Computer modelling to evaluate the risks of damage to objects exposed to varying indoor climate conditions in the past, present, and future

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ABSTRACT: Within the European project Climate for Culture, we are trying to evaluate the risks for valuable historical objects exposed to changing indoor conditions due to outdoor climate change. We have used building simulation models to calculate the expected indoor climate in historic buildings subjected to a varying outdoor climate. This outdoor climate can be constructed from a historical data file (more than 100 years ago), recent meteorological data (less than 50 year ago) or predicted future data from outdoor climate scenarios (for the next 100 years). The simulated indoor climate is coupled with damage functions to predict the damage risk for objects directly. This paper deals with the modelling approach and shows the potential for damage risk evaluation. The historic, present and future indoor climate conditions in a characteristic historic building have been modelled and the damage risk to historical objects has been compared when the building is virtually placed on 468 different locations in Europe. In this way, the impact of future climate change on the indoor climate conditions in a building and damage risk to its collection can be assessed for areas all over Europe.

1 INTRODUCTION

Future outdoor climate scenarios indicate that the outdoor climate is changing and will continue to do so in the near future. This change in outdoor climate might greatly affect vulnerable historic buildings and their valuable interiors and objects. In the EU project Noah’s Ark, the impact of global climate change on European built heritage and cultural landscapes was analysed (Sabbioni et al. 2010). This project mainly focused on the damage potential of outdoor climate change to historic building facades. The results indicated that buildings might be at risk in many areas in Europe, due to increased amounts of precipitation as well as longer periods of consecutive precipitation. Within the European project Climate for Culture (CfC), we want to assess the impact of climate change on the indoor climate in historic buildings. We have used outdoor climate data from historical and recent weather files and numerical weather prediction models, provided by our partners in the CfC project, to analyse outdoor climate changes. The outcomes are data files with (hourly) values of the historical, present and future outdoor climate. We had already developed building physical computer simulation models to predict indoor climate of buildings, using (hourly measured) weather data files compiled by meteorological institutes over the past 50 years. For example, Meteonorm (Meteotest 2009) provides hourly weather data files for over 100 weather stations across Europe that represent an average climate for that location over a period of one year. Up to now, these data have generally been used to predict the indoor climate and energy use of buildings in the design stage of a building, or later. A study that compared the future indoor climate within a historic house for several locations in Europe and coupled the results with damage functions for paper and salts can be found in (Lankester & Brimblecombe 2012). The authors of this article derived a linear transfer function between the indoor and outdoor climate for each month during their research period. However, linear transfer functions may not accurately take into account climate control systems and variable internal heat loads due to irregular use of shading devices and differences in building use. With hygrothermal building simulation models it is possible to vary internal heat loads, ventilation rate and climate control set points per hour to obtain an accurate prediction of the indoor climate. Two preliminary studies that used hygrothermal building simulation models to predict the impact of future climate change on two historic buildings in Western Europe and that compared the present indoor climate conditions in a historic church for different locations in Europe can be found in
(Huijbregts et al. 2012a) and (Huijbregts et al. 2012b), respectively. In the present paper, historical, present and future outdoor climate data are used as input for building simulation models to predict the changing indoor climate in a historic building all over Europe. The impact of the predicted indoor climate conditions on possible future damage to valuable objects has been estimated by using so-called damage functions. Damage functions have been derived from literature and are based on laboratory experiments. In these experiments, typical objects were subjected to artificial indoor climate conditions. The damage risk to the objects is based on the way the object responds to (or the damage caused by) certain indoor climate variations.

To date, there is little literature providing a coherent approach from outdoor to indoor climate, microclimate and predicted damage to objects. In this paper we attempt both to provide and to evaluate such an approach. In Section 2, we will describe the computer simulation method that was used to predict the indoor climate as a result of the outdoor climate and building properties, the meteorological data that were used and the historic reference building that was investigated. In Section 3, we will describe the damage functions, used to evaluate the risk on deterioration of valuable objects that is induced by the indoor climate conditions. Furthermore, we will describe results of one case study using the simulation approach for the indoor climate evaluation in the past, present and future (Section 4). The conclusion and discussion will be given in Section 5.

