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Modeling multiple indoor climates in historic buildings due to the effect of climate change

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SUMMARY: Within the new EU project ‘Climate for Culture’ researchers are investigating climate change impacts on UNESCO World Heritage Sites. Simulation results are expected to give information on the possible impact of climate change on the built cultural heritage and its indoor environment. This paper presents the current and new modeling approaches necessary for obtaining the required simulation result by: Firstly, in order to put the new developments in the right context and because we elaborate on comprehensive existing work it is important to present an overview of our current state of the art on the modeling of historic buildings. Secondly, we present an approach on how to incorporate the effect of climate change into the building models. Thirdly, we provide a preliminary method for up-scaling building spatial level models onto a continental level. The latter provides maps that visualize the impact of external climate change on indoor climates of similar buildings spread over Europe.

1. Introduction

Effects of climate change on ecosystems and on the global economy have been researched intensively during the past decades but almost nothing is known about our cultural heritage. Within the new EU project ‘Climate for Culture’ researchers are investigating climate change impacts on UNESCO World Heritage Sites. Although these historical monuments are exposed to extensive loads caused by stampedes of visitors, there are many other factors deteriorating World Heritage Sites. The impacts of climate change are a long-term and substantial menace to the sites. For the first time completely new high resolution climate simulation modeling until 2100 will be coupled with building simulation software adapted for historic buildings. The simulation results are expected to give information on the possible impact of climate change on the built cultural heritage and its indoor environment.

The current scale levels incorporated in the research area Computational Building Physics succeeded from (van Schijndel 2007) are shown in Figure 1.

FIG 1. The current scale levels of the research area Computational Building Physics: Urban, Building, Human, Material

Currently, the largest present scale is the urban level (~ km). However a continental scale is necessary for the new EU project ‘Climate for Culture’. This paper presents the current and new modeling.
approaches, necessary for obtaining the required scale level. The paper is organized as follows: Section 2 provides an overview of our current state of the art on the modeling of historic buildings at several scales using scientific computational software. Section 3 presents an approach on how to incorporate the effect of climate change into current models. Section 4 shows a preliminary method for up-scaling building spatial level models onto a continental level.

2. Current modeling approaches of historic buildings

The modeling and simulation laboratory HAMLab (Heat, Air & Moisture Laboratory) is used (van Schijndel 2007, HAMLab 2010). This in-house developed tool is implemented using state of the art scientific software packages MatLab, SimuLink & Comsol. Using HAMLab, the following general modeling facilities are available within the simulation environment SimuLink: (1) a whole building (global) modeling facility, for the simulation of the indoor climate and energy amounts; (2) a partial differential equation (PDE) solving facility, for the simulation of 2D/3D HAM responses of building constructions (i.e. materials) and 2D internal/external airflow; (3) an ordinary differential equation (ODE) solving facility, for the accurate simulation of building HVAC (Heating, Ventilating, and Air Conditioning) systems (see Figure 2).

![FIG 2. Schematic overview of the Heat, Air & Moisture Laboratory (HAMLab).](image)

Each facility is presented more elaborately in the following Sections.

2.1 The indoor climate modeling

*Description* - The whole building model originates from the thermal indoor climate model ELAN which was already published in 1987 (de Wit et al. 1987) (see Figure 3, top-left). Separately a model for simulating the indoor air humidity was developed. In 1992 the two models were combined and programmed in the MATLAB environment. Since that time, the model has constantly been improved using the newest techniques provided by recent MATLAB versions. Currently, the hourly-based model named HAMBase, is capable of simulating the indoor temperature, the indoor air humidity and energy use for heating and cooling of a multi-zone building. The physics of this model is extensively described by de Wit (2006).
FIG 3. Overview of the indoor climate model HAMBase. Top Left: The two node thermal network of the ELAN model representing the air ($T_a$) and radiant ($T_r$) temperatures. Top Right: Validation of the heat balance. Bottom Left: Application at the Anne Frank House. Bottom Right: Comparison between model and measurements.

**Validation** – The HAMBase model has been validated using the latest state-of-art measurement from the International Energy Agency (IEA) Annex 41 (2008). Measured data are obtained from a test room which is located at the outdoor testing site of the Fraunhofer-Institute of building physics in Holzkirchen. The room was heated by electric heating and controlled on 20°C air temperature. The measurements were carried out during a winter season. A comparison of the simulated heat supply and the measured one is shown in Figure 3 (top-right). The mean difference between simulation and experiment equals 10W and is less than 2% of the measured mean heating power. Also the results of the relative humidity (RH) simulation agree well with the measurements (mean error less than 4%).

