The impact of climate change on the indoor climate of monumental buildings
An analysis by computer simulations using HAMBase for the years 2000 until 2099.

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Master project 1 report.

Master project 1: The impact of climate change on the indoor climate of monumental buildings

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Preface

After completing the premaster in April 2010, I sequentially started the master program of Building Services. The master consists of courses and master projects. I started the first master project before June 2010 and therefore I was already up to speed begin September when the master course officially started. By then I already had a defined problem and was able to work independently between the project reviews.

The project reviews were planned every two to three weeks. During these reviews, I discussed together with dr.ir. Jos van Schijndel and ir. Zara Huijbregts the progress and results I had so far. These reviews were very helpful to maintain the progress of the project and were educational regarding the approach of the problem. Therefore I would like to thank them sincerely.
# Table of contents

PREFACE .......................................................................................................................................................... I

TABLE OF CONTENTS ................................................................................................................................... II

SUMMARY ................................................................................................................................................... IV

1 INTRODUCTION .................................................................................................................................. 1
  1.1 Problem description ........................................................................................................................... 2
  1.2 Project objective ................................................................................................................................ 2
  1.3 Project approach ................................................................................................................................ 2
  1.4 Structure of the report ....................................................................................................................... 3
  1.5 Castle of Gaasbeek ............................................................................................................................. 3
  1.6 Begijnhof museum ............................................................................................................................. 4

2 MODELING ......................................................................................................................................... 5
  2.1 Climate ............................................................................................................................................... 5
  2.2 Case studies ........................................................................................................................................ 6
    2.2.1 Castle of Gaasbeek .................................................................................................................... 7
    2.2.2 Begijnhof museum .................................................................................................................... 7
  2.3 Used simulation software: HAMBase and the MMM-model. ............................................................ 8
    2.3.1 Validation of HAMBase ............................................................................................................ 8

3 RESULTS ............................................................................................................................................ 10
  3.1 Results climate data ......................................................................................................................... 10
  3.2 Results building simulations ............................................................................................................. 15
    3.2.1 Results castle of Gaasbeek ..................................................................................................... 16
    3.2.2 Results of museum Begijnhof ................................................................................................. 24

4 CONCLUSIONS AND RECOMMENDATIONS ...................................................................................... 32
  4.1 Conclusions ...................................................................................................................................... 32
  4.2 Recommendations for future research ............................................................................................ 32

5 REFERENCES ..................................................................................................................................... 33

6 APPENDICES ..................................................................................................................................... 34
  6.1 MATLAB-function remotest1 ........................................................................................................... 34
  6.2 MATLAB-function zon2zon ............................................................................................................. 35
  6.3 MATLAB m-file climateperyeartest ................................................................................................. 38
  6.4 Models of castle of Gaasbeek: MATLAB m-files .............................................................................. 38
  6.5 Models of Begijnhof museum: MATLAB m-files .............................................................................. 42
6.6 MATLAB-files of the Multi Museum Model................................................................. 57
6.7 MATLAB-files for generating output in step 5 of MMM-model................................. 62
6.8 MATLAB-file ‘solcum’ .............................................................................................. 66
6.9 MATLAB-file histoT and histoT_2000_2009............................................................ 67
6.10 Explanation of the Climate Evaluation Chart............................................................ 70
6.11 Results Begijnhof museum volumes 5 to 12. .......................................................... 72
Summary

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 the influence to our cultural heritage. Within the new EU project ‘Climate for Culture’ researchers are investigating climate change impacts on UNESCO World Heritage Sites. This report focuses on the indoor climate of these monumental buildings.

Lots of monumental buildings are used as a museum or storage for paintworks, books and other artifacts. The indoor climate conditions of monumental buildings are very important for the conservation of these objects. The influence of the changing climate on the indoor climate of monumental buildings is unknown. It is impossible to prepare adequately for the future, by anticipating on this change and adapting the installations, because of this lack of knowledge. The result is that the conservation of the buildings and the collections are at risk.

The objective of this research is to gain insight on the impact of climate change on the indoor climate of the built cultural heritage with free floating conditions and with controlled climatic conditions (heating and cooling). Also the impact on energy demands is assessed. A sub objective is to analyze the simulated climate data generated by the REMO model.

To meet the objective, building performance simulations of two monumental buildings are executed: the Castle of Gaasbeek and the Begijnhof museum. The used simulation software is HAMBase. The used climate data range from the year 2000 until 2099 and are generated by the climate model REMO, which is provided by the Max Planck Institute in Hamburg (Germany).

The research shows that there are some discrepancies between measured and simulated values regarding temperature, relative humidity and solar radiation. Nevertheless, the climate data are suitable for performing the building simulations with HAMBase. Not to predict exactly the future climate, but to indicate the impact of the changing climate in the future. For computers with limited RAM-memory, it is allowed to perform one separate simulation per year, since the influence of the incubation time on the results is negligible.

According to the REMO climate data, the simulated mean temperature will change more than the mean relative humidity. It seems to be contrarily to the latter, but the high relative humidity will become more of a problem than the temperature, especially in the conditioned situation. The climate change will affect heated and cooled monumental buildings relatively more than free floating monumental buildings. Heated and cooled buildings will become more moist in the future: the relative humidity will rise more frequently above 60% and drop less below 40%. Dehumidification will be more needed in the future, humidification is already barely needed and will become even less needed in the future. Heating will become less important, but remains highly important to reduce the relative humidity, since it can reduce the time that the relative humidity is above 60% with a factor two. Cooling will become more important, but not highly important for monumental buildings. The total energy use will decrease in the future significantly for conditioned buildings. Because the daily fluctuations of the relative humidity are most extreme in summer, heating can't help to stabilize these fluctuations since there's no need for heating in summer. This will become more of a problem in the future.
1 Introduction

Climate change is not something new to the earth and the global temperature has been much higher in the past than it is now. However, what is new, is the correlation between the growth of the human population and the increase in global temperature, see Figure 1.1. Also new, due to the exponential growth of the population and the correlation to global warming, is the high rate at which the global temperature rises: the global temperature increased 1.5°C from 8100 BC to 5200 BC (2900 years), the same rise of 1.5°C took place from 1810 AD to 2000 AD (only 190 years).

![Figure 1.1: The correlation between growth of population and climate change [1, 2, 3].](image)

Next to the growth of the world human population, more people are living in urban environments. This, combined with the effects of global warming, can have huge consequences for billions of people in everyday life [7].

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 the influence to 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.

In general, it can be expected that in a warming climate, heating energy usage will decrease and the cooling energy usage will increase over time. The increased ambient temperature will also lead to an increased overheating risk [4, 5, 6]. Specific building location and building characteristics have a large impact on results for any given building [7, 8]. Especially the huge thermal mass of monumental buildings influences the response to the changing climate significantly.
1.1 Problem description

Lots of monumental buildings are also used as museum or storage for paintworks, books and artifacts. The indoor climate conditions of monumental buildings are very important for the conservation of these objects [9]. The influence of the changing climate on the indoor climate of monumental buildings is unknown. It is impossible to prepare adequately for the future, by anticipating on this change and adapting the installations, because of this lack of knowledge [10]. The result is that the conservation of the buildings and the collections are at risk.

1.2 Project objective

The objective of this research is to gain insight on the impact of climate change on the indoor climate of the built cultural heritage with free floating conditions and with controlled climatic conditions (heating and cooling). Also the impact on energy demands is assessed. A sub objective is to analyze the simulated climate data generated by the REMO model.

The impact on the deterioration of the building and on the collections is out of the scope of this research. However, the results of this research are needed to gain insight on that topic as well.

1.3 Project approach

To meet the objective, building performance simulations of two monumental buildings are executed: the Castle of Gaasbeek and the Begijnhof museum. The used simulation software is HAMBase. The used climate data range from the year 2000 until 2099 and are generated by the climate model REMO, which is provided by the Max Planck Institute in Hamburg (Germany).

First the climate data have been checked to verify no strange or abnormal values are contained and simple statistical checks are performed: average, maximum, minimum temperature and relative humidity per decade. Also temperature distributions have been generated per decade. Sequentially, the global, direct and diffuse solar radiation have been checked. Since simulated and measured climate data are available for the years 1971-2010, the previous mentioned checks have been performed for both the simulated and measured data and compared to each other. Then, the climate data have been prepared for use with the simulation model HAMBase. The simulated global radiation has been split up in direct and diffuse radiation, because HAMBase needs them separately. This split up has been performed using a MATLAB-algorithm.

The next step was to find relevant indicators to reflect the impact of the changing climate on the indoor climate of the monumental buildings and to visualize this impact properly. To be able to qualify an indoor climate as good or bad for conservation of collections, the ASHRAE standard has been used to find the criteria that a climate has to meet in order to conserve a collection properly. If in the future the criteria are exceeded more than now, the climate can be qualified as changing negatively. If the opposite is true, a climate may be qualified as changing positively. The other objective was to gain insight on the annual heating demands and cooling demands. By creating box plots of the hourly heating and cooling energies, with one box plot per decade, the impact can be visualized orderly.

The castle of Gaasbeek has been simulated with free floating conditions, meaning no heating and no cooling. The indicators, inspired by the ASHRAE standard, are used to investigate the impact. Secondly, the castle of Gaasbeek has been simulated with unlimited heating and
cooling capacities and maintaining the air temperature between 15°C and 25°C. The capacities are unlimited to be able to compare different buildings to each other and to be sure that there’s no influence of a restricted heating/cooling capacity on the annual heating/cooling demand. The same procedure has been applied to the Begijnhof museum.

1.4 Structure of the report

The structure of the report is as follows: Chapter 2 elaborates on the background information. The background of the used simulation software, the used meteorological data and the observed buildings (Castle Gaasbeek and the Begijnhof museum) is explained. Chapter 3 gives the simulation results from the year 2000 until the year 2099. Chapter 4 consists of the discussion of these results and chapter 5 consists of the conclusions and recommendations for how to proceed in the future with this topic of research.

1.5 Castle of Gaasbeek

The castle of Gaasbeek is situated in Gaasbeek, Belgium. It's built around the year 1240 AD. Since that time, the castle has been ruined, rebuilt and modified multiple times. Since the year 1924 AD, the castle has functioned partly as a museum. Via the main entrance on the north east side, the inner court is accessible, see Figure 1.2. The wing on the north west side of the main entrance functions as museum. The side on the south east side of the main entrance houses offices and storage rooms.

The castle is accessible for public from April 1st to November 15th. The opening hours are, from Tuesday to Sunday, from 10 am to 6 pm. The average annual number of visitors is 70,000. The castle is only accessible by tour with a guide.

The interior is a cultural heritage object on its own with rich and detailed decorated walls and ceilings. Next to the interior, the following objects are part of the collection:

- Wall carpets from the 16th to 18th century.
- Oil paintings from the 15th to 19th century.
- Wooden furniture and statues.
- Historical weapons.
- Ceramics and metal objects like statues, vases and plates.
- Books and documents.
1.6 Begijnhof museum

The Begijnhof is situated in Turnhout, Belgium, and it’s built in the 13th century AD. Since 1998 it’s an UNESCO world cultural heritage site. The Begijnhof consist of antique houses and a baroque church in a green environment. The museum has been housed since 1953 in the Saint Jean covenant, see Figure 1.3. This was originally the house of Pastor Mermans in the 17th century. He founded the Mermans Foundation in his testimonial. This foundation helped the less wealthy Begijns.

![Figure 1.3: The Begijnhof museum in Turnhout, Belgium.](image)

The museum has two aims: it gives an impression of the life of the Beguines and it gives an impression of how the woman lived and worked in these houses. Therefore the collection consists of:

- Antique kitchen tools.
- Furniture.
- Clothes.
- Paintings.
- Religious objects: bibles and statues.
2 Modeling

The raw climate data are provided by the Max Planck institute. The climate data have been checked, see results in paragraph 3.1, and made suitable for this project. In paragraph 2.1 it is explained how the climate is modeled and implemented in the simulation software HAMBase.

Prior to this project, the observed buildings have already been modeled by former students. Paragraph 2.2 explains the modeling and validation procedure that is followed.

2.1 Climate

To be able to predict the influence of the changing climate on the cultural heritage and museum collections, it is necessary to possess climate data for the next hundred years. Within the EU Climate for Culture project, future climate scenarios for Europe have been developed by researchers of the Max Planck institute [15]. These artificial data will contain the hourly values of the necessary climate parameters for several locations spread over Europe. These climatic data are generated using the regional climate model REMO, which is developed by the Max Planck Institute in Hamburg, Germany. The provided simulated climate data for this research cover the period from 1950 until 2099. The climate data are not valid for one exact location, but are averaged from the data of several locations near De Bilt in the Netherlands. The raw data are provided in .txt-files and contain the variables as tabulated in Table 2.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Used?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>Yes</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>°C</td>
<td>No</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>%</td>
<td>Yes</td>
</tr>
<tr>
<td>Wind speed</td>
<td>m/s</td>
<td>Yes</td>
</tr>
<tr>
<td>Wind direction</td>
<td>degrees (0-360)</td>
<td>Yes</td>
</tr>
<tr>
<td>Cloud coverage</td>
<td>- (0-100)</td>
<td>Yes</td>
</tr>
<tr>
<td>Albedo</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>Precipitation</td>
<td>mm/h</td>
<td>No</td>
</tr>
<tr>
<td>Global radiation</td>
<td>W/m²</td>
<td>Yes</td>
</tr>
<tr>
<td>Global count radiation</td>
<td>W/m²</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2.1: The variables provided by the REMO-model.

HAMBase uses the variables as described in Table 2.2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse solar radiation</td>
<td>W/m²</td>
<td>1</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.1 °C</td>
<td>2</td>
</tr>
<tr>
<td>Direct solar radiation</td>
<td>W/m²</td>
<td>3</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.1 m/s</td>
<td>4</td>
</tr>
<tr>
<td>Wind direction</td>
<td>degrees (0-360)</td>
<td>5</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>%</td>
<td>6</td>
</tr>
<tr>
<td>Extra long wave radiation to the sky dome</td>
<td>- (not used)</td>
<td>7</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.1 mm/h</td>
<td>8</td>
</tr>
<tr>
<td>Cloud coverage</td>
<td>- (0-8)</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 2.2: The variables used by HAMBase and the designated columns in the mt-files.
The first step was to import the .txt files with MATLAB and create the climate files (9 columns) needed for HAMBase. The used m-file (remote1) is included in appendix 6.1. The global radiation is for now used in both columns 1 and 3.

