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Indoor climate assessment and improved HVAC control for energy savings in museums
a case study for the Amsterdam Museum

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Preface

This report is the result of my graduation project on indoor climate assessment and improved HVAC control for energy savings in museums. The research is part of K. Kompatscher's PhD study in which several museums are analyzed regarding this topic. This research specifically focusses on the Amsterdam Museum, the Netherlands. The project is part of the master specialization Building Physics and Services at Eindhoven University of Technology and was conducted from March 2015 to June 2016.

I would like to thank my supervisors Henk Schellen, Karin Kompatscher and Rick Kramer for the guidance and critical reflection during the process. They were always cheerful and helpful to me which motivates a lot. I really appreciate that they were always available and willing to answer my questions.

I would also like to say a word of thanks to other staff members of the Eindhoven University of Technology. Marcel van Aarle, Jan Diepens and Wout van Bommel of the laboratory provided advice and prepared and processed measurements. Jos van Schijndel taught me how to calibrate the HAMBASE model. Marco Martens answered questions about his thesis and the measurement database.

I would like to say a word of thanks to the employees of the Amsterdam Museum. Special thanks to Peter Jacobs (head of building department & facility's), Patrick de Boer (technical and facility services) and Jeroen Boersma (system administrator) for providing information on the museum and for giving their consent for carrying out measurements. It was a pleasant cooperation. I was able to perform the project my own way and support was provided when needed. In addition, I would like to thank Marysa Otte (management and conservation) for the explanation of museum objects during a guided tour.

In addition, I want to express my gratitude to Dick Severijnse of the company Honeywell for providing information on the control strategy and Building Management System. Finally, I would like to thank Vincent Alexander of the company Imtech/Kropman for installing measurement equipment to the Air Handling Unit and for providing information on this system.

Finally, I would like to thank my friends and family for keeping me motivated and debating issues. I would like to express my gratitude for their support in every way.

I hope you will enjoy reading.

Silke Seuren

Eindhoven, June 29, 2016

Abstract

In the 20th century, climate control went hand in hand with the development of advanced techniques. The capability of HVAC system determined the level of climate conditioning. The notion of an optimal museum climate had evolved to 'the more stable, the better.' Therefore, (historical) buildings were equipped with a lot of Air Handling Units, which had an irreversible impact. Due to the strict indoor climates, historical buildings often suffer from condensation damage. Increased damage risks for collection were also introduced by malfunctioning of the Heating Ventilation and Air Conditioning System. Besides it was hard or even impossible to condition the indoor climate strictly, applying strict climates resulted in excessive energy demands.

Currently, the energy efficiency and sustainability of museums are increasingly important. Because strict indoor climates are rarely met in museums (housed in historical buildings), less strict indoor climates are more feasible. In addition, the need for collection conservation is under discussion. Very strict climates are probably not needed from collection's perspective. This gives rise to reduce the energy demand in museums. Because less strict climates dispute the thermal comfort requirements, the importance of thermal comfort in the museum environment increases.

Research has already been performed regarding energy savings in a state-of-the-art museum in The Netherlands. However, this research excludes the energy-saving potential of museums housed in historical buildings. This thesis therefore describes a comparable study to energy savings for a museum building with a historical, uninsulated building envelope. The thesis firstly assesses the current indoor climate in the museum and microclimates near the building objects and envelope. Secondly, the impact of alternative setpoint strategies is assessed. In both the current and alternative situations, the preservation of museum objects and thermal comfort are considered.

The case study for this research is the Amsterdam Museum. In this historical building, a number of Air Handling Units are installed to condition the indoor climate of the exhibition rooms. This results in high energy demands. The *'Regentenkamer'* has been addressed in more detail due to its highly valued objects as a memory to the orphanage. The room is also interesting, because the south facing façade has influence on the indoor conditions. Moreover, this room is ideal for modeling, because it has its own Air Handling Unit.

Short-term measurements were performed to gain insight in the spread of temperature and relative humidity over the museum. Infrared thermal imaging was used for assessing microclimates near the building envelope and objects surfaces in the current situation. Long-term measurements on temperature and relative humidity were executed on the outdoor and indoor climate. Subsequently, the impact of alternative setpoint strategies on energy savings was assessed by making use of building simulations. Therefore, a numerical model was made of the *Regentenkamer*. Heating, cooling, humidification and dehumidification were simulated.

The indoor climate of the current and alternative situations was assessed by several tools. By using the experimentally obtained data and simulated data for temperature and relative humidity, results were obtained. Measurement data was visualized by the Climate Evaluation Chart (CEC). Preservation of museum objects was assessed by the general and specific climate risk assessment method, in which the latter considers the response of museum objects to the indoor climate. The Adaptive Temperature Guidelines for museums were used for assessing thermal comfort. Finally, critical humid areas of microclimates were revealed by converting infrared thermal images to hygric images.

The indoor climate in some rooms was affected by the replacement of central distributors. The results for these rooms show therefore no average indoor climate assessment of the museum. Nevertheless, the impact of risks to the museum collection caused by the deviating indoor climate is visualized. In order to obtain reliable results for the risk assessment methods, measurement data of at least one year is needed. Because only seven months were analyzed, estimations on the indoor climate assessment are displayed. Thermal comfort may be assessed too strictly, because the used thermal comfort guidelines were developed for a state-of-the-art museum. Alternative

setpoint strategies were predicted by building simulations, based on a zone model. More accurate predictions may be performed by a complemented HVAC model.

In the current situation, 73-96% of the indoor climate is within the set limits according to the CEC. The indoor climate out of these limits is mostly too humid. According to the general risk assessment method, the indoor climate of exhibition rooms is within ASHRAE climate class B or C. This means small and moderate risks to mechanical degradation, and tiny and moderate risks for most paintings respectively. According to ASHRAE, both climate class B and climate class C are granted for historical buildings. The specific risk assessment method only shows increased risks on chemical degradation in all exhibition rooms. Regarding thermal comfort, the indoor climate in the museum is too cold. From the results, it can be concluded that *Room D* has the best and the *Schuttersgalerij* the worst indoor climate regarding preservation of museum objects and thermal comfort. However, *Room D* shows microclimates caused by cracks in the exterior wall and cold edges. Other microclimates near the building envelopes are thermal bridges near window sills. Retention walls in front of both a window and a massive exterior wall also cause microclimates.

From the simulation study, it can be concluded that the optimum overall setpoint strategy depends on the museum's weighting of the aspects energy use, risks to objects and thermal comfort. Strategy 7 may be implemented in the control strategy if the focus is on energy savings (33%) without improving the preservation of museum objects. This strategy uses CO_2 controlled ventilation and temperature setpoints based on the Running Mean Outdoor Temperature during opening hours. During closing hours, temperature setpoints are based on free floating. Relative humidity setpoints are 35-55% throughout the day. However, unexpected risks to collection may be introduced by the absence of temperature setpoints during closing hours. Strategy 16 may be implemented if the focus is on preservation of museum objects and to a lesser extent on energy savings (10%). In this strategy temperature setpoints are based on the Running Mean Outdoor Temperature during opening hours and on ASHRAE climate classes during closing hours. The relative humidity setpoint is based on ASHRAE climate classes throughout the day. For both strategies, thermal comfort is improved.

In order to obtain more accurate results, further research is needed to the Amsterdam Museum. Where estimations on risk assessment are available, actual risks to objects still have to be determined. In addition, the HVAC system has to be modeled in order to do accurate predictions on energy savings due to alternative setpoint strategies. Further research is also needed to the energy-saving potential of inconsistencies in the control strategy. Finally, thermal comfort guidelines for museums housed in historical buildings have to be investigated.

Nomenclature

Symbols and abbreviations

AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMS	Building Management System
HVAC	Heating Ventilating and Air Conditioning
LM	Lifetime Multiplier
LoC	Level of Control [-]
QoE	Quality of Envelope [-]
RH	Relative Humidity [%]
RHavg	Average Relative Humidity [%]
RHmax	Relative humidity setpoint for dehumidification [%]
RHmin	Relative humidity setpoint for humidification [%]
RMOT	Running Mean Outdoor Temperature
T	Air temperature [°C]
Tavg	Average air temperature [°C]
Tmax	Temperature setpoint for cooling [°C]
Tmin	Temperature setpoint for heating [°C]

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1 Introduction

In the 20th century, climate control went hand in hand with the development of advanced techniques. The capability of HVAC system determined the level of climate conditioning (Brown & Rose, 1996). Because little attention was paid to collection preservation in Dutch museums, the Ministry of Health and Culture launched the Deltaplan in 1990 ('d Ancona, 1990). In this plan, the focus is on registration, preservation, restoration, accommodation and security of museum collection. However, climate specifications were not defined. Therefore, each museum controlled the indoor climate to their needs. The notion of an optimal museum climate had evolved to 'the more stable, the better.' In order to provide a safe indoor climate for art collection, museums decided to control on strict climate specifications with small fluctuations in temperature and relative humidity.

At the end of the 20th century, guidelines on museum climates were included in the ASHRAE Handbook (2011). For general museums, galleries, archives and libraries, different indoor climate classes are distinguished: AA, As, A, B, C and D, in which AA is the most strict. A wide range of options for seasonal adjustments in order to save energy are included. Nevertheless, the indoor climate was often conditioned according to class AA, because the best indoor climate was obtained regarding museum collection. However, no evidence has been found that less strict indoor climates result in collection damage (Martens, 2012).

In addition, there was a growing awareness that very strict climates are very hard or even impossible to reach in museum buildings (Brown & Rose, 1996). Historical buildings are equipped with a lot of Air Handling Units (AHUs) for controlling on these strict climate guidelines. The impact on these buildings is irreversible and applying strict guidelines results in excessive energy demands. Moreover, museums located in uninsulated historical buildings often suffer from condensation damage during cool periods (Padfield, 1994). In addition, increased damage risks are introduced by malfunctioning of the Heating Ventilation and Air Conditioning (HVAC) system, because then the climate suddenly deviates from the average climate.

In the 21th century, the energy efficiency and sustainability of museums became important topics. Moreover, the need for collection conservation was under discussion. Until recently, there was a lack of knowledge on the impact of climate control on the energy demand. Therefore, Martens (2012) performed a study to the impact of building quality and climate system on the indoor climate. In this study, the influence of setpoints for temperature and relative humidity on energy use and degradation of art objects was investigated. In order to assess the degradation of art objects, the general and specific climate risk assessment methods were introduced. Kramer, Schellen et al. (2015) investigated the energy use relating to different envelope quality when conditioned according to ASHRAE's climate classes.

Conditioning the indoor temperature less strictly from collection's perspective increases the interest in thermal comfort of the visitors and employees in museums. Because thermal comfort guidelines are only available for office buildings, Adaptive Temperature Guidelines for museums were developed by Kramer (to be published). These guidelines are based on a survey study, measurements and an intervention study in a strictly conditioned state-of-the-art museum in the Netherlands: the Hermitage. Kramer, Maas et al. (2015) performed a simulation study to the energy-saving potential of different setpoint strategies in the "Hermitage Amsterdam". The museum is air tight and well insulated. In this study, degradation risks for the collection and thermal comfort are considered.

In this thesis, a comparable study to energy savings is conducted for the Amsterdam Museum. The subject of this thesis is related to the indoor climate assessment and improved HVAC control for energy savings in museums. Due to the lack of insight in microclimates, attention is paid to this topic in the indoor climate assessment. The museum is located in a historical building in the Netherlands. In contrast to the "Hermitage Amsterdam", the building has air leakages and is uninsulated.

The objectives of this study are:

1. *Assessing the current indoor climate and microclimates in the Amsterdam Museum, regarding preservation of museum objects, thermal comfort and the building envelope.*

2. *Assessing the impact of alternative set point strategies on energy use, preservation of museum objects and thermal comfort.*

The current indoor climate will be assessed by measuring indoor temperature and relative humidity. Measurement data will be visualized by using the Climate Evaluation Chart developed within Martens' (2012) PhD study. Infrared thermal imaging will be used for assessing microclimates. The impact of alternative setpoint strategies will be assessed by making use of building simulations. For each setpoint strategy, the indoor climate will be simulated. By using Martens' (2012) general and specific climate risk assessment methods, the preservation of museum objects will be determined for both the current and the alternative situations. The Adaptive Temperature Guidelines for museums of Kramer's ongoing study will be used for assessing thermal comfort for both situations. By combining the individual outcomes of different setpoint strategies, an optimum setpoint strategy may be developed for the Amsterdam Museum.

This thesis is organized as follows:
Chapter 2 describes the details of the case study. In Chapter 3, the methodology is presented, including measurements, numerical modeling and analysis tools. Chapter 4 presents the results. In Chapter 5 and 6, the discussion and conclusion are described. Finally, recommendations to the museum staff and for further research are presented in Chapter 7.

2 Case study: Amsterdam Museum

The Amsterdam Museum is housed in a series of interconnected historical buildings in Amsterdam, The Netherlands. The museum buildings have been constructed in the Middle Ages and were used as a monastery (Meischke, 1975). In 1579 an orphanage was located in the building. Boys and girls had their own housing next to each other. Each accommodation was facing the courtyard, see Figure 2.1. In 1634-1635 several parts of the buildings were replaced. Between 1960 and 1975 the building was renovated and transformed into a museum. Because the museum staff presumed to gain the best indoor climate regarding collection, a lot of Air Handling Units (AHUs) were installed in the newly built basements. In order to incorporate the air ducts, some walls were thickened.

This chapter explains the building structure, exhibitions and objects, internal heat and moisture gains, and the HVAC system of the Amsterdam Museum. For this case study, the *Regentenkamer* in particular has been explored in more depth, because it exhibits highly valued objects, see Figure 2.2. In addition, this room is ideal for modeling because only one room is connected to one AHU.

2.1 The building

The museum buildings have an uninsulated historical envelope with air leakages and thermal bridges. Because an extra sheet of polycarbonate positioned in front of the single glass, the Quality of Envelope is classified to level 2 of Martens' (2012) classification matrix.

Figure 2.3 shows the museum plans for the first floor, second floor and the attic (third floor). Original plans are displayed in Figure B.1 - Figure B.3 of Appendix B (Architectenbureau Jowa, 2007). Unfortunately, structure drawings, sections and elevations are not available. Figure 2.3 also shows the functions of the building. The figure shows that in addition to exhibition rooms, a lot of space is needed for other functions, e.g. offices.

The Amsterdam Museum has some very typical and interesting exhibition rooms. Between museum building A and C, there is a covered street which is also known as the *Schuttersgalerij*. This gallery is a public area which is free of any entrance fees. When doors open, museum collection is directly exposed to outdoor climate conditions. *Room OQ (11)* at the second floor is a characteristic room, because of its height, reflective walls and shed roof with glazing. The *Regentenkamer* (*Room B*) is of utmost importance due to its highly valued objects as a memory to the orphanage. In addition, the indoor climate is influenced by the south facing façade. The orientation of this façade causes the greatest fluctuations in indoor climate in case of no climate control.

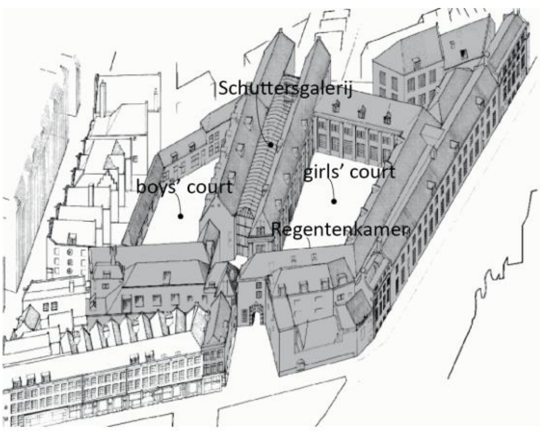

Figure 2.1 Amsterdam Museum (Meischke, 1975)

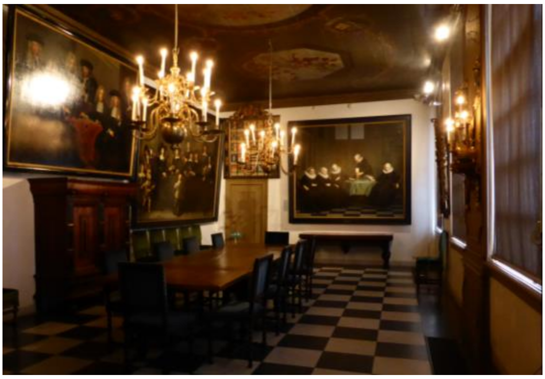 

Figure 2.2 The Regentenkamer with highly valued objects; east direction (left), west direction (right)

2.2 Exhibitions and objects

The Amsterdam Museum has an extensive collection of the city Amsterdam. Half of the collection is obtained by donations and legacies. The other half is preserved by the city itself. Portraits of regents, militia paintings, David and Goliath are typical for the museum. Due to the large proportion of the collection, lots of objects are stored in an external depot. A part of the collection is also exhibited in other museums in Amsterdam. The exhibition program of the Amsterdam Museum in displayed in Figure 2.4. Art from different periods is exhibited. In addition, loan collection is exhibited in the temporary exhibition rooms. The Schuttersgalerij exhibits militia paintings of the 17th century. As a memorial to the orphanage the orphans' cabinets and the *Regentenkamer* have remained intact (https://www.amsterdammuseum.nl).

Different type of objects are exhibited in the Amsterdam Museum: paintings in oil on canvas, panel paintings, photos, prints, drawings, books, textile (e.g. banners and clothing), wooden furniture, wooden sculptures (e.g. David and Goliath) and stone sculptures. The most common objects are paintings in oil on canvas. Several objects are displayed in unconditioned showcases, which protect objects from vandalism. Detailed information on the collection can be found on https://www.amsterdammuseum.nl/en/collection. In Figure 2.4, highly valued objects are denoted in red. These objects include important and very sensitive objects of the museum.

Figure 2.2 and Figure 2.4 show that the *Regentenkamer* exhibits a lot of highly valued objects of the orphanage. After renovating the Regentenkamer in 1634-1635, decorative painting on the orphanage were created on the ceiling of the room in 1656. In addition, the wall was covered with 18th century paintings of sea views. The room also displays four regent paintings in oil on canvas dated from the 17th and 18th century. Finally, the room exhibits an 18th century coat of arms, a nameplate of the orphanage's board (dated 1861) and a cabinet of oak wood. For a detailed description of objects, see Meischke (1975).

2.3 Internal heat and moisture gains

The museum is open seven days a week from 10am to 5pm and welcomes about 4,300 visitors per week. Most of the visitors are tourists or citizens of Amsterdam. Because the *Regentenkamer* (B) is positioned far from the entrance (A), this room is not visited by everyone.

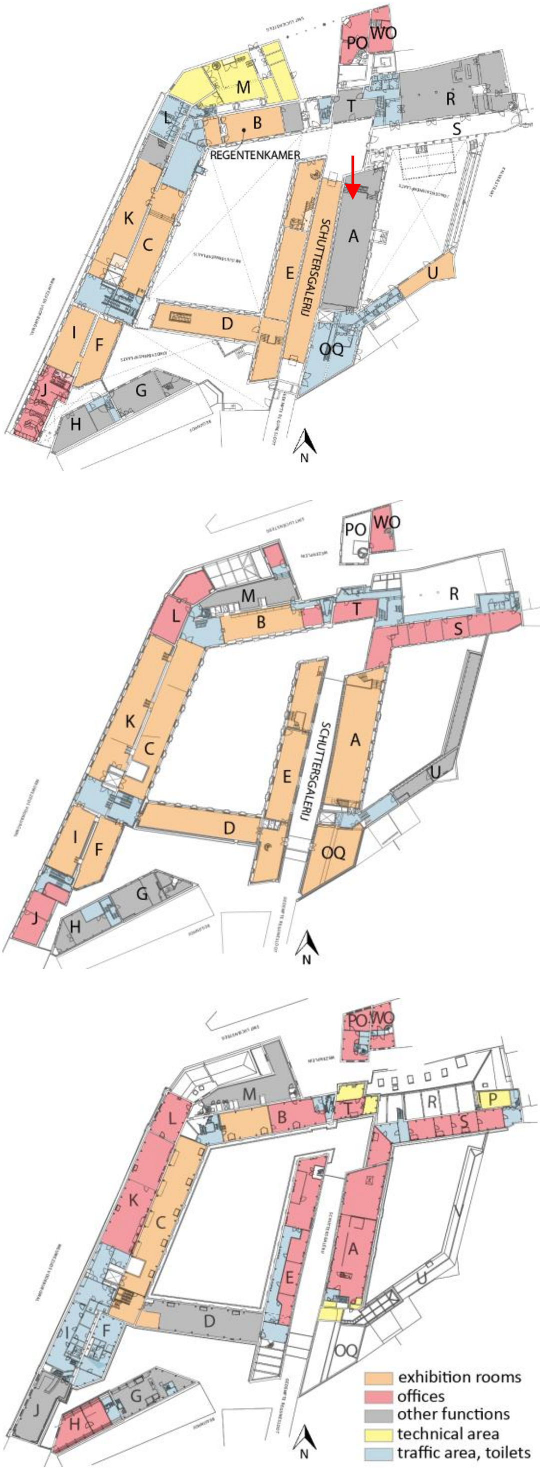

Figure 2.3. Building functions on: the first floor (top), second floor (center) and third floor (bottom)

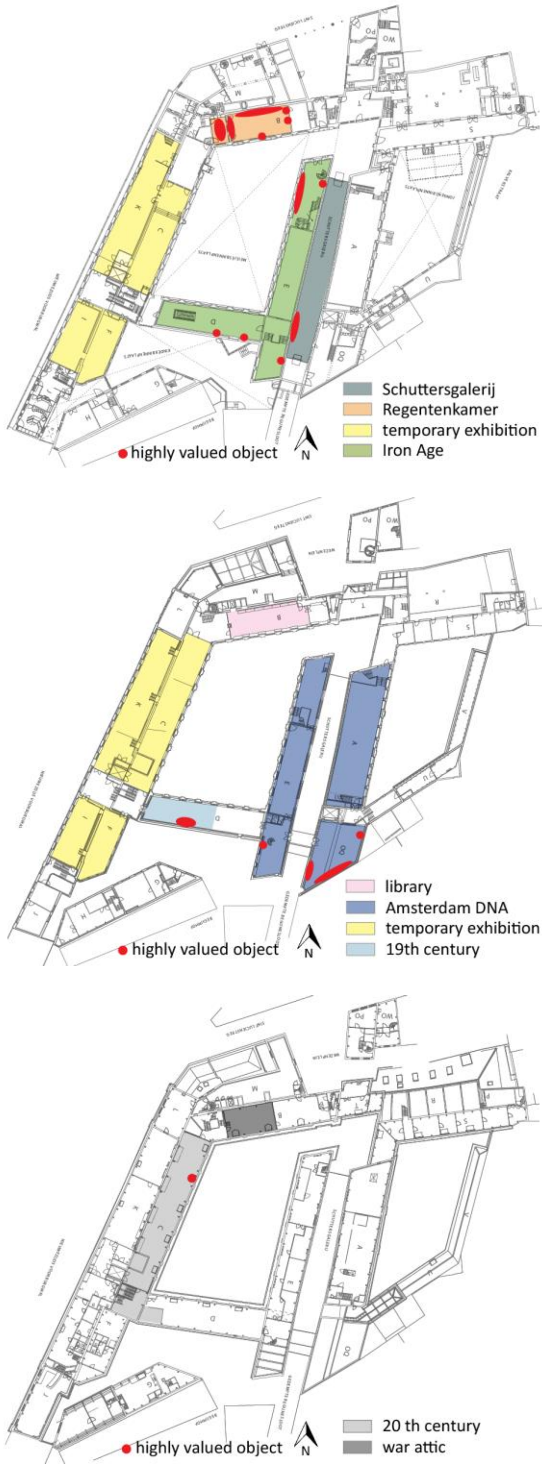

Figure 2.4. Exhibitions and highly valued objects on: the first floor (top), second floor (center) and third floor (bottom)

2.4 HVAC system

The HVAC system of the Amsterdam Museum is controlled by the Honeywell Building Management System (BMS). In the basement of the museum, many AHUs are installed in order to ensure a safe indoor climate for museum collection. Outdoor air enters the basement and is preconditioned by 3 AHUs before it enters the AHUs of the exhibition rooms. The HVAC system is an all-air system provided with heating, cooling, humidification and dehumidification. Therefore, the Level of Control of the museum is 4 according to Martens' (2012) classification matrix. Heating and cooling of the AHUs is provided by three central distributors. The energy use of gas is around 420,000 m^3 per year.