2 METHOD

2.1 Simulation model

The indoor climate simulation model HAMBase (De Wit 2006) was used to evaluate the climate conditions within a historic building. With HAMBase, the thermal and hygric indoor climate and energy use for heating and cooling of multi-zone buildings can be simulated using building material properties, outdoor air temperature and relative humidity (RH), diffuse solar radiation on a horizontal plane, direct normal radiation and cloud coverage. The program makes use of a standard weather file with boundary conditions for air temperature, RH, wind velocity and direction, solar radiation and cloud cover. These data are usually derived from measured weather data from meteorological weather stations. In our case the data were obtained from KNMI (Royal Netherlands Meteorological Institute 2013). We made use of hourly measured data from 1960-2012 in a standard format, delivered by KNMI. For these so-called recent past files, the measured meteorological are: diffuse solar radiation [W/m²], air temperature outside [°C], direct solar radiation (plane normal to the direction) [W/m²], cloud coverage [1...8], RH outside [%], wind velocity [m/s] and wind direction [°]. The indoor climate (derived from HAMBase) is characterized by three properties that are assumed to be uniform in the zone: air temperature, radiant temperature and RH.

2.2 Artificially generated historical climate data

To evaluate the effects of climate change over a much longer period, we can make use of historical measured handwritten, and afterwards digitized, weather data. From the KNMI database, ancient climatic data from the 1850s can be obtained for six weather station locations in the Netherlands. These data consist of meteorological data that involve wind directions, wind pressure, temperatures, daily precipitation, surface air pressure, cloud cover and RH and that were manually recorded three times a day. However, to use these data in a simulation model, we need semi-continuous data with time intervals of an hour. So the manually recorded data had to be interpolated to hourly data. The interpolation was calculated based on hourly measured data from KNMI over the years 1971 to 2005: the recent past files. In general, the MATLAB interpolation function balances the smoothness of the missing data in the ancient files with the recent past files. As mentioned previously, the data in the ancient files are based on three time intervals, and the interpolation will estimate the values that are in-between these known data points to match the unknown missing data with known data from the recent past files. The data were selected on the basis of a best fit in a period in the recent past files, comparable with the period during the examined year, i.e. with comparable sun elevation and azimuth. The interpolation searched for the same value at a certain time within the same time interval of the given available data in the ancient climate file. In this way, historical outdoor climate data files for the years 1881 until 1896 were created. For example, on 1 January 1881, the cloud cover at one of three recorded times was 5. So, in the weather file from 1971 to 2005, also on 1 January, the interpolation function would look for the same value of cloud cover of 5 in a comparable time interval. This cloud cover value was used to calculate the ratio of the solar radiation in the historical weather file. The missing hourly values for temperature and RH were calculated by linear interpolation.

2.3 Present meteorological data

Meteorological data from the regional climate model REMO of the Max Planck Institute for Meteorology (Jacob 2012) were used to analyse the outdoor climate all over Europe. The REMO model is based on the former Europe model: a numerical weather prediction model from the German Weather Service (Majewski 1991). REMO can be used for weather forecast and future climate simulations on a grid with a minimum horizontal resolution of approxi-
mately 10km. In REMO, climate data from the reference period 1961 to 1990 were used for a control run. The weather forecast, however, could not be predicted for individual days, but it is possible to generate an assumption for the average conditions for an area and the probability and magnitudes of the deviations from this average. The general averaging period is 30 years. REMO data for air temperature, surface temperature, RH, precipitation, wind speed and direction and global radiation were provided with a temporal resolution of one hour. For the evaluation of the present climate, a dataset was composed of climate measurements from multiple weather stations throughout Europe from 1960 until 1990 to represent characteristic climates for the different regions and locations. The meteorological data were thereafter interpolated on a regular grid over Europe. Figure 1 shows an overview of locations and altitudes of the 468 grid points which were used. Some weather locations are located at very high altitudes (>1000m). The weather data provided for these locations may considerably differ from weather data of nearby stations at lower altitudes. The Alps and Dolomites are examples of such locations.

2.4 Future outdoor climate scenarios
REMO recently produced ‘future’ outdoor climate scenarios for two 31-year periods: near future (2020-2050) and far future (2070-2100) for all 468 grid locations over Europe. The scenarios were based on the IPCC A1B emission scenario for the period 2001-2100 (IPCC 2007). This emission scenario assumes a world of very rapid economic growth, a global population that peaks in the mid-century, and a rapid introduction of new and more efficient technologies that balance between fossil intensive energy sources and non-fossil energy sources.

2.5 Reference building
Three requirements have been defined for the reference building: it has to be a historic building, it has to represent a typical building style that can be found all over Europe and it has to be in use for its original function. A small church near Eindhoven, the Netherlands, was selected (Fig. 2). The church, which was built in the nineteenth century, has been registered as a state monument since 1968. Massive brick walls, slate roofing, and single glazing characterize the building. The church is frequently used for services, marriages and funerals. Continuous on-site measurements of the air temperature, surface temperature, and RH at various locations in and around the church were started in March 2011. In addition, measurements of the air exchange rate and heat flux through the walls were carried out.