Table 2.2 shows that HAMBase needs diffuse solar radiation and direct solar radiation separately. However, as Table 2.1 shows, the climate data from REMO come with global radiation which is the sum of diffuse and direct radiation. A MATLAB function called zon2zon is used to convert the global radiation file to a diffuse radiation file and a direct radiation file, see Figure 2.1. A check of the result of this converting is shown in paragraph 3.1. The MATLAB-function script of zon2zon is included in appendix 6.2.

![Figure 2.1: process of function zon2zon.](image)

The last step was to create separate climate files per year from the combined climate files (climate_1950_2000 and climate_2001_2099). Appendix 6.3 shows the used m-file.

### 2.2 Case studies

The castle of Gaasbeek and the Begijnhof museum are modeled and validated according to an exact procedure (executed in prior to this project). The following strategy has been followed:

- **A quick scan** - consists of a first visit to the building and a conversation with the conservation specialist and the technical staff. This gives a first impression of the complexity of the building.
- **A full inventory** - is made of the situation. Floor plans, technical drawings and details of the building and the climate system are requested. The use of the building is examined. Also the positions of the artifacts are determined, and their vulnerability is noted. Finally also the building management system sensors are drawn up.
- **Measurement** - In the initial stage some short measurements are executed, e.g. infrared thermal imaging, short temperature and relative humidity checks and inlet air conditions. Together with the inventory, this leads to a full measurement setup for the whole building. Permanent measurements on air temperature, relative humidity and surface temperature are executed by a combined sensor. This sensor contains a transmitter that sends the measured data to a wireless data logger that is placed centrally in the building. The function of the logger is to temporarily store the data. A GSM connection is used to download the data from the logger to a central server. This server processes the data and makes it available on an Internet application.
- **Modeling** – The indoor climate model HAMBase is used to calculate the indoor temperature and humidity based on the outdoor climate measured by the Royal Netherlands Meteorological Institute (KNMI). This output of the model is compared to the measured climate. The model can be used to determine some physical parameters e.g.
the humidity buffering capacity. Differences between the model and reality are examined.

- Analysis - Measurements and simulation results are analyzed and the model is validated by fine tuning the model.

2.2.1 Castle of Gaasbeek

To reduce the complexity, a representative part of the castle is modeled. Rooms that are strongly connected and exhibit the same climate, can be modeled as one zone [11]. Figure 2.2 shows the part of the castle that is modeled (right) and the four zones (left):

- Basement (red).
- Gallery room (blue).
- Scocket room and Gotic room (yellow).
- Loft (green).

![Simplified model of the simulated part of the north west wing.](image)

Originally, the rooms are not heated and cooled, so free floating. For this research, the castle is simulated free floating and conditioned between 15°C and 25°C with unlimited heating and cooling capacities.

The used MATLAB-files of the models, free floating and conditioned, are included in appendix 6.4.

2.2.2 Begijnhof museum

The museum is divided into twelve zones which are modeled in HAMBase, see Figure 2.3. Some rooms are heated with radiators, some with convection heaters and some not at all. For this research, the museum is simulated free floating and conditioned between 15°C and 25°C with unlimited heating and cooling capacities.

The used MATLAB-files of the models, free floating and conditioned, are included in appendix 6.5.
2.3 Used simulation software: HAMBase and the MMM-model.

The simulation software originates from the thermal indoor climate model ELAN which was already published in 1987 [11]. 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 [12]. The physics of this model is extensively described by de Wit [13].

2.3.1 Validation of HAMBase.

The HAMBase model has been validated using the latest state-of-art measurement from the International Energy Agency (IEA) [14]. 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 2.4. 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%).

Figure 2.4: Measured, at the test room from the Fraunhofer Institute, and simulated heat supply.
For this project the Multi Museum Model is used, a variant of the HAMBase model, in which multiple buildings can be simulated simultaneously. The simulation is executed in five steps:

- Step 1: initializing of the building models.
- Step 2: validation of the models (optional: not needed every time).
- Step 3: creating variants: one can add changes without disturbing the original model. For computers with limited calculation capacity, this step can be used to create one variant per simulated year instead of simulating the period of hundred years at once.
- Step 4: Calculation. The output is the .mat-file in which all the output is organized.
- Step 5: Creating the output from the .mat-file ‘buildings’.

Figure 2.5 shows the influence, on the energy demand per year, of simulating a building at once over the entire simulation period of hundred years, or creating one variant per year, which means that every year a new simulation is started.

The graphs show that the difference between the two variants is marginal. This means that it is allowed to simulate every year separately by making a variant in step 3 for every year. This reduces the needed RAM-memory significantly for performing the simulation. This also shows how good the model HAMBase performs the incubation time by using a few dummy days in advance of the actual simulation period.

![Figure 2.5: energy demand per year if simulation period (100 years) is simulated at once or if every year a new simulation is executed. Left: the four volumes of castle Gaasbeek. Right: zoomed in to show the marginal difference between the two variants.](image)

The MATLAB files of the MMM-model are included in appendix 6.6 and the MATLAB-files which generate the output (step 5 in MMM-model) are included in appendix 6.7.
3 Results

In order to gain insight in the reliability of the provided climate data and the expectations towards the influence of the changing outdoor climate on the indoor climate, an analysis is conducted. The results of the analysis are presented in paragraph 3.1. The building simulation results for the castle of Gaasbeek and the Begijnhof museum are presented in paragraph 3.2.1 and paragraph 3.2.2 respectively.

3.1 Results climate data

In Table 3.1, the temperature and relative humidity are analyzed and measured values are compared to simulated values. For the period 1971-2009, the simulated values are compared with measured values and analyzed. For the period 2001-2099, the simulated values are analyzed. The mean, maximum and minimum values are calculated for the temperature and relative humidity respectively.

<table>
<thead>
<tr>
<th>Period</th>
<th>mean T [°C]</th>
<th>max T [°C]</th>
<th>min T [°C]</th>
<th>mean RH[%]</th>
<th>max RH[%]</th>
<th>min RH[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971-1980</td>
<td>measured</td>
<td>9.42</td>
<td>34</td>
<td>-17</td>
<td>81.69</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>simulated</td>
<td>9.95</td>
<td>32</td>
<td>-20</td>
<td>83.91</td>
<td>100</td>
</tr>
<tr>
<td>1981-1990</td>
<td>measured</td>
<td>9.75</td>
<td>35</td>
<td>-18</td>
<td>81.34</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>simulated</td>
<td>10.09</td>
<td>32</td>
<td>-9</td>
<td>83.05</td>
<td>100</td>
</tr>
<tr>
<td>1991-2000</td>
<td>measured</td>
<td>10.20</td>
<td>34</td>
<td>-16</td>
<td>82.62</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>simulated</td>
<td>10.62</td>
<td>32</td>
<td>-7</td>
<td>83.15</td>
<td>100</td>
</tr>
<tr>
<td>2001-2009</td>
<td>measured</td>
<td>10.60</td>
<td>36</td>
<td>-14</td>
<td>81.79</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>simulated</td>
<td>10.16</td>
<td>31</td>
<td>-11</td>
<td>83.38</td>
<td>100</td>
</tr>
<tr>
<td>2011-2020</td>
<td>simulated</td>
<td>10.89</td>
<td>33</td>
<td>-9</td>
<td>82.01</td>
<td>100</td>
</tr>
<tr>
<td>2021-2030</td>
<td>simulated</td>
<td>10.55</td>
<td>33</td>
<td>-10</td>
<td>83.57</td>
<td>100</td>
</tr>
<tr>
<td>2031-2040</td>
<td>simulated</td>
<td>11.09</td>
<td>33</td>
<td>-10</td>
<td>83.27</td>
<td>100</td>
</tr>
<tr>
<td>2041-2050</td>
<td>simulated</td>
<td>11.20</td>
<td>33</td>
<td>-8</td>
<td>83.38</td>
<td>100</td>
</tr>
<tr>
<td>2051-2060</td>
<td>simulated</td>
<td>11.74</td>
<td>33</td>
<td>-6</td>
<td>82.91</td>
<td>100</td>
</tr>
<tr>
<td>2061-2070</td>
<td>simulated</td>
<td>11.94</td>
<td>35</td>
<td>-7</td>
<td>84.17</td>
<td>100</td>
</tr>
<tr>
<td>2071-2080</td>
<td>simulated</td>
<td>12.20</td>
<td>34</td>
<td>-5</td>
<td>83.30</td>
<td>100</td>
</tr>
<tr>
<td>2081-2090</td>
<td>simulated</td>
<td>12.56</td>
<td>34</td>
<td>-5</td>
<td>83.46</td>
<td>100</td>
</tr>
<tr>
<td>2091-2099</td>
<td>simulated</td>
<td>12.65</td>
<td>36</td>
<td>-6</td>
<td>83.24</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3.1: Temperature and relative humidity analyzed for the periods 1971-2009 (measured values compared to simulated values) and 2001-2099.

The temperature change in perspective

Regarding the temperature it can be seen that, in the period from 2001-2099, the mean temperature increases from 10.16°C to 12.65°C according to the simulated climate data. The data suggest a temperature increase of 2.49°C in just 100 years. Referring to Figure 1.1, the same increase happened from the year -9600 BC to -5210 BC: a period of 4390 year!

A comparison between measured and simulated values for temperature and relative humidity is visualized graphically in Figure 3.1.
The impact of climate change on the indoor climate of monumental buildings

The simulated mean temperature per decade matches the measured mean temperature almost exactly. The simulated maximum temperature per decade is 2°C to 5°C lower than the measured maximum temperature. The simulated minimum temperature is in the first decade lower than the measured temperature, but the rest of the decades higher. In the decades with the biggest difference, the simulated minimum temperature is 9°C higher than the measured minimum temperature, which is a significant difference. These observations are in line with which is shown in Figure 3.2 (left). The dynamic behavior of the simulated temperature is less extreme as the dynamics of the measured temperatures. The same yields for the relative humidity, see Figure 3.1 (right).

There might be two explanations for this difference in dynamics regarding temperature and relative humidity. First, the measured data are measured in ‘de Bilt’ at the Royal Meteorological Institute of the Netherlands, which collects data of this particular location. The simulated climate data are not generated for exactly one geographical location, but are values which are averaged over several locations near ‘de Bilt’. The second reason is that the REMO-model can generate
climate scenarios on different levels: ranging from a mild scenario to more extreme scenarios. The used scenario here is an averaged one. The reality of the following hundred years will learn whether the climate will develop less or more extreme than the used climate data suggest.

Figure 3.3 and Figure 3.4 show the hourly distribution of simulated temperatures for each decade of the 21st century and Figure 3.5 shows a compares the distribution between measured and simulated temperatures for the years 2000 to 2009 (decade 1). The used MATLAB code is included in appendix 6.9.

Figure 3.3: Hourly distribution of simulated temperatures for the decades 1 to 6 of the 21st century.
The impact of climate change on the indoor climate of monumental buildings

Figure 3.4: Hourly distribution of the temperatures of the decades 7 to 10 of the 21st century.

Figure 3.5: Comparison of hourly temperature distribution between simulated (left) and measured (right) temperatures for the years 2000 to 2009.

The plots show that two tops will occur in the decades 3 to 6, 8 and 9 at 8°C and 15°C. This is a strange effect, because the hourly distribution of temperature normally is a Gaussian distribution. Also a strange effect is the peak at 0°C in the decades 1 to 5 and 7. The other decades show at 0°C a discontinuous curve. Figure 3.5 shows clearly the absence of these effects for the measured temperatures (years 2000 to 2009).
Also the solar radiation has been analyzed. The provided simulated climate data contained the global radiation as parameter. Global radiation is the sum of direct and diffuse radiation, as explained in paragraph 2.1. The simulation model HAMBase needs the direct and diffuse radiation separately. Therefore a MATLAB-script is used to convert the provided global radiation into direct and diffuse radiation.

Figure 3.6 shows the cumulative energy per square meter from diffuse and direct solar radiation for the years 2001 to 2004. At the end of the year, the energy per square meter from the simulated radiation is less than from the measured radiation. It’s important to be aware of this difference, but for this research it’s not a problem, because the objective is to find the influence of the change of the climate.

Figure 3.6: Cumulative energy from direct and diffuse solar radiation for the years 2001 to 2004.

Also Figure 3.6 indicates that the MATLAB-script, mentioned earlier, separates the simulated global radiation correctly into diffuse and direct radiation since the difference between the simulated global radiation and the measured global radiation is also visible in the simulated and measured diffuse and direct radiation.

The used m-file ‘solcum’ is included in appendix 6.8.
3.2 Results building simulations

The two simulated buildings, castle of Gaasbeek and Begijnhof museum, have been simulated with free floating conditions and with the climate controlled between 15 and 25 °C, with unlimited heating and cooling capacities. The simulation period is from the year 2000 until the year 2099 using the REMO climate data.

To investigate the results from the simulations with free floating and controlled conditions, there are eight relevant criteria regarding the conservation of the collection. These criteria are based on the ASHRAE standard for museums and galleries, class B, which is most appropriate for monumental buildings [9]. The criteria concern the percentage of time that:

- The temperature is below the minimum temperature limit: %time \( T < 15 \) °C.
- The temperature is above the maximum temperature limit: %time \( T > 25 \) °C.
- The temperature change per hour is bigger than allowed: %time \( \Delta T/h > 5 \) °C/h.
- The temperature change per day is bigger than allowed: %time \( \Delta T/day > 5 \) °C/day.
- The relative humidity is below the minimum RH limit: %time RH < 40%.
- The relative humidity is above the maximum RH limit: %time RH > 60%.
- The relative humidity change per hour is bigger than allowed: %time \( \Delta RH/h > 10 \) %.
- The relative humidity change per day is bigger than allowed: %time \( \Delta RH/day > 10 \) %.

To investigate the simulation results of the conditioned climate, the following criteria are used:

- Heating demand per 10 years.
- Cooling demand per 10 years.
- Total energy per 10 years: cooling + heating.
- Hourly averaged heating and cooling powers visualized in one box plot per 10 years.

Figure 3.7 shows an example of a box plot. A box plot is suitable for visualizing the heating and cooling powers, because it is a robust way of visualizing a data set, which means that it is resistant to outliers. The blue lined boxes represent the middle 50% of the ranked data set, called the interquartile range (IQR). The median, the red line, divides the IQR in an upper quartile range (upper 25%) and lower quartile range (lower 25%). The whiskers, the dashed black line, above it represents the upper 25% of the data set and the whiskers beneath the blue box represents the lower 25% of the data set. Outliers are represented by the red markers and represent values which are above ‘the upper quartile range + 1,5 x the IQR’ (blue box) and beneath ‘lower quartile range - 1,5 x the IQR’.