In Figure 2.5, the AHU of the *Regentenkamer* is displayed. The setpoint for temperature (T) is 20°C ±1.5°C and for relative humidity (RH) is 50% ±10%. The components of the AHU from left to right are: filter, preheater (18.33 kW), cooling coil (31.94 kW), fan (3152 t/min), infrasonic humidifier (24.6 kg/s) and heating coil (12.22 kW). The cooling coil cools and dehumidifies the air. The preheater is superfluous and therefore not connected to the central distributor.

The climate control of the *Regentenkamer* is not based on CO_2, but on the exhaust temperature and relative humidity. During opening hours, a part of the volume air flow is recirculated. From 5pm to 8am, recirculation of the air is 100%. The exhaust temperature and relative humidity are measured in the exhaust air duct, just before the air recirculates in the AHU. Sensors are of the type Honeywell H7015B1004. Specifications are displayed in Appendix C. The supply conditions are measured in the supply air duct, just after leaving the AHU. The measured T and RH of the exhaust and supply are recorded by the BMS. Due to the long air ducts, the distance between the sensors and the room is significant.

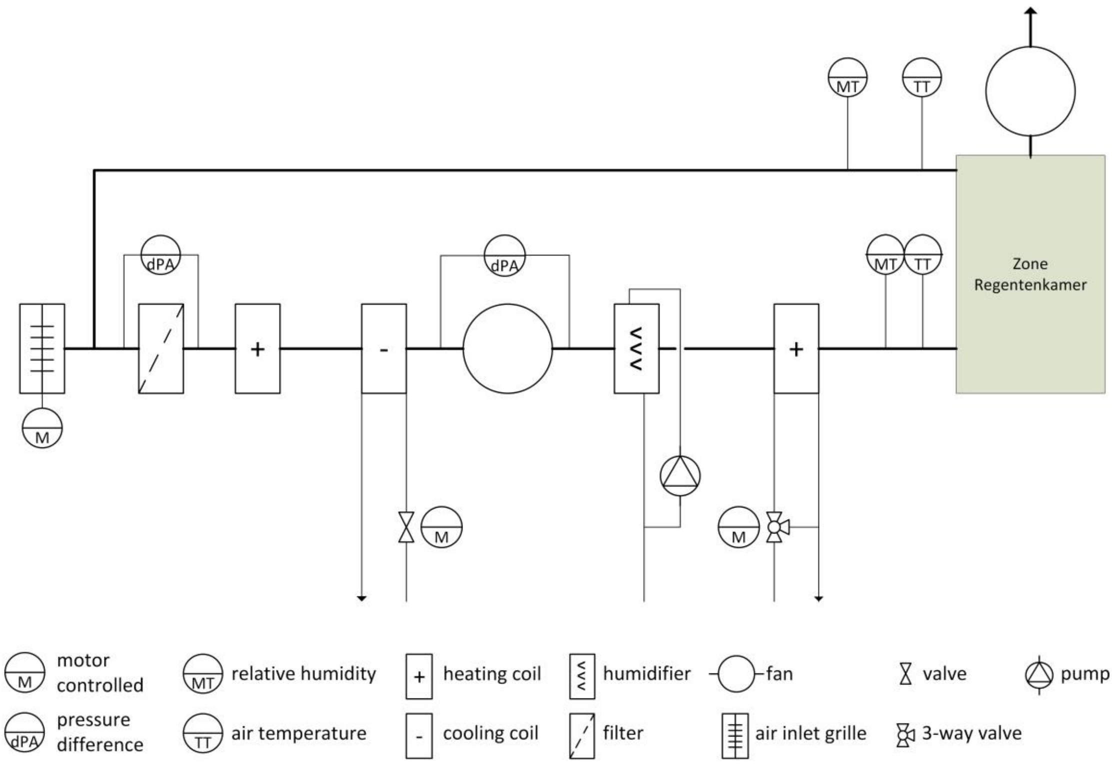

Figure 2.5 The Air Handling Unit of the Regentenkamer

3 Methodology

The purpose of this research is to determine the influence of the indoor climate and possible energy conservation on the preservation of museum objects, thermal comfort and the building envelope in the Amsterdam Museum. In order to achieve these goals, the museum was analyzed at building, room, micro and HVAC level, based on short-term measurements, long-term measurements and numerical modeling.

In Paragraph 3.1 short-term measurements in different rooms of the Amsterdam Museum are described. Paragraph 3.2 explains the long-term measurements. For the *Regentenkamer*, measurements were performed on both room and HVAC level. Subsequently, the case study input and the measurement data were used as input for a numerical model of the *Regentenkamer*, further explained in Paragraph 3.3. Paragraph 3.4 introduces tools for assessing indoor climate for museum objects and for thermal comfort in which the measured and simulated data of the previous paragraphs were inserted. . The measured and simulated data of the previous paragraphs are the inputs for these assessment methods. By using the numerical model of the third paragraph and climate assessment methods of the fourth paragraph, energy conservation can be predicted regarding preservation of objects and thermal comfort.

3.1 Short-term measurements

Paragraph 3.1.1 describes short-term measurements on temperature and relative humidity. Infrared thermal imaging is described in Paragraph 3.1.2.

3.1.1 Temperature and relative humidity

By measuring T and RH in different rooms, the spread of these parameters over the museum was determined. Measurements were executed by a combined T and RH hand meter at several positions in the rooms. The average values per room were obtained. Warm, cool, dry and humid areas have been visualized in a range of colors. A first insight was obtained into critical areas with increased risks in different zones. Because the hand meter is not very accurate, results only show an indication. The measurements are only a snapshot and hard conclusions could therefore not be drawn.

3.1.2 Infrared thermal imaging

By infrared thermal imaging, microclimates were established in the museum. A microclimate is a local climate in which T and RH significantly differ from the average indoor climate. These local gradients may increase risks on museum objects and building envelopes. For example, cracks or thermal bridges in the exterior wall caused by incorrect detailing.

Infrared thermal images were taken by using a thermographic camera. This camera records the intensity of infrared radiation (radiant exitance) for a lot of pixels per image. Via an electronic signal, each pixel is converted into a surface temperature according to equation 3.1. Because each surface temperature has its own color, the thermal image is created in a range of colors. In this way, warm and cool areas could be traced easily.

$$M = \varepsilon \cdot \sigma \cdot T_{surf}^{\;4} \qquad (3.1)$$

where M is the radiant exitance [W/m^2], ε is the emissivity [-], σ is the Stefan-Boltzmann constant [5.67×10^{-8} W/m^{2}K^4] and T_{surf} is the surface temperature [K]. The emissivity for the most building materials is 0.9.

The radiant exitance is the sum of the emitted and reflected radiation (de Wit, 2009). Therefore, high reflective surfaces and differences in emissivity may influence the results (FLIR, 2011). Reflecting surfaces show lower or higher temperatures depending on temperatures of the reflective element. Equation 3.1 shows that a lower set emissivity results in higher surface temperatures and vice versa.

3.2 Long-term measurements

In Paragraph 3.2.1 measurements on the outdoor climate are described. Paragraph 3.2.2 describes measurements on the indoor climate. Measurements were performed in several museum rooms and the *Regentenkamer* in particular. In Paragraph 3.2.3, measurements on the AHU of the Regentenkamer are described.

For each type of measurement a measurement plan was made. It describes type, positions, ID-numbers and accuracy for different sensor types. In order to provide accurate results, the sensors used were calibrated by the BPS laboratory at the Eindhoven University of Technology.

3.2.1 Outdoor climate

A combined outdoor sensor for T and RH was included in the measurement plan. In case of missing measurement data, data from the Netherlands Meteorological Institute's database with a logging interval of 60 minutes was used over the years 2015 and 2016 (https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens). The data is subtracted from the weather station 'Schiphol', 11 km southwest of the museum.

3.2.2 Indoor climate

The indoor climate was measured by 13 Eltek combined T and RH sensors. A measurement plan was made according to the guidelines established by Ankersmit (2010) and Climate for Culture (2013). Sensors were positioned at representative, interesting locations spread over the museum, where they could not be moved by visitors, i.e. if a sensor was moved, the data was considered unusable. See Figure D.1 and Figure D.2 for the measurement setup and Table D.1 for sensor specifications (Appendix D). Measurements were performed in the *Temporary exhibition (room C), Schuttersgalerij* (Figure 3.1, left)*, Entrance (room A), Room D* and *Regentenkamer* at the first floor and *room 11* (OQ) at the second floor. The sensors were connected to an Eltek datalogger with a logging interval of 10 minutes. Data from the logger was transmitted to a central server at the university, using a GSM connection (Maestro GSM modem). From this server, the data was processed into a database and provided to the museum staff by using an internet application developed by Martens (2012) (http://www.monumenten.bwk.tue.nl/). In case of missing measurement data, and BMS data for T and RH of the exhaust air was in the same range, measurement data was supplemented by BMS data. The interval of BMS data was 6 minute averaged. See Appendix E for further explanation.

The *Regentenkamer*, was equipped with seven Eltek combined T and RH sensors of which four had an extra sensor for the surface temperature (T_{surf}). Figure D.2 shows the measurement setup and Table D.1 the sensor specifications (Appendix D). The sensors were positioned nearby the supply air grille (two sensors), paintings nearby the exhaust grille (two sensors), under the table, on a cabinet (Figure 3.1, right) and behind a painting. For investigating the impact of wall temperatures on objects T_{surf} was measured near paintings and the cabinet. In addition to T and RH measurements, CO_2 was measured by one Eltek CO_2 sensor. The CO_2 sensor was positioned on the cabinet. The measurement data should provide an estimate in Air Change Rate (ACR) and visitors profiles needed for numerical modeling on room level.

By using the measured data, the quality of mixing air and risks to objects (Paragraph 3.4.3) were assessed. The most representative sensors were used for calibrating the numerical model (Paragraph 3.3) and for assessing thermal comfort (Paragraph 3.4.4). The sensors nearby the supply and exhaust air grille were compared to BMS sensors. It was investigated whether the HVAC system is controlled on accurate measurement data.

 

Figure 3.1 Measurement positons Schuttersgalerij Goliath (left) and Regentenkamer cabinet (right). Eltek combined T and RH sensors are circled.

3.2.3 Air Handling Unit

Measurements were also performed on the AHU of the *Regentenkamer*. The measurement data will be used in a follow-up of this study.

Figure D.3 of Appendix D depicts the measurement plan of the HVAC system with measurement positions. Specifications of the sensors are shown in Table D.2 of Appendix D. The water temperature (T_w) of the cooling coil was measured by two NTC thermistors for both the supply and return water. For the heating coil the same measurements were performed. Two flow meters were used for measuring the water mass flow of heating and cooling coils by TA link sensors. Combined T and RH sensors of the type E+E Elektronic EE160 were installed at five positions: before the filter, between the preheater and cooling coil, between the cooling coil and fan, between the humidifier and heating coil and after the heating coil. Because the preheater was not operational, sensors were not installed between the filter and preheater. The control signals of the fan and humidifier still have to be measured in the control box connected to the AHU. Both components will be equipped with a PRO38-0-s sensors.

A wired connection was made between the sensors and the datataker (DT85 Series 3 Data Logger (Thermo Fischer Scientific, 2016)). The logging interval was set to 30 seconds, so that rapid changes could be registered. Data from the datataker was transmitted to a central server at the university by a mobile network.

3.3 Numerical modeling

A model of the *Regentenkamer* was made in order to approach reality and perform some predictions on energy use, thermal comfort and deterioration of objects. Paragraph 3.3.1 describes the software used for modeling the room, Paragraph 3.3.2 the model input and Paragraph 3.3.3 the calibration of the model.

3.3.1 Software

At room level the *Regentenkamer* was modeled in HAMBASE (de Wit, 2008; van Schijndel, 2007). HAMBASE (Heat Air and Moisture model for Building and System Evaluation) is a simulation model for heat and vapour flows in a building within the software MATLAB. It describes the building, building profiles, heating, cooling and (de)humidification. The model simulates indoor T, indoor RH and energy use for heating and cooling and (de)humidification of a multi-zone building. By using the ASHRAE test (ASHRAE, 2001), HAMBASE has been validated. For detailed information on the HAMBASE model, refer to de Wit (2008) and van Schijndel (2007).

3.3.2 Model input

General model input for the *Regentenkamer* is derived from the case study in Chapter 2. This paragraph describes additional information on the building structures and building profiles.

A floor plan of the *Regentenkamer*, including building structure layers, is displayed in Figure 3.2. The room has one exterior south facing massive masonry wall with four composed windows provided with shading (no. 1). The composed windows are assumed as double glazing with an U-value of 2.8 W/m^{2}K (Bone, Kemps, Peters & Post, 2007). Due to the absence of technical drawings, assumptions were made for the buildup and thickness of the structure layers, based on personnel's knowledge.

The building profiles of the model distinguish daily and weekly profiles. The daily profile is divided in shifts based on HVAC activation and opening hours of the museum. Due to data loss of CO_2 measurements, the amount of persons and the Air Change Rate (ACR) could not be derived. These parameters were therefore derived from the model calibration which is described in the next paragraph. An overview of the model input can be found in Appendix G.

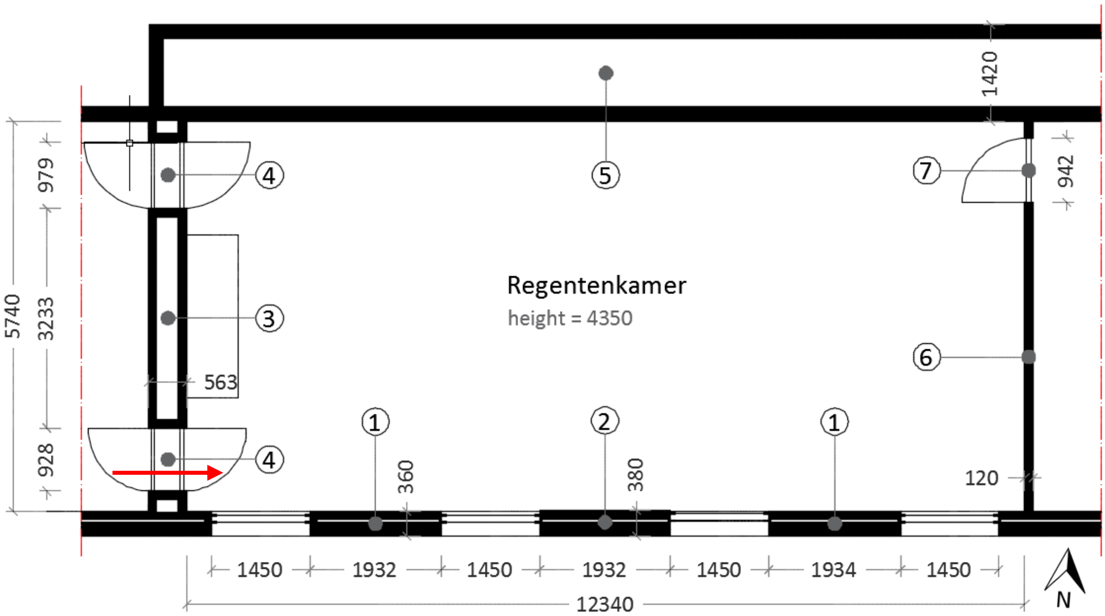

Figure 3.2 Floor plan of the Regentenkamer including structure types. Structure layers from inside to outside: 1: plaster-brick-cavity-brick, 2: wood-brick-cavity-brick, 3: wood-brick-air-brick-plaster, 4: solid wood-air-solid wood, 5: plaster-brick-cavity-brick, 6: plaster-brick-plaster, 7: solid wood, 8 (floor): tiles-concrete, 9 (ceiling): wood-plenum-wood-timber flooring.

3.3.3 Calibration

For calibrating the room model, simulation results were compared to measurement data. Due to missing data and work on the HVAC system, the model was only calibrated over the relatively cool measurement period from December 2015 to March 2016. Initially, the capacities for heating, cooling and (de)humidification were set to an unrealistically high value to make sure setpoints were actually achieved.

The most representative sensor of the *Regentenkamer (Exhaust 1)* was compared to simulated temperature and relative humidity, and calculated absolute humidity (x_{air}) and energy use (P). The absolute humidity was calculated from the measured or simulated temperature and relative humidity according to:

$$x_{air} = P_{sat}(T) \cdot RH \cdot 0.62^{-5} \qquad (3.2)$$

where x_{air} is the air moisture content [kg/kg], *RH* is the relative humidity of the indoor air [-] and $p_{sat}(T)$ is the vapour saturation pressure [Pa] of the indoor temperature *T* [K], according to:

$$p_{sat}(T) = 611 \cdot \exp\left(\frac{17.08 \cdot T}{234.18 + T}\right) \text{ for T} \geq 0°\text{C, and} \qquad (3.3a)$$

$$p_{sat}(T) = 611 \cdot \exp\left(\frac{22.44 \cdot T}{272.44 + T}\right) \text{ for T} < 0°\text{C} \qquad (3.3b)$$

The energy use was obtained from the measured data and was calculated from the room and supply temperature, according to:

$$P = \dot{m} \cdot c \cdot \Delta T \qquad (3.4)$$

where P is the heating or cooling energy [W], $\dot{m}$ is the mass flow [kg/s], c is the specific heat [1006 J/kgK] and ΔT is the temperature difference between the supply temperature and indoor air temperature [°C]. Because the mass flow of the supply air was unknown, the mass flow was varied until the simulated data corresponds to the calculated data. Similarly, the ACR, internal heat and vapour sources were varied. Setpoints were set more precisely after the measured and simulated data showed the same trend.

Table 3.1 Model input used for calibration

Input type	Value
Internal heat sources lighting	847 W
Internal heat sources persons (2-3)	216 W
Vapour sources persons (2-3)	$4 \cdot 10^{-5}$ kg/s
ACR, 90% recirculation	0.97 h^{-1}

Results for the calibration of the model are depicted in Appendix G. Measured and simulated data are displayed for temperature, relative humidity, absolute humidity and energy use. Because the model is a simplification of reality, it is impossible to exactly match the simulated data to the measured data. Nevertheless, mean deviations between the measured and simulated data are small: 0.02°C, 1.34% and 0.20 g/kg respectively.

3.4 Analysis tools

In this paragraph analysis tools for assessing microclimates, indoor climate, risks to objects and thermal comfort are described. Paragraph 3.4.1 describes the conversion of infrared thermal images to hygric images. In Paragraph 3.4.2, the Climate Evaluation chart is described. Assessment methods for assessing risks to objects are described in paragraph 3.4.3. Paragraph 3.4.4 describes the method used for evaluating thermal comfort.

3.4.1 Infrared thermal image to hygrogram

Microclimates were established by infrared thermal imaging, as can be seen in Paragraph 3.1.2. The thermographic camera only measured surface temperatures, while the relative humidity is of great importance for the preservation of objects and building envelope. Therefore, Schellen (2002) developed a tool in which measured surface temperatures are converted to relative humidity levels. For applying this tool the indoor temperature and relative humidity have to be measured. By using the measured indoor conditions, the surface temperature of each pixel of the thermal image is converted into a relative humidity level.

At first, the vapour saturation pressure of the measured indoor temperature $p_{sat}(T_i)$ [Pa] is calculated according to equation 3.3a or 3.3b. Thereafter, the vapour pressure of the indoor air is calculated from the measured indoor relative humidity RH_i [-] and the vapour saturation pressure of the indoor temperature according to:

$$p_v = RH_i \cdot p_{sat}(T_i) \qquad (3.5a)$$

By using the calculated vapour pressure and the saturation pressure near the surface $p_{sat}(T_s)$ [Pa], the relative humidity near the surface RH_s [-] is determined according to equation 3.5b. Therefore, $p_{sat}(T_s)$, is also calculated according to equation 3.3a or 3.3b.

$$RH_s = \frac{P_v}{P_{sat}(T_s)} \qquad (3.5b)$$

Merging the converted relative humidity levels of all pixels results in a hygric image.

3.4.2 Climate Evaluation Chart

The Climate Evaluation Chart (CEC) is a psychometric chart that integrates temperature and relative humidity data (Martens, van Schijndel & Schellen, 2005). Figure 3.3 depicts an example of a CEC. The seasons are expressed by different colors and seasonal weekly averages by the symbols o, *, > and +. The blue box represent the performance guideline the indoor climate is compared to. The 3-by-3 matrices in the graph show whether the indoor climate is OK, too dry or humid and too hot or cold. The bar charts show the indoor climate change rate for hourly and daily fluctuations in temperature and relative humidity: ΔT/hour, ΔT/day, ΔRH/hour and ΔRH/day. The blue lines in these figures depict the boundaries for the performance guideline set. The fungal growth curve is depicted in grey. If this line is exceeded, mould may occur.

