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CULTURAL HERITAGE FACING CLIMATE CHANGE: EXPERIENCES AND IDEAS FOR RESILIENCE AND ADAPTATION

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Climate Change Modelling and Whole Building Simulation as a Tool for Assessing Indoor Climates in Buildings

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Abstract: The present publication reports results from the large-scale integrated EU project "Climate for Culture". It focuses on implementing high resolution regional climate models together with new building simulation tools in order to predict future outdoor and indoor climate conditions. The potential impact of gradual climate change on historic buildings and on the vast collections they contain has been assessed. Two moderate IPCC emission scenarios A1B and RCP 4.5 were used to predict indoor climates in historic buildings from the recent past until the year 2100. By using different standardized and exemplary artificial buildings in modelling climate change impact, a comparison between different regions in Europe has become possible for the first time. The methodology has been applied at the case study site of Amerongen castle in the Netherlands. This will show how it can serve for heritage owners and managers as a decision tool, helping them to plan more effectively mitigation and adaption measures at various levels.

Résumé: La présente publication rapporte les résultats du projet européen intégré à grande échelle "Climate for Culture". Celui-ci est focalisé sur l'implémentation de modèles climatiques régionaux à haute résolution avec des outils de simulation des bâtiments, en vue de prédire les conditions futures extérieures et intérieures. L'impact potentiel du changement climatique graduel sur les bâtiments historiques et sur les vastes collections qu'ils contiennent a été évalué. Deux scénarios IPCC modérés, A1B et RCP 4.5, ont été utilisés pour prédire les climats intérieurs des bâtiments historiques du passé récent jusqu'en 2100. En utilisant différents bâtiments artificiels standardisés et exemplaires, une comparaison entre différentes régions d'Europe est devenue possible pour la première fois. La méthodologie a été appliquée au cas d'étude du site du Château d'Amerongen aux Pays-Bas. Cela montre comment elle peut servir aux propriétaires et aux gestionnaires du patrimoine comme outil de décision, les aidant à planifier plus efficacement les mesures de mitigation et d'adaptation à différents niveaux.

Key-words: climate change, building simulation, future indoor climates, energy demand, preventive conservation strategy.

Mots-clés: changement climatique, simulation des bâtiments, futures conditions climatiques extérieures et intérieures, planification de mesures d`adaption, gestionnaires du patrimoine, conservation préventive.

Background

Sustainability is strongly linked to Climate Change as it is one of the most critical global challenges of our time. Since many decades a huge number of scientists from all over the world are researching this topic and are developing complex climate models suitable to make future climate projections. Climate change in itself is not the main concern; more important is its impact on the planet. But less certain information is available how the changing climate affects mankind and its environment. Although many studies have been conducted to explore the impact of climate change on economy, biodiversity and agriculture or on fresh water availability, only little is known whether and how climate change influences our cultural heritage. Within the European funded project Climate for Culture (2009 – 2014), a multidisciplinary research team consisting of 27 partners from the EU, Croatia and Egypt has performed research to make substantial contributions to estimate the impacts of climate change on the indoor environments in historic buildings and their vast collections in Europe and the Mediterranean.

For this purpose, the CLIMATE FOR CULTURE project has started for the first time ever to couple climate modelling with whole building simulation tools: Completely newly developed high resolution climate change evolution scenarios provide the necessary climate indices for the

From the global climate model => to high resolution regional climate simulation => to case study historic buildings => to whole building simulation => to indoor environments and => to individual cultural heritage items

1. - The Climate for Culture project short cut.
Le projet Climate for Culture en raccourci.

period from 1960 until 2100. This set of climate indices is used in whole building simulation tools to assess future projections of outdoor climate changes on the indoor environments in historic buildings and its impacts on cultural heritage items in Europe and Egypt. This coupling allows estimates on future indoor climates and energy demands and suitable mitigation strategies can be developed and tested. Valuable collections in historic buildings from different climate zones are included for in situ investigation of contemporary and past problems and for the projection of future demanding issues (fig. 1).

For the high resolution climate simulations within the Climate for Culture project two scenarios are investigated, the A1B scenario and the recent RCP4.5 scenario for the IPCC assessment report 5 (AR5) released in 2014 (IPCC, 2007). For the mid-line A1B scenario, a greater CO_2 emission increase is assumed until 2050 and a decrease afterwards. RCP 4.5 stands for Representative Concentration Pathway (RCP) 4.5 and is a scenario of long-term, global emissions of greenhouse gases, short-lived species, and land-use-land-cover which stabilizes radiative forcing at 4.5 Watts per meter squared (W m-2, approximately 650 ppm CO_2 equivalent) in the year 2100 without ever exceeding that value.