A HAMBase model was created of the entire church, consisting of four zones: the sanctuary, the consistory, the attic above the sanctuary and the attic above the consistory. This study focuses on the results for the main zone in the church: the sanctuary. A comparison between the measured and simulated indoor temperature, RH and humidity ratio is presented in Figure 3. It should be noticed that in the simulation model, the number of visitors during ceremonies was kept constant and only ceremonies on Sunday morning were taken into account. Additionally, a constant value was assumed for the air exchange rate. The simulated temperature generally varied within ±2°C of the measured temperature, RH was predicted within ±10% of the measurements and the humidity ratio was predicted within ±2g/kg of the measurements.

Figure 1. Overview of the locations and altitude of the modelled meteorological datasets on a uniform grid over Europe.

Figure 2. The historical reference building.
3 DAMAGE FUNCTIONS

Martens (2012) developed a new method to assess damage in objects due to the indoor climate. His method is based on the indoor climate an object is experiencing due to the response time of the object. The response time is defined as the time, needed for an object to react for 95% to a step change in RH. The RH of the object is derived from the measured indoor climate, using the response time of the object according to Equation 1:

$$RH_{response,i} = \frac{RH_{response,i-1} + \frac{3}{n} \cdot RH_i}{1 + \frac{3}{n}}$$

where n equals the number of measured data points in the response time and RH_{response} of the object at time i is determined by taking the previous RH_{response} at (i-1), adding a fraction of the current RH in the room and dividing by 1 plus that fraction. For a 95% reaction, the fraction equals 3/n.

3.1 Biological degradation

A method of Sedlbauer (Sedlbauer 2001) is used to determine biological degradation by fungal growth. Combinations of temperature and RH determine whether the fungus germinates or grows.

3.1.2 Chemical degradation

The concept of the Lifetime Multiplier (LM) is used to describe the time an object is usable, compared to a reference indoor condition (20°C and 50%RH). Apart from T and RH, the LM also depends on the activation energy, which is a material property (Michalski 2002). A small risk on chemical damage may occur when LM > 1, a medium risk may occur when 0.75 ≤ LM < 1 and a high risk is predicted when LM ≤ 0.75.

3.1.3 Mechanical degradation

Hygroscopic materials react to changes in RH by absorbing or desorbing moisture from the air. The changes in moisture content imply dimensional changes of the materials. If these materials are not free to expand or contract, stresses occur in the object, which may lead to damage by mechanical degradation. As panel paintings are representative objects in many historic buildings, the hygroscopic and mechanical behaviour of panel paintings have been subject of a number of extensive studies, e.g. (Mecklenburg et al. 1998), (Rachwal et al. 2012a) and (Rachwal et al. 2012b). In this paper, therefore, panel paintings are chosen as reference objects for mechanical degradation. For this kind of paintings, two types of mechanical damage are important: damage to the wood support and damage to the pictorial layer. Damage to the wood support may occur when the entire object responds to a slow change of RH over time. The dimensionally changes of the object may be hindered by the construction of the object and lead to damage, such as cracks. Damage to the pictorial layer may occur when RH variations last longer than the response time of the panel. The moisture content within the panel changes and the object will swell or shrink. As the response of the gesso layer to RH variations is very fast, the mismatch in the response of gesso and the unrestrained wood support can lead to fracturing of the pictorial layer.

4 RESULTS

4.1 Predicted historical indoor climate in the reference building

A prediction of the historical indoor climate in the reference building was generated by combining the HAMBase model with the artificially generated historical climate data as was described in the Method section. In the simulation model, it was taken into account that the building remained unheated and 50 persons on average attended weekly ceremonies on Sunday morning. The estimated temperature, RH and humidity ratio in the year 1882 are shown in Figure 4. It is predicted that the minimum indoor temperature is slightly below freezing point and that...
the maximum indoor temperature is around 25°C. High RH values are predicted: RH remains above 60% for most of the year and regularly exceeds 90% in winter.

4.2 Present indoor climate in the reference building, virtually placed all over Europe

The calculated meteorological data and damage risks were interpolated to a grid over Europe. The grid used has a resolution of 376x226 data points and covers the area between 30°N to 75°N and 28°W to 45°E. The mean indoor temperature and humidity ratio in the recent past (1960-1990) are shown in Figures 5-6. The mean temperature inside the church when it is virtually placed all over Europe varies between -5 and 25°C, while the mean humidity ratio varies between approximately 3 and 9g/kg. In Northern Europe, the average indoor climate in the 31-year period is characterized by low mean temperatures (-5 to 10°C) and mean humidity ratios varying between 3 to 6g/kg, which leads to high mean RH values (80 to 90%). The indoor climate in the Mediterranean area is generally warm (10 to 20°C) and has a mean humidity ratio of 4 to 7g/kg inland and 7 to 9g/kg in coastal areas, leading to a medium mean RH (40 to 60%). In between, the area around the United Kingdom and Ireland shows a temperate climate (5 to 15°C) and a medium mean humidity ratio (5 to 7g/kg) leading to a high mean RH (75 to 80%).