Regarding the uninsulated, massive building envelope of the Amsterdam Museum, the indoor climate should be compared to ASHRAE climate class B, see Table H.2 of Appendix H. However, the climate control of the museum is in the range of climate class A (Table H.1 of Appendix H). In order to get insight in the actual situation, the indoor climate was compared to climate class A. This means short fluctuations and spatial gradients of ±10% and ±2K. Because the museum uses a constant setpoint strategy throughout the year, seasonal adjustments were excluded in the assessment.

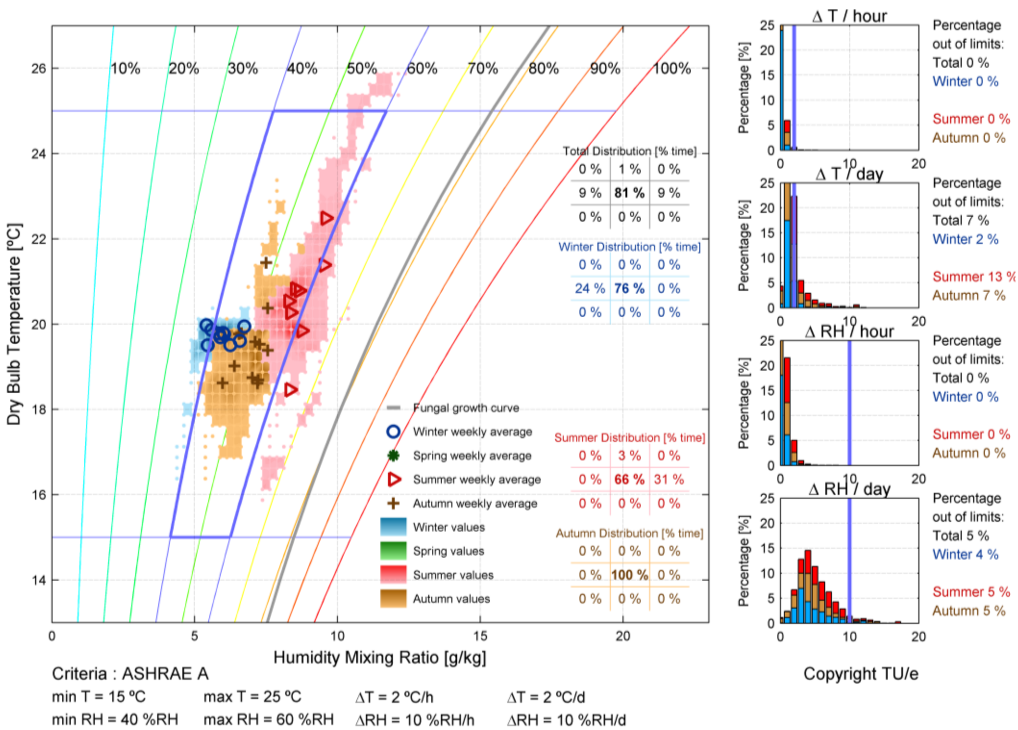

Figure 3.3 Example of a Climate Evaluation Chart

3.4.3 Climate risk assessment

Martens' (2012) thesis shows two different methods for assessing indoor climate and risks to objects: the general and specific climate risk assessment method.

General climate risk assessment

General risks for the collection were assessed by using the general climate risk assessment method (Martens, 2012). The method describes the percentage of time that the climate falls within ASHRAE climate classes. Each climate class ranging from AA to D has its own ranges in temperature and relative humidity, where AA is the most strict class which is related to the lowest risks. Specifications of ASHRAE climate classes are displayed in Appendix G.

For this method, measured or simulated temperature and relative humidity were used as the input. Results are obtained by combining ASHRAE climate classes and statistical operations. See Figure 3.4 for an example. By using the online application developed within Martens' (2012) PhD study, general risks to objects were assessed for the Amsterdam Museum (http://www.monumenten.bwk.tue.nl/).

It is important to mention that within the general climate risk assessment method risks are only valid when the class is met 100% of time and that outliers determine whether damage occurs. The method lacks the response of objects to the indoor climate and risks for short deviations. In addition, results are only valid when at least one whole year of data is used as input.

Specific climate risk assessment

The specific climate risk assessment method (Martens, 2012) considers the actual response of museum objects to the indoor temperature and relative humidity. In this method, biological, chemical (LM) and mechanical degradation are assessed for four typical objects: paper, panel paintings, furniture and sculptures. Panel paintings have an additional risk on mechanical degradation of the pictorial layer. Risk analysis determines whether objects are safe, possibly damaged or likely damaged. See Figure 3.5 for an example. For detailed information on the risk analysis per degradation principle, refer to Martens (2012).

The online application developed within Martens' (2012) PhD study was used in order to assess specific risks to objects in the Amsterdam Museum (http://www.monumenten.bwk.tue.nl/). After uploading measured or simulated temperature and relative humidity data, specific risks to objects were determined. In this method as well, results are only valid when at least one whole year of data is used as input. The method is easy to use and provides more reliable results than the general climate risk assessment method.

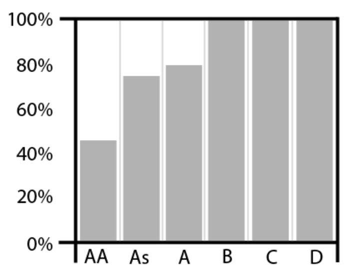

Figure 3.4 Example of the general climate risk assessment

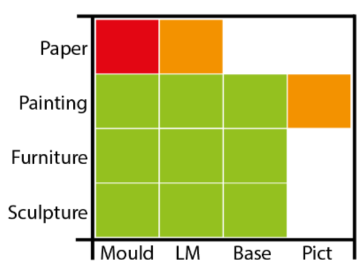

Figure 3.5 Example of the specific climate risk assessment

3.4.4 Thermal comfort assessment

The introduction shows that the interest in thermal comfort of the visitors and the employees in museums is increasing. However, thermal comfort requirements in the museum environment are lacking. The existing thermal comfort requirements EN-ISO 7730 and ASHRAE standard 55 are only based on the office environment. Therefore, thermal comfort limits specified to museums were developed in Kramer's ongoing research to Adaptive Temperature Limits for air-conditioned museums in temperate climate regions. These guidelines are based on a survey study, measurements and an intervention study in a strictly conditioned state-of-the-art museum in the Netherlands, the "Hermitage Amsterdam".

Figure 3.6 depicts the developed temperature limits according to the 90% acceptance class, i.e. 90% of the people are satisfied if the climate fits into these limits. In these limits, the adaptive behavior of people is taken into account: temperature limits are a function of the running mean outdoor temperature of the last four days ($T_{e,ref}$). The lower and upper temperature limits are ±1.2°C from the neutral line, which is described as follows:

$$SP_{neutral} = 19.5 + 0.175 \cdot T_{e,ref} \quad \text{for } 5°C < T_{e,ref} < 20°C\text{, and} \tag{3.6a}$$

$$SP_{neutral} = 23.0 \quad \text{for } T_{e,ref} \geq 20°C \tag{3.6b}$$

$$SP_{neutral} = 20.4 \quad \text{for } T_{e,ref} \leq 5°C \tag{3.6c}$$

By plotting the measured or simulated temperature in museum rooms against $T_{e,ref}$, thermal comfort in the Amsterdam Museum was evaluated. Thermal comfort was only assessed during museum opening hours: between 10am and 5pm. By summing the hours the temperature limits are exceeded during opening hours, thermal discomfort was quantified. $T_{e,ref}$ was calculated from KNMI data according to:

$$T_{e,ref} = \frac{T_{e,i}+0.8 \cdot T_{e,i-1}+0.4 \cdot T_{e,i-2}+0.2 \cdot T_{e,i-3}}{2.4} \tag{3.7}$$

where $T_{e,i}$ the average of the maximum and minimum outdoor temperature [°C] of the day in question.

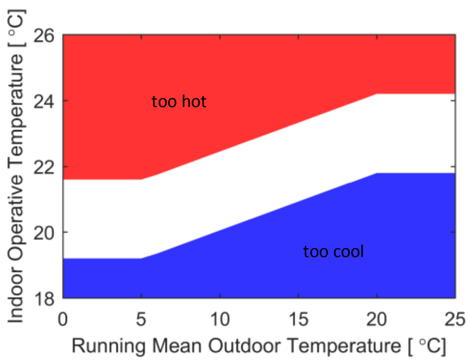

Figure 3.6 Adaptive Temperature Guidelines (ATG) for museums, according to the 90% acceptance class

4 Results

In this chapter, results on the current and alternative situations are displayed. Paragraph 4.1 shows general results on the building climate and building envelope. In Paragraph 4.2, the current indoor climate is described by using analysis tools of Paragraph 3.4. Microclimates in the current situation are displayed in Paragraph 4.3. Results for the alternative situations due to different setpoint strategies are shown in Paragraph 4.4.

4.1 Building (envelope)

Figure 4.1 depicts the analysis on the building climate and building envelope for the first floor. The second and third floor are added in Appendix I. The figure shows the irradiated facades, the segments of the building envelope and a snapshot of the temperature and the relative humidity.

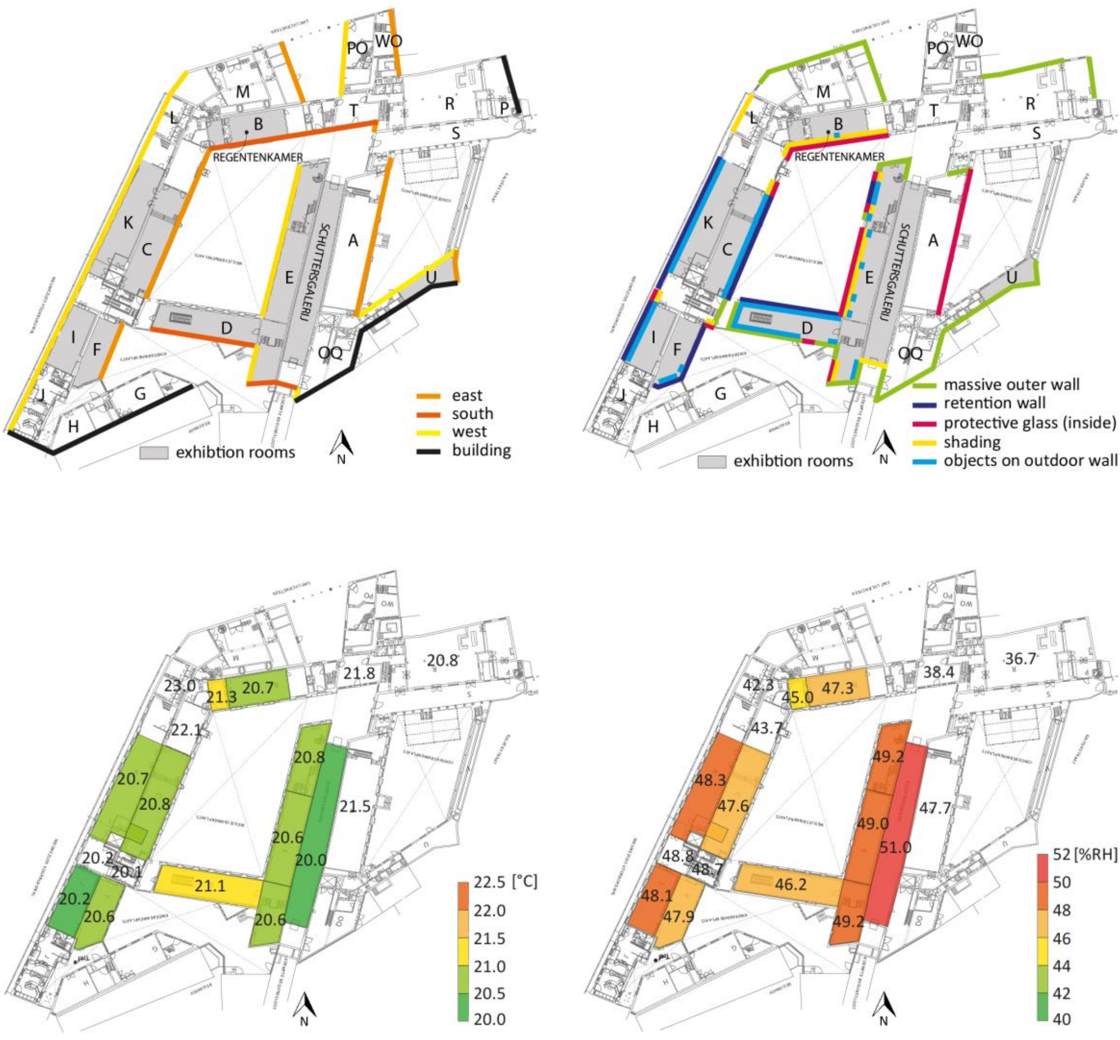

Figure 4.1 First floor analysis of: irradiated facades (top left), segments of the building envelope (top right), temperature (bottom left) and relative humidity (bottom right). June 10th, 2015, 11:30am – 1:00pm

The figure shows that most of the museum areas are oriented to the east or to the west. However, room B (*Regentenkamer*) and D are south facing. Because these rooms are oriented south, increased room temperature and large temperature variations of the exterior wall may occur. The figure on segments of the building envelope shows that museum objects are positioned at practically all retention walls. When exterior walls have no retention wall the museum objects are positioned at the walls between the windows. All windows in museum areas are equipped with shading and protective glass at the inside. However, the entrance connected to the museum area on the second floor has no shading.

Short-term measurements on T and RH were carried out on June 10th, 2015. During these measurements the outdoor conditions were 19°C and 43%. The T and RH range in museum rooms at the first floor are 20-21.3°C and 45.0-51.0%. The second and third floor show higher T and lower RH. De spread for T and RH is the greatest at the second floor: 1.4°C and 10.9% respectively. At the first floor the warmest and driest rooms are facing south; room D and the zone in front of room B, the *Regentenkamer*. The *Schuttersgalerij* shows the lowest T and the highest RH.

4.2 Indoor climate

Long-term measurements on the indoor climate started at 27 July and are still ongoing. For the assessment methods, measurement data was used from 1 August 2015 to 1 March 2016. The measurement period includes 213 days of which 51 in the summer, 91 in the autumn and 71 in the winter. Figure 4.2 shows the measurement positions and corresponding central distributor of the room for which results are displayed: *Schuttersgalerij Goliath, Temporary exhibition, Room 11 door, Room D* and *Entrance*. Similarly, Figure 4.3 displays the measurement positions for the room of interest, the *Regentenkamer*. These positions are: *Exhaust 1, Exhaust 2, Behind painting, Cabinet, Under table* and *Supply 2.* Because the position *Cabinet* shows the average results of the *Regentenkamer's* indoor climate, this is the most representative sensor. The measurement sensors for the position *Exhaust 1* and *Exhaust 2* are positioned next to panel paintings, nearby the exhaust grilles.

This paragraph visualizes the measurement data in graphs and CECs. In addition, results are displayed for the general and specific risk assessment. Finally, thermal comfort is assessed for every room.

Measurement data

Figure 4.4 displays the measurement data for the *Regentenkamer* for temperature and relative humidity. Results are shown for the measurement position *Exhaust 1* and *Cabinet*, which show more fluctuating and more constant temperatures respectively. The numbers in the figure denote the remarks from the logbook, according to Appendix A. The grey line shows the museum setpoints of 20°C and 50% RH and the grey area shows the museum bandwidths of 18.5-21.5°C and 40-60% RH.

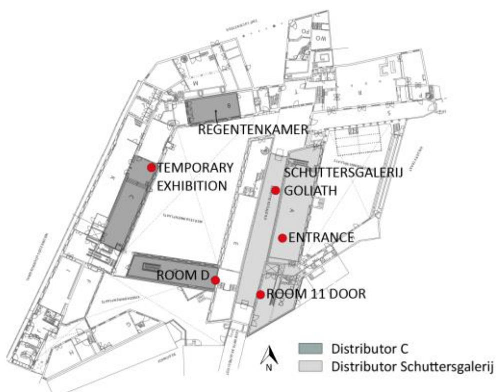

Figure 4.2 Measurement positions

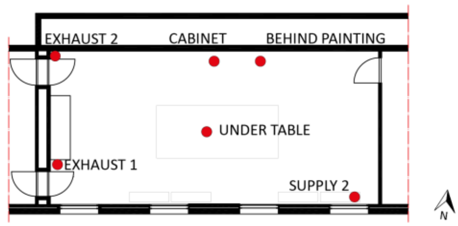

Figure 4.3 Measurement positions of the Regentenkamer

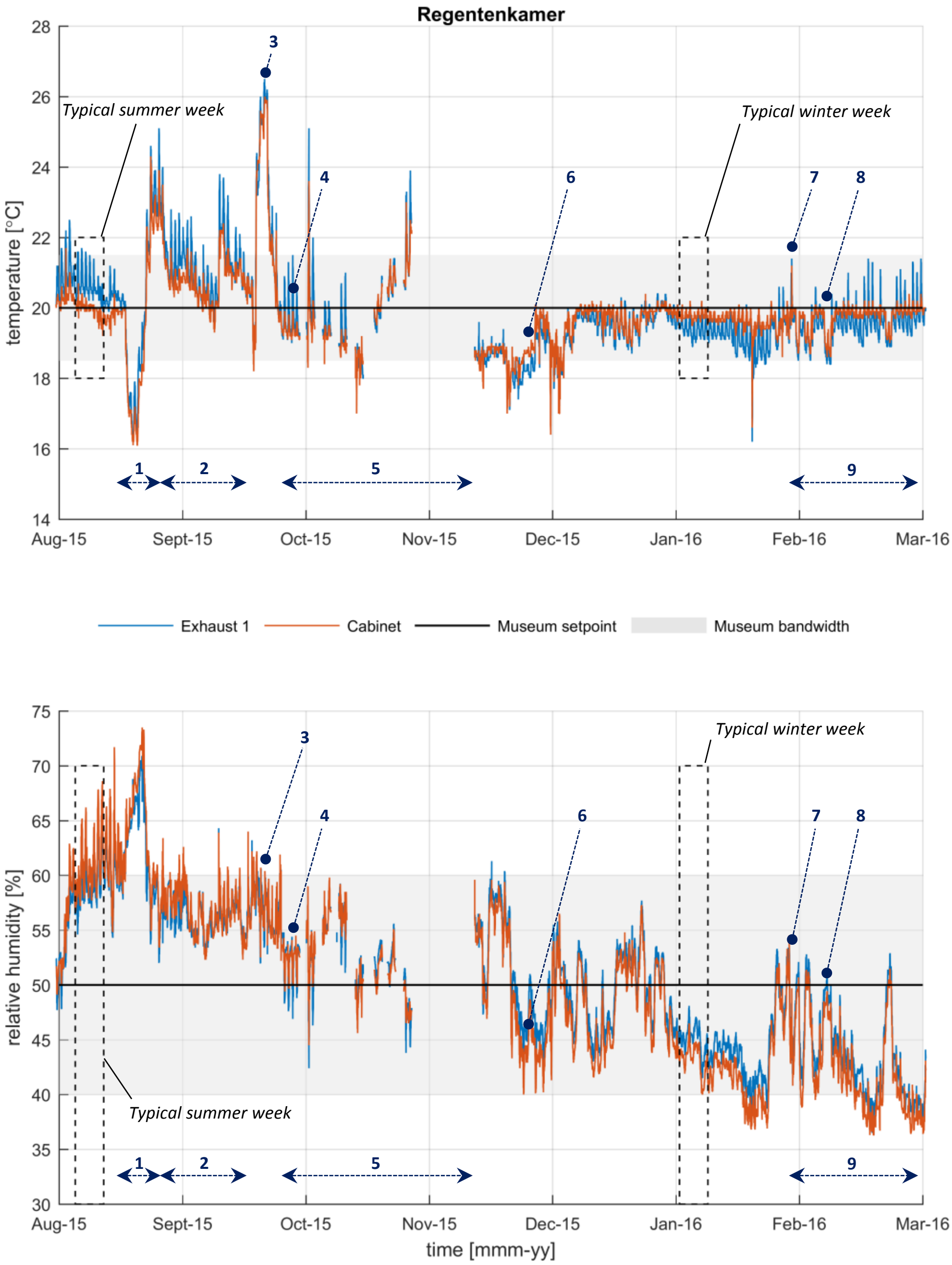

Figure 4.4 Measured temperature and relative humidity for the measurement positions Exhaust 1 and Cabinet of the Regentenkamer. Events during the measurement period: 1: replacing distributors, 2: connecting water pipes, 3: regulation? 4: heating/cooling in operation, 5: data loss, 6: sensors AHU calibrated, 7: farewell director, 8: power failure and 9: Regentenkamer closed

The figure shows large variations in measurement data. In August, these variations were caused by replacing distributor C of the HVAC system. The high peak in September might be caused by regulating the water flow of the HVAC system. The set indoor climate was therefore not met. The graph also shows data loss which was caused by a defect logging system. Due to the large difference between measurement data and BMS data, measurement data was not supplemented by BMS data (see Figure K.2 of Appendix K). From December to March, most of temperature data were within the set control strategy. However, relative humidity setpoints were not met. The air was too humid in the summer and too dry in the winter. Figure K.5 of Appendix K shows that in January low RH levels were supplied, while the indoor RH exceeded the lower RH limit. Significant differences were also noticed between supply temperatures derived from measurement and BMS data. In December, supplied air was heated according to BMS, while it was cooled according to measurement data.

The dashed boxes of Figure 4.4 display a typical summer and winter week. Data from these weeks are displayed in Figure 4.5 and Figure 4.6 respectively. The typical summer week shows that the measurement data for *Exhaust 1* rarely exceeded the museum bandwidth for temperature. *Exhaust 1* also shows larger fluctuations in temperature compared to the *Cabinet*, probably caused by the impact of the outdoor climate on the bad insulated building envelope and windows (sun, heating), see Figure J.2 of Appendix J. These fluctuations may be enhanced by the supply air grille which is positioned near *Exhaust 1*, see Figure K.6 of Appendix K. These large variations might be caused by visitors, however not all visitors enter this room due to its location in the museum. In contrast, the indoor temperature near the *Cabinet* is more stable around the setpoint. During the night, temperatures are also more stable for *Exhaust 1*.