For the development of the whole building simulation tools, sets of climate indices were defined (see Table I below). The test datasets were prepared for the period from 1960 to 2100. The calculations made for the period of 2001 to 2010 are based on the A1B IPCC scenario. Modelled climate data needs to be verified and processed to be suitable for building simulation. New methods and modules for the simulation tools have to be developed, implemented, tested and used. The successful application of suitable simulation tools allows computational testing of active and passive adaptation and preservation strategies.

The following tools were suggested for assessment and tested in two common exercises: Hambase, IDA, EnergyPlus, ESP-r, WUFIPlus, TRNSYS. As first common exercise case for comparison of the above mentioned simulation tools, the IEA (International Energy Agency) ECBCS ANNEX41 common exercise was applied. The results suggested that Hambase, WUFIplus and possibly IDA-ICE are suitable to model the change in relative humidity fluctuations due to moisture buffering. For some buildings already software models for case study buildings exist, like for the Linderhof castle, The Kings House on the Schachen, the church of Roggersdorf or

Amerongen Castle. Those case study building models allowed to produce first results, derive suggestions for software development and improvement and to apply different active and passive measures in the model.

The development of the building simulation tool is also based on real data from historic buildings collected as case studies. For this purpose a survey with a specially designed, virtual usable questionnaire was performed to set up a range of case studies from all over Europe and Egypt. The questionnaire covers up to now over 106 case studies in eleven countries. Parameters like type of building, specific site-related factors, available indoor and outdoor climate data, observed damages and suitability for other work packages are reviewed and are transferred into a *Climate for Culture* database which has several layers of information. The list of case study buildings is continuously updated and further extended.

Based on the climate data received from the high resolution regional climate model a climate classification map over entire Europe and Northern Africa was produced. The climate map is derived from an overlay of temperature and humidity for the baseline climate 1960-1990 since temperature and humidity changes have a great influence on most degradation processes of materials. The climate zones were established to organize the collection of crucial data from various historic buildings: For each climate zone, a zone leader is responsible for a harmonized data collection.

The case study buildings served for the development of the whole building simulation tool including a generic building model and for the assessment of the effects of climate change. Therefore, in situ investigations of existing problems are carried out which will then be used for the projection of future challenging issues using whole building simulation and different in situ monitoring technologies. The in situ measurements are performed by laser speckle interferometry which was developed in a previous EU project (Laseract) and by 3D microscopy. The two methods have been already successfully applied at the test site at Fraunhofer Institute for Buildings Physics in Holzkirchen (Germany) and at several case study sites in Croatia and Crete and show good complementarity. Further investigations by glass sensors from the previous EC project AMECP to assess the corrosivity impact of indoor and outdoor conditions at cultural heritage sites throughout Europe have also been installed at case study sites in Crete and Croatia and Germany. These examinations allow a much more precise and integrated assessment of the real damage impact of climate change on cultural heritage at regional scale. In terms of climatisation of historic buildings a survey of the state of the art has been finalized and has been used to develop appropriate mitigation/adaptation strategies. This means that active and passive measures have been discussed and defined which resulted in the implementation of humidistat heating and equal sorption as well as an absolute humidity control algorithm in WUFI®Plus; also different existing and new microclimate control approaches were considered in the Hambase and MATLAB/Simulink environment.

1. Introduction - Climate Change and historic buildings

Climate change, the worldwide energy and resource deficiency problem are serious threats of our time. These factors have put the concept of sustainability to the top of the European political agenda. Therefore many initiatives are now investigating how to make new and existing buildings more sustainable. Europe has a rich and vast historic building stock – a large part of our European cultural heritage is historic buildings and their collections. Scientific research shows that the preservation of the cultural heritage is particularly vulnerable to the long term impacts of climate change: the outdoor climate influences the building envelope and governs the indoor climate. Its buffering and insulating capacities have a strong effect on temperature and relative humidity and these parameters establish either a safe or an unsafe environment for the cultural heritage displayed. Currently a big debate is going on among cultural heritage preservation professionals about the appropriate indoor climate in museums and historic buildings: rising energy bills are demanding sustainable solutions to save energy and reduce the carbon footprint while guaranteeing a stable indoor environment for the collections. The initiative of the so called Bizot group, the International Group of Organizers of Large Scale Exhibitions, are asking for a redefinition of internationally accepted museum indoor conditions of temperature and relative humidity. Against this background, it will be vital for managing sustainably our cultural heritage to know how the future changing climate will influence the indoor climates in buildings. As a non-renewable resource of intrinsic importance to our identity, there is a need to develop more effective and efficient sustainable adaptation and mitigation strategies in order to preserve these invaluable cultural assets for the long-term future. More reliable assessments will lead to better prediction models, which in turn will enable preventive measures to be taken, thus reducing energy and the use of resources.