**Application** – We successfully applied our indoor climate model for the Anne Frank House (see Figure 3 bottom left) (van Schijndel et al. 2008). This famous museum in the Netherlands reported possible damage to important preserved wallpaper fragments. An evaluation of the current indoor climate by measurements showed that the indoor climate performance did not satisfy the requirements for the preservation of old paper. To solve this problem we developed an integrated heat air & moisture (HAM) model consisting of models for respectively: the indoor climate, the HVAC system & controller and a showcase. The presented models were validated by a comparison of simulation and measurement results (see Figure 3 bottom-right). The model was used for the evaluation of a new HVAC controller design and the use of a showcase. It was concluded that it was not possible to satisfy the indoor climate within the recommended limits, exclusively by the use of a new control strategy. Furthermore in order to meet the recommendations, the wallpaper fragments should be placed in a
showcase and a more robust control strategy had to be implemented in order to limit the room air temperature change.

2.2 The materials modeling

Description - Many scientific problems in building physics can be described by PDEs. The commercially available software Comsol is developed specifically for solving PDEs where the user in principle can simulate any system of coupled PDEs. The heat and moisture transport in materials can be described by two PDEs using temperature and LPC (logarithmic of capillary pressure) as potential for moisture transfer. An exemplary result of a 3D temperature distribution is shown in Figure 4 (top-left). Details on the modeling can be found in (van Schijndel 2007).

Validation - Benchmarks are important tools to verify computational models. In the research area of building physics, the so-called HAMSTAD (Heat, Air and Moisture STAnDardization) project is a very well known reference for the (1D) testing of modeling tools on heat and moisture transport in materials (Hagentoft et al. 2002). The results of our HAMLab models are quite satisfactory. This shows that the modeling approach is valid for all kinds of materials. Furthermore, in Comsol, the mathematical modeling (i.e. PDE) part and geometry part are strictly separated. This means that (validated) models in 1D are extendable to 3D without the necessity of (re)validation.

Application - The application is part of the measurement program at the Hunting Lodge St. Hubertus site, performed during 2006-2007 by Briggen et al. (2009). One of the problems was the high moisture content at the inside surface of the façade of the tower. The inside air temperature and relative humidity together with the inside surface conditions were measured using standard equipment. The construction is made of brick and concrete. We used these measurements to estimate the necessary materials properties. Figure 4 shows the simulated and measured internal surface conditions for the relative humidity (left) and temperature (right). This so-called inverse modeling approach is currently under investigation. Nevertheless, the model was successfully used to simulate the effect of possible measures to solve the high moisture contents at the inside surfaces.

2.3 The building systems modeling

Description - The main idea is to model the building systems as systems of ODEs and implement them into Simulink (van Schijndel 2007). In this case, each model has the following general characteristics: a vector of inputs, u, a vector of outputs, y, and a vector of states, x, as shown by Figure 5 top-left. As
shown by (van Schijndel 2007) a large range of buildings systems (and controllers) can be modeled and simulated using this approach.

**Validation** - For the preventive conservation of an important museum collection a controlled indoor climate is necessary. One of the most important factors is controlling relative humidity. So-called ‘conservational heating’ uses a hygrostatic device to control relative humidity’s by the heating system. High relative humidity is prevented by starting heating and reaching low relative humidity will stop heating.

**Application** - In the Walloon Church in Delft a monumental church organ is present which has been restored in the spring of 2000. The main task was to protect the wooden monumental church organ from drying induced stresses (van Schijndel 2007). The best solution to prevent high peak drying rates is not to heat the building. Due to thermal discomfort, this is not an acceptable solution. The worst solution to prevent high peak drying rates is full heating capacity. The peak drying rate is seen as the main cause for the damage to the previous church organ of the Walloon church and is therefore not acceptable. The peak drying rate is limited by a limitation of air temperature change rate. As a result of this research several adjustments have been made to the heating system. Afterwards measurements showed that the indoor climate did meet the requirements for preservation of the church organ.