In summer, the relative humidity exceeds the museum bandwidth for both measurement positions. The highest relative humidity is measured near the *Cabinet*, which is related to the lower temperature, compared to the *Exhaust 1*. During the day, relative humidity often increases. This is caused by high supply air conditions: the system is not able to dehumidify the air, see Figure K.6Figure K.7 of Appendix K. During closing hours, fluctuations in relative humidity were recorded. It seems that the system is then controlling on a relative humidity level around 58%. The reason for this is unknown.

In contrast to the summer situation, the winter situation shows measured temperatures below the setpoint, see Figure 4.6. However, temperatures are still within the museum bandwidth. The largest variations between day and night are still recorded for measurement position *Exhaust 1*. This may also be caused by the varying supply air conditions (Figure K.7 of Appendix K) and the impact of the bad insulated envelope and window (sun), see Figure J.3 of Appendix J. This position also shows the lowest temperatures during the winter. Small fluctuations for the *Cabinet* may be caused by varying supply conditions, see Figure K.7.

In the winter situation, relative humidity levels are much lower compared to the summer. This is caused by heating in the winter. The lowest relative humidity level is recorded near the *Cabinet*. The winter situation does not show a day and night rhythm for relative humidity. However, small disruptions of the indoor climate are recorded during opening hours. This may be caused by visitors or by climate control, see Figure K.7.

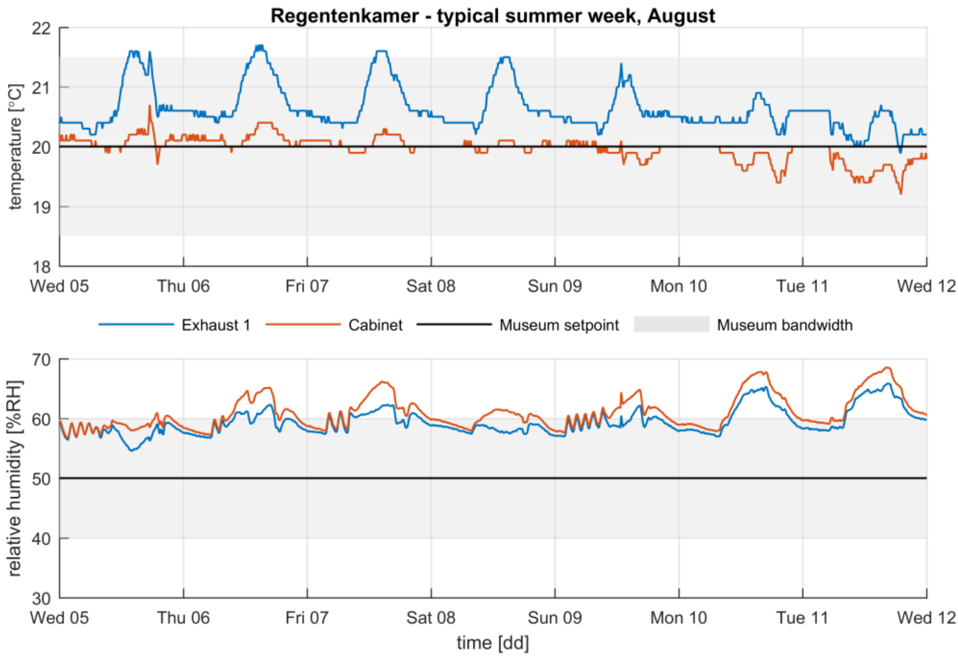

Figure 4.5 Measured temperature and relative humidity for a typical summer week in August for the measurement positions Exhaust 1 and Cabinet of the Regentenkamer

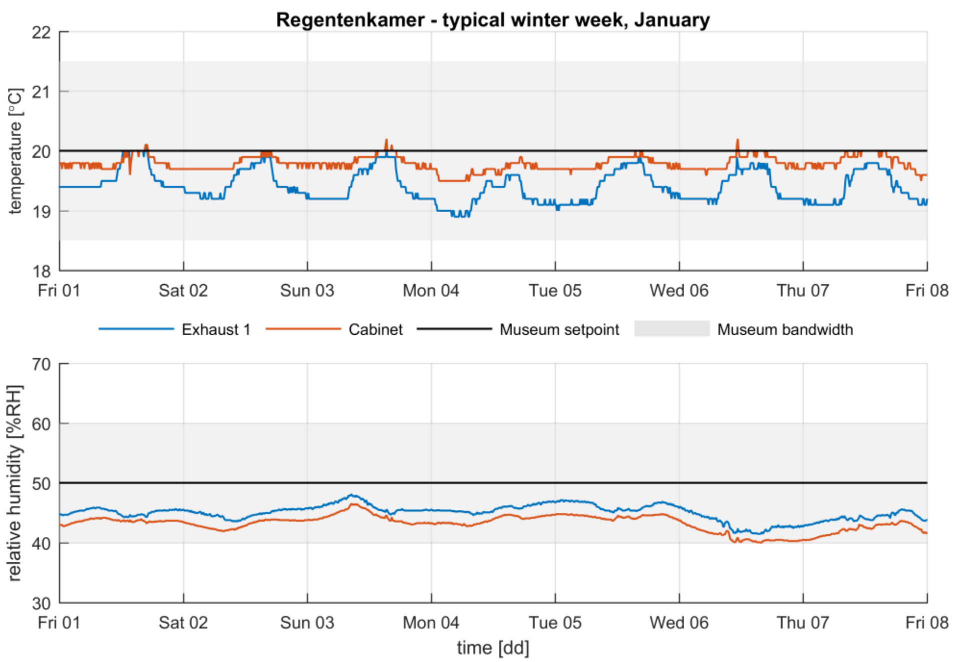

Figure 4.6 Measured temperature and relative humidity for a typical winter week in January for the measurement positions Exhaust 1 and Cabinet of the Regentenkamer

Measurement results for all measurement positions of the *Regentenkamer* are summarized in Table 4.1. The spread of the mean temperature over the room (supply 2 excluded) is 0.6°C. For relative humidity, this spread is 3.7%. Considering the accuracy of sensors, ±0.4°C for temperature and ±2% for relative humidity, the indoor climate is stable and the quality of mixing air is good. The lowest temperature and highest relative humidity level were measured at the measurement position *Behind painting*. In contrast, the highest temperature and the lowest relative humidity were measured near the *Exhaust 2*. Extreme ranges between the minimum and maximum temperature were caused by the replacement of central distributors. This also applies to relative humidity. These ranges are even higher for the supply temperature and relative humidity.

In Table 4.2, the same results are summarized for different exhibition rooms. Extensive graphs of these positions are displayed in Appendix L. The spread of the mean temperature over different exhibition rooms is 1.2°C (excluding the entrance). For relative humidity, this mean spread is 6.7%. The lowest and highest mean temperature were measured in the *Schuttersgalerij* and in *Room 11/Room D* respectively. The lowest mean relative humidity was measured in the *Regentenkamer* and the highest in the *Schuttersgalerij*.

Table 4.1 Overview of temperature and relative humidity for the measurement positions of the Regentenkamer

Regentenkamer	Temperature [°C]				Relative humidity [%]			
	mean	min	max	range	mean	min	max	range
Behind painting	19.5	15.6	25.8	10.2	52.3	38.4	72.6	34.2
Cabinet	19.9	16.2	25.9	9.7	50.1	36.4	72.1	35.7
Under table	19.6	15.0	25.3	10.3	51.7	37.8	74.7	36.9
Exhaust 1	19.9	16.4	26.3	9.9	50.7	37.4	70.4	33.0
Exhaust 2	20.1	16.6	26.0	9.4	48.6	35.7	69.9	34.2
Supply 2	19.3	12.2	28.8	16.6	53.8	35.4	84.0	48.6

Table 4.2 Overview of temperature and relative humidity for the measurement positions of different rooms

Room	Temperature [°C]				Relative humidity [%]			
	mean	min	max	range	mean	min	max	range
Schuttersgalerij Goliath	19.5	16.2	22.6	6.4	56.8	44.4	66.8	22.4
Temporary exhibition	20.0	17.2	26.9	9.7	53.2	34.7	66.6	31.9
Room 11 door	20.7	17.4	24.0	6.6	54.3	46.9	68.8	21.9
Room D	20.7	18.8	24.2	5.4	51.9	42.1	63.9	21.8
Entrance	19.5	18.4	23.4	5.0	59.2	40.2	76.1	35.9
Cabinet	19.9	16.2	25.9	9.7	50.1	36.4	72.1	35.7

Climate Evaluation Chart

Figure 4.7 displays the CEC for the most representative sensor of the *Regentenkamer: Cabinet.* In this CEC, ASHRAE climate class A has been set. Seasonal adjustments were excluded because the control strategy of the museum is also set to constant values. Limits for this class are a minimum temperature (T_{min}) of 15°C, a maximum temperature (T_{max}) of 25°C, a minimum relative humidity (RH_{min}) of 40% and a maximum relative humidity (RH_{max}) of 60%. Hourly and daily fluctuations in temperature and relative humidity may not exceed 2°C and 10%. These fluctuations are also displayed in Figure 4.7. It has to be noted that the temperature limits according to ASHRAE climate class A are much wider compared to the museum temperature limits of 18.5°C and 21.5°C.

The figure shows that 81% of the measurement data is within the standard of climate class A, 1% is too hot, 9% too dry and 9% too humid. Those dry periods were measured in the winter and humid periods in the summer. However, the fungal growth curve is not exceeded by these humidity levels, so mould will probably not occur. Daily fluctuations in T and RH are exceeded, respectively 7% and 5% of the measurement data. These fluctuations are noticed in all seasons. Hourly fluctuations for T and RH are not exceeded.

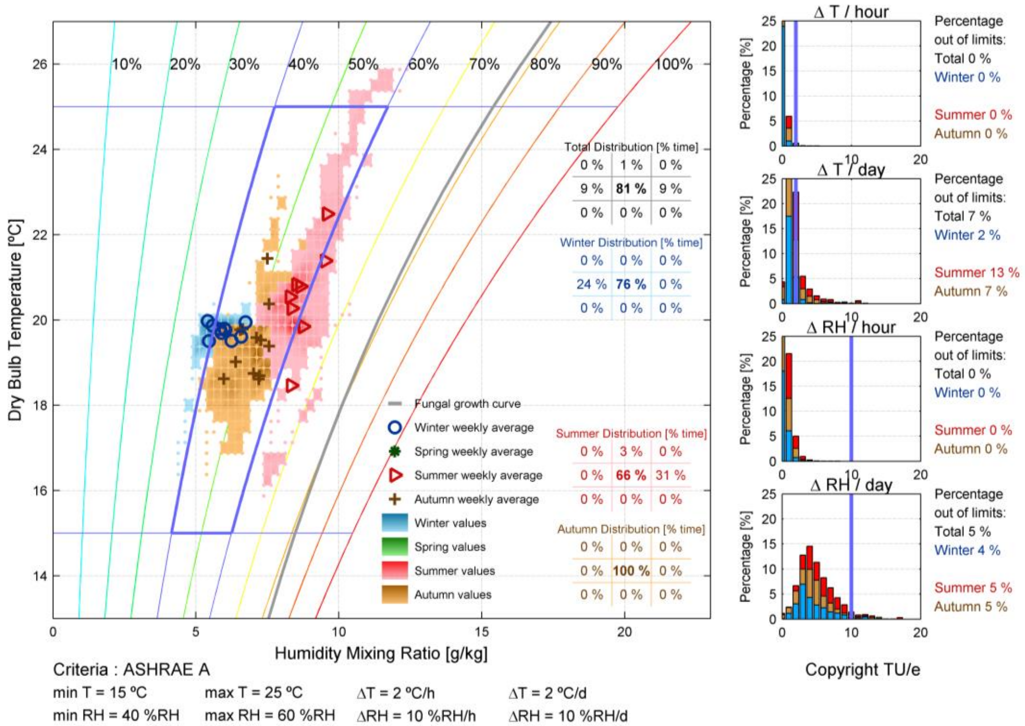

Figure 4.7 CEC of the measurement position Cabinet

The results of the CECs for the measurement positions *Schuttersgalerij Goliath*, *Temporary exhibition*, *Room 11 door* and *Room D* can be found in Appendix M. Table 4.3 shows a summary of the total distribution of T and RH and the percentage that short fluctuation limits for T and RH are exceeded. The table shows that 73% to 96% of the data is within ASHRAE climate class A. *Room D* has the best performance and the *Schuttersgalerij* the worst performance. The *Regentenkamer* is somewhere in between. In general, data outside the ASHRAE climate class A is too humid. The relative humidity limit is mostly exceeded in the summer. These excessive values may be amplified by the replacement of distributors, which cause very high relative humidity levels in the summer.

Table 4.3 Overview of CEC results using ASHRAE climate class A: total distribution of T and RH (left) and percentage that ΔT/hour, ΔT/day, ΔRH/hour and ΔRH/day are out of limits (right)

	OK [%]	too hot [%]	too cold [%]	too humid [%]	too dry [%]	ΔT/h [%]	ΔT/d [%]	ΔRH/h [%]	ΔRH/d [%]
Schuttersgalerij Goliath	73	0	0	27	0	0	8	0	15
Temp. exhibition	84	1	0	13	1	0	11	0	9
Room 11 door	84	0	0	16	0	0	12	0	5
Room D	96	0	0	4	0	0	8	0	1
Regentenkamer cabinet	81	1	0	9	9	0	7	0	5

Daily fluctuation limits for T and RH are exceeded in all rooms. For temperature, the percentage of exceedance is between 7% and 12%. For relative humidity, these percentages are between 1% and 15%. Looking at daily fluctuations, *Room D* has the best and the *Schuttersgalerij* the worst performance. Hourly fluctuations for temperature and relative humidity are not exceeded for any measurement position. Because fungal growth curves are not exceeded at every measurement position, mould will probably not occur.

Climate risk assessment

Before interpreting the results, it has to be noted that results of both methods are only 100% reliable when at least one whole year of data is used as input. Only seven months were used in this research and therefore, results show an estimation and no actual values.

Figure 4.8 depicts the percentage of time the climate in four museum rooms fits into ASHRAE climate classes using the general climate risks assessment method. In this method, risks are only valid when the class is met 100% of time. Outliers determine whether damage occurs. For the *Schuttersgalerij* and *Temporary exhibition*, the indoor climate is within class C. For *Room 11 door* and *Room D*, the indoor climate is within class B. According to ASHRAE, both climate class B and climate class C are granted for historical buildings. By preventing outliers, the indoor climate in the *Schuttersgalerij* and *room D* is within class A and in the *Temporary exhibition* within class B. Outliers were caused by too high and too low temperatures and relative humidity. Replacing and presetting central distributors of the HVAC system is one of the causes for the *Temporary exhibition* and *Room D*. The causes for other outliers are unknown.

Figure 4.9 depicts an overview of risk for four rooms for different types of collection using the specific climate risk assessment method. All rooms show a Lifetime Multiplier (LM) < 1 for all types of objects, which denotes an increased risk on chemical degradation. Risks are caused by average temperature and/or relative humidity levels higher than the reference conditions of 20°C and 50%. The *Schuttersgalerij* and *Temporary exhibition* show the lowest LM for furniture and *Room 11 door* and *Room D* for paper. No risks are shown for other types of degradation.

Figure 4.10 displays the general climate risk assessment for the measurement positions of the *Regentenkamer*. For the measurement positions *Behind painting, Cabinet, Under table, Exhaust 1* and *Exhaust 2,* the indoor climate is within class C. Climate class B is met 98% or 99 % of the time. Replacing and presetting central distributors of the HVAC system is the main cause of the outliers in climate class B. Because objects are positioned above the supply air grille, results are also shown for measurement position *Supply 2*. For this position, no climate class is met 100% of time due to high RH.

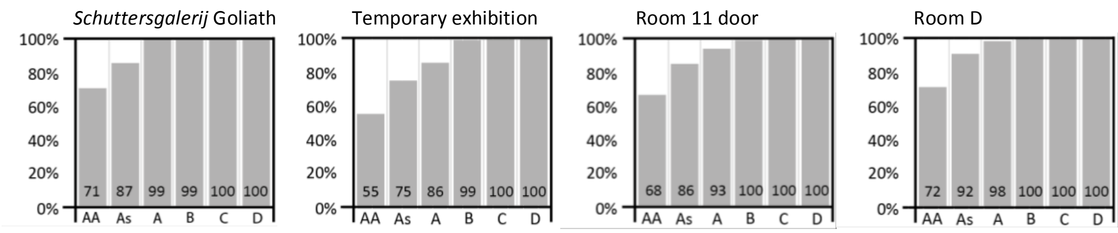

Figure 4.8 General risk assessment for the measurement positions Schuttersgalerij Goliath, Temporary exhibition, Room 11 door and Room D

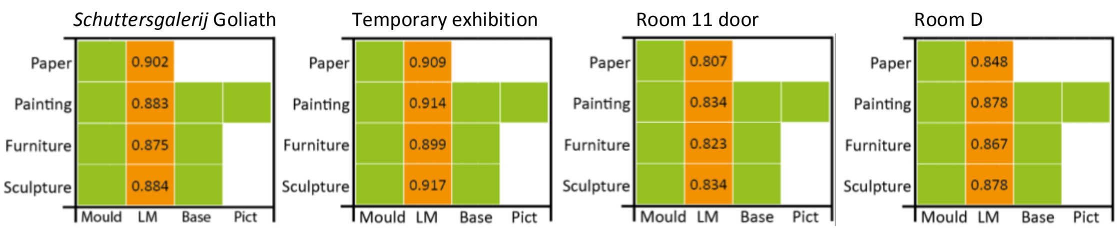

Figure 4.9 Specific risk assessment for the measurement positions Schuttersgalerij Goliath, Temporary exhibition, Room 11 door and Room D

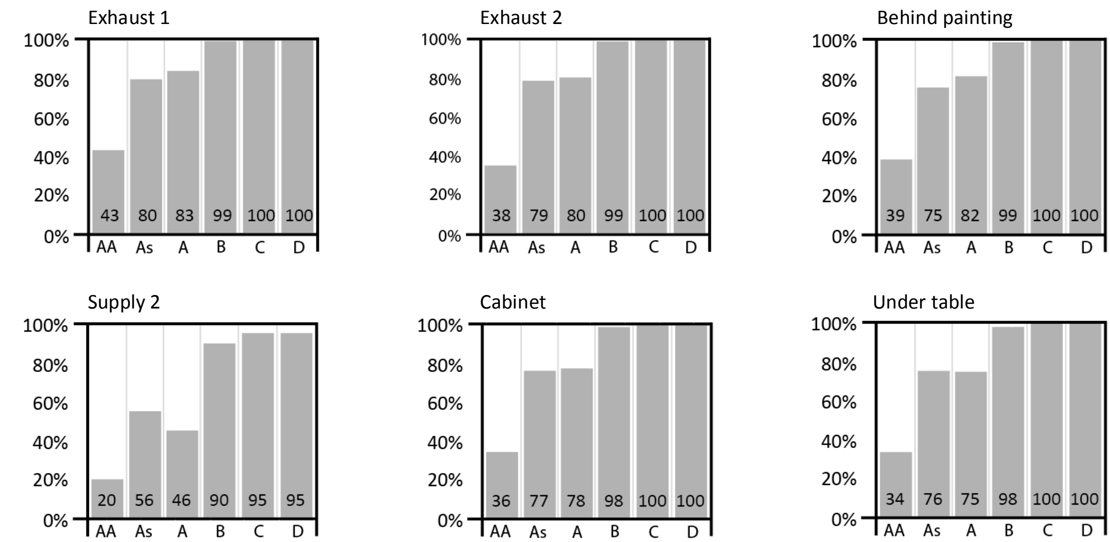

Figure 4.10 General risk assessment for the measurement positions of the Regentenkamer: Exhaust 1, Exhaust 2, Behind painting, Supply 2, Cabinet and Under table

Figure 4.11 displays the specific climate risk assessment for the measurement positions of the *Regentenkamer*. The red box in the figures depicts the type of objects which are located near the measurement position. All positions show a LM < 1 for all types of objects, which denotes an increased risk on chemical degradation. However, risks are limited because the high relative humidity levels during the replacement of distributors are compensated by lower relative humidity levels in winter.

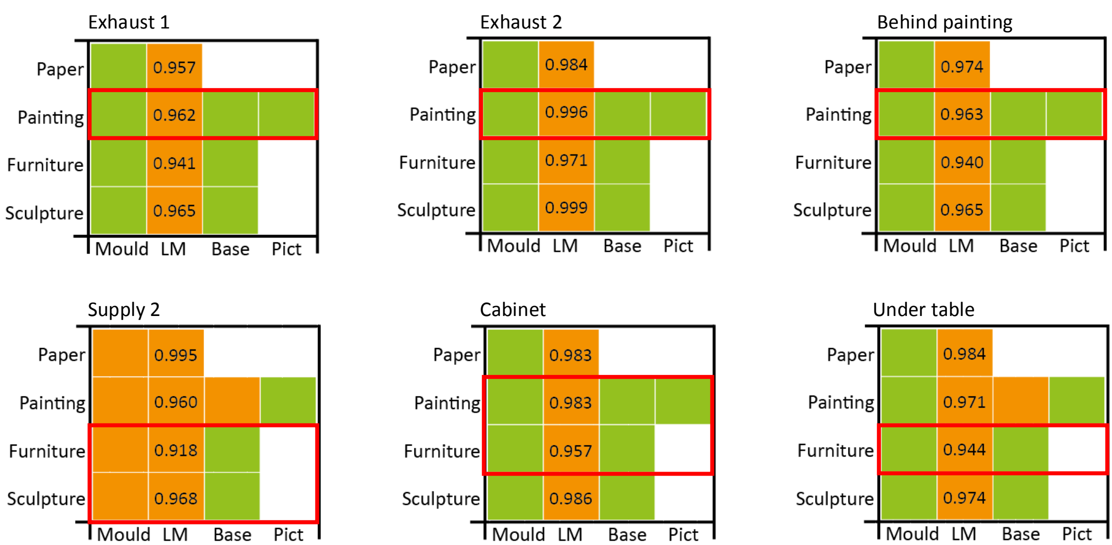

Figure 4.11 Specific risk assessment for the measurement positions of the Regentenkamer: Exhaust 1, Exhaust 2, Behind painting, Supply 2, Cabinet and Under table. The red box denotes the object type which is positioned near the measurement position.