For this purpose the CLIMATE FOR CULTURE project is connecting new high resolution climate change evolution scenarios with whole building simulation tools to identify the most urgent risks for specific regions. The innovation of the project lies in the elaboration of a more systematically and reliable damage/risk assessment which will be deduced by correlating the projected future climate data (with the spatial resolution of up to 10x10 km grid size) with whole building simulation models and new damage assessment functions. Thus not only the impact on historic buildings and future energy demands can be evaluated, but also the possible effects on the related indoor climates in which the valuable works of art are kept. In situ measurements and investigations at cultural heritage sites throughout Europe (fig. 2) and the Mediterranean will allow a much more precise and integrated assessment of the real damage impact of climate change on cultural heritage at regional scale. Sustainable (energy and resource efficient) and appropriate mitigation/adaptation strategies, are further developed and applied on the basis of these findings simultaneously.

2. Climate change modeling and building simulation tools

According to the World Meteorological Organisation the term CLIMATE can be defined as “the statistical description in terms of the mean and variability of relevant weather quantities over a period of time”. These elements all determine the state and dynamics of the Earth’s climate. Climate covers different weather elements like temperature, air humidity, wind, clouding, precipitation, sun shine duration, air pressure, snow fall, radiation and evaporation. All these parameters including their interactions with the atmosphere, the hydrosphere, the cryosphere, the surface lithosphere, the biosphere and the resulting carbon cycles are integrated into so called general circulation models, nowadays called global climate models (GCM) which are the most complex computer models existing up to now. Furthermore global climate models also must take into account parameters which cannot be calculated and for which no values from the past are available. For example, it has to be assessed how the future population will grow or which technologies will be applied to curb CO_2 emissions. These assumptions are called scenarios for which the climate models calculate climate projections [Jacob, 2001; Jacob *et al.*, 2007).

For the high resolution climate simulations within the Climate for Culture project two scenarios were investigated, the A1B scenario and the recent RCP4.5 scenario from the IPCC assessment report 5 (AR5) released in 2014 (IPCC, 2007). For the mid-line A1B scenario, a greater CO_2 emission increase is assumed until 2050 and a decrease afterwards. The second scenario - the RCP 4.5 - stands for Representative Concentration Pathway (RCP) 4.5 and is a scenario of long-term, global emissions of greenhouse gases, short-lived species, and land-use-land-cover which stabilizes radiative forcing at 4.5 Watts per meter squared (Wm-2, approximately 650 ppm CO_2 equivalent) in the year 2100 without ever exceeding that value.

Computer simulation is not only used to model climate change but more and more it is also used to model the effects of temperature (heat), relative humidity, solar radiation and water vapour on buildings and resulting indoor climates. Up to now these building simulation tools are using only present outdoor climate data and not future climate data from high resolution regional climate models. A further obstacle was that computer simulation tools exist partly but for modern buildings and are not appropriate for cultural heritage buildings. Current research within Climate for Culture is thus to further develop existing computer tools to model and simulate indoor climates of historic buildings through: analysing the buildings, introducing various modelling steps and validating the model by real measurement data. Two approaches are followed: development of a „full-scale multizone dynamic hygro-thermal whole building simulation“ and a simplified hygro-thermal building model.

For the development of the building simulation tools, sets of climate indices were defined (see Table I below). The test datasets were prepared for the period from 1960 to 2100. The calculations made for the period of 2001 to 2010 were based on the A1B IPCC scenario. A main objective was the assessment of available and applicable tools to convert modelled exterior climate data into interior climate conditions to assess the climate change impact. Modelled climate data needed to be verified and processed to be suitable for building simulation. Therefore, new methods and modules for the simulation tools had to be developed, implemented, tested and used. The successful application of suitable simulation tools allowed computational testing of active and passive adaptation and preservation strategies.

