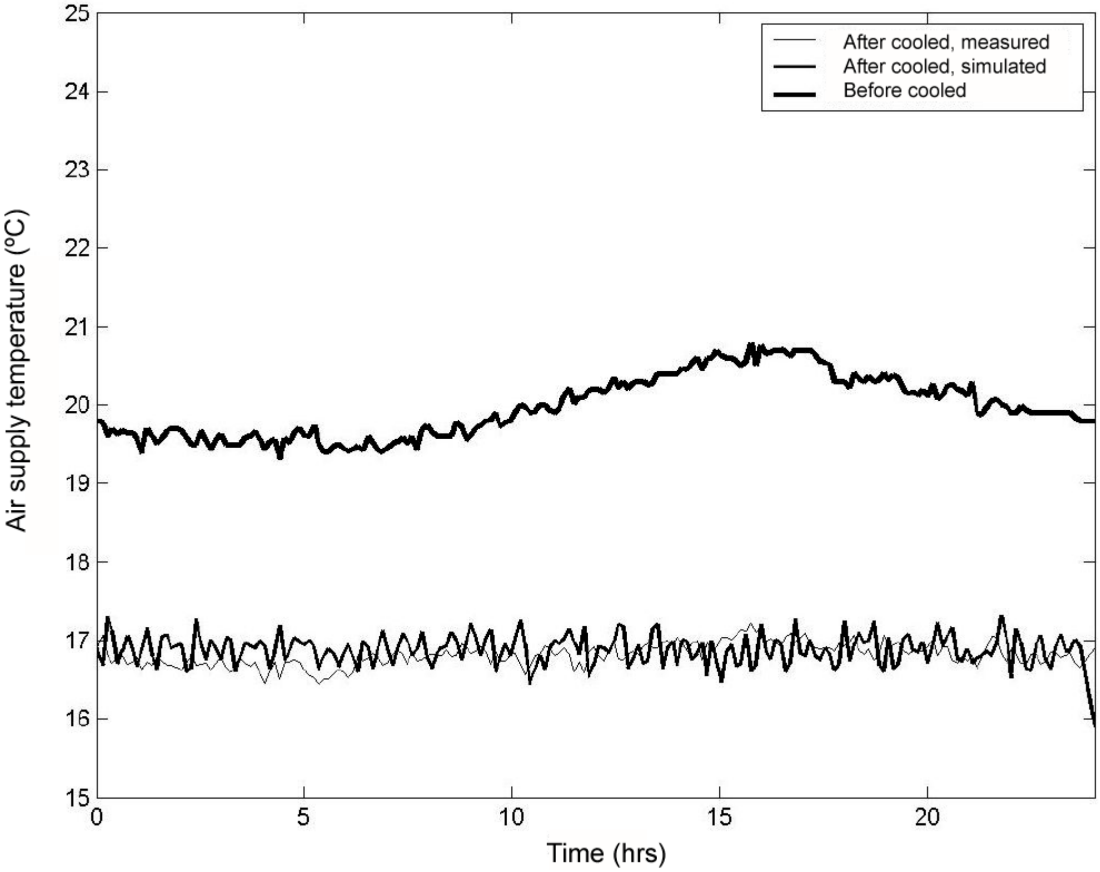
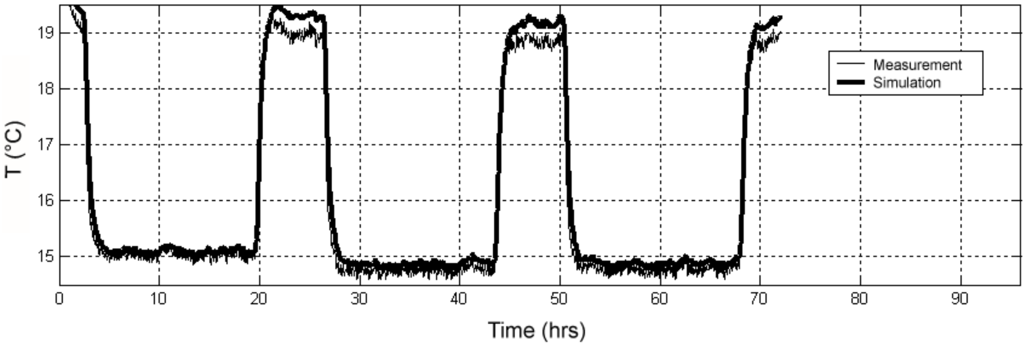
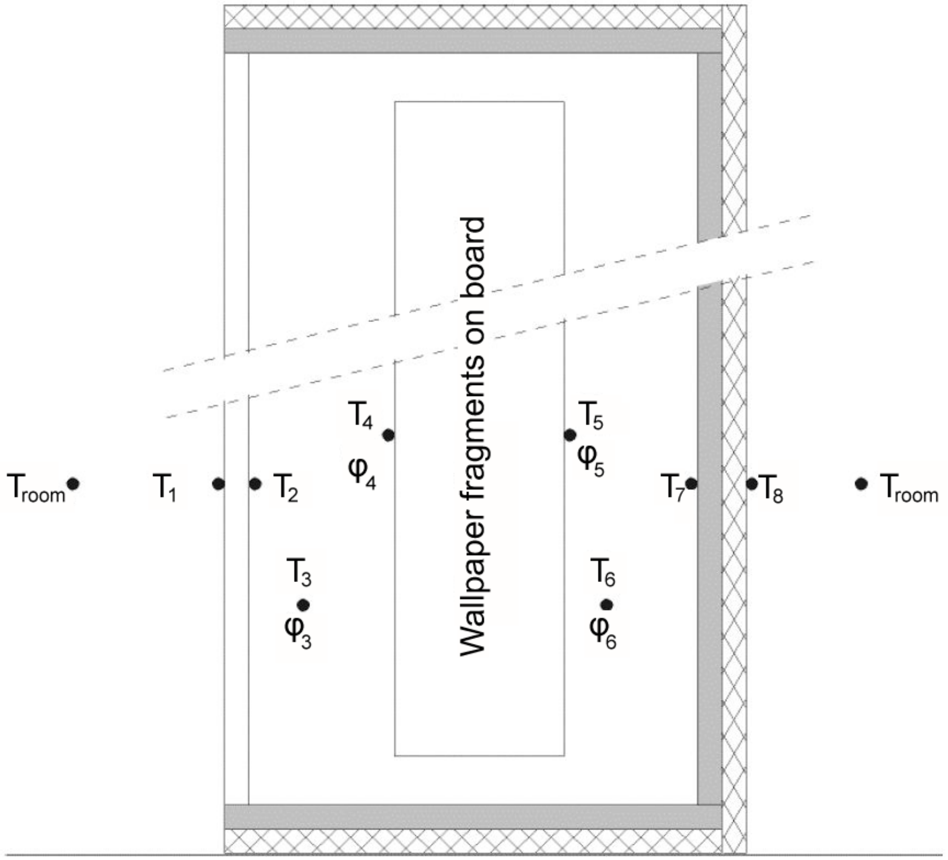


Figure 16

Air supply temperature before and after being cooled by the cooling coil of the HVAC system at the National Maritime Museum's storage facilities.



a



b

Figures 17a and 17b

Measured and simulated air temperature in a museum showcase (a) and a schematic view of the modeled quantities (T = temperature; φ = RH).

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