Measurement position *Under table* and *Supply 2* also show an increased risk on mechanical degradation of the base layer of panel paintings. However, there are no paintings located at these positions. In addition, *Supply 2* displays an increased risk on biological degradation. The chair and wooden nameplate above the supply air grille may therefore be affected by fungal growth. High temperature and relative humidity levels result in limited chemical degradation. For biological degradation, mainly high relative humidity levels decrease the germination time and increase fungal growth. Mechanical degradation is only caused by changes in relative humidity.

Comparing the most representative sensor of the *Regentenkamer* to the other rooms, shows no exceptional indoor climate performance according to the general risk assessment method. A better performance is shown for the *Schuttersgalerij* and *Room D*. In contrast, the performance of the *Regentenkamer* is the best according to the specific risk assessment method due to the highest LM.

Thermal comfort

Figure 4.12 displays thermal comfort assessment in five exhibition rooms and in the *Entrance*. For the *Regentenkamer,* results are shown for the most representative measurement position *Cabinet*. Thermal comfort was assessed during opening hours (10am to 5pm) by using the Adaptive Temperature Guideline for museums. The corresponding underheating, overheating and discomfort hours are shown in Table 4.4. Due to data loss and supplemented data, the total amount of assessed hours differs per room. In order to compare the rooms, the exceeding hours are expressed in percentages.

Figure 4.12 and Table 4.4 show that overheating hours in the rooms are limited to 2.3%. Overheating is mostly caused by replacing the distributor of the AHU. However, underheating shows many exceeding hours in a range of 20.8% and 88.3%. Thermal comfort is the best in *Room 11* and the worst in the *Entrance*. The *Regentenkamer* is somewhere in between. In general, the indoor climate in museum rooms and in the *Entrance* are too cold regarding thermal comfort.

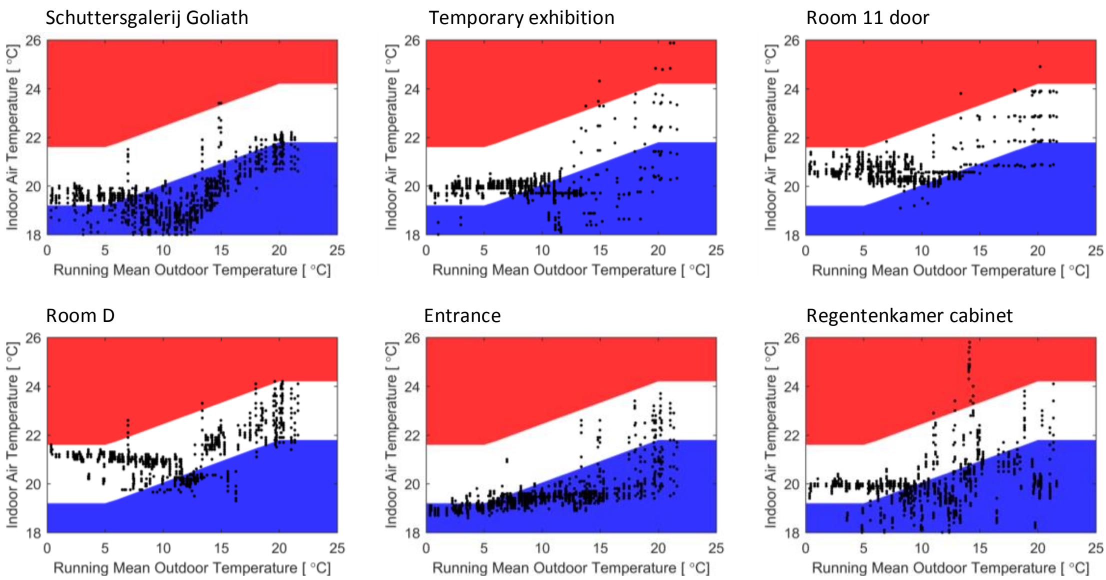

Figure 4.12 Thermal comfort assessment using the Adaptive Temperature Guideline for museums for the measurement positions Schuttersgalerij Goliath (top left), Temporary exhibition (top middle), Room 11 door (top right), Room D (bottom left), Entrance (bottom middle) and Regentenkamer cabinet (bottom right).

Table 4.4 Percentage of overheating, underheating and total discomfort hours

Measurement position	overheat [%]	underheat [%]	Total discomfort [%]	Total hours
Schuttersgalerij Goliath	0.2	67.9	68.1	4360
Temporary exhibition	2.3	48.4	50.7	5112
Room 11 door	0.6	20.8	21.4	4885
Room D	0.5	23.9	24.4	5042
Entrance	0.0	88.3	88.3	4983
Regentenkamer cabinet	1.6	49.8	51.4	4413

4.3 Microclimates

In this paragraph, microclimates in the Amsterdam Museum are visualized. Paragraph 4.3.1 displays the spread of temperature and relative humidity in the *Regentenkamer*. Paragraph 4.3.2 visualizes microclimates near building and objects surfaces by infrared thermal imaging.

4.3.1 Temperature and relative humidity

Figure 4.13 depicts the distribution of temperature and relative humidity for the *Regentenkamer* on June 10th, 2015. The measurement grid and interpolated temperature and relative humidity are displayed. Warm and dry areas are displayed near the entrance door. For temperature, maximum differences are 0.6°C and for relative humidity 1.9%. These small differences indicate a good quality of mixing air.

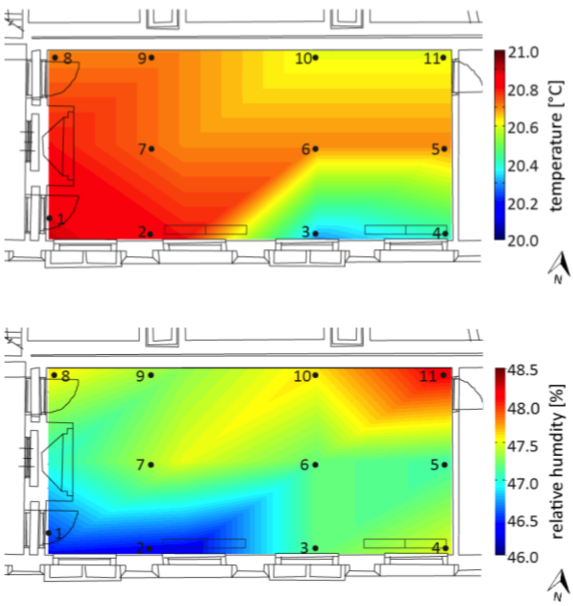

Figure 4.13 Distribution of T (top) and RH (bottom) over the room, June 10th, 2015, 0:30pm

4.3.2 Infrared thermal imaging

The microclimates near building and object surfaces were investigated making use of infrared thermal imaging. For each microclimate, surface temperature and relative humidity are visualized for a winter situation (January 13th, 2016). For some positions, surface temperatures are depicted for a summer situation (July 2nd, 2015) as well. An overview of the positions of microclimates is depicted in Figure 4.20 at the end of the paragraph.

Figure 4.14 depicts the images of a painting lighted by a warm spot in *room D* at the 2nd floor. The painting shows a surface temperature of 21.0°C and relative humidity of 46.5%. However, the light spot causes unevenly distributed surface temperatures and relative humidity over the painting with a local surface temperature of 25.7°C and relative humidity of 35%. As a result, cracks due to mechanical degradation may occur. Besides, the high surface temperature increases risks on chemical and biological degradation. It has to be noticed that the varnish on the painting reflects the heat of the light spot. Therefore, too high surface temperatures and too low relative humidity are displayed. Risks may be lower than expected. Actual temperatures could be measured by installing a surface temperature sensor on the painting.

Figure 4.15 depicts *room 11 (OQ)* at the 2nd floor, of which the walls are covered with gold reflective paint. The high temperatures on the wall show reflections of the light spots. In the same way, windows in the top of the roof result in incorrect wall temperatures. Too low surface temperatures are displayed during the winter and to high surface temperature during the summer. Actual surface temperatures and microclimates could therefore not be determined.

winter

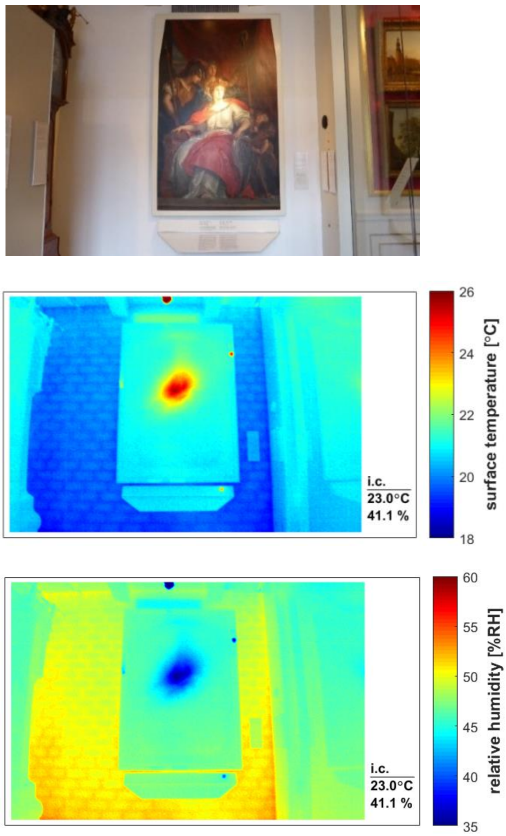

Figure 4.14. Room D (2nd floor), position 1; visual image (top), infrared thermal image - winter (center) and calculated infrared hygric image - winter (bottom). January 13th, 2016, 2:44pm

winter

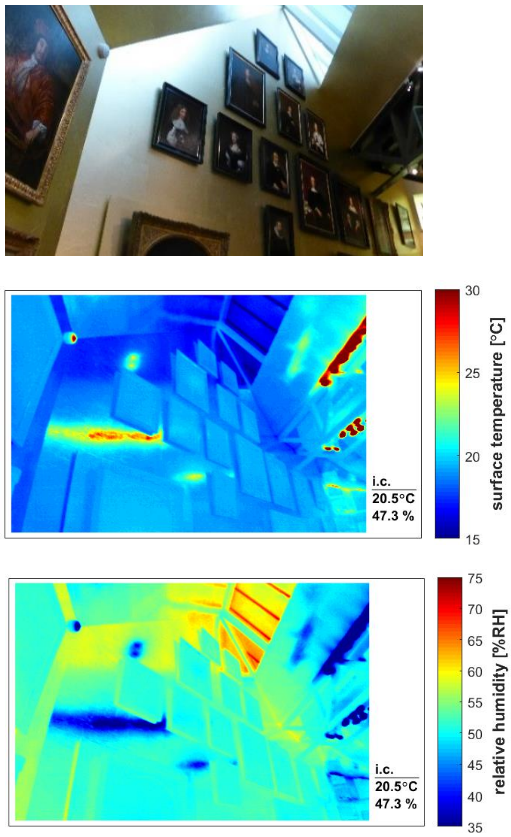

Figure 4.15. Room 11 (2nd floor), position 2; visual image (top), infrared thermal image - winter (center) and calculated infrared hygric image - winter (bottom). January 13th, 2016, 2:50pm

The thermal image of *room D* at the 1st floor (Figure 4.16) shows cracks in the south facing wall. Lower temperatures and higher relative humidity are visible near the cracks. Because the temperature and relative humidity are unevenly distributed over the highly valued painting, mechanical degradation may occur.

Figure 4.17 depicts a building corner of the same room. Near the edges, cold areas with a high relative humidity are displayed. The corner has a minimum temperature of 14.0°C and a maximum relative humidity of 70.9%. There is an increased risk on mould growth near the corner due to the high relative humidity. Different causes are: 1) in corners, the air velocity is lower and the surface coefficient of the convective heat transfer is smaller than elsewhere; 2) the radiant exchange between the surface close to the corner and these surfaces exchange less heat with the room (de Wit, 2009).

winter

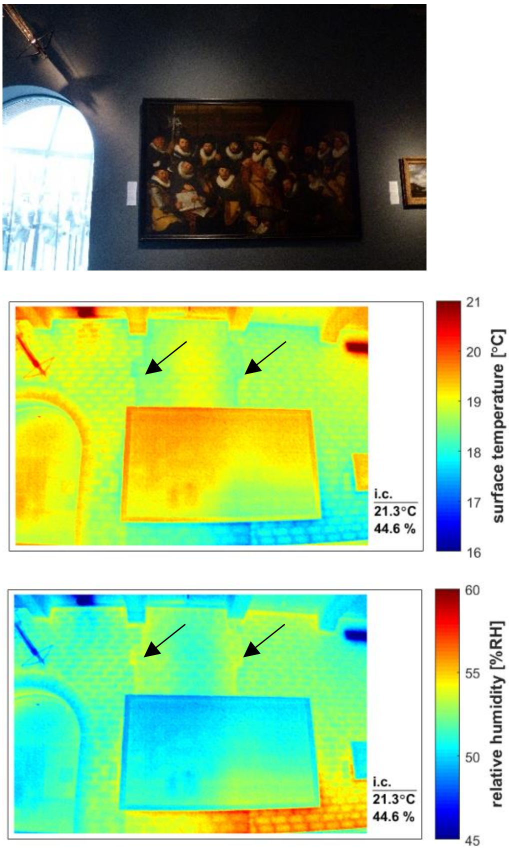

Figure 4.16. Room D (1st floor), position 3; visual image (top), infrared thermal image - winter (center) and calculated infrared hygric image - winter (bottom). January 13th, 2016, 3:06pm

winter

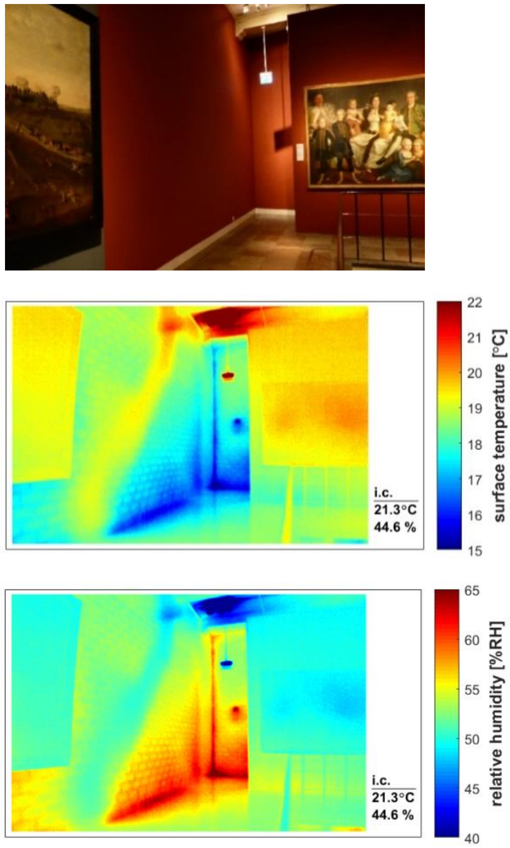

Figure 4.17. Room D (1st floor), position 4; visual image (top), infrared thermal image - winter (center) and calculated infrared hygric image - winter (bottom). January 13th, 2016, 3:10pm

The impact of a painting on a retention wall in front of a window is depicted in Figure 4.18. For the same measurement position a summer (left) and winter situation (right) are displayed. However, the collection has been changed between both recordings. In winter, a highly valued object is positioned in front of the wall. The summer situation differs a lot from the winter situation, regarding temperature and relative humidity near the uninsulated exterior wall and painting. Surface temperatures near the painting can be 31.3°C in summer and 15.9°C in winter. For the relative humidity, these levels are 42.8% and 56.5% in summer and winter respectively. In addition, temperature and relative humidity are unevenly distributed over the painting, because the painting is positioned both in front of a window and a massive exterior wall. In this way, the panel painting may be exposed to mechanical and chemical degradation. Cracks may appear in the exterior wall as well. The building envelope is not affected by biological degradation, because fungal growth curves are not exceeded at a maximum relative humidity of 62.4%.

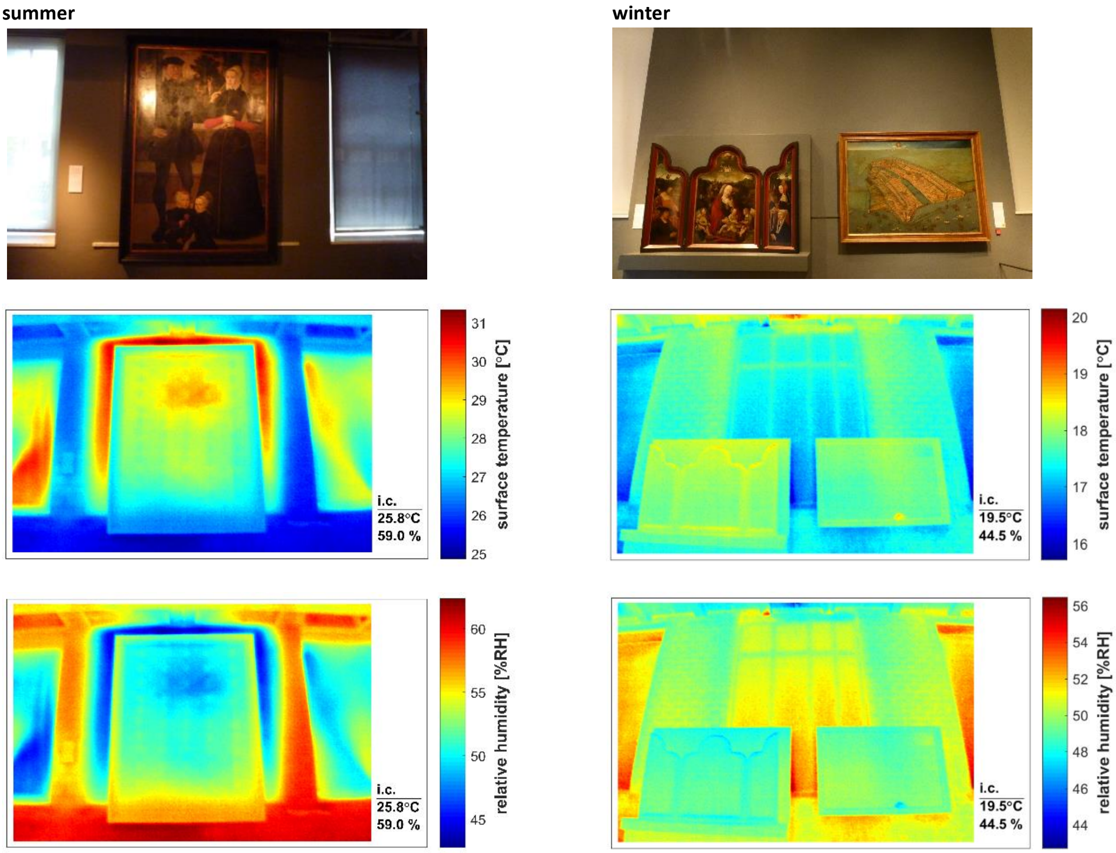

Figure 4.18. Room E (1st floor), position 5; summer - July 2nd, 2015, 1:05pm (left) and winter - January 13th, 2016, 2:59pm (right). The collection has been changed between both recordings. Visual image (top), infrared thermal image (middle) and calculated infrared hygric image (bottom).

In Figure 4.19 the exterior wall of the *Regentenkamer* is depicted. The uninsulated exterior wall provided with objects is warm in the summer and cool in the winter. This may result in mechanical damage. Due to heating in the winter, the indoor climate is dryer compared to the summer. The figure also displays thermal bridges near window sills. Biological degradation will not occur at these conditions (RH 67.0% in the winter). However, the extreme high relative humidity near the window and objects may cause biological degradation.

The objects, a chair and a highly valued wooden nameplate, are partly positioned above the supply air grille. In this way, they are exposed to a microclimate with unevenly distributed climate conditions. In addition, the objects are exposed to cool and dry air in the winter, and warm and humid air in the summer. The continuously changing supply conditions cause improved risks on different degradation principles.

It has to be noted that measured surface temperature of the metallic supply air grill are too high, see equation 3.1. This is caused by the lower emissivity of metallic compared to other building materials. The calculated relative humidity is therefore too low.

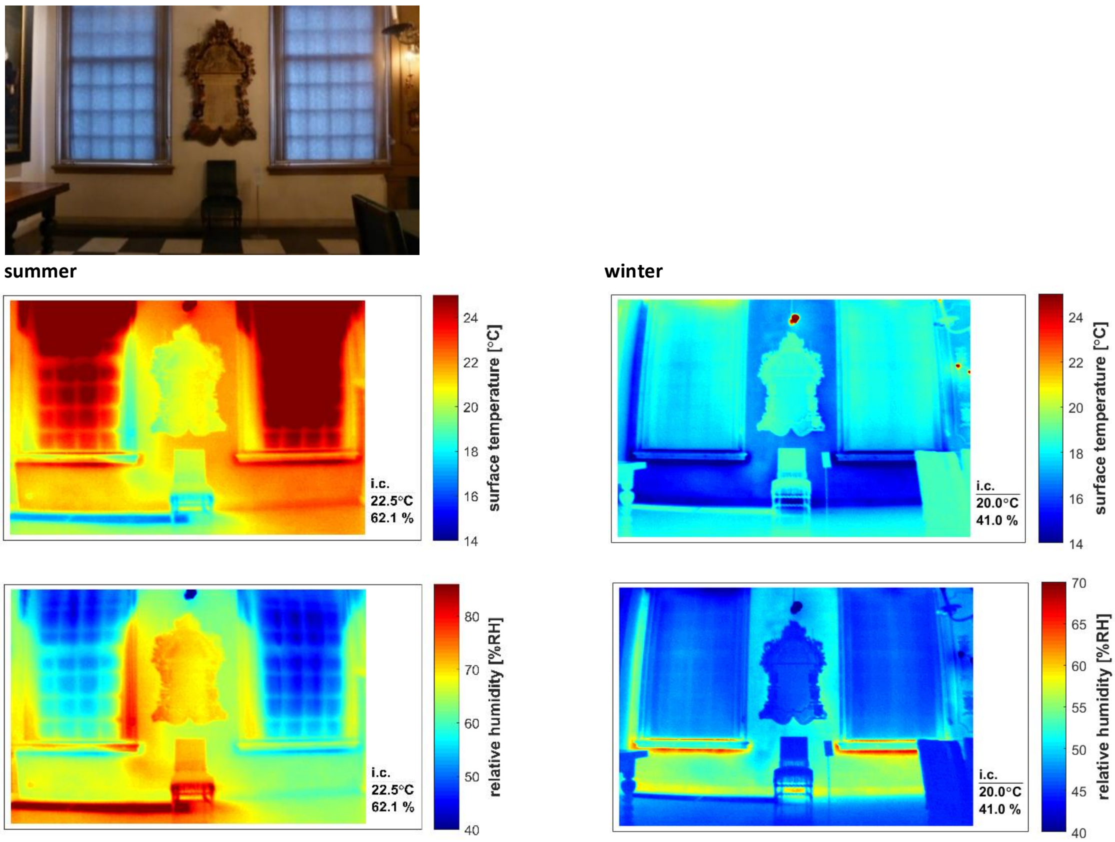

Figure 4.19. Regentenkamer (1st floor), position 6; summer - July 2nd, 2015, 11:59am (left) and winter - January 13th, 2016, 2:17pm (right). Visual image (top), infrared thermal image (middle) and calculated infrared hygric image (bottom).