For risk assessment in cultural heritage buildings the exact indoor humidity fluctuations and the moisture profiles in the building envelope are extremely relevant. Therefore models that combine thermal building simulation with the hygrothermal component simulation have to be applied. These computational models are usually used for simulating water and temperature distributions in modern building components like insulated walls or roofs. Whole building simulations will also take into account the type of use (e.g. visitors, events) and HVAC climatisation components to assess the indoor environment. Their applicability to existent historic buildings with often unknown constructions and material properties is still limited.

The whole building model WUFI® PLUS (Holm *et al.*, 2003) is a combination of thermal building simulation with the hygrothermal envelope calculation model WUFI®. This holistic model takes into account the main hygrothermal effects, like moisture sources and sinks inside a room and the moisture input from the envelope due to capillary action and diffusion as well as vapour ad- and desorption as a response to the exterior and interior climate conditions. Also different heat sources and sinks inside the room, heat input from the envelope, the solar energy input through walls and windows as well as hygrothermal sources and sinks due to natural or mechanical ventilation are considered.

Besides WUFI® PLUS, the following tools were suggested for assessment and tested in two common exercises: Hambase (de Wit, 2006), ESP-r[1], EnergyPlus[2], IDA-ICE[3]. As first common exercise case for comparison of the above mentioned simulation tools, the IEA (International Energy Agency) ECBCS ANNEX41 common exercise was applied. The results suggest that Hambase, WUFIplus and possibly IDA-ICE are suitable to model the change in relative humidity fluctuations due to moisture buffering. Some software models for case study buildings already exist, like for the Linderhof castle, The Kings House on the Schachen (Kilian *et al.*, 2008), the church of Roggersdorf and Amerongen Castle. Those case study building models allowed producing first results to derive suggestions for software development and improvement and to apply different active and passive measures in the model (Table 1) (fig. 2).

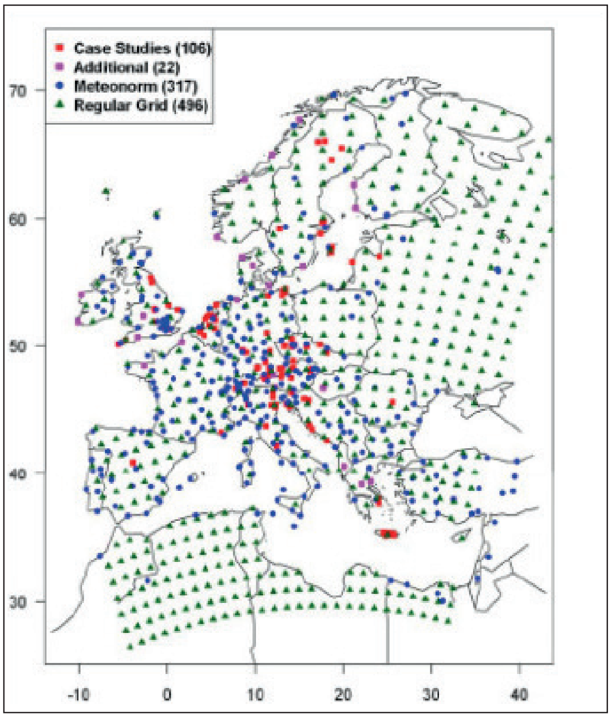
The development of the building simulation tool is also based on real data from historic buildings collected as case studies. For this purpose a survey with a specially designed, virtual usable questionnaire was performed to set up a range of case studies from all over Europe and Egypt. The questionnaire covers up to now over 106 case studies in eleven countries (see figure 2, red square). Parameters like *type of building*, *specific site-related factors*, available *indoor* and *outdoor climate data*, observed *damages* and *suitability* for other work packages are reviewed and are transferred into a Climate for Culture database which has several layers of information (fig. 3).

Value	Unit
Temperature	°C
Relative Humidity	%
Normal Rain	Mm
Wind Speed	m/s
Wind Direction	Degree
Global Radiation	W/m2
Diffuse Radiation	W/m2
Global Counterradiation	W/m2
Cloud Coverage	%
Ground Temperature	°C
Ground Reflectance	-
Air Pressure	Pa

Tab. I - List of climate indices used in the building simulation tools.
Liste des indicateurs climatiques utilisés dans les outils de simulation des bâtiments.