4.3 Future indoor climate in the reference building, virtually placed all over Europe

The impact of future climate change on the indoor climate conditions in the reference building was predicted by calculating the difference in mean temperature and humidity ratio between the recent past, near future and far future. Figure 7 shows that in the near future, the average indoor temperature may increase by approximately 1°C in Western Europe and 1 to 2°C in Southern, Eastern and Northern Europe. A small increase in the mean humidity ratio is predicted in all areas, varying between circa 0 to 0.4g/kg in Southern Europe and 0.4 to 0.8g/kg in Eastern Europe (Fig. 8). Consequently, the mean RH may slightly decrease in most areas, in particular in Southern Europe. Larger changes are predicted in far future: the mean indoor temperature increase in Western Europe is approximately 2°C, while a mean indoor temperature rise up to 4°C may occur in Northern and Southern Europe (Fig. 9). The predicted mean humidity ratio change is highest in Eastern Europe and the coastal areas (1.2 to 1.6g/kg) and smallest in parts of Great Britain, Norway and in the inlands of Southern Europe (Figure 10).
4.4 Damage functions

The previously described damage functions were used to predict the risks of biological, chemical, and mechanical degradation, based on the calculated indoor climate for the unheated reference building in the recent past, near future and far future. For the recent past weather data, a high risk on mould growth is predicted in Great Britain and the coastal areas of Western Europe and Scandinavia. The risk on mould growth may considerably increase in near future and far future in and around these areas, while the predicted mould growth risk in Southern Europe remains low (Fig. 11). In the recent past, LM > 1 for most areas in Europe, except for part of the coastal areas in Southern Europe. The LM gradually decreases in near future and far future, which causes an increased risk on chemical degradation of objects particularly in coastal areas in Southern and Western Europe (Fig. 12). No location in Europe has been found where the indoor climate conditions in the reference building may prevent mechanical degradation of the wood support or pictorial layer of panel paintings. Damage to the wood support is likely in some areas in Northern Europe in the three periods, but no consistency is found between the locations where this high damage risk is predicted (Fig. 13). Damage to the pictorial layer is likely in the recent past and near future in many areas in Northern, Eastern, and Southern Europe. In far future, damage is likely in almost all areas (Fig. 14).
5 CONCLUSION AND DISCUSSION

This study presents a modelling approach to predict the historical, present and future indoor climate conditions in a historic building, when it is virtually subjected to an outdoor climate at various locations over Europe. The indoor climate conditions were calculated by a hygrothermal building simulation model. Based on the predicted indoor climate conditions, the damage potential of biological, chemical and mechanical degradation was evaluated for the recent past, near future and far future.

The preliminary results suggest that it could be possible to predict the indoor climate conditions and risk for damage in a building over a large area, using regional climate data from the past, present and future. Based on the applied future outdoor climate scenario, a small increase in indoor temperature and
humidity ratio is predicted in the near future, while a considerable rise in temperature and humidity ratio may occur in far future. Damage evaluation shows that there are no places in Europe where no damage to objects is to be expected in recent past, near future and far future. In cold, humid climates, the risk for chemical degradation is regularly low, while the risk for mould growth and mechanical damage is rather high. In contrast, in warmer, dry climates, mould growth risks are rather low, while chemical and mechanical degradation are more important. Climate change may considerably increase the mould growth risk in Northern and Western Europe. Additionally, a higher risk on chemical degradation may occur particularly around coastal areas in Western and Southern Europe. No consistent impact of climate change on the predicted mechanical degradation of panel paintings was found.

One of the most critical problems in using this approach is the uncertainty in people’s use of the building and its HVAC systems. Also the fact that materials will adapt to the long term local situation is not taken into account. Besides that, the current outdoor future climate scenario is based on only one IPCC emission scenario, which means that there is a high uncertainty in these data. In the near future, more generic building types for different areas in Europe will be selected to acquire more appropriate reference buildings for each location. Furthermore, the microclimate around objects could have an essential influence on the risk evaluation of objects and should be object of research in future. More objects will be included in the potential damage analysis, e.g. wooden organs, and the impact of climate control systems and climate adaptive measures will be investigated as well. The presented risk maps are not yet suitable for climate management in historic buildings, but should be seen as illustrative examples of potential impacts and risks.

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7 REFERENCES