The different microclimates in the Amsterdam Museum are summarized in Figure 4.20. The red dots show the microclimates caused by the building envelope and the orange dots the microclimates caused by building equipment. Microclimates as a result of the building envelope are caused by cracks in the wall (no. 3), building edges (no. 4) and thermal bridges near window sills (no. 6). Microclimates due to building equipment were caused by a light spot (no. 1), retention wall (no. 5) and supply air grilles (also no. 6). Microclimates near the reflective walls (no. 2) could not be determined. In the figure, this microclimate is indicated as unknown.

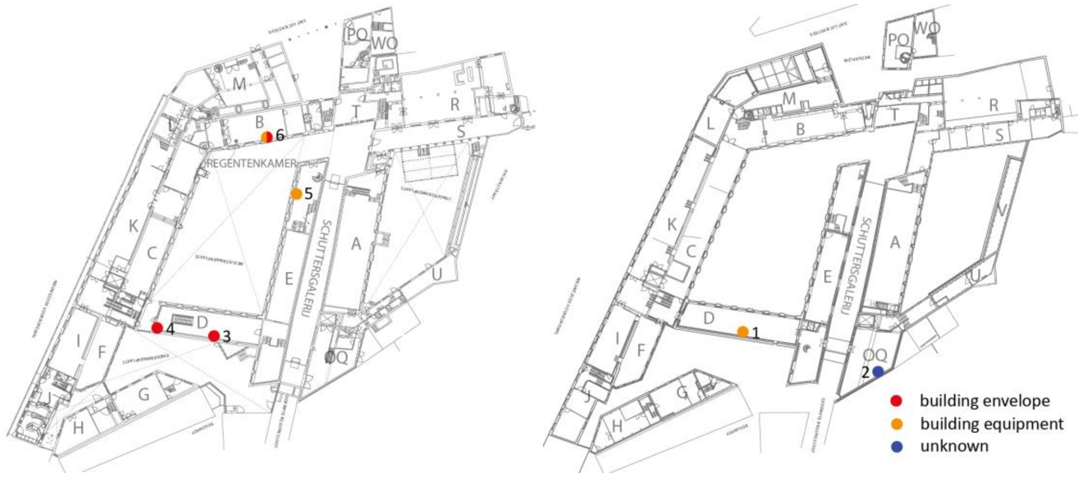

Figure 4.20 Overview of microclimates in the museum; first floor (left) and second floor (right)

4.4 Building simulation

The *Regentenkamer* was simulated using different setpoint strategies for T and RH. The impact of alternative setpoint strategies on energy use was assessed regarding preservation of museum objects and thermal comfort. Energy savings were calculated by comparing the alternative setpoint strategies (strategy 2-16) to the reference situation (strategy 1), see Table 4.5, Figure 4.21 and Figure 4.22. The comparison of general risks to the reference situation is shown in Table 4.6. Simulations were performed over the year 2015. The specifications of energy demand for the setpoint strategies are depicted in Figure 4.23. Figure 4.24 shows thermal comfort assessment according to ATG guidelines for museums (Kramer, to be published).

Reference – strategy 1

The reference situation describes the *Regentenkamer* in the current situation, with constant setpoints of 20°C ±1.5°C for T and 50% ±10% for RH, all year round, 24 h/day. The used Air Change Rate (ACR) during opening hours is 0.97%, based on 90% recirculation. During closing hours, the air handling unit recirculates 100% of the air. Due to infiltration, the ACR is assumed as 0.1 h^{-1} in this period. Table 4.5 and Table 4.6 show the results. The energy use of the reference situation is 84.55 kWh/m^2/year, of which the most is used for heating, as can be seen in Figure 4.23. Due to the large bandwidth for RH (20%), little energy is needed for humidification and dehumidification. No risks are noted for the collection. Considering thermal comfort, the indoor climate is too cold according to ATG guidelines for museum, which is considered unacceptable, see Figure 4.24.

CO_2 controlled ventilation and T/RH setpoint based on RMOT and night setback – strategy 2-7

In strategy 2, the reference situation is provided with CO_2 controlled ventilation. Fresh outdoor air is only used when the CO_2 level is too high. It is assumed that the maximum ACR of 0.97 h^{-1} is only used between 1pm and 4pm. As a result, thermal comfort improves and energy savings increase to 17%. Due to recirculation, the heating energy demand decreases. Chemical degradation increases, but objects are still save for all degradation principles. The indoor climate slightly improves according to the general risk assessment.

T setpoints based on RMOT (strategy 3) are determined by applying the lower and upper limit of ATG for museums. The setpoint depends on the running mean outdoor temperature and has a bandwidth of ±1.2°C. Thermal comfort in this strategy is enhanced, see Figure 4.24. However, chemical degradation and energy use are increased (2%) by higher T setpoints. More energy is needed for heating and little energy for cooling. As a result, the energy use for humidification increases and for dehumidification decreases. According to the general risk assessment, the indoor climate slightly improves in class AA, A and B.

Because thermal comfort is only assessed during opening hours, other setpoint strategies can be applied during closing hours. Letting T free floating (FF) (strategy 4) results in decreased energy consumption of 13% and increased chemical degradation due to high T setpoint. Due to the absence of setpoints during the night, the heating energy decreases in this period compared to strategy 3. Thermal comfort is improved by less underheating hours, see Figure 4.24. According to the general risk assessment, the indoor climate improves in class AA and deteriorates in class As and A.

The T setpoint of strategy 4 (RMOT/FF) is used for setpoint strategy 5. By using RH setpoints of 45% ±10%, chemical degradation decreases compared to strategy 4 due to low RH. Thermal comfort is unchanged and energy savings increase to 15%. The distribution of energy for heating and cooling is comparable to strategy 4. Due to the lower RH setpoint, more energy is needed for dehumidification and less for humidification. The general risk assessment shows a slightly improved indoor climate in climate class AA and B. The indoor climate deteriorates in class As and A.

In strategy 6, strategy 4 (RMOT/FF) is combined with CO_2 control (strategy 2). Risks on chemical degradation are possible due to high T setpoint. However, thermal comfort improves and energy savings increase to 33%. Due to recirculation during several opening hours, mainly the amount of heating energy decreases. According to the general risk assessment, the indoor climate improves in class AA and B, and deteriorates in class As and A.

In strategy 7, setpoint strategy 6 (RMOT/FF/CO_2) is used where the RH setpoint is lowered to 45% ±10%. Increased chemical degradation is shown compared to the reference situation. This is caused by higher T setpoints. Due to the lower RH setpoint, objects are still safe within this strategy. Thermal comfort and energy savings remain unchanged compared to strategy 6 (33%). The energy distribution of heating and cooling energy is comparable to strategy 6. Due to the lower setpoint for RH, more energy is needed for dehumidification and less for humidification. According to the general risk assessment, the indoor climate improves in class AA and B, and deteriorates in class As and A.

Table 4.5 Indoor climate prediction for different setpoint strategies. The energy use, specific risks and thermal comfort are assessed. LM in the specific risk assessment is average for four object types. Mechanical degradation of the base and pictorial layer are only displayed for panel paintings. Thermal comfort is assessed by using the Adaptive Temperature Guideline for museums.

Stra-tegy	Setpoint		Energy		Specific risk assessment				Discom-fort [h]
	T [°C]	RH [%]	Total [kWh/m²/year]	Vs. ref [%]	Mould	LM	Base layer	Pictorial layer	
1. Ref	18.5-21.5	A	84.55	0		1.05			1833
2.	CO_2	A	70.20	-17		1.02			1513
3.	RMOT	A	86.64	+2		0.95			659
4.	RMOT/ FF	A	73.14	-13		0.98			233
5.	RMOT/ FF	45±10	72.28	-15		1.04			233
6.	2 + 4	A	56.89	-33		0.95			171
7.	2 + 5	45±10	56.75	-33		1.00			171
8.	AA	AA	32.59	-61		1.02			2081
9.	As	As	24.93	-71		1.05			2081
10.	A	A	22.05	-74		1.05			2081
11.	B	B	3.53	-96		1.01			2151
12.	C	C	0.63	-99		1.02			2154
13.	D	D	0.63	-99		1.02			2154
14.	RMOT	A	85.43	+1		1.00			659
15.	RMOT ±1.5	A	79.99	-5		0.99			1688
16.	RMOT/ A	A	76.29	-10		1.02			300

Table 4.6 The simulated strategies are assessed according to the general risk assessment method. The percentage that the indoor climate falls within each ASHRAE climate class is displayed.

Stra-tegy	Setpoint		General risk assessment - ASHRAE climate classes					
	T [°C]	RH [%]	AA	As	A	B	C	D
1. Ref	18.5-21.5	A	27.2	74.6	82.9	95.7	100	100
2.	CO_2	A	28.6	80.3	87.1	97.4	100	100
3.	RMOT	A	34.7	71.6	87.2	96.2	100	100
4.	RMOT/FF	A	38.7	58.6	74.8	95.9	100	100
5.	RMOT/FF	45±10	34.6	60.0	79.9	96.8	100	100
6.	2 + 4	A	41.0	63.3	77.3	97.7	100	100
7.	2 + 5	45±10	40.0	69.3	81.3	98.3	100	100
8.	AA	AA	64.5	75.3	83.5	100	100	100
9.	As	As	31.3	72.2	78.7	100	100	100
10.	A	A	23.0	58.7	72.8	95.4	100	100
11.	B	B	16.4	37.3	34.8	94.1	100	100
12.	C	C	15.5	35.1	32.0	80.2	100	100
13.	D	D	15.5	35.1	32.0	80.2	100	100
14.	RMOT	A	32.8	75.2	85.6	96.9	100	100
15.	RMOT ±1.5	A	34.1	72.9	85.0	96.8	100	100
16.	RMOT/A	A	34.9	72.5	85.0	96.3	100	100

T/RH setpoint based on ASHRAE climate classes – strategy 8-13

Strategy 8-13 describe T and RH setpoints based on ASHRAE climate classes. See Table H.1 of Appendix H for setpoint specifications and Figure N.1 of Appendix N for simulation results for all ASHRAE climate classes. Simulation results for strategy 10 are displayed in Figure 4.22.

Strategy 8-10 show energy savings of 61-74%. Conditioning the indoor climate more strictly, from class A to AA decreases the energy savings with 13%. The wide range in T due to seasonal adjustments saves a relatively large amount of heating and cooling energy. The RH bandwidth for strategy 8 and 9 is smaller than the bandwidth of the reference situation. The energy needed for humidification and dehumidification is therefore higher compared to the reference situation. The indoor climate is safe for the museum collection. Thermal comfort is unfavorable compared to the reference situation and therefore very unacceptable: both too cold and too hot, see Figure 4.24.

Strategy 11-13 show increased energy savings (96-99%) and discomfort hours. Thermal comfort is experienced as both too hot and too cold, see Figure 4.24. In addition, mechanical degradation of the base layer and mechanical degradation of the pictorial layer will increase. For strategy 11, the energy savings are caused by the wide range in T and seasonal adjustments in T and RH. For strategy 12-13, these savings are caused by the absence of limits for T and a wide bandwidth for RH.

The general risk assessment for the simulation strategies based on ASHRAE climate classes are displayed in Table 4.6. For the climate class on which is controlled, the indoor climate should be met 100% of time. However, minimum exceedances of the climate classes are shown. Because the ASHRAE limits are just not met, the displayed percentages are distorted and should be much higher for the class on which is controlled. Actually, simulation strategies based on ASHRAE climate classes decrease general risks to the collection.

T/RH setpoint based on RMOT and ASHRAE climate classes – strategy 14-16

Strategy 14 describes T setpoints based on RMOT and RH setpoints based on ASHRAE climate class A (±10%), see Figure 4.22. Simulation results for all ASHRAE classes are shown in Figure N.2. Thermal comfort is improved due to RMOT based on ATG. Despite chemical degradation increases, objects are still safe for all degradation principles. However, no energy savings are registered. The energy use is similar to strategy 3, because of comparable setpoints: T setpoint based on RMOT and RH setpoint ±10%. Because the RH setpoint for this strategy is lower compared to strategy 3 (see Figure 4.21 and Figure 4.22), the dehumidification energy is increased and the humidification energy decreased. Due the lower RH setpoint, there is no more risk on chemical degradation. Because the RMOT limits are within the ASHRAE limits, the ASHRAE class on which is controlled (A), should actually be met 100% of time. General risks to the collection therefore decrease.

Strategy 15 includes the museum bandwidth of ±1.5°C in the setpoint strategy in which T is based on RMOT, see Figure 4.22. The RH setpoint is only based on ASHRAE climate class. Simulation results for all ASHRAE classes are shown in Figure N.3. Discomfort hours are decreased in this strategy: more underheating than overheating hours. Due to the wider bandwidth for T, energy savings increase to 5%. Lowering the lower limit for T mainly decreases the heating energy compared to the strategy 14. Risks to objects are hardly unchanged compared to the previous strategy. Because the adjusted RMOT limits are still within the AHSRAE limits, the ASHRAE class on which is controlled (A), should actually be met 100% of time. General risks to the collection therefore also decrease for this strategy.

In strategy 16, the T setpoint is based on RMOT during opening hours and on ASHRAE climate class A during closing hours, see Figure 4.22. The RH setpoint is only based on the ASHRAE climate class. Simulation results for all ASHRAE classes are shown in Figure N.4. Because the temperature bandwidth is wider during closing hours, energy savings increase to 10% compared to the reference situation. Energy savings are 11% higher compared to the setpoint strategy in which T setpoint is controlled on RMOT during day and night (strategy 14). Due to the lower temperature limit during closing hours, the heating energy demand is reduced compared to strategy 14. There are no risks for the collection. Because the combined control strategy is within the ASHRAE limits, the ASHRAE class on which is controlled (A) should actually be met 100% of time. This strategy therefore also decreases general risks to the collection. Thermal comfort is improved due to controlling on RMOT during opening hours.

The optimum control strategy regarding energy use, risks to objects and thermal comfort depends on the museum's weighting of the individual aspects. Therefore, several improved strategies are possible to implement in the museum control strategy. The most interesting strategies are strategy 7 and 16. Strategy 7 does not improve the preservation of museum objects, while energy use and thermal comfort improve significantly. In this strategy, energy savings of 33% are met. Strategy 16 shows smaller energy savings of 10%, but improves thermal comfort and preservation of museum objects significantly.