Based on the climate data received from the climate models, a climate classification map over entire Europe and Upper Mediterranean was set up. The climate map is derived from an overlay of temperature and humidity for the baseline climate 1960-1990 since temperature and humidity changes have a great influence on most degradation processes of materials. Applying this procedure, four climate zones were defined as shown in figure 4.

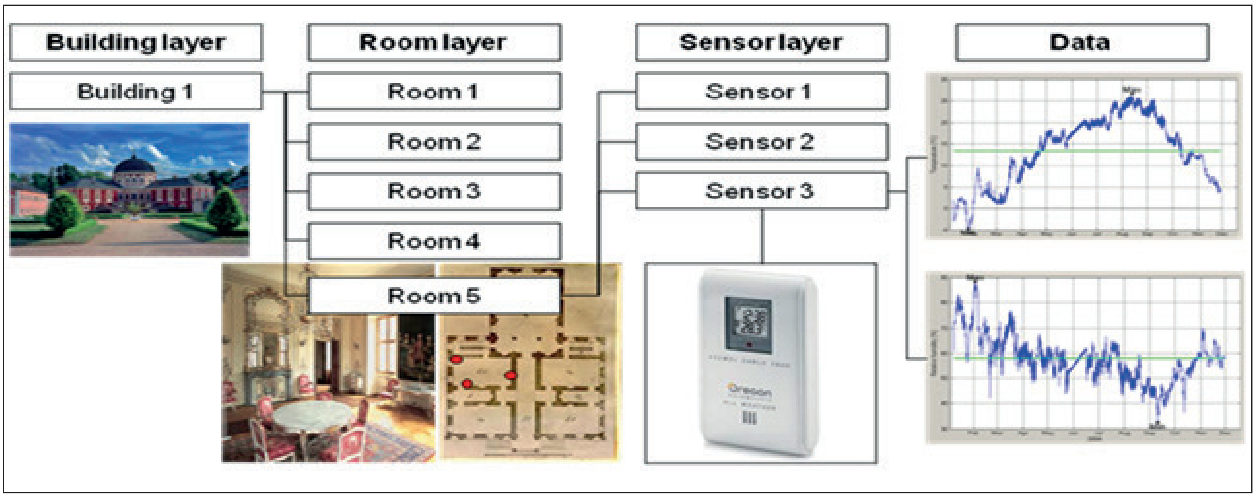
The case study buildings serve for the development of the whole building simulation tool including a generic building model and for the assessment of the effects of climate change.



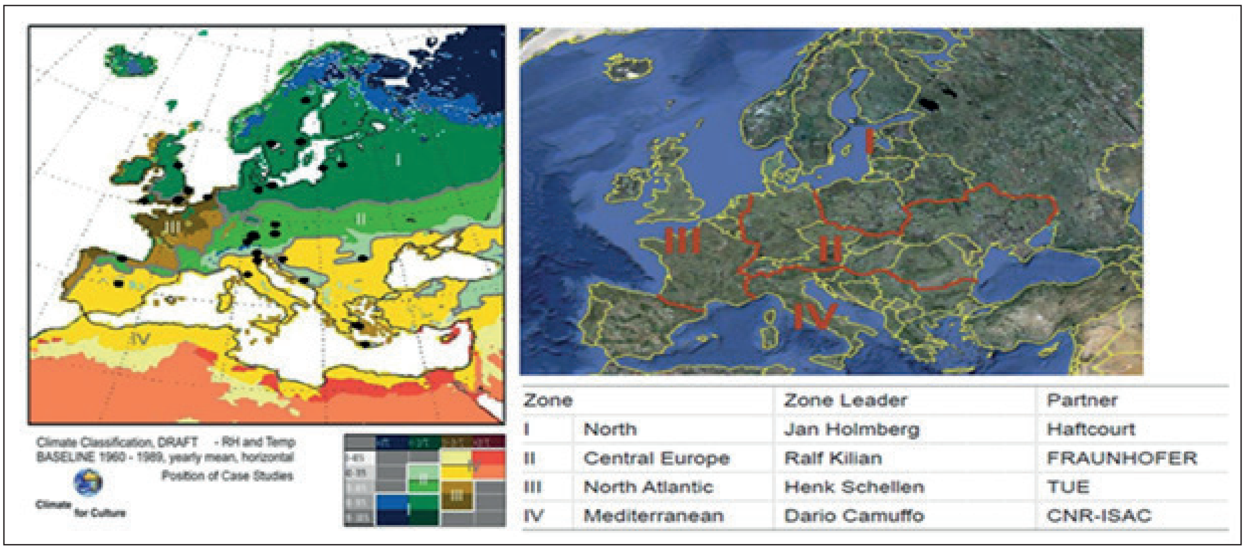
2. - Location sites for which climate indices are provided.
Localisation des sites pour lesquels les indicateurs climatiques sont fournis.