3. **Incorporate the effect of climate change into the models**

Within the EU Climate for Culture project, future climate scenarios for Europe will be developed by researchers of the Max Plank institute (Jacob 1997). These artificial data will contain the hourly values of the necessary climate parameters for several locations spread over Europe. One of the first locations, already preliminary simulated is ‘de Bilt’ Netherlands. In Figure 5, a first comparison between measured and simulated climate data for the period 1971 – 2010 is shown, as well as the future prediction. The reader should notice that the simulated climate data are not generated for exactly one geographical location, but are values which are averaged over several locations (10km x 10 km grid) near ‘de Bilt’.

![Figure 5](image)  
**FIG 5.** Comparison between measured and preliminary simulated values of temperature and relative humidity for the decades 1971 to 2010 and future predictions for location ‘de Bilt’ Netherlands
4. Towards a continental scale level

4.1 Scale level Netherlands

The first step was to use our database with measurements of historic buildings and museums. The locations are shown in Figure 6.

![Figure 6](image)

**FIG 6.** An overview of the locations of historic buildings and museums in our database including the measurement periods.

4.2 Classification

The second step was to develop a classification system that allows comparing similar buildings and especially indoor climates. The buildings are divided using the complexity of the construction. For the climate system the ventilation, thermal influence, hygric influence, the medium type and the control are assessed. The buildings under research are placed in matrix (see Figure 7). The Dutch situation consists of various simple monumental buildings that have all types of climate systems. The newer, more complex buildings however show less diversity in their climate systems.

![Figure 7](image)

**FIG 7.** The classification system

4.3 Multi-buildings modeling

The third step was to include several buildings from the previous Section in a single multi-buildings model. We adapted our building model HAMBase (see Section 2.1) in such a way that we could
simulate several buildings in a single model. The model complexity is obvious: 93 indoor climate zones each including zonal climate control systems together with the heat and moisture gains, 776 walls and 210 windows. The output of the model i.e. indoor climates and heat and moisture flows of the systems are also complicated. The results of a preliminary application of the Multi-buildings model are shown in Figure 8. The top row presents 93 indoor climates (T and RH) of 11 buildings simulated during 10 days in winter including present systems and internal gains. All these data are validated. So they also represent the measured values in reality. However, what we almost never can measure (for obvious reasons: we are not allowed to do this), are the responses of the indoor climates in historic buildings without systems and internal gains. Such responses could be very important when trying to classify the indoor climates of historic buildings. In Figure 8, the bottom row shows the virtual free floating simulation results similar as the top row but now without systems and internal gains. These latter results also represent the influence of the external climate on the indoor climate. This could be an important tool when studying the effect of climate change.

**FIG 8.** The simulated 96 indoor climates of 11 buildings during 10 days in winter. Top: ‘As is’ including present systems and internal gains, Left: Temperature, Right: Relative Humidity. Bottom: ‘Virtual Free Floating’ similar but now without systems and internal gains. Left: Temperature, Right: Relative Humidity.

4.4 Mapping

Finally, after applying the previous steps on a European scale level, we have data for the indoor climate impact for several locations spread over Europe. In order to visualize these results we have to interpolate results on a map of Europe similar to the work of Bonazzaa et al (2009)
5. Discussion and Conclusions

This paper presents the current and new modeling approaches, necessary for obtaining the simulation results on the possible impact of climate change on the built cultural heritage and its indoor environment. The approach consists of three main topics: Firstly, we provided an overview of the current state of the art on the modeling of historic buildings at several scales using scientific computational software. It is concluded that the presented modeling and simulation laboratory is well equipped for simulating heat, air and moisture transport at the scale levels ranging from materials to buildings. Secondly, we presented a method on how to incorporate the effect of climate change into the building models by using artificial climate data. Currently, future climate scenarios for Europe are under development by researchers of the Max Plank institute. These artificial data will contain the hourly values of the necessary climate parameters for several locations spread over Europe. This enables us to simulate the effect of expected climate change on buildings in Europe in near future.

Furthermore we provided visualization tools to compare indoor climates of building zones with each other. Thirdly, we showed a preliminary method for up-scaling building spatial level models onto a continental level by the following steps: (1) Classification of buildings; (2) simulation of the same type of buildings at several locations spread over Europe; (3) simulation of the effect of climate change using artificial local climate data sets; (4) visualization of the results using EU maps. Currently we are able to apply step (1) and (2) for the Netherlands. For Europe, this can be done in the same way. Step (3) has been discussed in the previous paragraph. Step (4): We are able to produce maps for the Netherlands as well as for Europe. Overall we may conclude that this approach is very promising for simulating the impact of climate change on the indoor climates of historic buildings.

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