![Box plot example](image)

**Figure 3.7:** example of a box plot.
3.2.1 Results castle of Gaasbeek

3.2.1.1 Free floating conditions

The indoor climate of the castle of Gaasbeek is in real life mainly free floating. Figure 3.8 shows the Climate Evaluation Chart\(^1\) of volume 3 for the year 2010. These charts can be generated for each year and are very useful to visualize the hourly values distribution in the psychometric chart for air, which forms the background. But it’s not suitable for visualizing the change in time over a period of hundred years, since this would result in hundred CEC’s. Just to get a good feeling of the characteristics of the indoor climate, one CEC is presented with typical values for volume 3.

The indoor climate of the castle of Gaasbeek is in reality mainly free floating. The CEC, in Figure 3.8, shows clearly that the requirements are not met in the major part of the year for volume 3. According to the matrices in the CEC, all criteria are met simultaneously only 18% of the time. The temperature in the winter drops regularly to 7°C and the relative humidity reaches 70% and sometimes even exceeds 80%. This enhances the chance that mould growth will occur. The subplots on the right side of the CEC show the dynamical criteria. The \(dT/h\) and \(dRH/h\) criteria are not exceeding the limits. The limit for \(dT/day\) is exceeded in spring and summer. In summer time, the temperature is mostly between the limits of 15°C and 25°C, but the temperature changes 5% of the time too quickly. In spring time, the temperature is more often beneath 15°C and changes 9% of the time too quickly. In autumn and winter time, the temperature is mostly beneath 15°C, but does not change too quickly. In all four seasons the relative humidity exceeds 60% RH and changes often too quickly.

\(^1\) Explanation of the Climate Evaluation Chart (CEC) is provided in appendix 6.10.
Figure 3.9 shows the plots of the ASHRAE inspired criteria for the four volumes of castle of Gaasbeek with free floating conditions. The plots show the percentage of time that the criteria are met. For example, the relative humidity in volume 1 is approximately 80% of the time in decade 1 and 90% of the time in decade 10 above the limit of 60% RH.

Figure 3.9: the plots show the percentage of time, that the criteria are met.

Figure 3.9 shows for each volume the percentage of time that the criteria exceed the limits, but not specified per season and averaged per decade. Volume 1 is the basement of the castle and therefore only the static limits are exceeded significantly: around 80% of the time the relative humidity is above 60% and around 55% of the time the temperature is below the limit of 15°C. The other volumes experience much more the daily variations in temperature and relative humidity. Volume 4 is the loft and is therefore very sensitive to daily and hourly variations in temperature and relative humidity. Regarding the static limits, the 60% RH limit is exceeded more than 80% of the time and the temperature drops around 60% of the time below 15°C. Also the limit of 5°C/day is exceeded for 60% of the time and the limit of 10% RH/day is exceeded for 70% of the time. The volumes 2 and 3 perform between 1 and 4. Especially heating and dehumidification is needed now and in the future for all simulated volumes of this castle. Humidification is unnecessary for all the volumes, also in the future.
The plots in Figure 3.10 show the percentage change of time, that the criteria are met. These are the same plots as in Figure 3.9, but normalized: the first value is subtracted from the dataset to show the change. For example, the time that the relative humidity in volume 1 exceeds the limit of 60 % RH, increases by 12 % in the coming hundred years. And the time that the temperature in volume 1 drops below the limit of 15 °C, decreases by 5 % in the coming hundred years.

Figure 3.10: the plots show the percentage change of time, that the criteria are met. These are the same plots as in Figure 3.9, but normalized (the first value is subtracted from the dataset).

Figure 3.10 shows how the volumes perform in the future regarding the mentioned criteria. The changing climate influences in volume 1 the least number of criteria, only the static criteria, but the RH limit of 60% is influenced here more than in any of the other volumes. The percentage of time that the relative humidity is above 60% will increase with 12%. The percentage of time that the temperature drops below 15 °C decreases with 5%. In volume 4, the percentage of time that the temperature drops below 15 °C decreases with 8 to 10%. In the volumes 2 and 3 the percentage of time that the relative humidity exceeds 60% increases with 6% and that the temperature is below 15 °C decreases with 5%. Also the time that the temperature is above 25 °C increases with 6%. So in the future heating is needed less often, dehumidification becomes even more necessary and cooling will be more desired.
3.2.1.2 Conditioned with unlimited capacities

The indoor climate of the castle of Gaasbeek is in real life mainly free floating, but for this project it is also simulated with a conditioned climate (only heating and cooling). Figure 3.11 shows the Climate Evaluation Chart of the conditioned climate of volume 3 for the year 2010. Just to get a good feeling of the characteristics of the indoor climate, one CEC is presented with typical values for volume 3.

![Climate Evaluation Chart](image)

Figure 3.11: the Climate Evaluation Chart (CEC) shows the hourly values of the indoor climate (volume 3, year 2010), plotted in a psychometric chart, and the relevant statistics at the right side. The criteria are graphically represented by the blue lined area (40% ≤ RH ≤ 60% and 15° C ≤ T ≤ 25° C).

The CEC shows clearly that the climate is now conditioned and maintained between the limits for temperature (15°C ≤ T ≤ 25°C). According to the matrices, the percentage of time that all the criteria are met, is still only 58%, due to the relative humidity. The climate is kept very constant in the winter and by heating also the relative humidity of the air is lowered which results in the elimination of the risk for mold growth in the winter. However, this effect is so big, that the relative humidity even drops below 40% for some hours. According to the matrices in the CEC this is the case during 26% of the time in winter. Because the indoor climate can still fluctuate between 15°C and 25°C, there are still some hours that the dT/day and dRH/day limits are exceeded.

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2 Explanation of the Climate Evaluation Chart (CEC) is provided in appendix 6.10.
Figure 3.12 shows the plots of the ASHRAE inspired criteria for the four volumes of castle of Gaasbeek with conditioned climate (heating and cooling). The plots show the percentage of time that the criteria are met. For example, the relative humidity in volume 1 is approximately 45% of the time in decade 1 and 62% of the time in decade 10 above the limit of 60% RH.

According to Figure 3.12, the earlier mentioned drop below 40% RH is indeed present, in all the volumes. Especially volume 4 is obviously sensitive to daily fluctuations of the relative humidity as we’ve also seen in the free floating situation: 65% of the time above 10% RH/day. The percentage of time that the relative humidity exceeds 60% is much lower than in the free floating situation, ranging from 40-60% in volumes 1 and 4 and from 25-40% in volumes 2 and 3. This is due to the effect of heating.
The plots in Figure 3.13 show the percentage change of time, that the criteria are met. These are the same plots as in Figure 3.12, but normalized: the first value is subtracted from the dataset to show the change. For example, the time that the relative humidity in volume 1 exceeds the limit of 60% RH, increases 16% in the coming hundred years. And the time that the temperature in volume 1 drops below the limit of 15°C, remains 0% of course, due to the unlimited heating and cooling capacities.

![Graphs showing changes in time percentage](image)

**Figure 3.13:** the plots show the percentage change of time, that the criteria are met. These are the same plots as in Figure 3.12, but normalized (the first value is subtracted from the dataset).

Interesting to see is that the percentage of time that the relative humidity exceeds 60% increases in all the volumes with 15%, which is much more change than in the free floating situation, and the percentage of time that the relative humidity drops below 40% decreases with 10% in all volumes. This is the explanation: in the relatively cold climate of middle Europe, the high relative humidity in winter is reduced by heating. Because the temperature rises in the future, there’s less need for heating and the effect of decreasing the relative humidity by heating will be less, so the percentage of time that the relative humidity exceeds 60% will increase. The percentage of time that the relative humidity fluctuates more than 10%/day increases in all the volumes with 4-5%. The need for humidification is new in the conditioned situation, but this need decreases in the future. Heating and cooling are not only influencing the criteria regarding the temperature, but also the criteria regarding the relative humidity and the influence of the changing climate on the latter is bigger than in the free floating situation.
The plots in Figure 3.14 show the energy demand per decade for heating, cooling and the total demand (heating + cooling). The heating demand decreases and the cooling demand increases slightly which results in a reduction of the overall energy consumption.

The total energy consumption of the castle of Gaasbeek, as visualized in Figure 3.14, is decreasing in the future for all volumes. This is explained by the fact that the heating demand is decreasing significantly, while the cooling demand is increasing just slightly. The total energy demand for the volume 1 is decreasing 32% and for the volumes 2, 3 and 4 it decreases 25%.
The impact of climate change on the indoor climate of monumental buildings

Besides the energy demands per decade also the dynamical behavior of the heating and cooling plant is assessed by plotting the hourly powers for heating and cooling in one box plot per decade, see Figure 3.15. So, one box plot contains 87660 hourly values. Positive values represent heating and negative values represent cooling. Because the climate was conditioned between 15 and 25 °C, there is no need for heating or cooling during a lot of hours, which results in a lot of zero powers in the dataset. This in combination with more heating than cooling hours results in the fact that the minimal value of the IQR (blue lined box) is not below zero.

Figure 3.15: power demands of Gaasbeek presented in one box plot per 10 years, positive values represent heating and negative values represent cooling.

Volume 1, the basement, shows little outliers because the range of the values is quite narrow. This means that no peak powers are required to keep the basement above 15 °C, which is obviously because this volume is influenced little by the outdoor climate. Also no cooling is necessary. The maximum power per decade decreases from 1200W to 900W, again a reduction of 25%. Volume 2 and 3: here are a lot of outliers because the volume are influenced a lot by the outdoor climate. The number of outliers increase in the future, especially for cooling. This is a result from the dataset with more zero values, because there are more hours with no need for heating. To explain more about this: if there are a lot of zero’s in the data set and a low number of non-zero values, the IQR (blue box) is small. Because a value is considered to be an outlier if the value is 1,5x the height of the IQR, a value is quicker considered as outlier if the IQR is smaller. Why the lower limit of the IQR (bottom of the blue box) is always zero and not negative is also due to the large amount of zero values in the data set: the IQR represents the middle 50% of the ranked values and if the dataset contains a lot of zero values and more positive than negative values, the middle 50% of the ranked data ranges from zero to some positive value.
3.2.2 Results of museum Begijnhof

3.2.2.1 Free floating conditions

The indoor climate of the Begijnhof museum is in real life mainly free floating. Figure 3.16 shows the Climate Evaluation Chart\(^3\) of volume 3 for the year 2010. These charts can be generated for each year and are very useful to visualize the hourly values distribution in the psychometric chart for air, which is the background. But it’s not suitable for visualizing the change in time over a period of hundred years, since this would result in hundred CEC’s. Just to get a good feeling of the characteristics of the indoor climate, one CEC is presented with typical values for volume 3.

![Climate Evaluation Chart](Image)

Figure 3.16: The Climate Evaluation Chart (CEC) shows the hourly values of the indoor climate (volume 3, year 2010), plotted in a psychometric chart, and the relevant statistics at the right side. The criteria are graphically represented by the blue lined area (40% ≤ RH ≤ 60% and 15 ≤ T ≤ 25 °C).

The CEC in Figure 3.16 shows that the hourly values are only 8% of the time simultaneously within the limits for temperature and relative humidity. Of course this CEC is only for volume 3 and for the year 2010, but it is representative for most other volumes. Also in the Begijnhof museum the hourly values are in winter and autumn completely outside the criteria: the temperature is always far below 15°C and the relative humidity is always above 60% and exceeds regularly 80%. But the dynamic criteria are less outside their limits: the dT/h and dRH/h are never exceeded and the dT/day and dRH/day are less exceeded than in summer and spring. The same yields for the Begijnhof museum as for the castle of Gaasbeek: in summer and spring the changes of temperature and relative humidity are too quick (around 65% of the time) and in winter and autumn it is too cold and moist (respectively 100% and 95% of the time).

\(^3\) Explanation of the Climate Evaluation Chart (CEC) is provided in appendix 6.10.
Figure 3.17 shows the plots of the ASHRAE inspired criteria for the first four volumes of museum Begijnhof with free floating conditions. The plots show the percentage of time that the criteria are met. For example, the relative humidity in volume 1 is approximately 90% of the time in decade 1 and 92% of the time in decade 10 above the limit of 60% RH.

Figure 3.17: the percentage of time, that the criteria are met for volumes 1 to 4.

Figure 3.17 shows for each volume the percentage of time that the criteria exceed the limits, but not specified per season and averaged per decade. In all the volumes, the relative humidity exceeds more than 80% of the time the limit of 60%, the temperature is more than 60% of the time below 15°C and the dRH/day is exceeded around 50% of the time, but for volume 4 even 90% of the time. In the volumes 3 and 4 also the dT/day is exceeded respectively for 50% and 60% of the time. Especially heating and dehumidification is needed now and in the future for all simulated volumes of this museum. Humidification is needless for all the volumes, also in the future.
The plots in Figure 3.18 show the percentage change of time that the criteria are met. These are the same plots as in Figure 3.17, but normalized: the first value is subtracted from the dataset to show the change. For example, the time that the relative humidity in volume 1 exceeds the limit of 60% RH, increases by 4% in the coming hundred years. And the time that the temperature in volume 1 drops below the limit of 15°C, decreases by 8% in the coming hundred years.

Figure 3.18: the plots show the percentage change of time that the criteria are met for volumes 1 to 4. These are normalized (the first value is subtracted from the dataset).

Figure 3.18 shows how the volumes perform in the future regarding the mentioned criteria. For all volumes: the percentage of time that the relative humidity exceeds 60% and the time that the temperature is above 25°C will increase with only 3%, the time that the temperature is below 15°C will decrease with 8%. In the Begijnhof museum, these criteria are less influenced than in the castle of Gaasbeek. So in the future heating is needed less often, dehumidification becomes even more necessary and cooling will be insignificantly more desired.
3.2.2.2 Conditioned with unlimited capacities

The indoor climate of the Begijnhof museum is also simulated with a conditioned climate (only heating and cooling). Figure 3.19 shows the Climate Evaluation Chart of the conditioned climate of volume 3 for the year 2010. Just to get a good feeling of the characteristics of the indoor climate, one CEC is presented with typical values for volume 3.

![Climate Evaluation Chart](image)

The CEC shows clearly that the climate is now conditioned and maintained between the limits for temperature ($15 ^\circ C \leq T \leq 25 ^\circ C$). According to the matrices, the percentage of time that all the criteria are met, is still only 48%, due to the relative humidity. The climate is kept very constant in the winter and by heating also the relative humidity of the air is lowered which results in the elimination of the risk for mold growth in the winter and reduces the risk in autumn. However, this effect is so big, that the relative humidity even drops below 40% for some hours. According to the matrices in the CEC this is the case 27% of the time in winter and 11% in autumn. Because the indoor climate can still fluctuate between $15 ^\circ C$ and $25 ^\circ C$, the $dT$/day and $dRH$/day limits are exceeded in spring and summer around 55% of the time, which is much more than in the castle of Gaasbeek, but less compared to the free floating situation. The summer time is the most problematic season if heating and cooling are applied.