Therefore, *in situ* investigations of existing problems are carried out which will then be used for the projection of future challenging issues using whole building simulation and different in situ monitoring technologies.

These examinations allow a much more precise and integrated assessment of the real damage impact of climate change on cultural heritage at regional scale. In terms of climatisation of



3. - Database structure and information layers.
Structure de la base de données et niveaux d'information.



Zone		Zone Leader	Partner
I	North	Jan Holmberg	Haftcourt
II	Central Europe	Ralf Kilian	FRAUNHOFER
III	North Atlantic	Henk Schellen	TUE
IV	Mediterranean	Dario Camuffo	CNR-ISAC

4. - Climate classification zones based on Temperature and relative Humidity.
Classification des zones climatiques basée sur la Température et l'Humidité relative.

historic buildings a survey of the state of the art has been finalized and is used to develop appropriate mitigation/adaptation strategies. This means that active and passive measures are discussed and defined which resulted in the implementation of humidistat heating and equal sorption as well as an absolute humidity control algorithm in WUFI®Plus; also different existing and new microclimate control approaches are considered in the Hambase and MATLAB/Simulink environment.

3. The case study buildings - results from modelling indoor climates and future energy demands

Historic buildings usually show elevated indoor humidity levels and a high variation of the climatic conditions, which can be dangerous to cultural heritage materials. This requires the detailed consideration of all hygrothermal interactions between the indoor air, the usage, the furnishing and the building envelope. The hygrothermal behaviour of a building component exposed to weather is an important aspect of the overall performance of a building. The calculation of the hygrothermal performance of a part of the envelope is state-of-the-art and a realistic assessment of all relevant effects can be carried out, but until now the total behaviour of the actual whole building is not accounted for.

Questions which are addressed within Climate for Culture:

How much ventilation and additional heat energy is required to ensure safe indoor conditions for cultural heritage when a historic building is exposed to extreme climate conditions or up to 4000 visitor per day? What will happen to the hygrothermal behaviour of walls and ceiling when a historic cellar is changed in its use and is turned for example into a restaurant? How do the indoor air conditions and the envelope of buildings with temporary use react to different heating and ventilation strategies? Can sorptive finish materials improve and stabilise the microclimate in historic buildings?

3.1 Case study: Amerongen Castle

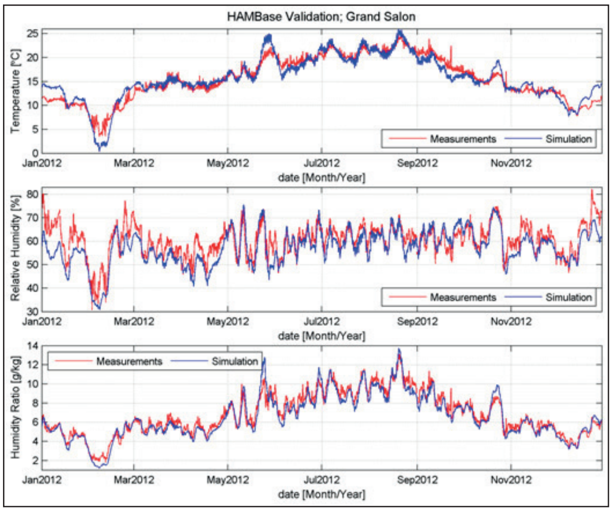
Amerongen Castle, a Dutch state monument, was built in the 17th century. The building currently functions as a museum and provides room to a collection of valuable furniture and paintings. The building is characterised by high masonry walls with a thickness varying between 0.7 and 1.5m and single glazed windows and exterior shutters. In recent years the indoor environment in the exhibition rooms has been hygrostatically controlled by a floor heating system. In the past,

Variable	Value
Minimum temperature set point for conservation heating	15°C
Maximum temperature set point for conservation heating	22°C
Minimum RH set point for conservation heating	40%
Maximum RH set point for conservation heating	70%
Maximum heating capacity	1000W

Tab. II - Set points and capacity of conservation heating system. *Niveaux déterminés et capacité de conservation d'un système de chauffage.*

the building remained mainly unheated. The multi-zone hygrothermal building simulation model HAMBase /5/ was used to calculate the indoor temperature and RH inside the castle as a result of the outdoor climate conditions, the building properties, the climate control system and the building use. HAMBase characterizes the indoor climate by uniform values for radiant temperature, air temperature and RH per zone. A preliminary study on a proposed method to assess the impact of climate change on the indoor climate in the castle can be found in (Huijbregts *et al.*, 2012).