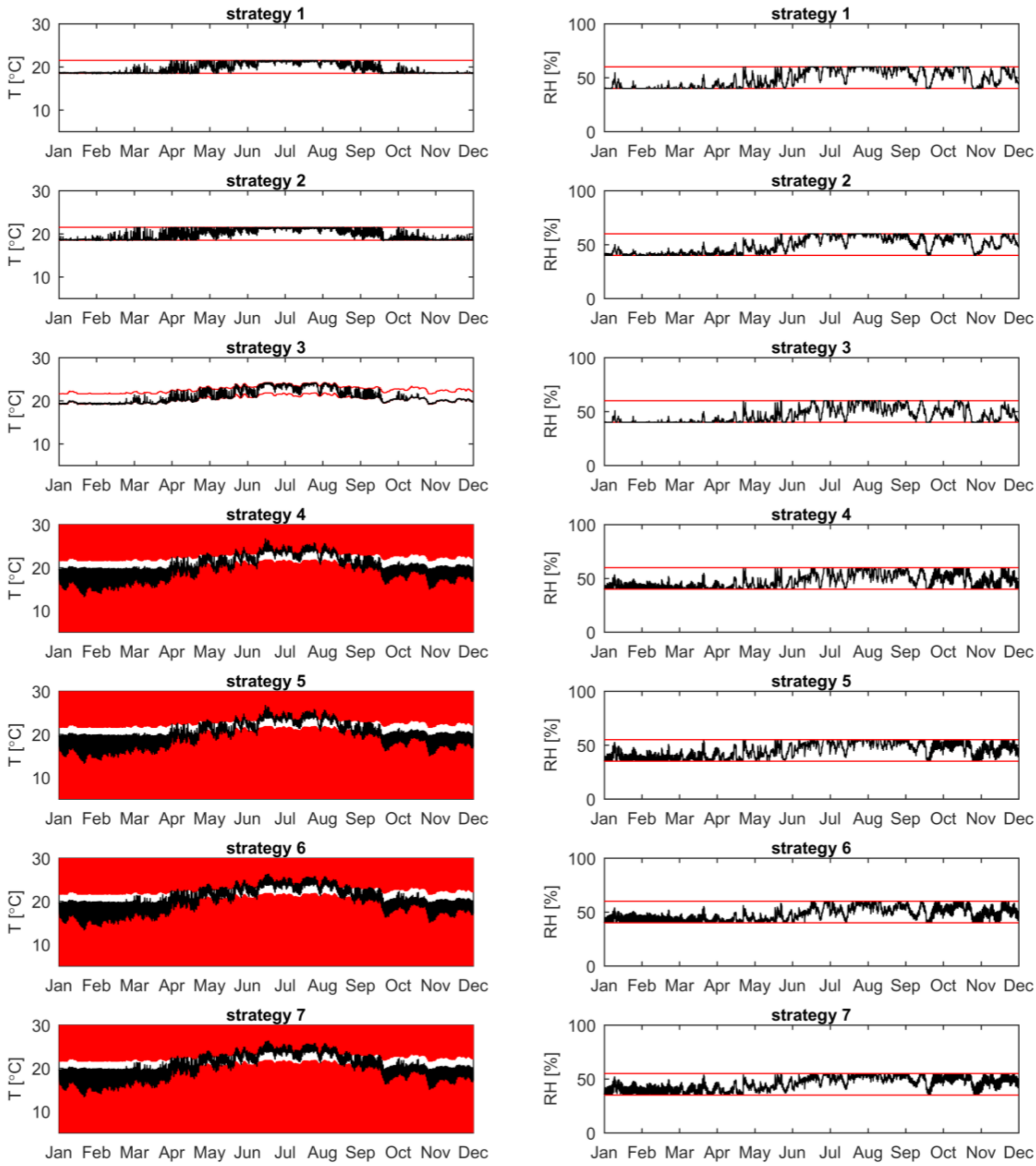

Figure 4.21 Overview of simulated setpoint strategies 1-7

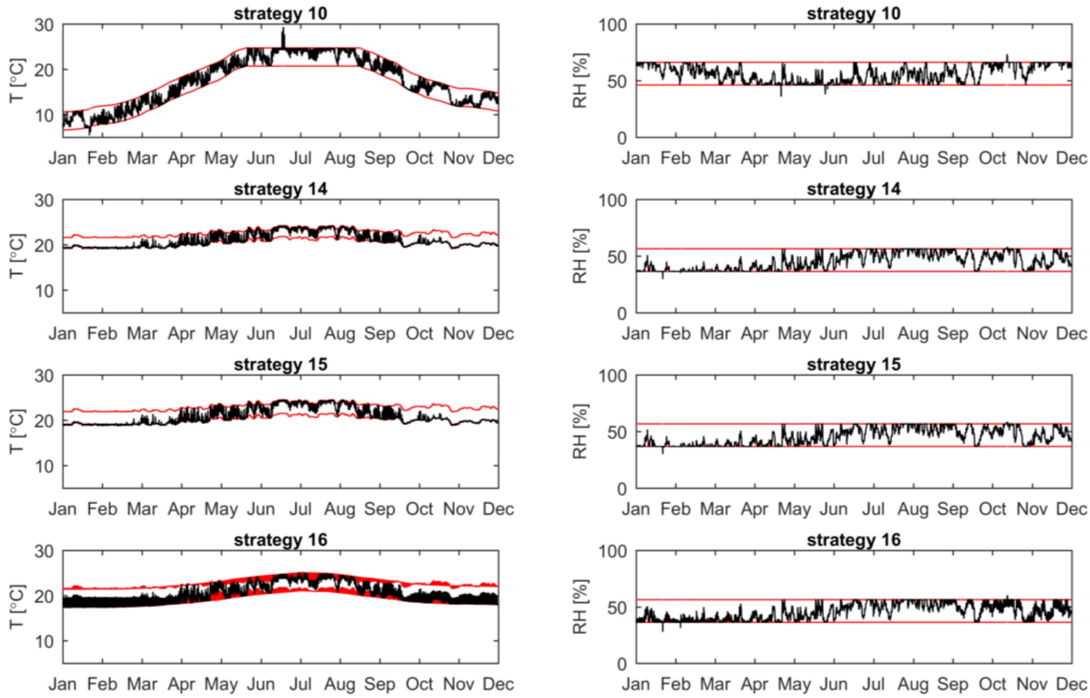

Figure 4.22 Overview of simulated setpoint strategy 10, 14, 15 and 16

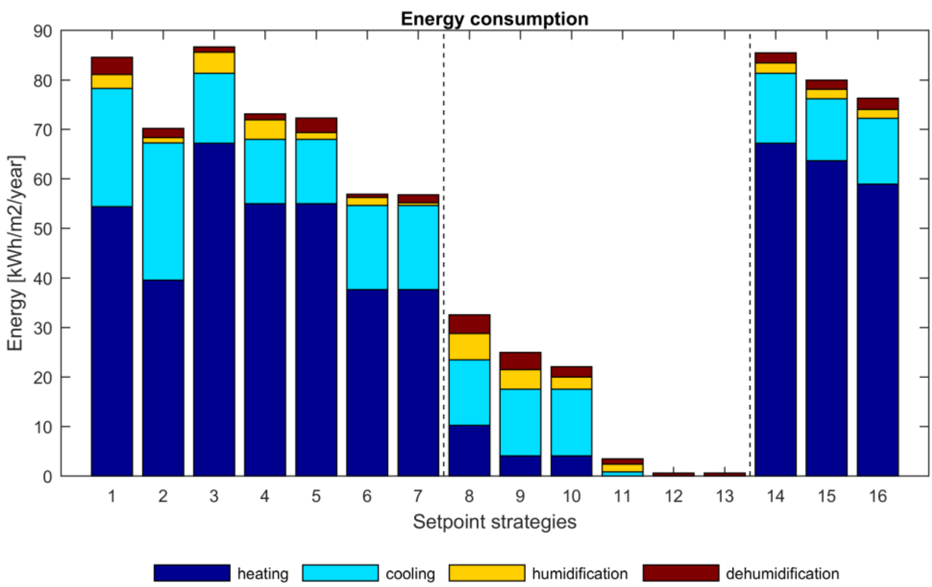

Figure 4.23 Specifications of energy demand per setpoint strategy

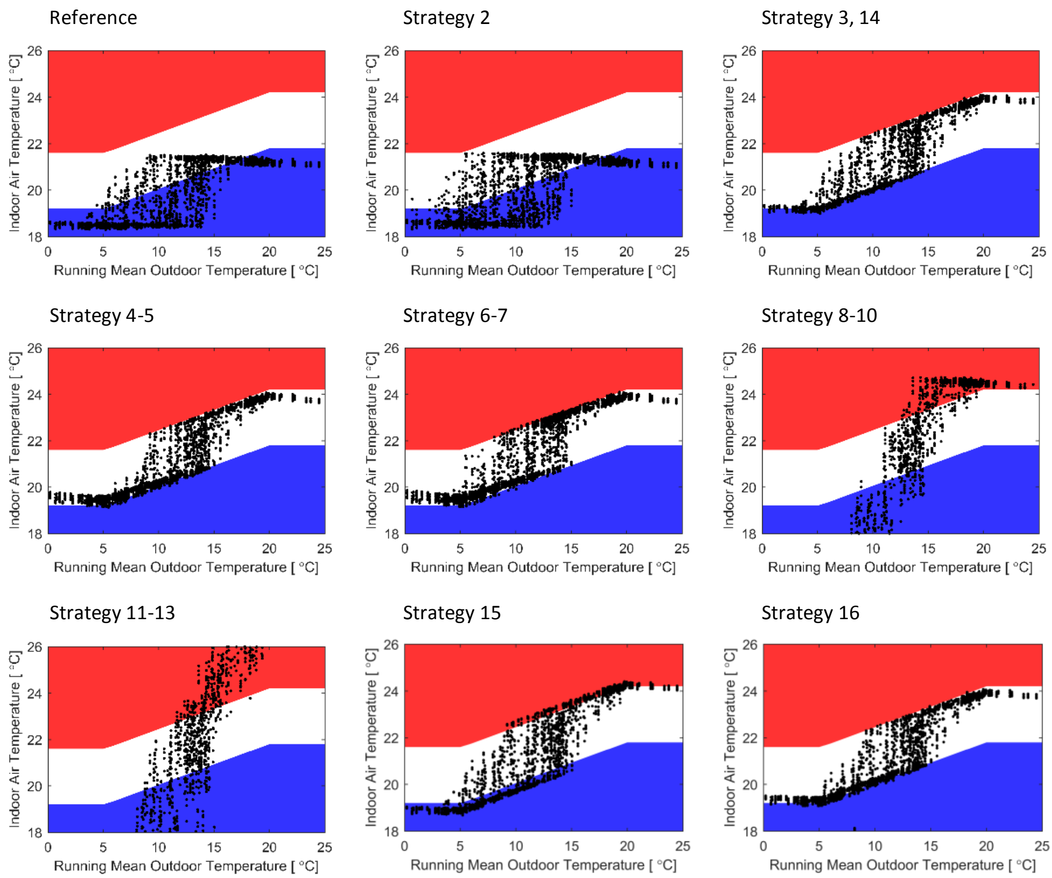

Figure 4.24 Thermal comfort assessment. Setpoint strategies of the reference situation are for T 20°C ±1.5°C and for RH 50% ±10%. Specifications of the other setpoint strategies can be found in Table 4.5.

5 Discussion

This chapter discusses the indoor climate assessment and improved HAC control for the Amsterdam Museum. The case study, measurements, indoor climate assessment (tools) and the numerical model are discussed successively. Subsequently, results on energy savings are compared to previous research performed on energy savings.

The Amsterdam Museum is housed in a large historical building. After the renovation in 1975, a lot of AHUs were installed in order to condition the indoor climate. Some components of the HVAC system have been replaced during the years. Drawings and specifications on the building and HVAC system were often hard to find or not available. Assumptions on building structures and climate control were therefore made in the numerical model. Simulation output may therefore deviate from reality.

Long-term measurements in the Amsterdam Museum are still ongoing. It has to be noted that measurement sensors in museum rooms were often not positioned at representative locations in the room, because sensors may not be in sight of the visitors and may not be moved. Therefore, deviations in results have to be considered. Due to the completion of this graduation project, measurement data for only seven months were analyzed, from August 2015 to March 2016. During the measurement period, outdoor climate data was lost due to the bad connection between the logger and the system. Because KNMI data was in the same range, KNMI data was used for assessing thermal comfort, see Appendix J. The measurement data of the sensor *Schuttersgalerij David* could not be used because the sensor was moved during the renovation of the *Schuttersgalerij*. Data for measurement position *Room 11 light gutter* was comparable to data for measurement position *Room 11 door* and was therefore excluded in the results.

Data was also lost due to a defect adapter of the logging system. If the trends of BMS data of the exhaust air and measurement data in the room were similar, measurement data was supplemented by BMS data. Because BMS data displays six minute averages, data was interpolated to the measurement interval of 10 minutes. An approximation of missing data could therefore still be made. For the Regentenkamer, measurement data was not supplemented because large deviations (>10%) were registered between measurement and BMS data, see Figure K.2 of Appendix K. These deviations arose just after replacing central distributors. The sensor may be affected by activating heating and cooling of the AHU. In case of an actual indoor RH smaller than 40%, the air handling unit still measures RH levels of 50%. Therefore, the air is not humidified. However, the air is not dehumidified in case of too high measured relative humidity levels (Figure K.5 of Appendix K). It seems that the BMS system is not controlling properly. In general, measurement data could deviate from BMS data due to the large distance between both measurement positions. BMS sensors are positioned in the exhaust and supply air duct near the AHU and the Eltek sensors are positioned in the rooms.

The methodology shows that for the general and specific risk assessment method measurement data of at least one year is needed in order to obtain reliable results. Because only seven months were used in this thesis, the results show an approximation. The indoor average temperature and relative humidity will probably increase after including the measurement data of the spring and the summer. This might result in increased chemical degradation. If the indoor temperature increases up to the adaptive temperature limits, thermal comfort will improve.

During the measurement period, the indoor climate was affected by the replacement of central distributors of the HVAC system. This resulted in extreme peaks in the measurement data, mainly a large variation in temperature. These extreme indoor conditions affected the general and specific risk assessment of the museum. More strict ASHRAE climate classes could not be met because outliers determined whether damage occurs. By preventing the large outlier caused by replacing distributors, the indoor climate in most of the rooms falls within a more strict climate class than is indicated now.

The general and specific risk assessment method show contradictory results for the Regentenkamer. The extreme peaks caused by the replacement of distributors resulted in a worse indoor climate according to the general climate risk assessment method. Because the specific risk assessment method uses the average lifetime multiplier, the high relative humidity levels during the replacement are compensated by the low relative humidity levels during the winter. Therefore, the Regentenkamer shows the most risks according to the general risk assessment method and the least risks according to specific climate risk assessment method, compared to other exhibition rooms.

Despite the specific risk assessment shows more reliable results than the general risk assessment method, the amount of objects in the method is limited. Because the assessment tool is easy to use, it is worth expanding the object types. Insight in risks to the whole museum collection could then be obtained. In addition, risks to damaged objects have to be included in the method, because museum objects have often been damaged over the years.

Thermal comfort was assessed by new developed Adaptive Temperature Guidelines for museums (to be published by Kramer). However, these guidelines were developed in a state-of-the-art museum. In addition, the limits were based on 90% acceptance class. Therefore, these limits may be too strict for museums housed in historical buildings. Further research is needed on Adaptive Temperature Guidelines for museums housed in historical buildings.

Due to the lack of information of the museum building and the HVAC system, a lot of assumptions were made for the numerical model. The lack of CO_2 measurement data, resulted in additional assumptions. Assumptions were made for building structures, actual air flow rate and the amount of visitors in the room. Due to missing measurement data and the replacement of central distributors in summer, the model was not calibrated during a warm period. Dehumidification was therefore excluded in the calibration study. Deviations may therefore be considered in the simulation results.

The simulation strategy based on the RMOT should display simulation data within the Adaptive Temperature Guidelines. However, minimum exceedances caused by simulating are shown. Limits are just not met. Each data point which exceeds the thermal comfort limits counts for one exceedance hours. Because the exceedances are very small, the displayed discomfort hours are distorted and should be much lower. Similarly, simulation strategies based on ASHRAE climate classes should display indoor climates which are met 100% of time for the class on which is simulated. Because the ASHRAE limits are just not met, the displayed percentages are distorted and should be much higher.

Setpoint strategies based on ASHRAE show large seasonal changes in temperature. Despite these conditions improve the preservation of museum objects and increase energy savings, they are very unfavorable for thermal comfort. These large seasonal adjustments may therefore not be applied in the museum environment. The optimum control strategy regarding energy use, risks to objects and thermal comfort depends on the museum's weighting of the single aspects. The simulation study shows favorable results for more than one aspect for strategy 7 and 16. Strategy 7 does not improve the preservation of museum objects, while energy use and thermal comfort improve significantly. In contrast to strategy 7, strategy 16 shows smaller energy savings of 10%, but improves thermal comfort and preservation of museum objects significantly. From comfort's perspective, temperature setpoints of strategy 7 are based on free floating during closing hours. Due to the large temperature differences between day and night, this strategy may be critical to the preservation of the collection. Despite the simulation results show no increased risks to museum objects, unexpected risks may be introduced in reality due to the absence of temperature setpoints.

In this thesis, the impact of setpoint strategies was only determined based on building simulation. By developing a model of the HVAC system of the Regentenkamer, more accurate predictions on setpoint strategies may be obtained. It has to be noted that the proportion of humidification and dehumidification is much larger in the HVAC model compared to the zone model. The HVAC model firstly cools the air in order to dehumidify and thereafter, heats the air (waterside). In contrast, the zone model simulates the most ideal situation (airside).

Comparing simulation results to literature
Martens (2012) determined general and specific risks for different qualities of building envelope in relation to different levels of control. For the Amsterdam Museum, which has a QoE 2 and LoC 4, 100% of all ASHRAE climate classes should be met according to Martens general risks assessment. Results for the exhibition rooms are more in

line with the combination QoE 2 / LoC 3 and QoE 1 / LoC 4. The replacement of central distributors is one of the causes for the worse assessment. In addition, the improper functioning of the AHU of the *Regentenkamer* affects the results. Nevertheless, results for the specific risk assessment method are in line with the results for the Amsterdam Museum: only increased risks on chemical degradation occur.

Martens (2012) also investigated the energy saving potential for different QoE and LoC. It was concluded that for QoE 2 and LoC 4 energy savings of 18% could be met if the temperature setpoint is based on weather (RMOT) and the relative humidity setpoint is based on a sine curve. Because Kramer et al. (2015) concluded that seasonal adaptation for RH has no added value for collection preservation, this strategy was excluded in this thesis. The temperature strategy based on RMOT of this thesis could not be compared, because the setpoint for RMOT is higher due to thermal comfort requirements. Finally, the bandwidth for RH is much smaller in Martens simulation study compared to this case study.

More advanced setpoint strategies were implemented in Kramer's simulation study to energy conservation in museums (Kramer, Maas et al., 2015). In this study, preservation of museum objects and thermal comfort were considered. Temperature setpoints based on RMOT during opening hours and on free floating during closing hours, together with relative humidity setpoints of 40-50%, resulted in energy savings of 77% compared to the reference situation. In this thesis, the same temperature setpoints were combined with relative humidity setpoints of 35-55%. This resulted in energy savings of 15%. These savings are much smaller, because the reference situation has the same bandwidth for RH (20%) as in the adjusted situation. The reference situation of Kramer's thesis is much stricter compared to the adjusted situation and therefore, energy savings are much higher (62%). It also has to be noted that setpoints based on the RMOT in Kramer's study are based on Adaptive Thermal Guidelines for offices, while in this research, the Adaptive Thermal Guidelines for museums are included. This may also cause difference in the amount of energy savings.

A study to the energy impact of ASHRAE's museum climate classes for different qualities of envelope was performed by Kramer, Schellen et al. (2015). The simulation results on ASHRAE climate classes for the Amsterdam Museum (strategy 8-13 in this thesis) were compared to the simulation results for QoE 2, see Figure 5.1. The figure shows that the energy use for both simulations are within the same range. The spread of temperature and relative humidity are also comparable. The energy needed for humidification and dehumidification is a bit higher compared to QoE 2. The cooling energy is a bit lower. The same conclusions of Kramer's research can therefore be drawn for this research: class B saves a lot of energy compared to class A. However, it has to be noted that energy savings were not related to thermal comfort requirements, despite thermal comfort requirements are more strict than the temperature setpoints according to ASHRAE climate classes.

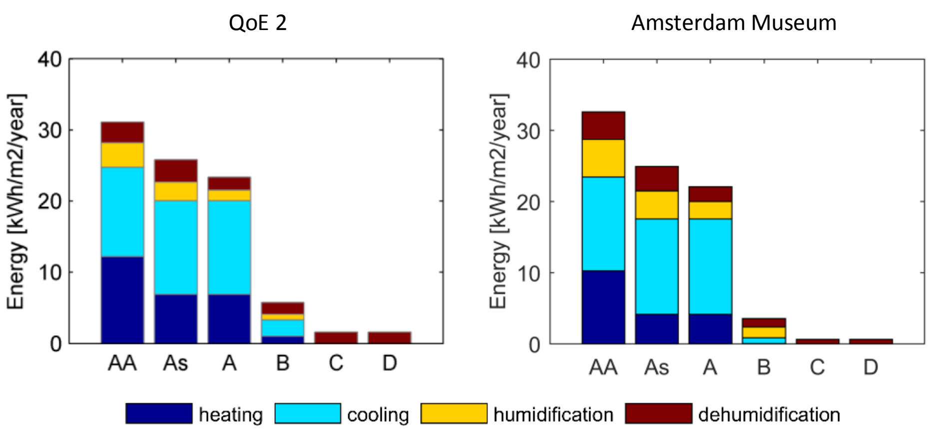

Figure 5.1 Comparison of the energy use for QoE 2 (Kramer, Schellen et al., 2015) and the Amsterdam Museum, when simulating according to ASHRAE climate classes

6 Conclusion

In this chapter conclusions are presented regarding the objectives of this thesis. Paragraph 6.1 describes conclusions on the current situation. In Paragraph 6.2 conclusions are drawn on the alternative situations.

6.1 Current situation

Quality of building envelope and HVAC system

The building envelope of the museum is qualified as a slightly modified monumental building envelope: it is equipped with an extra sheet of protective glazing. Several microclimates are distinguished near this envelope: cracks in the exterior wall, thermal bridges near window sills, cold building edges and retention walls in front of both a window and a massive exterior wall.

The HVAC system in the museum is qualified for advanced T and RH control. Heating, cooling humidification and dehumidification are present. The HVAC system in the museum is outdated, but several components have been upgraded over the years. The AHU of the *Regentenkamer* is from 2008 and is rather new.

Indoor climate assessment

Table 6.1 summarizes the results regarding the indoor climate for the measurement period from August 2015 to March 2016. From the table it can be concluded that average temperature differences in exhibition rooms are limited in the historical building (1.2°C). A larger range is noticed for the average relative humidity in exhibition rooms (6.7%). From Figure 4.13 and Table 4.1 it can be concluded that there is a good quality of mixing air in the *Regentenkamer*.

According to the general risk assessment, the indoor climate in the Amsterdam Museum is within ASHRAE climate class B or C, see Table 6.1. Climate class C has a high risk on mechanical damage to high vulnerability artifacts and a moderate risk to most paintings and photographs. For class B these risks are moderate and tiny respectively. According to ASHRAE, both climate class B and climate class C are granted for historical buildings. However, by preventing incidental peaks in T and RH most of the rooms improve by one climate class. These classes are denoted in the table between brackets.

From the specific risk assessment, it can be concluded that objects have an increased risk on chemical degradation in all museum rooms, see Table 6.1. Risks on other degradation phenomena are excluded. However, the highly valued objects in the *Regentenkamer* near the supply air grille also show risks on biological and mechanical degradation of the base layer.

From the discomfort hours due to underheating (Table 4.4) it can be concluded that the indoor climate is too cold regarding thermal comfort. In some rooms, applying no seasonal adjustments in temperature in the current situation results in relatively large amount of underheating hours during the summer (Figure 4.12). Table 6.1 also shows that T_{avg}/RH_{avg} is not depending on the central distributor to which the HVAC system is connected. This means that the indoor climate is determined by the operation of the AHU itself and the room dependent parameters, e.g. visitors, lamps and irradiated facades. The individual AHUs For the orientation, it can be concluded that warmer rooms are faced up or south.

From Table 6.1 it can be concluded that the *Schuttersgalerij* has the worst indoor climate: 73% within ASHRAE climate class A, 8% exceedance of ΔT/day, 15% exceedance of ΔRH/day and 68.1% discomfort hours due to underheating. Most of the exceeded measurement data is too humid which results in the highest average relative humidity level of all exhibition rooms. In contrast, the average temperature is the lowest of all exhibition rooms. General risks are classified to class C. However, chemical degradation is not the worst in this room. The best indoor climate is noticed in *Room D*: 96% within ASHRAE climate class A, 8% exceedance of ΔT/day, 1% exceedance of ΔRH/day and only 24.4% discomfort hours due to underheating. General risks are classified to class B. The room shows an increased risk on chemical degradation. However, a microclimate is noticed near a highly valued object in this well-conditioned room. The indoor climate of the *Regentenkamer* is somewhere in between these rooms and has therefore no exemplary performance. In contrast to the relative worse evaluation of this room according to the general risk assessment method, the specific risk assessment method shows the best results of all rooms.

6.2 Alternative situations

Simulation results of alternative setpoint strategies for the *Regentenkamer* are displayed in Table 4.5.

- Strategy 2-7: A temperature setpoint based on running mean outdoor temperature (RMOT) during opening hours significantly improves thermal comfort. Applying CO_2 control during opening hours and free floating during closing hours results in significant energy savings. Lowering the RH setpoint decreases chemical degradation. No strategy significantly increases or decreases general risks to the indoor climate.
- Strategy 8-13: temperature and relative humidity setpoints based on ASHRAE climate classes save a lot of energy. However, thermal comfort is affected considerably. ASHRAE class B, C and D even cause risks on mechanical degradation. General risks are decreased for the climate class on which is controlled.
- Strategy 14-16: Combining the temperature setpoint based on RMOT with the relative humidity setpoint based on ASHRAE climate classes does not result in energy savings. Widening the temperature bandwidth based on RMOT to the museum bandwidth reduces the energy demand but affects thermal comfort. Combining temperature setpoints for RMOT during opening hours with ASHRAE setpoints during closing hours results in the highest energy savings of these three strategies. For these strategies, general risks are decreased for the climate class on which is controlled.

The optimum control strategy regarding energy use, risks to objects and thermal comfort depends on the museum's weighting of the single aspects. Therefore, several improved strategies are possible to implement in the museum control strategy. Table 6.2 shows an overview of the most interesting strategies: 7 and 16. Strategy 7 (CO_2 controlled ventilation, T setpoint based on RMOT during opening hours and T setpoint based on free floating during closing hours, RH setpoint 35-55%) does not improve the preservation of museum objects, while energy use and thermal comfort improve significantly. In this strategy, energy savings of 33% are met. However, unexpected risks may be introduced in strategy 7 due to the absence of temperature limits during closing hours. Strategy 16 (T setpoint based on RMOT during opening hours and on ASHRAE climate classes during closing hours, RH setpoint based on ASHRAE climate classes) shows smaller energy savings of 10%, but improves thermal comfort and preservation of museum objects significantly.

Table 6.1. Summary of the results for the measured rooms. From left to right: the distributor to which the HVAC system of the room is connected to, the orientation of the room's facades and the presence of highly valued object in the room. The indoor climate is described by the average temperature and relative humidity and the Climate Evaluation Chart (CEC) assessed according to ASHRAE climate class A. The CEC describes the percentage time the indoor climate is OK and of exceeded data is too dry/humid. It also displays the percentage that limits for ΔT/day and ΔRH/day are exceeded. Risks to objects are assessed according to the general and specific assessment method. The letter in the general risk assessment indicates the best ASHRAE climate class which is met 100% of time and the letter between brackets the class which is met 98 or 99% of time. Thermal comfort is expressed in discomfort hours, based on the Adaptive Temperature Guideline for museums. Finally, the presence and type of microclimates in the room is displayed.

Measurement position	Distri-butor HVAC system	Room orien-tation	Highly valued object	Averages		CEC				Risks to objects					Discom-fort [%h]	Microclimate
				T_{avg} [°C]	RH_{avg} [%]	OK [%]	Dry/ humid	ΔT/ day [%]	ΔRH/ day [%]	gene-ral	specific: mould	LM	base layer	pict. layer		
Schuttersgalerij	S	Up**	yes	19.5	56.8	73	humid	8	15	C (A)		0.89			68.1	-
Temp exhibition	C	east	no	20.0	53.2	84	humid	11	9	C (B)		0.91			50.7	-
Room 11	S	up	yes	20.7	54.3	84	humid	12	5	B		0.83			21.4	Reflective wall?
Room D	C	south, north	yes*	20.7	51.9	96	humid	8	1	B (A)		0.87			24.4	Cracks in the wall, cold edge
Entrance	S	east	n.a.	19.5	59.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	88.3	-
Regentenkamer	C	south	yes	19.9	50.1	81	dry/ humid	7	5	C (B)		0.98			51.4	Thermal bridge window sills
Regentenkamer supply	C	n.a.	yes*	19.3	53.8	n.a.	n.a.	n.a.	n.a.	None		0.96			n.a.	Object on supply air grill

* highly valued objects near microclimate

** windows are positioned in the roof

Table 6.2 Optimum setpoint strategy compared to the reference situation. Results are shown for the energy use, general risk assessment, specific risk assessment and thermal comfort. The letter in the general risk assessment indicates the best ASHRAE climate class which is met 100% of time and the letter between brackets the class which is met 98 or 99% of time. The specific risk assessment method shows average values for four object types. Thermal comfort is assessed by using the Adaptive Temperature Guideline for museums.