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4 Explanation of the Climate Evaluation Chart (CEC) is provided in appendix 6.10.
Figure 3.20 shows the plots of the ASHRAE inspired criteria for the four volumes of Begijnhof museum with conditioned climate (heating and cooling). The plots show the percentage of time that the criteria are met. For example, the relative humidity in volume 1 is approximately 45% of the time in decade 1 and 60% of the time in decade 10 above the limit of 60% RH.

According to Figure 3.20, the earlier mentioned drop below 40% RH is indeed present, in all the volumes. Especially volume 4 is obviously sensitive to daily fluctuations of the relative humidity as we’ve also seen in the free floating situation: 93% of the time above 10% RH/day. For the volumes 1 to 3 this is the case around 45% of the time. The percentage of time that the relative humidity exceeds 60% is much lower than in the free floating situation, ranging from 40-60% in all volumes. This is due to the effect of heating.

The results for the volumes 5 to 12 are included in appendix 6.11.
The plots in Figure 3.21 show the percentage change of time, that the criteria are met. These are the same plots as in Figure 3.20, but normalized: the first value is subtracted from the dataset. The results for the volumes 5 to 12 are included in appendix 6.11.

The percentage of time that the relative humidity exceeds 60% increases in all the volumes by 15%, which is much more change than in the free floating situation, and exactly the same as in the castle of Gaasbeek. Also here yields: in the relatively cold climate of middle Europe, the high relative humidity in winter is reduced by heating. Because the temperature rises in the future, there’s less need for heating and the effect of decreasing the relative humidity by heating will be less, so the percentage of time that the relative humidity exceeds 60% will increase.

The percentage of time that the relative humidity fluctuates more than 10%/day increases in the volumes 1 to 3 by 4-5% (same as castle of Gaasbeek). The need for humidification is new in the conditioned situation, but this need decreases in the future by 10% for all the volumes. Heating and cooling are not only influencing the criteria regarding the temperature, but also the criteria regarding the relative humidity and this influence of the changing climate on the latter is bigger than in the free floating situation.

Figure 3.21: the plots show the percentage change of time that the criteria are met for volumes 1 to 4. These are normalized (the first value is subtracted from the dataset).
The plots in Figure 3.22 show the energy demand per decade for heating, cooling and the total demand (heating + cooling). The heating demand decreases and the cooling demand increases slightly which results in a reduction of the overall energy consumption.

The total energy consumption of the Begijnhof museum, as visualized in Figure 3.22, is decreasing in the future for all volumes. This is explained by the fact that the heating demand is decreasing significantly, while the cooling demand is increasing just slightly (just as in the castle of Gaasbeek). The total energy demand for the volume 1 and 2 is decreasing 32% and for the volumes 3 and 4 it decreases 27% (the same order of magnitude as in the castle of Gaasbeek).

The results for the volumes 5 to 12 are included in appendix 6.11.
Figure 3.23 shows the power demands of Gaasbeek presented in one box plot per 10 years: positive values represent heating and negative values represent cooling. Because the indoor climate was conditioned between 15 and 25 °C, there is no need for heating or cooling during a lot of hours, which results in a lot of zero powers in the dataset. This in combination with more heating than cooling hours results in the fact that the IQR (blue lined box) has it’s minimal value of zero and not below zero.

The general trend is also in the Begijnhof museum, that the heating and cooling powers are in the future more in a focused range: the length of the whiskers decreases and the number of outliers increase. The differences between the volumes are not as big as in the castle of Gaasbeek. The number of outliers increase in the future, especially for cooling. This is a result from the dataset with more zero values, because there are more hours with no need for heating (see for more explanation castle of Gaasbeek). However, the median is not zero, which indicates that the ratio of zero values to non-zero values is smaller than in the castle of Gaasbeek.

There’s no significant reduction of the maximum used power per decade, but there seem to be less hours in which the peak powers are needed.

The results for the volumes 5 to 12 are included in appendix 6.11.
4 Conclusions and recommendations

4.1 Conclusions

*Climate data*

1. The climate data are suitable for performing the building simulations with HAMBase.
2. The simulated mean temperature changes more than the mean relative humidity.
3. There are discrepancies between measured and simulated values of solar radiation and hourly distributions of temperature.

*Building simulations*

The conclusions apply for the two investigated buildings, with the used climate data.

1. It is allowed to perform a separate simulation per year (paragraph 2.3).
2. The used criteria are suitable to show the influence of the changing climate.
3. It may seem contrarily to the conclusion at *climate data* (2.), but the high relative humidity’s will become more of a problem than the temperatures, especially in the conditioned situation (paragraphs 3.2.1.2 and 3.2.2.2).
4. Heating can reduce the time that the relative humidity is above 60% with a factor 2.
5. Because the dRH/day is mostly exceeded in summer, this will not be improved by heating since there’s no need for heating in summer.
6. The climate change will affect heated and cooled monumental buildings more than free floating monumental buildings, related to (3).
7. Heated and cooled buildings: more moist in the future (more above 60% RH and less below 40%), related to (3).
8. Dehumidification will be more needed in the future.
9. Heating will become less important, but significantly important to reduce the RH.
10. Cooling will become more important, but not significantly for monumental buildings.
11. Humidification is already insignificantly needed and will become less needed in the future.
12. Total energy use will decrease in the future (if heated and cooled).

4.2 Recommendations for future research

*Climate data*

- Research on the effect of the level of climate scenario: repeat simulations with more extreme climate data.
- Research on the cause of the peak and discontinuity at 0°C in the hourly distributions of temperature (Figure 3.5).
- Research on the cause of the difference between simulated and measured solar radiation (Figure 3.6).

*Building simulations*

- Simulate more buildings and compare outputs.
- Search for better ways to visualize the huge amount of output.
- Check how to use the box plots properly in order to get more information of them: e.g. should separate box plots be used for heating and cooling or is it allowed to combine them in one box plot as in this report?
5 References


6 Appendices

6.1 MATLAB-function remotest1

This file imports the variables as provided by REMO (.txt-files) and creates climate files in which the variables are imported in the column where HAMBase needs them and in the right unit.

%REMOTest 1
T2:
T2_1950_2000=importdata('DeBilt_TEMP2_1950_2000.txt','
T2_2001_2099=importdata('DeBilt_TEMP2_2001_2099.txt','

%RH:
RH_2001_2099=importdata('DeBilt_Relative_humidity_2001_2099.txt','

%Wind speed:
wind_speed_1950_2000=importdata('DeBilt_WindSpeed_1950_2000.txt','
wind_speed_2001_2099=importdata('DeBilt_Wind_speed_2001_2099.txt','

%Cloud cover:
cloud_cover_2001_2099=importdata('DeBilt_Cloud_cover_2001_2099.txt','
cloud_cover_1950_2000=importdata('DeBilt_CloudCover_1950_2000.txt','

%Wind direction:
wind_direction_2001_2099=importdata('DeBilt_WindDirection_2001_2099.txt','

%Precipitation:
Precipitation_2001_2099=importdata('DeBilt_Precipitation_2001_2099.txt','

%Global radiation:
global_radiation_2001_2099=importdata('DeBilt_Global_radiation_2001_2099.txt','

RH_1950_2000(:,3), zeros(447071,1), (Precipitation_1950_2000(:,3))*10,
round((cloud_cover_1950_2000(:,3))/100*8),
cloud_cover_1950_2000(:,1)];
% the last column (cloud_cover_1950_2000(:,1)) is to include the year.
%samenstellen climate file 2001 - 2099.
climatemeasured_2001 = [global_radiation_2001_2099(:,3),
(T2_2001_2099(:,3))*10, global_radiation_2001_2099(:,3),
(wind_speed_2001_2099(:,3))*10, wind_direction_2001_2099(:,3),
RH_2001_2099(:,3), zeros(447071,1), (Precipitation_2001_2099(:,3))*10,
round((cloud_cover_2001_2099(:,3))/100*8),
cloud_cover_2001_2099(:,1)];

The impact of climate change on the indoor climate of monumental buildings
6.2 MATLAB-function zon2zon

The file zon2zon is used to convert global radiation into diffuse and direct solar radiation. This file makes use of the file 'solposf' which is also included in this appendix.

```matlab
function zon2zon2(file)
eval(['load ' file])
eval(['A = ' file ';' ])

Asize=length(A);
n=Asize(1);

%correctie voor UT tijd naar MET
C=[A(1,:); A(1:n,:)];
A=C;
Asize=length(A);
n=Asize(1);
ndag=n/24;
tel=1:n;
dag=1:ndag;
uur=1:24;
dn=floor(tel/24)+1;

geopos=[52.1,5+11/60,15]; % De Bilt
surfpos=[0,0]; % horizontal

%1 elevat is de gemiddelde elevatie van tijdstip -0.5 uur en + 0.5 uur
[elevat1,azimuth1,cosinc1]=solposf(uur-1,dag,surfpos,geopos);
[elevat2,azimuth2,cosinc2]=solposf(uur,dag,surfpos,geopos);
elevat=0.5*elevat1+0.5*elevat2;

G=(10/3.6)*A(:,1);
G= A(:,1);
G0=( 1367*sin((pi/180)*elevat) .* ( 1+ 0.033*cos(2*pi*(dn-3)/365) ) )';
elesin=sin((pi/180)*elevat)';

%2
i1=find( G>0 & elesin==0);
disp(['totaal ' num2str(sum(G(i1))) ' Watt.uren/m2 op 0 gesteld. '])
G(i1)=0;
Gvar=zeros(n,1);
iG0=find(G>0);
Gvar(iG0)=G(iG0)/G0(iG0); %G/G0
B=zeros(n,1);
i1=find(Gvar>0.8);
B(i1)=G(i1)*0.86;
i1=find(Gvar<=0.8 & Gvar>0.35);
```

B(i1)=G(i1).*(1.66*Gvar(i1)-0.47);
i1=find(Gvar<=0.35 & Gvar>0.22);
B(i1)=6.4*(Gvar(i1)-0.22).^2;
i1=find(Gvar<0.22);
B(i1)=0;
D=G-B;
A(:,1)=D;
A(:,3)=B;
eval([file 'c= A;'])
eval([' save ' file 'c ' file 'c -v6'])

%Ib=zeros(n,1);
i1=find(elesin>0);
%Ib(i1)=B(i1)./(elesin(i1));
%plot(Ib)
i2=find(Ib>1000);
elesin(i2)

File solposf:
function [elevat,azimuth,cosinc]=solposf(ihour,iday,surfpos,geopos);
% Calculation of the solar position (elevation and azimuth)
% [elevat,azimuth,cosinc]=solposf(ihour,iday,surfpos,geopos);
% geopos  = [Local latitude (in degrees),Local longitude (degrees),Local Standard
time Meridian (in degrees east of Greenwich)].e.g. De Bilt:gepos=[52.1,5+11/60,15]
% surfpos = [angle between surface and horizontal (degrees),azimuth of surface
% with respect to south (degrees)],e.g. vertical:surfpos(1)=90;east:surfpos(2)=-90
% iday    = number of day starting with 1 the 1st of january (1<iday<365)
ihour   = the local standard time (in hours) (1<ihour<24)
% elevat  = solar elevation (degrees). Before sunrise and after sunset elevation=0
% azimuth = solar azimuth (degrees). Before sunrise and after sunset azimuth=0
% cosinc  = cosinus of angle between solar rays and surface normal (incident angle)
% If iday and ihour are vectors the function returns three column vectors or three row vectors
% depending on whether ihour is a column or a row vector. The size of each vector is
% length(iday)*length(ihour) in such a way that the first element contains the values for the first
% hour on the first day and the last element contains the values for the last hour on the last day.
% Example
% ihour=[12:14];
% iday=[1,6];
% geopos=[52.1,5+11/60,15]; % De Bilt
% surfpos=[0,0]; % horizontal
% [elevat,azimuth,cosinc]=solposf(ihour,iday,surfpos,geopos);
% elevat = azimuth = cosinc =
% 14.3111 -10.1579 0.2472
% 14.7988  4.0940 0.2554
The impact of climate change on the indoor climate of monumental buildings

% iday can be calculated from the date by idaycalf.m
% elevat,azimuth,cosinc can be used in irradf.m, solclrf.m
%
% Author: Martin de Wit 22-May-1998

rad=pi/180;
LAT=geopos(1);
LON=geopos(2);
LSM=geopos(3);
beta=surfpos(1)*rad;
gamma=surfpos(2)*rad;
LST=ihour; %Local standard time
L=LAT*rad;
l=0;
s=size(ihour);
if s(1)==1
  m=s(2);
  elevat=zeros(1,m*length(iday));
  azimuth=zeros(1,m*length(iday));
  cosinc=zeros(1,m*length(iday));
else
  m=s(1);
  elevat=zeros(m*length(iday),1);
  azimuth=zeros(m*length(iday),1);
  cosinc=zeros(m*length(iday),1);
end

for day=iday
  l=l+1;
  theta=2*pi*(day-1)/365.25;
  el=4.901+0.033*sin(-0.031+theta)+theta; % longitude
  delta=asin(sin(23.442*rad)*sin(el)); % declination
  q1=tan(4.901+theta); %
  q2=cos(23.442*rad)*tan(el); %tan(right ascension)
  ET=(atan((q1-q2)./(q1*q2+1)))*4/rad; % equation of time
  %a1=sin(L)*sin(delta);
  %a2=cos(L)*cos(delta);
  %hh=acos(-a1./a2);
  %sunr=(12-hh/(15*rad)-ET/60+(4/60)*(LSM-LON)); % sunrise
  %suns=(12+hh/(15*rad)-ET/60+(4/60)*(LSM-LON)); % sunset
  AST=LST+ET/60-(4/60)*(LSM-LON);
  h=(AST-12)*15*rad;
  alpha=asin( cos(L)*cos(delta)*cos(h) + sin(L)*sin(delta) );
  phi=acos( (sin(alpha)*sin(L)-
  sin(delta))./(cos(alpha)*cos(L))).*sign(h);
  gam=phi-gamma;
  cai=cos(alpha).*cos(gam)*sin(beta)+sin(alpha)*cos(beta);
  cai=(cai>0).*cai;
  k=find(alpha<0);
  alpha(k)=0*alpha(k);
  phi(k)=0*phi(k);
The impact of climate change on the indoor climate of monumental buildings

\begin{verbatim}
elevat(1+(l-1)*m:l*m)=alpha/rad;
azimuth(1+(l-1)*m:l*m)=phi/rad;
cosinc(1+(l-1)*m:l*m)=cai;
end;  %day