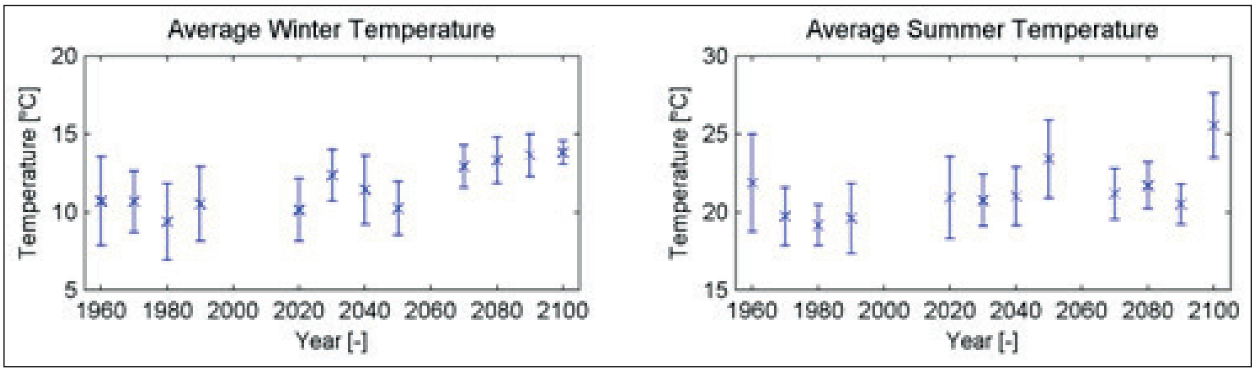
This study focuses on the indoor climate conditions in one of the main exhibition rooms within the castle: the Grand Salon. Constant values for the set points and capacity of the conservation heating system were used in the HAMBase model (Table II). The HAMBase model was validated with on-site measurements from 1 January until 31 December 2012 (fig. 5). It should be kept in mind that the capacity of the current heating system is not sufficient to maintain a minimum temperature of 15°C during the whole year. Also, the minimum temperature set point in the room seems to have slightly been lowered during the winter months. Excluding this period, the model shows an adequate agreement with the measurements: the simulated indoor temperature is generally within a range of 2°C from the measurements, the difference between simulated and measured RH is about ±10% and the humidity ratio is predicted within a range of ±1g/kg from the measurements .



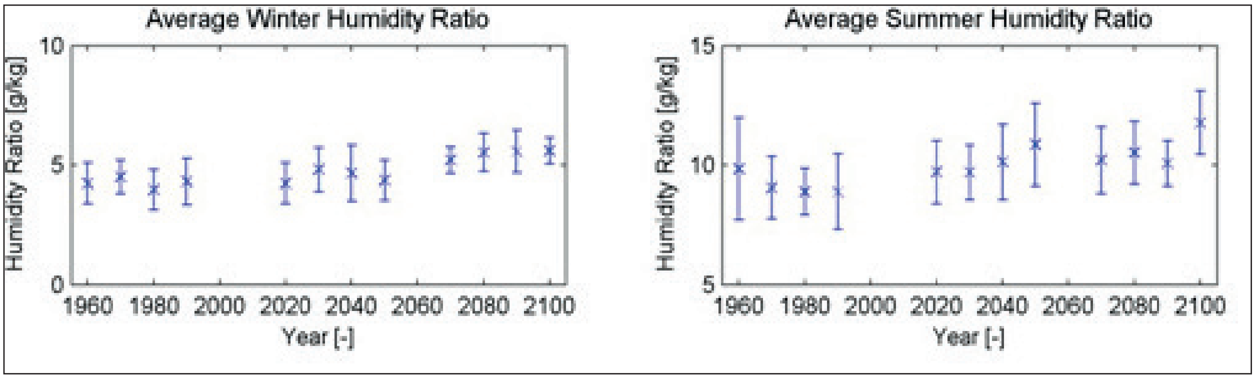
5- Validation of the HAMBase model for the year 2012. *Validation du modèle HAMBase pour l'année 2012.*

Next, the HAMBase model was coupled with future outdoor climate data from the weather station nearby the building site (distance: approximately 20km). The future outdoor climate data were based on the IPCC A1B emission scenario. The predicted indoor temperature, humidity ratio and annual energy demand for heating were compared for the years 1960, 1970, 1980, 1990, 2020, 2030, 2040, 2050, 2070, 2080, 2090 and 2100. Fig. 6 shows the average indoor temperatures in winter and summer. The difference between the average conditions for the recent past and far future is clearly more significant than the differences between recent past and near future, however, the future outdoor climate data of for the far future have a larger uncertainty than the near future data. It can be seen that the average winter temperature may slightly increase from 11°C in the recent past to 13°C in the far future. A similar temperature increase is predicted in summer: in the recent past, the average summer temperature is about 20°C, while in the far future an average summer temperature of 22°C is predicted. The average humidity ratio may slightly increase by 1g/kg in winter and 1.5g/kg in summer (fig. 7). In average, the annual energy demand for heating in the room may slightly decrease in future by approximately 350kWh (fig. 8).

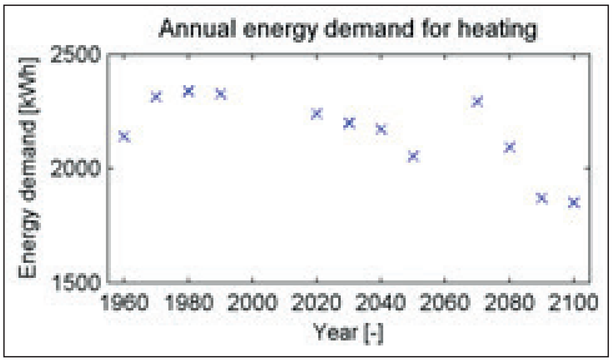
The results indicate that indoor temperatures above 25°C could occur more frequently in future (fig. 9). Additionally, the hygrostatically controlled



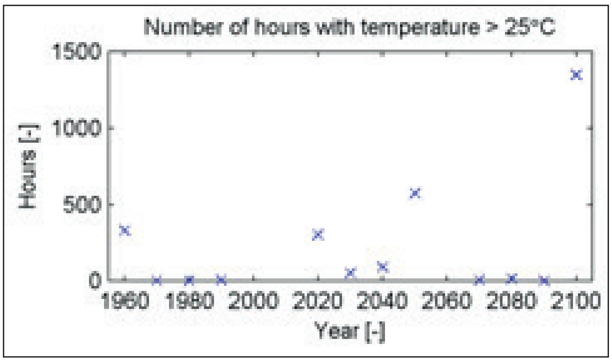
6- Predicted average indoor temperature in winter and summer. *Température moyenne intérieure prévue en hiver et en été.*



7- Predicted average indoor humidity ratio in winter and summer. *Taux d'Humidité relative moyenne prevue en hiver et en été.*



8 - Predicted annual energy demand for heating.
Demande annuelle d'énergie prévue pour le chauffage.



9 - Predicted number of hours per year with indoor temperatures exceeding 25°C.
Nombre prévu d'heures par an avec une température excédant 25°C.

heating system may not be appropriate in future summer periods when both indoor temperature and absolute humidity rise. Additional measures should be taken to avoid overheating risks and decrease humidity levels.

4. Conclusions

The CLIMATE FOR CULTURE project has coupled for the first time ever high resolution regional climate models with a whole building simulation software developed especially for historic buildings. Thus, a set of climate indices was produced and verified for the periods from 1960 to 2100 with an hourly resolution which were used in building simulation softwares to estimate more systematically future thermohygrometric changes in indoor climates and the future energy demand as well as damage potential for the collections inside the buildings. The procedure of coupling climate modelling with building simulation can deliver valuable results not only for historic buildings but especially for modern buildings and for future building designs. To cope with climate change impacts it is necessary to have suitable tools available to assess the impacts of climate change on buildings and their resulting energy demand and indoor climate conditions.

Notes

[1] http://www.esru.strath.ac.uk/Programs/ESP-r.htm
[2] http://apps1.eere.energy.gov/buildings/energyplus/
[3] http://www.equa.se/ice/

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