6.3 MATLAB m-file climateperyeartest

% This file generates a climate file per year as HAMBase needs it.
clear all
load climate1950_2000
load climate2001_2099

for k=1950:2000
    i1=find(climate1950_2000(:,10)==k);
    eval(['mt' num2str(k) ' = climate1950_2000(i1,1:9);'])
    eval(['save mt' num2str(k) ' mt' num2str(k) ']);
end

for k=2001:2099
    i1=find(climate2001_2099(:,10)==k);
    eval(['mt' num2str(k) ' = climate2001_2099(i1,1:9);'])
    eval(['save mt' num2str(k) ' mt' num2str(k) ']);
end

6.4 Models of castle of Gaasbeek: MATLAB m-files.

For the free floating condition, the used model is called ModelKG:

% -------------------------------------------
% HAMBASE Kasteel van Gaasbeek mei 2009 Edgar Neuhaus
% -------------------------------------------

BAS.Vol{1}=110;
BAS.Vol{2}=400;
BAS.Vol{3}=400;
BAS.Vol{4}=340;
BAS.Con{1}=[0.13,0.01,502,0.5,238,0.04,0.9,0.9];
BAS.Con{2}=[0.13,0.01,502,0.7,238,0.04,0.9,0.9];
BAS.Con{3}=[0.13,1.7,238,0.04,0.9,0.8];
BAS.Con{4}=[0.13,0.1,501,0.13,0.9,0.9];
BAS.Con{5}=[0.13,0.07,501,0.13,0.9,0.9];
BAS.Con{6}=[0.13,0.03,501,0.01,202,0.04,0.9,0.9];
BAS.Glas{1}=[5,0.01,0.8,0.8,0.01,5];
BAS.Or{1}=[90,-45];
BAS.Or{2}=[90,45];
BAS.Or{3}=[90,135];
BAS.Or{4}=[90,-135];
BAS.Or{5}=[50,-45];
BAS.Or{6}=[50,135];
BAS.wallex{1}=[1,25,3,3,0];
BAS.wallex{2}=[2,65,2,1,0];
BAS.wallex{3}=[2,65,3,3,0];
\end{verbatim}
The impact of climate change on the indoor climate of monumental buildings
The impact of climate change on the indoor climate of monumental buildings

For the controlled condition, the used model is called ModelKGv1:

% HAMBASE Kasteel van Gaasbeek mei 2009 Edgar Neuhaus
The impact of climate change on the indoor climate of monumental buildings

The following variables are defined:

- `BAS.wallia{6}`: [4, 16, 1];
- `BAS.wallia{7}`: [4, 16, 1];
- `BAS.wallin{1}`: [1, 2, 70, 4];
- `BAS.wallin{2}`: [2, 3, 95, 4];
- `BAS.wallin{3}`: [3, 4, 95, 5];
- `BAS.Ers{1}`: 300;
- `BAS.dayper{1}`: [0, 11, 17];
- `BAS.vvmin{1}`: [1, 1, 1];
- `BAS.vvmax{1}`: [0.4, 0.4, 0.4];
- `BAS.Tfc{1}`: [100, 100, 100];
- `BAS.Qint{1}`: [0, 0, 0];
- `BAS.Gint{1}`: [0, 0, 0];
- `BAS.Tsetmin{1}`: [15, 15, 15];
- `BAS.Tsetmax{1}`: [25, 25, 25];
- `BAS.RVmin{1}`: [-1, -1, -1];
- `BAS.RVmax{1}`: [101, 101, 101];
- `BAS.Ers{2}`: 300;
- `BAS.dayper{2}`: [0, 10, 17];
- `BAS.vvmin{2}`: [0.8, 1, 0.8];
- `BAS.vvmax{2}`: [0.8, 1, 0.8];
- `BAS.Tfc{2}`: [100, 100, 100];
- `BAS.Qint{2}`: [700, 1000, 700];
- `BAS.Gint{2}`: [0, 0.2/3600, 0];
- `BAS.Tsetmin{2}`: [15, 15, 15];
- `BAS.Tsetmax{2}`: [25, 25, 25];
- `BAS.RVmin{2}`: [-1, -1, -1];
- `BAS.RVmax{2}`: [65, 65, 65];
- `BAS.Ers{3}`: 300;
- `BAS.dayper{3}`: [0, 10, 17];
- `BAS.vvmin{3}`: [0.6, 0.8, 0.6];
- `BAS.vvmax{3}`: [0.6, 0.8, 0.6];
- `BAS.Tfc{3}`: [100, 100, 100];
- `BAS.Qint{3}`: [500, 500, 500];
- `BAS.Gint{3}`: [0, 0, 0];
- `BAS.Tsetmin{3}`: [15, 15, 15];
- `BAS.Tsetmax{3}`: [25, 25, 25];
- `BAS.RVmin{3}`: [-1, -1, -1];
- `BAS.RVmax{3}`: [65, 65, 65];
- `BAS.Ers{4}`: 300;
- `BAS.dayper{4}`: [0, 9, 17];
- `BAS.vvmin{4}`: [1.5, 1.5, 1.5];
- `BAS.vvmax{4}`: [1.5, 1.5, 1.5];
- `BAS.Tfc{4}`: [100, 100, 100];
- `BAS.Qint{4}`: [0, 0, 0];
- `BAS.Gint{4}`: [0, 0, 0];
- `BAS.Tsetmin{4}`: [15, 15, 15];
- `BAS.Tsetmax{4}`: [25, 25, 25];
- `BAS.RVmin{4}`: [-1, -1, -1];
- `BAS.RVmax{4}`: [101, 101, 101];
- `BAS.weekfun{1}`: [1, 1, 1, 1, 1, 1, 1];
- `BAS.weekfun{2}`: [2, 2, 2, 2, 2, 2, 2];
- `BAS.weekfun{3}`: [3, 3, 3, 3, 3, 3, 3];
- `BAS.weekfun{4}`: [4, 4, 4, 4, 4, 4, 4];
- `BAS.Plant{1}`: [-1, -100000, 0.00, -0.00];
- `BAS.Plant{2}`: [-1, -100000, 0.00, -0.00];
- `BAS.Plant{3}`: [-1, -100000, 0.00, -0.00];
- `BAS.Plant{4}`: [-1, -100000, 0.00, -0.00];
- `BAS.convfac{1}`: [0.8, 1, 0.5];
- `BAS.convfac{2}`: [0.8, 1, 0.5];
- `BAS.convfac{3}`: [0.8, 1, 0.5];
6.5 Models of Begijnhof museum: MATLAB m-files.

For the free floating condition, the used model is called ModelBTv1:

```matlab
% HAMBASE Begijnhofmuseum 2008 Martijn Kivits
BAS.Vol{1}=206;
BAS.Vol{2}=115;
BAS.Vol{3}=106;
BAS.Vol{4}=51;
BAS.Vol{5}=161;
BAS.Vol{6}=138;
BAS.Vol{7}=58;
BAS.Vol{8}=65;
BAS.Vol{9}=116;
BAS.Vol{10}=71;
BAS.Vol{11}=354;
BAS.Vol{12}=23;
BAS.Con{1}=[0.13,0.010,361,0.04,0.9,0.9];
BAS.Con{2}=[0.13,0.010,361,0.05,0.9,0.9];
BAS.Con{3}=[0.13,0.010,361,0.10,0.9,0.9];
BAS.Con{4}=[0.13,0.010,361,0.15,0.9,0.9];
BAS.Con{5}=[0.13,0.010,361,0.20,0.9,0.9];
BAS.Con{6}=[0.13,0.010,361,0.25,0.9,0.9];
BAS.Con{7}=[0.13,0.010,361,0.30,0.9,0.9];
BAS.Con{8}=[0.13,0.010,361,0.35,0.9,0.9];
BAS.Con{9}=[0.13,0.010,361,0.40,0.9,0.9];
BAS.Con{10}=[0.13,0.010,361,0.45,0.9,0.9];
BAS.Con{11}=[0.13,0.010,361,0.50,0.9,0.9];
BAS.Con{12}=[0.13,0.010,361,0.55,0.9,0.9];
BAS.Con{13}=[0.13,0.010,361,0.60,0.9,0.9];
BAS.Con{14}=[0.13,0.010,361,0.65,0.9,0.9];
BAS.Con{15}=[0.13,0.010,361,0.70,0.9,0.9];
BAS.Con{16}=[0.13,0.010,361,0.75,0.9,0.9];
BAS.Con{17}=[0.13,0.010,361,0.80,0.9,0.9];
BAS.Con{18}=[0.13,0.010,361,0.85,0.9,0.9];
BAS.Con{19}=[0.13,0.010,361,0.90,0.9,0.9];
BAS.Con{20}=[0.13,0.010,361,0.95,0.9,0.9];
BAS.Con{21}=[0.13,0.010,361,1.00,0.9,0.9];
BAS.Con{22}=[0.13,0.010,361,1.05,0.9,0.9];
BAS.Glas{1}=[5.7,0.01,0.80,0.80,0.01,5.7];
BAS.Glas{2}=[5.7,0.01,0.80,0.31,0.35,5.7];
BAS.Glas{3}=[3.2,0.03,0.70,0.70,0.03,3.2];
BAS.Or{1}=[90.0,180.0];
BAS.Or{2}=[90.0,-90.0];
BAS.Or{3}=[90.0,0.0];
BAS.Or{4}=[90.0,0.0];
BAS.Or{5}=[45.0,180.0];
BAS.Or{6}=[45.0,-90.0];
BAS.Or{7}=[45.0,0.0];
```

The impact of climate change on the indoor climate of monumental buildings
The impact of climate change on the indoor climate of monumental buildings

BAS.Or(8)=[45.0,90.0];
BAS.wallex(1)=[1,5.4,2,2,0];
BAS.wallex(2)=[1,47.4,2,3,0];
BAS.wallex(3)=[1,19.3,2,4,0];
BAS.wallex(4)=[1,14.1,6,5,0];
BAS.wallex(5)=[1,14.1,6,7,0];
BAS.wallex(6)=[2,26.7,2,3,0];
BAS.wallex(7)=[2,17.5,6,5,0];
BAS.wallex(8)=[2,17.5,6,7,0];
BAS.wallex(9)=[3,12.9,2,2,0];
BAS.wallex(10)=[3,11.3,2,3,0];
BAS.wallex(11)=[3,12.7,2,4,0];
BAS.wallex(12)=[3,51.7,6,5,0];
BAS.wallex(13)=[3,51.7,6,7,0];
BAS.wallex(14)=[4,3.9,3,2,0];
BAS.wallex(15)=[4,15.8,5,2,0];
BAS.wallex(16)=[4,5.2,5,3,0];
BAS.wallex(17)=[4,2.6,3,3,0];
BAS.wallex(18)=[4,11.8,3,4,0];
BAS.wallex(19)=[4,3.9,5,4,0];
BAS.wallex(20)=[4,6.1,5,6,0];
BAS.wallex(21)=[4,6.1,5,7,0];
BAS.wallex(22)=[4,6.1,5,8,0];
BAS.wallex(23)=[4,6.1,5,9,0];
BAS.wallex(24)=[5,15.4,1,1,0];
BAS.wallex(25)=[5,25.2,1,2,0];
BAS.wallex(26)=[5,19.8,1,3,0];
BAS.wallex(27)=[6,30.9,1,3,0];
BAS.wallex(28)=[7,5.1,1,3,0];
BAS.wallex(29)=[8,19.3,1,1,0];
BAS.wallex(30)=[9,25.4,1,1,0];
BAS.wallex(31)=[9,12.0,1,2,0];
BAS.wallex(32)=[9,12.7,1,3,0];
BAS.wallex(33)=[9,15.9,1,4,0];
BAS.wallex(34)=[9,10.6,7,5,0];
BAS.wallex(35)=[9,10.6,7,7,0];
BAS.wallex(36)=[11,40.7,1,1,0];
BAS.wallex(37)=[11,26.6,1,2,0];
BAS.wallex(38)=[11,36.0,1,3,0];
BAS.wallex(39)=[11,4.7,1,4,0];
BAS.wallex(40)=[11,19.6,7,5,0];
BAS.wallex(41)=[11,19.6,7,7,0];
BAS.window(1)=[2,8.5,2,0];
BAS.window(2)=[5,1.4,2,0];
BAS.window(3)=[10,7.6,2,0];
BAS.window(4)=[15,14.0,1,0];
BAS.window(5)=[16,4.5,1,0];
BAS.window(6)=[19,3.5,1,0];
BAS.window(7)=[20,5.7,3,0];
BAS.window(8)=[21,5.7,3,0];
BAS.window(9)=[22,5.7,3,0];
BAS.window(10)=[23,5.7,3,0];
BAS.window(11)=[24,4.0,2,0];
BAS.window(12)=[24,6.7,2,0];
BAS.window(13)=[27,13.4,2,0];
BAS.window(14)=[29,5.0,2,0];
BAS.window(15)=[30,4.7,2,0];
BAS.window(16)=[33,3.9,2,0];
BAS.window(17)=[36,10.8,2,0];
BAS.window(18)=[38,12.6,2,0];
The impact of climate change on the indoor climate of monumental buildings

BAS.walli0{1}=[1,59.3,8,10.0,0];
BAS.walli0{2}=[2,29.4,8,10.0,0];
BAS.walli0{3}=[4,19.4,8,10.0,0];
BAS.walli0{4}=[5,50.4,9,10.0,0];
BAS.walli0{5}=[6,42.3,9,10.0,0];
BAS.walli0{6}=[7,7.3,9,10.0,0];
BAS.walli0{7}=[8,9.2,9,10.0,0];
BAS.walli0{8}=[9,43.1,9,10.0,0];
BAS.walli0{9}=[10,39.4,11,10.0,0];
BAS.walli0{10}=[10,57.6,12,10.0,0];
BAS.walli0{11}=[12,6.7,9,10.0,0];
BAS.wallia{1}=[1,23.4,15];
BAS.wallia{2}=[1,24.0,16];
BAS.wallia{3}=[2,26.7,16];
BAS.wallia{4}=[2,14.4,17];
BAS.wallia{5}=[6,14.3,4];
BAS.wallia{6}=[6,20.0,14];
BAS.wallia{7}=[12,11.2,4];
BAS.wallia{8}=[12,14.3,14];
BAS.wallia{9}=[12,7.5,21];
BAS.wallia{10}=[11,21.9,4];
BAS.wallia{11}=[11,103.0,13];
BAS.wallin{1}=[1,1,10.9,4];
BAS.wallin{2}=[1,2,11.9,4];
BAS.wallin{3}=[1,3,36,13];
BAS.wallin{4}=[5,10,21.7,10];
BAS.wallin{5}=[5,5,19.8,4];
BAS.wallin{6}=[5,7,25.2,4];
BAS.wallin{7}=[5,9,4.4,1];
BAS.wallin{8}=[5,11,50.4,14];
BAS.wallin{9}=[6,6,14.9,4];
BAS.wallin{10}=[6,7,20.0,4];
BAS.wallin{11}=[6,8,21.1,4];
BAS.wallin{12}=[6,11,22.3,13];
BAS.wallin{13}=[7,8,11.2,4];
BAS.wallin{14}=[7,9,8.2,21];
BAS.wallin{15}=[7,10,9.9,10];
BAS.wallin{16}=[7,11,17.2,13];
BAS.wallin{17}=[8,8,11.2,4];
BAS.wallin{18}=[8,10,9.3,10];
BAS.wallin{19}=[8,11,10.9,13];
BAS.wallin{20}=[9,9,10.5,4];
BAS.wallin{21}=[9,4,2.0,18];
BAS.wallin{22}=[9,11,28.0,13];
BAS.wallin{23}=[10,10,5.8,1];
BAS.wallin{24}=[11,11,57.3,4];
BAS.wallin{25}=[11,11,50.2,20];
BAS.wallin{26}=[11,11,12.6,1];
BAS.wallin{27}=[6,12,6.8,4];
BAS.wallin{28}=[8,12,11.2,22];
BAS.dayper{1}=[8,12,14,17];
BAS.vvmin{1}=[2.5,2.5,2.5,2.5];
BAS.vvmax{1}=[1,1,1,1];
BAS.Tfc{1}=[100,100,100,100];
BAS.Qint{1}=[0,620,740,0];
BAS.Gint{1}=[0,28e-6,70e-6,0];
BAS.Tsetmin{1}=[-100,-100,-100,-100];
BAS.Tsetmax{1}=[100,100,100,100];
BAS.RVmin{1}=[-1,-1,-1,-1];
BAS.RVmax(1)=[101,101,101,101];
BAS.Ers(2)=300;
BAS.dayper(2)=[8,12,14,17];
BAS.vvmin(2)=[2.5,2.5,2.5,2.5];
BAS.vvmax(2)=[1,1,1,1];
BAS.Tfc(2)=[100,100,100,100];
BAS.Qint(2)=[0,0,0,0];
BAS.Gint(2)=[0,0,0,0];
BAS.Tsetmin(2)=[-100,-100,-100,-100];
BAS.Tsetmax(2)=[100,100,100,100];
BAS.RVmin(2)=[-1,-1,-1,-1];
BAS.RVmax(2)=[101,101,101,101];
BAS.Ers(3)=300;
BAS.dayper(3)=[8,12,14,17];
BAS.vvmin(3)=[2.5,2.8,3.0,2.5];
BAS.vvmax(3)=[1,1,1,1];
BAS.Tfc(3)=[100,100,100,100];
BAS.Qint(3)=[0,810,590,0];
BAS.Gint(3)=[0,0,56e-6,0];
BAS.Tsetmin(3)=[-100,-100,-100,-100];
BAS.Tsetmax(3)=[100,100,100,100];
BAS.RVmin(3)=[-1,-1,-1,-1];
BAS.RVmax(3)=[101,101,101,101];
BAS.Ers(4)=300;
BAS.dayper(4)=[8,12,14,17];
BAS.vvmin(4)=[2.7,2.7,2.7,2.7];
BAS.vvmax(4)=[1,1,1,1];
BAS.Tfc(4)=[100,100,100,100];
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BAS.Ers(5)=300;
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BAS.vvmax(5)=[1,1,1,1];
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BAS.Ers(7)=300;
BAS.dayper(7)=[8,12,14,17];
BAS.vvmin(7)=[4.0,4.0,4.0,4.0];
BAS.vvmax(7)=[1,1,1,1];
The impact of climate change on the indoor climate of monumental buildings
The impact of climate change on the indoor climate of monumental buildings

BAS.RVmin(12)=[-1,-1,-1,-1];
BAS.RVmax(12)=[101,101,101,101];
BAS.Ers(13)=300;
BAS.dayper(13)=[8,12,14,17];
BAS.vvmin(13)=[3.5,3.5,3.5,3.5];
BAS.vvmax(13)=[1,1,1,1];
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BAS.RVmax(13)=[101,101,101,101];
BAS.Ers(14)=300;
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BAS.vvmin(14)=[4.0,4.0,4.0,4.0];
BAS.vvmax(14)=[1,1,1,1];
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BAS.dayper(18)=[8,12,14,17];
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The impact of climate change on the indoor climate of monumental buildings
For the controlled condition, the used model is called ModelBTv2:
% HAMBASE Begijnhofmuseum 2008 Martijn Kivits
BAS.Vol(1)=206;
BAS.Vol(2)=115;
BAS.Vol(3)=106;
BAS.Vol(4)=51;
BAS.Vol(5)=161;
BAS.Vol(6)=138;

The impact of climate change on the indoor climate of monumental buildings
The impact of climate change on the indoor climate of monumental buildings
The impact of climate change on the indoor climate of monumental buildings

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The impact of climate change on the indoor climate of monumental buildings

BAS.RVmin(8)=[-1,-1,-1,-1];
BAS.RVmax(8)=[101,101,101,101];
BAS.Ers(9)=300;
BAS.dayper(9)=[8,12,14,17];
BAS.vvmin(9)=[2.0,2.3,2.5,2.0];
BAS.vvmax(9)=[1,1,1,1];
BAS.Tfc(9)=[100,100,100,100];
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BAS.Tsetmin(9)=[15,15,15,15];
BAS.Tsetmax(9)=[25,25,25,25];
BAS.RVmin(9)=[-1,-1,-1,-1];
BAS.RVmax(9)=[101,101,101,101];
BAS.Ers(10)=300;
BAS.dayper(10)=[8,12,14,17];
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BAS.vvmax(10)=[1,1,1,1];
BAS.Tfc(10)=[100,100,100,100];
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BAS.Tsetmin(10)=[15,15,15,15];
BAS.Tsetmax(10)=[25,25,25,25];
BAS.RVmin(10)=[-1,-1,-1,-1];
BAS.RVmax(10)=[101,101,101,101];
BAS.Ers(11)=300;
BAS.dayper(11)=[8,12,14,17];
BAS.vvmin(11)=[4.0,4.0,4.0,4.0];
BAS.vvmax(11)=[1,1,1,1];
BAS.Tfc(11)=[100,100,100,100];
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BAS.Gint(11)=[300e-6,300e-6,300e-6,300e-6];
BAS.Tsetmin(11)=[15,15,15,15];
BAS.Tsetmax(11)=[25,25,25,25];
BAS.RVmin(11)=[-1,-1,-1,-1];
BAS.RVmax(11)=[101,101,101,101];
BAS.Ers(12)=300;
BAS.dayper(12)=[8,12,14,17];
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BAS.Tsetmax(12)=[25,25,25,25];
BAS.RVmin(12)=[-1,-1,-1,-1];
BAS.RVmax(12)=[101,101,101,101];
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BAS.dayper(13)=[8,12,14,17];
BAS.vvmin(13)=[3.5,3.5,3.5,3.5];
BAS.vvmax(13)=[1,1,1,1];
BAS.Tfc(13)=[100,100,100,100];
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BAS.Tsetmin(13)=[15,15,15,15];
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BAS.RVmin(13)=[-1,-1,-1,-1];
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BAS.Ers(14)=300;
BAS.dayper(14)=[8,12,14,17];
BAS.vvmin(14)=[4.0,4.0,4.0,4.0];
The impact of climate change on the indoor climate of monumental buildings

BAS.vvmax(14)=[1, 1, 1, 1];
BAS.Tfc(14)=[100, 100, 100, 100];
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BAS.Tsetmin(14)=[15, 15, 15, 15];
BAS.Tsetmax(14)=[25, 25, 25, 25];
BAS.RVmin(14)=[-1, -1, -1, -1];
BAS.RVmax(14)=[101, 101, 101, 101];
BAS.Ers(15)=300;
BAS.dayper(15)=[8, 12, 14, 17];
BAS.vvmin(15)=[4.0, 4.0, 4.0, 4.0];
BAS.vvmax(15)=[1, 1, 1, 1];
BAS.Tfc(15)=[100, 100, 100, 100];
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BAS.Tsetmin(15)=[15, 15, 15, 15];
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BAS.RVmin(15)=[-1, -1, -1, -1];
BAS.RVmax(15)=[101, 101, 101, 101];
BAS.Ers(16)=300;
BAS.dayper(16)=[8, 12, 14, 17];
BAS.vvmin(16)=[4.0, 4.0, 4.0, 4.0];
BAS.vvmax(16)=[1, 1, 1, 1];
BAS.Tfc(16)=[100, 100, 100, 100];
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BAS.Tsetmin(16)=[15, 15, 15, 15];
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BAS.RVmin(16)=[-1, -1, -1, -1];
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BAS.Ers(17)=300;
BAS.dayper(17)=[8, 12, 14, 17];
BAS.vvmin(17)=[4.0, 4.0, 4.0, 4.0];
BAS.vvmax(17)=[1, 1, 1, 1];
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BAS.RVmin(17)=[-1, -1, -1, -1];
BAS.RVmax(17)=[101, 101, 101, 101];
BAS.Ers(18)=300;
BAS.dayper(18)=[8, 12, 14, 17];
BAS.vvmin(18)=[4.0, 4.0, 4.0, 4.0];
BAS.vvmax(18)=[1, 1, 1, 1];
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BAS.Tsetmin(18)=[15, 15, 15, 15];
BAS.Tsetmax(18)=[25, 25, 25, 25];
BAS.RVmin(18)=[-1, -1, -1, -1];
BAS.RVmax(18)=[101, 101, 101, 101];
BAS.Ers(19)=300;
BAS.dayper(19)=[8, 12, 14, 17];
BAS.vvmin(19)=[2.0, 2.0, 2.0, 2.0];
BAS.vvmax(19)=[1, 1, 1, 1];
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The impact of climate change on the indoor climate of monumental buildings
The impact of climate change on the indoor climate of monumental buildings

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<td>BAS.Gint(22)</td>
<td>[0, 0, 0, 0]</td>
</tr>
<tr>
<td>BAS.Tsetmin(22)</td>
<td>[15, 15, 15, 15]</td>
</tr>
<tr>
<td>BAS.Tsetmax(22)</td>
<td>[25, 25, 25, 25]</td>
</tr>
<tr>
<td>BAS.RVmin(22)</td>
<td>[-1, -1, -1, -1]</td>
</tr>
<tr>
<td>BAS.RVmax(22)</td>
<td>[101, 101, 101, 101]</td>
</tr>
<tr>
<td>BAS.Ers(23)</td>
<td>300</td>
</tr>
<tr>
<td>BAS.dayper(23)</td>
<td>[8, 12, 14, 17]</td>
</tr>
<tr>
<td>BAS.vvmin(23)</td>
<td>[4.0, 4.0, 4.0, 4.0]</td>
</tr>
<tr>
<td>BAS.vvmax(23)</td>
<td>[1, 1, 1, 1]</td>
</tr>
<tr>
<td>BAS.Tfc(23)</td>
<td>[100, 100, 100, 100]</td>
</tr>
<tr>
<td>BAS.Qint(23)</td>
<td>[0, 0, 0, 0]</td>
</tr>
<tr>
<td>BAS.Gint(23)</td>
<td>[200e-6, 200e-6, 200e-6, 200e-6]</td>
</tr>
<tr>
<td>BAS.Tsetmin(23)</td>
<td>[15, 15, 15, 15]</td>
</tr>
<tr>
<td>BAS.Tsetmax(23)</td>
<td>[25, 25, 25, 25]</td>
</tr>
<tr>
<td>BAS.RVmin(23)</td>
<td>[-1, -1, -1, -1]</td>
</tr>
<tr>
<td>BAS.RVmax(23)</td>
<td>[101, 101, 101, 101]</td>
</tr>
<tr>
<td>BAS.weekfun(1)</td>
<td>[3, 3, 3, 3, 21, 21]</td>
</tr>
<tr>
<td>BAS.weekfun(2)</td>
<td>[1, 1, 1, 1, 2, 2]</td>
</tr>
<tr>
<td>BAS.weekfun(3)</td>
<td>[4, 4, 4, 4, 2, 2]</td>
</tr>
<tr>
<td>BAS.weekfun(4)</td>
<td>[5, 5, 5, 5, 22, 22]</td>
</tr>
<tr>
<td>BAS.weekfun(5)</td>
<td>[6, 6, 6, 6, 6, 23, 23]</td>
</tr>
<tr>
<td>BAS.weekfun(6)</td>
<td>[7, 7, 7, 7, 18, 18]</td>
</tr>
<tr>
<td>BAS.weekfun(7)</td>
<td>[8, 8, 8, 8, 17, 17]</td>
</tr>
<tr>
<td>BAS.weekfun(8)</td>
<td>[9, 9, 9, 9, 19, 19]</td>
</tr>
<tr>
<td>BAS.weekfun(9)</td>
<td>[10, 10, 10, 10, 10, 16, 16]</td>
</tr>
<tr>
<td>BAS.weekfun(10)</td>
<td>[11, 11, 11, 11, 11, 12, 12]</td>
</tr>
<tr>
<td>BAS.weekfun(11)</td>
<td>[15, 15, 15, 15, 15, 14, 14]</td>
</tr>
<tr>
<td>BAS.weekfun(12)</td>
<td>[13, 13, 13, 13, 13, 20, 20]</td>
</tr>
<tr>
<td>BAS.Plant(1)</td>
<td>[-1, -100000, 0, 0]</td>
</tr>
</tbody>
</table>
The impact of climate change on the indoor climate of monumental buildings

6.6 MATLAB-files of the Multi Museum Model.

Execution of all desired steps:

% HAMBASE Multi Museum Model
%
% execute all steps:
% Step 1: Initialization of all buildings
% Step 2: Validation of all buildings
% Step 3: Variants for all buildings
% Step 4: Calculate (this might take a long time)
% Step 5: Create output plots
%
% This might take a long time and a large amount of memory!
%
% Changes made to HAMbase:
% - Input extra-files in functional form
HambaseMMMstep1
%HambaseMMMstep2
HambaseMMMstep3
HambaseMMMstep4
HambaseMMMstep5v1

Step 1:
% HAMBASE Multi Museum Model
% Step 1: Initialization of all buildings
% Define the model file and the extra model file

clear all

% Kasteel Gaasbeek:
% Free floating:
% ModelKG
% conditioned between 15 and 25 degC:
% ModelKGv1
Building{1}.Original.Extra='ModelBTextra';
Building{1}.Original.BAS=BAS;
clear BAS

% Begijnhof museum:
% Free floating:
% ModelBTv1
% conditioned between 15 and 25 degC:
% ModelBTv2
Building{1}.Original.Extra='ModelBTextra';
Building{1}.Original.BAS=BAS;
clear BAS

Step 2 is omitted, because the models have already been validated.

Step 3:
% HAMBASE Multi Museum Model
% Step 3: Variants for all buildings
% No changes are allowed to the model and extra model file
% Individual changes in the original model parameters are included in
% the first part
% Changes in original model parameters FOR ALL BUILDINGS are included
% in the second part
% Individual changes in the extra file parameters are included in the
% third part
% Changes in the extra file parameters FOR ALL BUILDINGS are included
% in the fourth part
% MM 20091201
if ~exist('Building','var')
  load Buildings
end
% PART 1:
% CHANGES TO THE ORIGINAL DATA (construction, profiles, period etc.)
% Building{x}.Var{y}.BAS.Vol{n}
% Building{x}.Var{y}.BAS.Con{n}
% Building{x}.Var{y}.BAS.Glas{n}
% Building{x}.Var{y}.BAS.Or{n}
% Building{x}.Var{y}.BAS.wallex{n}
% Building{x}.Var{y}.BAS.window{n}
% Building{x}.Var{y}.BAS.walli0{n}
% Building{x}.Var{y}.BAS.wallia{n}
% Building{x}.Var{y}.BAS.wallin{n}
% Building{x}.Var{y}.BAS.Ers{n}
% Building{x}.Var{y}.BAS.dayper{n}
The impact of climate change on the indoor climate of monumental buildings

% Building{x}.Var{y}.BAS.vvmin{n}
% Building{x}.Var{y}.BAS.vvmax{n}
% Building{x}.Var{y}.BAS.Tfc{n}
% Building{x}.Var{y}.BAS.Qint{n}
% Building{x}.Var{y}.BAS.Gint{n}
% Building{x}.Var{y}.BAS.Tsetmin{n}
% Building{x}.Var{y}.BAS.Tsetmax{n}
% Building{x}.Var{y}.BAS.RVmin{n}
% Building{x}.Var{y}.BAS.RVmax{n}
% Building{x}.Var{y}.BAS.weekfun{n}
% Building{x}.Var{y}.BAS.Plant{n}
% Building{x}.Var{y}.BAS.convfac{n}
% Building{x}.Var{y}.BAS.heatexch{n}
% NB: start each variant with Building{x}.Var{y}=Building{x}.Original;

% simulate 100 years at once:
for i=1:1
Building{1}.Var{i}=Building{1}.Original;
Building{1}.Var{i}.BAS.Period=[2000-1+i,1,1,36525];
end

% simulate 1 variant per year:
% for i=1:100
% Building{1}.Var{i}=Building{1}.Original;
% Building{1}.Var{i}.BAS.Period=[2000-1+i,1,1,365];
% end

% PART 2:
% CHANGES IN THE ORIGINAL DATA FOR 1 VARIANT OF ALL BUILDINGS
j=1;% determine which variant
for i=1:length(Building)
    if isfield(Building{i},'Original')
        Building{i}.Var{j}=Building{i}.Original;
        for k=1:length(Building{i}.Var{j}.BAS.vvmin)
% make changes to 1 parameter for all zones in the model (e.g. increase by 20 percent)
            Building{i}.Var{j}.BAS.vvmin{k}=Building{i}.Var{j}.BAS.vvmin{k}*1.2;
        end
        Building{i}.Var{j}.BAS.Period=[2000,1,1,36];
    end
end
% clear i j k

% EXECUTE HAMBASEFUN1009: Do not change this part
for i=1:length(Building)
    if isfield(Building{i},'Var')
        for j=1:length(Building{i}.Var)
            [Building{i}.Var{j}.Control,Building{i}.Var{j}.Profiles,Building{i}.Var{j}.InClimate,Building{i}.Var{j}.InBuild]=Hambasefun1009(Building{i}.Var{j}.BAS);
            eval(['Building{i}.Var{j}.BAS=' Building{i}.Original.Extra '(Building{i}.Var{j}.BAS);']);
        end
    end
% PART 3:
% CHANGES TO THE EXTRA DATA (delTstook, hygrostatic heating etc.)
% Building{x}.Var{y}.BAS
% Building{x}.Var{y}.BAS.nin
% Building{x}.Var{y}.BAS.etainst
% Building{x}.Var{y}.BAS.rho
% Building{x}.Var{y}.BAS.oriennr
% Building{x}.Var{y}.BAS.maxuur
% Building{x}.Var{y}.BAS.station
% Building{x}.Var{y}.BAS.Fanger{x}
% Building{x}.Var{y}.BAS.betglas
% Building{x}.Var{y}.BAS.hcvlink{x}
% Building{x}.Var{y}.BAS.shadow
% Building{x}.Var{y}.BAS.shad{x}
% Building{x}.Var{y}.BAS.daylight
% Building{x}.Var{y}.BAS.furnish
% Building{x}.Var{y}.BAS.furnishings{x}
% Building{x}.Var{y}.BAS.Interzonal
% Building{x}.Var{y}.BAS.Linkv{x}
% Building{x}.Var{y}.BAS.weekfunlinkv
% Building{x}.Var{y}.BAS.infiltration
% Building{x}.Var{y}.BAS.Lekex{x}
% Building{x}.Var{y}.BAS.Lekin{x}
% Building{x}.Var{y}.BAS.mechvfac{x}
% Building{x}.Var{y}.BAS.ConcenX
% Building{x}.Var{y}.BAS.Xprod{x}
% Building{x}.Var{y}.BAS.Evap
% Building{x}.Var{y}.BAS.watermass{x}
% Building{x}.Var{y}.BAS.watersurface{x}
% Building{x}.Var{y}.BAS.Gint{x}
% Building{x}.Var{y}.BAS.Tempstrat
% Building{x}.Var{y}.BAS.Facstrat{x}=0;
% Building{x}.Var{y}.BAS.heatingtimeconstant
% Building{x}.Var{y}.BAS.taucontrol{x}
% Building{x}.Var{y}.BAS.heatingtemperaturediff
% Building{x}.Var{y}.BAS.delTstook{x}
% Building{x}.Var{y}.BAS.hygrostatcontrol
% Building{x}.Var{y}.BAS.hygrostat{x}
% Building{x}.Var{y}.BAS.surfheating
% Building{x}.Var{y}.BAS.Flheat
% Building{x}.Var{y}.BAS.airflowwindow
% Building{x}.Var{y}.BAS.Airflwin=Airflwin

% PART 4:
% CHANGES IN THE EXTRA DATA FOR 1 VARIANT OF ALL BUILDINGS
% j=1;% determine which variant
% for i=1:length(Building)
%    if isfield(Building{i},'Original')
%       Building{i}.Var{j}=Building{i}.Original;
%    for k=1:length(Building{i}.Var{j}.BAS.furnishings)
%        Building{i}.Var{j}.BAS.furnishings{k}=[100,0.2];%Make
%        changes to 1 parameter for all zones in the model
%    end
% end
% clear i j k
Step 4:

% HAMBASE Multi Museum Model
% Step 4: Calculate (this might take a long time)
% MM 20091201
if ~exist('Building','var')
    load Buildings
end

for i=1:length(Building)
    if isfield(Building(i),'Validation')
        disp(['Validating building ' num2str(i) ' of ' num2str(length(Building)) '.'])
        [Building(i).Validation.Control,Building(i).Validation.Profiles,Building{i}.Validation.InClimate,Building(i).Validation.InBuil]=Hambasefun1009(Building{i}.Validation.BAS);
        if isfield(Building{i},Var)
            for j=1:length(Building{i}.Var)
                disp(['Calculating building ' num2str(i) ' of ' num2str(length(Building)) '; variant ' num2str(j) ' of ' num2str(length(Building{i}.Var)) '.'])
                [Building{i}.Var{j}.Output,Building{i}.Var{j}.Control,Building{i}.Var{j}.Elan]=Wavox1009(Building{i}.Var{j}.Control,Building{i}.Var{j}.Profiles,Building{i}.Validation.InClimate,Building{i}.Var{j}.InBuil);
            end
        end
    end
end

clear i j

save -v7.3 Buildings Building

Step 5:

% HAMBASE Multi Museum Model
% Step 5: Output
% MM 20091201
if ~exist('Building','var')
    load Buildings
end

% validationstep % .m-file for validation.

% ASHRAEv2 % .m-file which generates the CETC's and calculates per year the percentage of time that the ASHRAE-criteria have not been met and stores the values in CETC_cell. ASHRAE criteria: dT/h, dT/day, dRH/h, dRH/day, minT, maxT, minRH, maxRH.
ASHRAEv2

% create CETC_cell1 (from per year to per decade) and CETC_cellNorm
% (subtract initial value).
normalize

% function that creates plot:
figure(1)
graph_type1(CETC_cell1)

% function that creates plot:
figure(2)
graph_type1_norm(CETC_cellNorm)

% Calculates the annual energy demand and stores the values in Qheat, Qcool and Qtot:
annual_energy_v1

% m-file that creates plot of energy demand, per volume:
figure(3)
graph_energy

% stores the powers for heating and cooling combined in a cell structure: per decade 1 column (total 10 columns)
power_cell

% m-file that creates one box plot per volume in a subplot:
figure(4)
power_boxplot

% print(figure(1),'-dpng','-r300','BegijnhofControlled_ASHRAE_3')
% print(figure(2),'-dpng','-r300','BegijnhofControlled_ASHRAE_normalized_3')
% print(figure(3),'-dpng','-r300','BegijnhofControlled_energyDemand_3')
% print(figure(4),'-dpng','-r300','BegijnhofControlled_powerDemand_3')
% clear all

6.7 MATLAB-files for generating output in step 5 of MMM-model.
ASHRAEv2:

% ASHRAEv2 % .m-file which generates the CETC's and calculates per year the percentage of time that the ASHRAE-criteria have not been met and stores the values in CETC_cell.
% ASHRAE criteria: dT/h, dT/day, dRH/h, dRH/day, minT, maxT, minRH, maxRH.
% This file works if per 100 year 1 simulation run is used, otherwise use file ASHRAEv1.
% preallocating CETC_cell for improving speed.
CETC_cell=cell(1,length(Building{1}.Var{1}.BAS.Vol));
load yearcolumn2000_2099

% correction for BAS.Period in order to provide the right input for CETC.
Building{1}.Var{1}.BAS.Period=[2000,1,1,365];

for k=1:length(Building{1}.Var{1}.BAS.Vol)
    CETC_array = zeros(100,8);
    for j=1:100
        y=find(yearcolumn2000_2099==(j+1999));
        disp(['Plotting building ' num2str(1) ' of ' num2str(length(Building)) '; variant ' num2str(1) ' of ' num2str(length(Building{1}.Var)) '; zone ' num2str(k) ' of ' num2str(length(Building{1}.Var{1}.BAS.Vol)) '; year ' num2str(j) ' of ' num2str(99) '.'])
        
        %percentage of time below Tmin criterion:
        numbTmin=find(Building{1}.Var{1}.Output.Ta(y,k)<15);
        percTmin=(length(numbTmin)/length(y))*100;

        %percentage of time above Tmax criterion:
        numbTmax=find(Building{1}.Var{1}.Output.Ta(y,k)>25);
        percTmax=(length(numbTmax)/length(y))*100;

        %percentage of time below RHmin criterion:
        numbRHmin=find(Building{1}.Var{1}.Output.RHa(y,k)<0.40);
        percRHmin=(length(numbRHmin)/length(y))*100;

        %percentage of time above RHmax criterion:
        numbRHmax=find(Building{1}.Var{1}.Output.RHa(y,k)>0.60);
        percRHmax=(length(numbRHmax)/length(y))*100;

        % output from CETC:
        [tover_dTperh, tover_dTperday, tover_dRHperh, tover_dRHperday
         ] = CETC(Tdata,RHdata,period,title,demname,mint,maxt,minrh,maxrh,uurrh,dagrh,Taxismin,Taxismax,Twidth,Xwidth,histo,adan,lang,ori,savename,quality)
        \{tover_dTperh, tover_dTperday, tover_dRHperh, tover_dRHperday
         
        CETC_array(j,:)=\{tover_dTperh, tover_dTperday, tover_dRHperh, tover_dRHperday
         
        close all
    end
% cell array CETC_cell(buildings, volumes)(in cells CETC_array's):
CETC_cell{1,k}=CETC_array;
The impact of climate change on the indoor climate of monumental buildings

Normalize:
% transform from per year to per decade and normalizing the data (subject initial value).

\[
k = \text{length(CETC\_cell)};
\]

\[
h = 10;
\]

\[
\text{for } i = 1:k
\]
\[
\text{for } j = 1:8
\]
\[
\text{for } t = 1:10
\]
\[
y = (t\times h - h + 1):1:(t\times h);
\]
\[
\text{CETC\_cell1{1,i}(t,j)} = \text{mean(CETC\_cell{1,i}(y,j))};
\]
\[
\text{end}
\]
\[
\text{end}
\]
\[
\text{end}
\]

\[
\text{for } i = 1:k
\]
\[
\text{for } j = 1:8
\]
\[
\text{m} = \text{CETC\_cell1{1,i}(1,j)};
\]
\[
\text{CETC\_cellNorm{1,i}(:,j)} = \text{CETC\_cell1{1,i}(:,j)} - m;
\]
\[
\text{end}
\]
\[
\text{end}
\]

\[
\text{clear } k\ y\ h\ m\ i\ j\ t
\]

\[
\text{graph\_type1(CETC\_cell1)}: \\
\text{function }\text{graph\_type1(a)}
\]
\[
% This file can plot the results of CETC\_cell1 and CETC\_cellNorm in graph (for every volume one subplot).
\]
\[
x = 1:10;\quad % x-as.
\]
\[
v = \text{length(a)};
\]
\[
t = \text{cell(v/2)};\quad \% \text{subplot always 2 rows, but } t \text{ columns.}
\]
\[
\text{for } k = 1:v
\]
\[
\text{subplot(t,2,k)}
\]
\[
\text{plot(x,a{1,k}(:,1),'-or',x,a{1,k}(:,2),'-og',x,a{1,k}(:,3),'-sr',x,a{1,k}(:,4),'-sg',x,a{1,k}(:,5),'-ok',x,a{1,k}(:,6),'-ob',x,a{1,k}(:,7),'-sk',x,a{1,k}(:,8),'-sb')}
\]
\[
\text{xlabel('time [decades]')}\]
\[
\text{ylabel('percentage of time [%]')}
\]
\[
\text{volumenaam=sprintf('volume %d')}
\]
\[
\text{title(volumenaam)}
\]
\[
%\text{legend('>5degC/h', '>5degC/day', '>10%RH/h', '>10%RH/day', '<15degC', '>25degC', '<40%RH', '>60%RH')}
\]
\[
\text{end}
\]

\[
\text{end}
\]

\[
\text{graph\_type1\_norm(CETC\_cellNorm)}: \\
\text{function }\text{graph\_type1\_norm(a)}
\]
The impact of climate change on the indoor climate of monumental buildings

% This file can plot the results of CETC_cell1 and CETC_cellNorm in graph (for every volume one subplot).

x=1:10; % x-as.
v=length(a);
t=ceil(v/2); % subplot always 2 rows, but t columns.
for k=1:v
    subplot(t,2,k)
    plot(x,a(1,k)(:,1),'-or',x,a(1,k)(:,2),'-og',x,a(1,k)(:,3),'-sr',x,a(1,k)(:,4),'-sg',x,a(1,k)(:,5),'-ok',x,a(1,k)(:,6),'-ob',x,a(1,k)(:,7),'-sk',x,a(1,k)(:,8),'-sb')
xlabel('time [decades]')
ylabel('percentage change of time [%]')
volumenaam=sprintf('volume %d', k);
title(volumenaam)
legend('>5degC/h', '>5degC/day', '>10%RH/h', '>10%RH/day', '<15degC', '<25degC', '<40%RH', '<60%RH', 'Orientation', 'horizontal')
end

end

annual_energy_v1:
% annual heating and cooling demand for the period 2000 - 2099.
% File building contains 1 building and 1 variant.
% Period is simulated at once over the period 2000-2099.

h=87660; % number of hours in 10 years (1 decade).
for k=1:length(Building{1}.Var{1}.BAS.Vol)
    for j=1:10
        y=(j*h-h+1):1:(j*h);
        y1 = Building{1}.Var{1}.Output.Qplant(y,k);
        Qcool(j,k)= ((sum(y1(y1<0)))/1000)*-1;
        Qheat(j,k)= (sum(y1(y1>0)))/1000;
        Qtot(j,k)= Qcool(j,k)+ Qheat(j,k); % total energy demand per decade.
    end
end

clear h y y1

graph_energy:
% plot heating demands in graph (for every volume one subplot).

x=1:10; % x-as.
[z, v]=size(Qheat);
t=ceil(v/2); % subplot always 2 rows, but t columns.
for k=1:v
    subplot(t,2,k)
    plot(x,Qheat(:,k),'-or',x,Qcool(:,k),'-ob',x,Qtot(:,k),'-.k')
xlabel('time [decades]')
ylabel('energy [kWh]')
volumenaam=sprintf('volume %d', k);
title(volumenaam)
end
clear x z v t

**power_cell:**
% power for heating and cooling for the period 2000 - 2099 visualized in a boxplot.
% File building contains 1 building and 1 variant.
% Period is simulated at once over the period 2000-2099.

\[ h = 87660; \] % hours in 10 years.

\[ v \text{=} \text{length(Building{1}.Var{1}.VOL}); \] % number of volumes

\[ \text{powercell} = \text{cell}(1,v); \]

\textbf{for} \[ k = 1:v \]
  \textbf{for} \[ j = 1:10 \]
    \[ y = (j*h-h+1):1:(j*h); \]
    \[ yl = \text{Building{1}.Var{1}.Output.Qplant}(y,k); \]
    \[ \text{power_array}(;,:j) = yl; \]
  \textbf{end}

\[ \text{powercell}(1,k) = \text{power_array}; \]
\textbf{end}

clear h v y yl power_array

**power_boxplot:**
% plots the box plots of the powers for heating (positive)
% and cooling (negative). One box plot per decade.

\[ v = \text{length(powercell)}; \] % number of volumes

\( t = \text{ceil}(v/2); \) % subplot always 2 rows, but \( t \) columns.

\textbf{for} \[ k = 1:v \]
  \textbf{subplot}(t,2,k)
  \textbf{boxplot(powercell}(1,k){:,:1:10));
  \textbf{xlabel('decades from 2000 to 2099')}
  \textbf{ylabel('\text{power [W]}')}
  \textbf{volume=sprintf('volume%d', k)};
  \textbf{title(volume)}
\textbf{end}

clear v t

6.8 **MATLAB-file ‘solcum’.**

This file calculates the cumulative energy per square meter of direct and diffuse solar radiation and compares these for respectively the measured and simulated climate data.
% First load the files (measured) mt2001, mt2002, mt2003, mt2004 and (simulated) climate2000_2099

% generating array with measured diffuse radiation.
gemeten_diffuse=zeros(8760,4);
gemeten_diffuse(:,1)=cumsum(mt2001(:,1))/1000;
gemeten_diffuse(:,2)=cumsum(mt2002(:,1))/1000;
gemeten_diffuse(:,3)=cumsum(mt2003(:,1))/1000;
gemeten_diffuse(:,4)=cumsum(mt2004(1:8760,1))/1000;
% generating array with measured direct radiation.
gemeten_direct=zeros(8760,4);
gemeten_direct(:,1)=cumsum(mt2001(:,3))/1000;
gemeten_direct(:,2)=cumsum(mt2002(:,3))/1000;
gemeten_direct(:,3)=cumsum(mt2003(:,3))/1000;
gemeten_direct(:,4)=cumsum(mt2004(1:8760,3))/1000;
% generating array with simulated diffuse radiation.
sim_diffuse=zeros(8760,4);
y=find(climate2000_2099(:,10)==2001);
sim_diffuse(:,1)=cumsum(climate2000_2099(y,1))/1000;
y=find(climate2000_2099(:,10)==2002);
sim_diffuse(:,2)=cumsum(climate2000_2099(y,1))/1000;
y=find(climate2000_2099(:,10)==2003);
sim_diffuse(:,3)=cumsum(climate2000_2099(y,1))/1000;
y=find(climate2000_2099(:,10)==2004);
sim_diffuse(:,4)=cumsum(climate2000_2099(y(1:8760),1))/1000;
% generating array with simulated direct radiation.
sim_direct=zeros(8760,4);
y=find(climate2000_2099(:,10)==2001);
sim_direct(:,1)=cumsum(climate2000_2099(y,3))/1000;
y=find(climate2000_2099(:,10)==2002);
sim_direct(:,2)=cumsum(climate2000_2099(y,3))/1000;
y=find(climate2000_2099(:,10)==2003);
sim_direct(:,3)=cumsum(climate2000_2099(y,3))/1000;
y=find(climate2000_2099(:,10)==2004);
sim_direct(:,4)=cumsum(climate2000_2099(y(1:8760),3))/1000;

x=1:8760;
for i=1:4
    subplot(2,2,i)
    plot(x,gemeten_diffuse(:,i),'-r',x,sim_diffuse(:,i),'-r',x,gemeten_direct(:,i),'-b',x,sim_direct(:,i),'-b')
xlabel('time [hours]')
ylabel('energy [kWh/m2]')
year=sprintf('year %d', 2000+i);
title(year)
legend('measured diffuse', 'simulated diffuse', 'measured direct', 'simulated direct', 'Orientation', 'Horizontal')
end

clear i x y


The file histoT generates sub plots of histograms to show the hourly distribution of temperatures per decade from 2000 to 2099.

% Extract temperatures in degC from file climate2000_2099 and round.
load climate2000_2099
Tround=round((climate2000_2099(:,2))/10);

The impact of climate change on the indoor climate of monumental buildings
The impact of climate change on the indoor climate of monumental buildings

% Add year column.
Tround(:,2)=climate2000_2099(:,10);

% First column of histoT is temperature range from -20 to +40 degC.
histo_T(:,1)=(-20:1:40);

% Number of hours in 10 years.
h=87660;

% Plot 10 figures with hour division of temperatures over a period of 10
% years. From 2001 to 2010 and from 2011 to 2020 etc...
for j=1:10
    % 10 periods.
    k=(j*h-h+1):1:(j*h);
    for i=1:61
        % outside temperatures i-21: -20 to +40 degC.
        y=find(Tround(k,1)==(i-21));
        y1=length(y);
        % counting number of rows, in other words:
        number of hours that T occurred.
        histo_T(i,j+1)=y1;
    end
    subplot(5,2,j)
    bar(histo_T(:,1),histo_T(:,j+1))
    periode=sprintf('decade %d', j);
    title(periode)
    axis([-10 35 0 7000])
end

clear h i j k y y1 periode Tround

The file histoT_2000_2009 generates subplots of histograms to compare between measured and simulated values of the hourly distribution of temperatures from 2000 to 2009.

% Extract temperatures in degC from file climate2000_2099 and round.
%load climate2000_2099

% Number of hours in 10 years.
h=87660;

Tround=round((climate2000_2099(1:h,2))/10);

% First column of histoT is temperature range from -20 to +40 degC.
histo_T(:,1)=(-20:1:40);

% Plot figure with hour division of temperatures over a period of 10
% years. From 2000 to 2009
for i=1:61
    % outside temperatures i-21: -20 to +40 degC.
    y=find(Tround(:,1)==(i-21));
    y1=length(y);
    % counting number of rows, in other words:
    number of hours that T occurred.
    histo_T(i,2)=y1;
end
The impact of climate change on the indoor climate of monumental buildings

T1=[mt2000(:,2); mt2001(:,2); mt2002(:,2); mt2003(:,2); mt2004(:,2);
    mt2005(:,2); mt2006(:,2); mt2007(:,2); mt2008(:,2); mt2009(:,2)];

T1round=round((T1)/10);

for i=1:61
    % outside temperatures i-21: -20 to +40 degC.
    y=find(T1round(:,1)==(i-21)); % looking for rows in which T occurs.
    y1=length(y); % counting number of rows, in other words:
                   % number of hours that T occured.
    histo_T(i,3)=y1;
end

subplot(1,2,1)
bar(histo_T(:,1),histo_T(:,2))
xlabel('temperature [degC]');
ylabel('number of hours [-]');
title('2000-2009');
axis([-10 35 0 6000])

subplot(1,2,2)
bar(histo_T(:,1),histo_T(:,3))
xlabel('temperature [degC]');
ylabel('number of hours [-]');
title('2000-2009');
axis([-10 35 0 6000])

print(figure(1),'-dpng','-r300','histoT1')
clear h i j k y y1 periode Tround
6.10 Explanation of the Climate Evaluation Chart.

The main primary quantities related indoor (air) climates of uniform single zones are the time series of the: Temperature T(t), Relative Humidity RH(t) and total power P(t) to the zone from the systems, where the total power is the sum of heating, cooling and (de)humidification. In order to analyze these key time series we developed so-called Climate Evaluation Charts (CEC) /11/, shown in Figure 6.

![Climate Evaluation Chart](image)

**Figure 6: The Climate Evaluation Chart (CEC)**

The interpretation of the chart is explained (the data itself are not important at this moment). The background of the chart is a standard psychometric chart for air, with on the horizontal axis the specific humidity, on the vertical axis the temperature and curves for the relative humidity. Area 2 shows the performance demands on: (1) indoor climate boundaries: minimum and maximum temperature and relative humidity (min T, max T, min RH and max RH) and (2) indoor climate change rate boundaries: maximum allowed hourly and daily changes in temperatures and relative humidities (DeltaTh, DeltaT24, DeltaRH, DeltaRH24). Area 1 shows the indoor climate boundaries and the simulated indoor climate of a building exposed to a Dutch standard test reference year. The simulated indoor climate is presented by seasonal (Spring from March 21 till June 21, etc.) colors representing the percentage of time of occurrence and seasonal weekly averages. The colors visualize the indoor climate distribution. For example, a very stable indoor climate produces a narrow spot, in contradiction to a free floating climate which
produces a large 'cloud' of data entries. Area 3 provides the corresponding legend. Area 5 shows the total percentage of time of occurrence of areas in the psychometric chart (9 areas). In this example 73% of the time the indoor climate is within the climate boundaries; the area to the left (too dry) occurs 10% of the time, the area to the right (too humid) occurs 17% of the time. The climates in the other 6 regions do not occur. Below area 5 the same information can be found for each season separately. Area 4 shows the energy consumption (unit: m³ gas / m³ building volume) and required power (unit: W/m³ building volume) used for heating (lower), cooling (upper), humidification (left) and dehumidification (right), assuming 100% efficiencies. In this example the energy amount is 3.92 m³ (gas / m³ building volume) and required power is 82.51 (W/m³ building volume) used for heating. Cooling, humidification and dehumidification are zero in this example. Area 6 presents the occurrence (in percentage of time) outside the climate change rate boundaries. In the example the demand of maximum allowed hourly change of temperature of 5 (°C/hour) is shown as a blue line. The distribution per season is provided together with the percentage of time of out of limits. In this example, area 6 shows that only 1% of the time, the hourly temperature rate of change is out of limits. This is also specified for each season. Below area 6 the same can be found for the other climate rate of change boundaries. Especially for comparing two indoor climates we developed also a so-called Multi Climate Evaluation Chart, shown in Figure 7.

Figure 7: The Multi Climate Evaluation Chart (MCEC)
6.11 Results Begijnhof museum volumes 5 to 12.

Free floating conditions:

Figure 6.1: the percentage of time per decade, that the criteria are met for volumes 5 to 10.
Figure 6.2: the percentage of time per decade, that the criteria are met for volumes 11 to 12.

Figure 6.3: the plots show the change of percentage of time per decade, that the criteria are met for volumes 5 to 8. These are normalized (the first value is subtracted from the dataset).
Figure 6.4: the plots show the change of percentage of time per decade, that the criteria are met for volumes 9 to 12. These are normalized (the first value is subtracted from the dataset).
Conditioned climate:

Figure 6.5: the percentage of time per decade, that the criteria are met for volumes 5 to 10.
Figure 6.6: the percentage of time per decade, that the criteria are met for volumes 11 to 12.
Figure 6.7: the plots show the change of percentage of time per decade, that the criteria are met for volumes 5 to 12. These are normalized (the first value is subtracted from the dataset).
Figure 6.8: the plots show the energy demand per decade (heating, cooling and the total demand: heating + cooling) for the volumes 5 to 12.
Figure 6.9: power demands of Begijnhof volumes 5 to 12, presented in one box plot per 10 years: positive values represent heating and negative values represent cooling.