Strategy	Setpoint		Energy		General risk assessment	Specific risk assessment				Discomfort [h]	Discomfort [%h]
	T [°C]	RH [%]	Total [kWh/m²/year]	Vs. ref [%]		mould	LM	base layer	pictorial layer		
1. Ref	20±1.5	50±10	84.55	0	C		1.05			1833	71.7
7.	CO2, RMOT/ FF	45±10	56.75	-33	C		1.00			171	6.7
16.	RMOT/A	A	76.29	-10	A*		1.02			300	11.7

*the ASHRAE class on which is simulated

7 Recommendations

In this chapter, recommendations to the museum staff and for further research are described.

7.1 Museum staff

The results show several microclimates near object surfaces and the building envelope. Objects on a retention wall positioned both in front of a window and a massive exterior wall show significant temperature and relative humidity gradients. Therefore, objects have to be moved or retention walls have to be better insulated. The impact of a light spot on paintings with a reflective varnish has to be investigated further by surface temperature sensors. If the measured surface temperatures over the painting differ significantly, the light spot has to be replaced by less powerful lamps (e.g. LED lamp) or removed. Finally, objects positioned near microclimates caused by cracks or supply air grilles have to be moved.

The discussion shows that the Building Management System records much higher relative humidity levels (>10%) for the *Regentenkamer* compared to the TU measurements. In case of an actual indoor RH smaller than 40%, the air handling unit still measures RH levels of 50%. Therefore, the air is not humidified. However, the air is not dehumidified in case of too high measured relative humidity levels. Besides the exhaust sensor has to be recalibrated, it has to be investigated why setpoints cannot be met in the *Regentenkamer*.

Based on building simulations, strategy 7 and 16 are interesting strategies to implement in the museum's control strategies. Both strategies improve thermal comfort. However, the optimum setpoint strategy depends on the museum's weighting of the aspects energy use, risks to objects and thermal comfort. Strategy 7 may be used if the focus is on increased energy savings, without improving the preservation of museum objects. Strategy 16 may be implemented if the focus is on preservation of museum objects and to a lesser extent on energy savings. However, unexpected risks may be introduced in strategy 7 due to the absence of temperature limits during closing hours. Therefore, it is advised to apply strategy 16 in the museum's control strategy.

7.2 Further research

In this thesis, the general and specific risk assessment only shows estimated results, because data of only seven months was available for the assessment. Because reliable results are only obtained if measurement data of at least one year is used, general and specific risks have to be assessed if more data is available.

Because the existing thermal comfort guidelines for museums were developed in a state-of-the-art museum, further research is needed to thermal comfort guidelines for museums housed in historical buildings. Thermal comfort might be assessed according to less strict guidelines.

In this study, the impact of setpoint strategies was only determined based on building simulation. By developing an additional model of the HVAC system of the *Regentenkamer*, more accurate predictions on setpoint strategies may be required. Therefore, the HVAC model may be validated by the measurement data of the HVAC system of Paragraph 3.2.3. By using the coupled zone and HVAC model, the impact of different setpoint strategies on energy savings, risks for collection and thermal comfort may be investigated more accurately. Energy may also be saved by revealing inconsistencies in the control strategy, which can be derived from the measurement data of the HVAC system. Finally, the optimum strategy may be implemented in the control strategy of the museum.

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Appendices

Appendix A. Inventory

Table A.1 Inventory list

Building (envelope)	**Available (Yes/No)**
Year of construction	No
Building specifications/documentation	No
Floor plans	Yes
Sections	No
Elevations	No
Structure drawings (thickness, thermal conductivity λ)	No
Glass (single/double)	Yes
HVAC system	**Available (Yes/No)**
BMS	Yes
- position of sensors	Yes
- sensor types	Yes
- software BMS	Yes
- setpoints BMS	Yes
- monitored parameters and data	Yes
Technical drawings of the HVAC system	No
Zoning of AHUs	Yes
Which HVAC components have already been replaced, which still need to be replaced	No
Specifications of the HVAC system and sensors	Yes
Contact information	Yes
Use of the museum	**Available (Yes/No)**
Amount of visitors per year	Yes
Average visit length	No
Visiting in guided in groups or freely wander around	No
Types of objects	Yes
Plan with position of the objects	No
Exhibition program (type of exhibition, temporary or permanent, when change)	Yes
Extra preventive measures	No
Building use during measurement period	**Available (Yes/No)**
Special events	Yes
- evening openings	Yes
- temporary exhibitions	Yes
- increase amount of visitors during special events	Yes
System malfunctions	Yes
Energy	**Available (Yes/No)**
Overview of energy consumption over the last three years	Yes, whole museum
- per zone	No, whole museum
- distribution of energy over sectors (lighting, ventilation etc.)	No

Table A.2 Logbook – Different opening or closing hours

Different opening or closing hours				
extra opened part	date	opening hour	closing hour	description
whole/~~partly~~	07-11-2015 08-11-2015	19:00	02:00	Museum night, 2600 people in whole the museum
~~whole~~/partly	28-01-2016	17:00	22:00	Extended opening hours for room K, C, F, I (0, 1, 2, 3) at the first floor, room K and C (17, 18, 19, 20) at the second floor, and the *Regentenkamer* at the first floor; Saying farewell to the director.

Table A.3 Logbook – Maintenance and malfunctioning of the HVAC system

Maintenance and malfunctioning of the HVAC system						
AHU no.	Distributor/ room	start date	end date	start time	end time	description
See des-cription	Distributor *Schuttersgalerij*	Week 24, 10-06-15	Week 28, 08-07-15	-	-	Replace distributor *Schuttersgalerij*. Coupled AHU's: 99AE, 100A, 105E, 109OQ, 110Galerij, 117Blucht + radiators.
		Week 29	Week 29	-	-	Operating distributor *Schuttersgalerij*.
		Week 32	Week 32	-	-	Insulate pipes of distributor *Schuttersgalerij*.
See des-cription	Distributor building T	Week 25/27, 17-06-15	Week 29, 16-07-15	-	-	Replace distributor building T. Coupled AHU's restaurant R, kitchen P and vault
		Week 33	Week 33			Insulate pipes of distributor building T.
See des-cription	Distributor building C	Week 34/35, 17-08-15	Week 39, 25-09-15	-	-	Replace distributor building C. Coupled AHU's: 101BM, 102C, 103CE, 104D, 106F, 107K, 108KI, 111Blucht, 112KIC, 115Reg + radiators.
		Week 40	Week 41	-	-	Insulate pipes of distributor building C.
101, 104, 107	Building B and M (upper floors), Building D and K	Week 40, ±28-09-15	-	-	-	Heating and cooling in operation
All	Whole museum	07-11-15	07-11-15	19:00	21:00	Low pressure, central heating.
110	*Schuttersgalerij*	07-11-15	12-12-15	-	-	Renovation of the *Schuttersgalerij*, AHU remains operational.
All	Whole museum	Week 48, 25-11-15	Week 48, 26-11-15	-	-	Calibration of sensors by Honeywell: supply T and exhaust T.
All	Whole museum	05-02-16	05-02-16	12:00	17:00	Power failure.

Table A.4 Logbook – Temporary exhibitons

Temporary exhibitions					
room no/ name	exhibition	start date exchange	end date exchange	start date exhibition	end date exhibition
Room K, C, F, I (0, 1, 2, 3) at the first floor and K,C (17, 18, 19, 20) at the second floor	*De IJzeren Eeuw* was replaced by *Graffiti - New York meets the dam*.	02-08-15	18-09-15	18-09-15	25-01-16
Room I, F (14, 15) at the second floor	*Mix & Match* was replaced by *Transmission*.	21-09-15	15-10-15	17-10-15	13-03-16
Room K, C, F, I (0, 1, 2, 3) at the first floor and K,C (17, 18, 19, 20) at the second floor	*Graffiti - New York meets the dam* at the first floor was replaced by *Made in Amsterdam*. *Regentenkamer* closed during this period. No exhibition at the second floor; rooms are empty.	29-01-16	10-03-16	11-03-16	31-07-16

Appendix B. Floor Plans

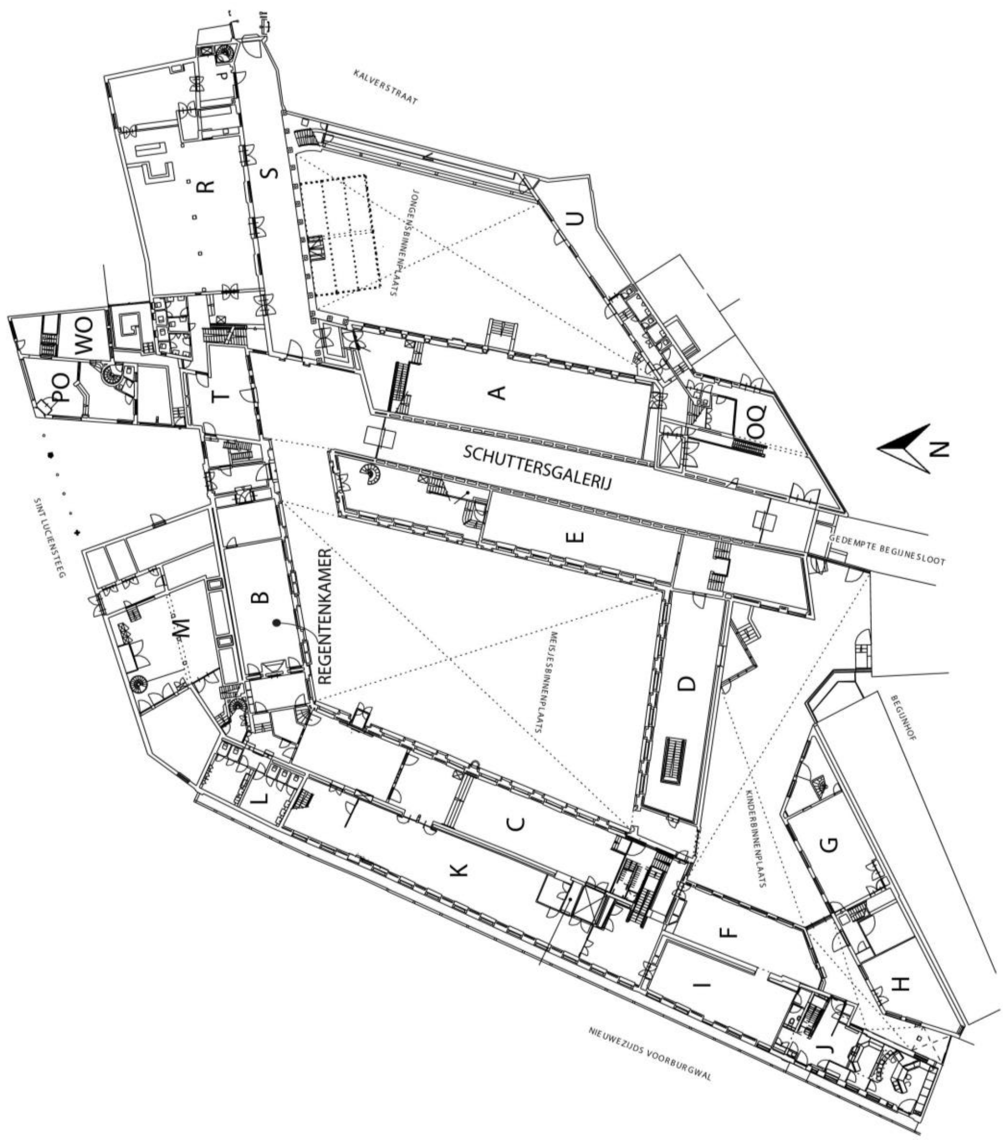

Figure B.1 Floor plan of the first floor

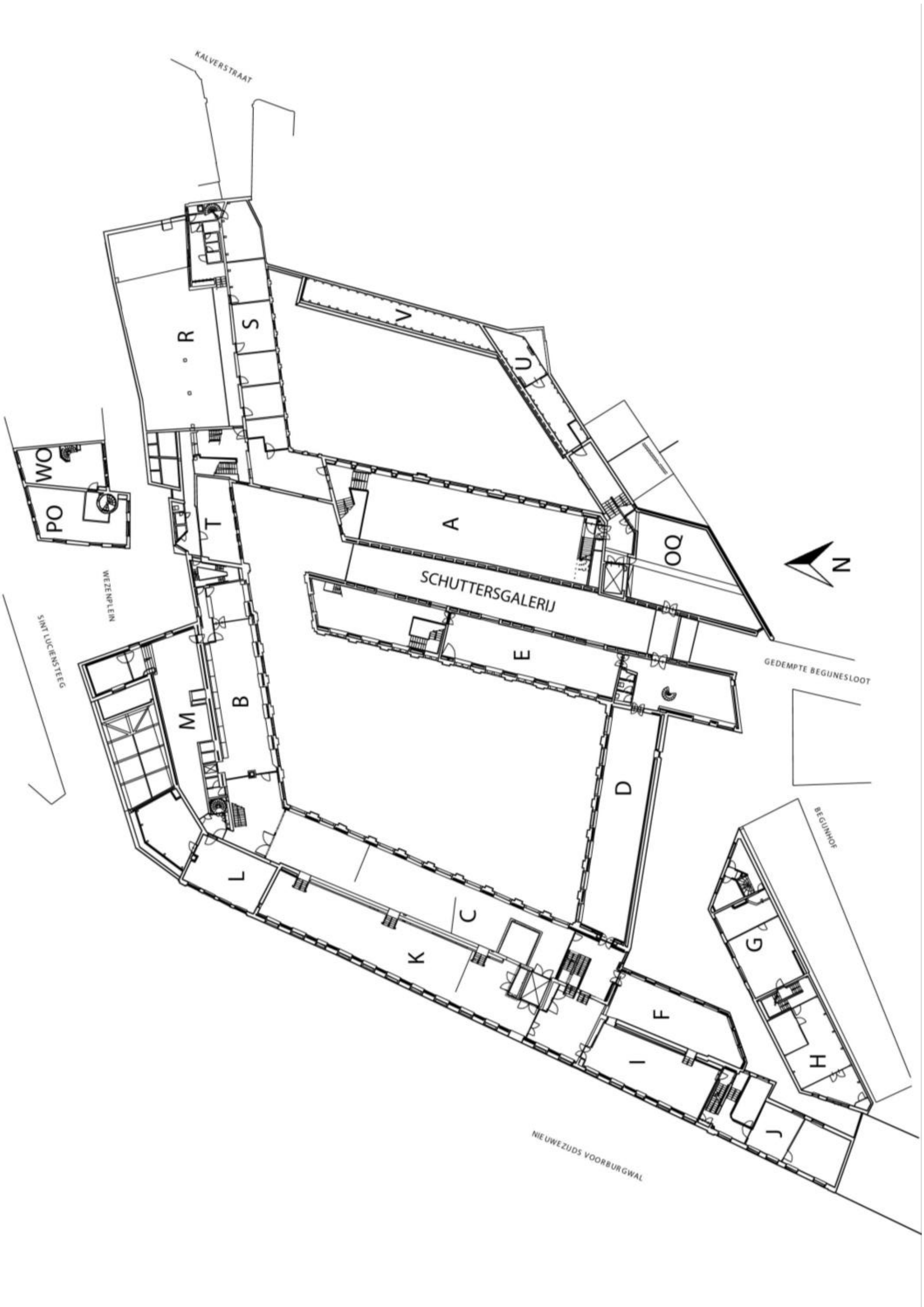

Figure B.2 Floor plan of the second floor

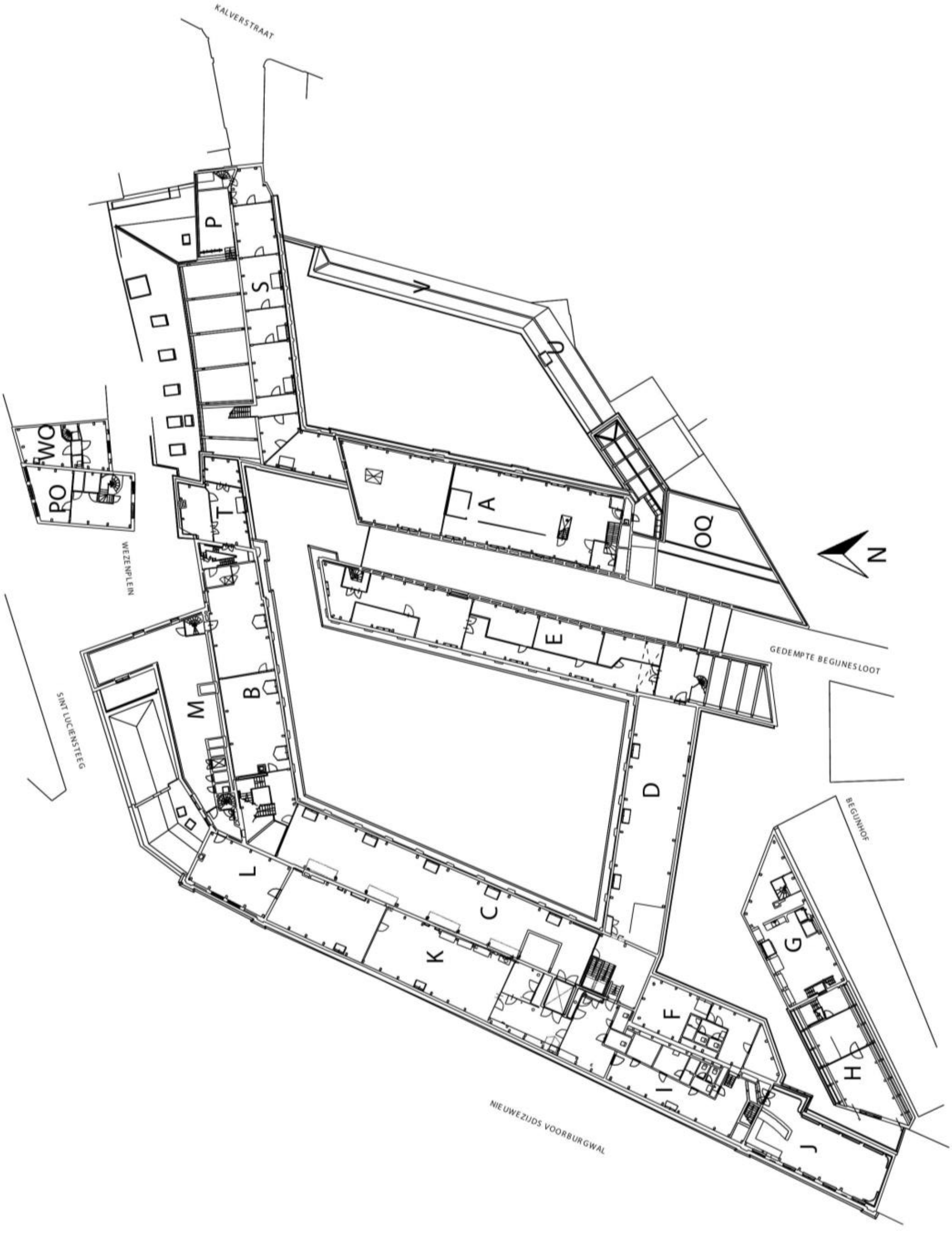

Figure B.3 Floor plan of the third floor

Appendix C. Air Handling Unit

General specifications

Airovision

Carrier holland heating

Datum: 11/1/2008

Technische Specificatie

Projektnaam : Amsterdams Historisch Museum te Amsterdam — Software versie: E4.0 (2-5-2007)/A
Offertenummer : 1581-07-o / 001

ALGEMENE GEGEVENS	**2008 1 0047**			
Produkt	Luchtbehandelingskast	Klantcode		LBK kelder Regentenkamer
Aantal	1	Bouwvorm		Horizontaal
Uitvoering	Binnenopstelling	Totaal gewicht (p/st)	kg	889
Aflevering	Stijlen en panelen	Afgestraald geluidsvermogen	dB(A)	64
LBK kleur	Uitwendig in standaard kleur (RAL 7042)	Eurovent energie classificatie	A	A

TOEGANG GEGEVENS

Handgreep type	L-greep

TOEVOER

Type	39HQ 05.04	Luchthoeveelheid	m3/s	0.72
Omkasting uitvoering	GP080 60 mm	Binnenbeplating		Polyester gecoat staal 0.80mm
Isolatie	Glaswol 20-30 kg/m3	Buitenbeplating		Polyester gecoat staal 0.80mm

Mechanische eigenschappen volgens EN1886							
	Geselecteerde kast	D2	L2	F7	T2	TB2	(R)
	Model box	D1	L2	F9	T2	TB2	(M)

Geluidsgegevens toevoer	Hz	125	250	500	1k	2k	4k	8k	dB(A)
Geluidsvermogen (intrede-links)	dB	75	74	75	68	59	45	34	74
Geluidsvermogen (intrede bodem)	dB	75	74	75	68	59	45	34	74
Geluidsvermogen (uittrede)	dB	70	62	50	37	35	40	38	58

UNIT TOEBEHOREN
LBK voorzien van de benodigde anti-trillingsmatjes

ALGEMENE OPMERKINGEN
Doorvoeropening BxH = 1000x2000 mm

In de luchtrichting bestaat de kast uit:

AFLEVERINGSDE(E)L(EN)

Afleverdeel	Breedte (mm)	Hoogte (mm)	Lengte (mm)	Ondersteuning (mm)	Gewicht (kg)
1	898	738	3778	160	440
2	898	738	3778	Geen	449

TOEVOER COMPONENTEN

MENG

Recirc opening, b x h	mm	418 x 578	Voorzien van:	
Luchtweerstand	Pa	56	Produkt op opening	Flexibele verbinding Enkelwandig
			Kleppenregister	Inbouw, Gelijk roterend, Geschikt voor servomotor
Aanzuig opening, b x h	mm	418 x 578	Voorzien van:	
Luchtweerstand	Pa	56	Produkt op opening	Kanaalaansluitflens
** (achterzijde)			Kleppenregister	Inbouw, Gelijk roterend, Geschikt voor servomotor

TOEBEHOREN
2 x Montage toegeleverde servomotor
**Buitenluchtaanzuigopening voorzien van filterdoek

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Airovision

Carrier holland heating

Datum: 11/1/2008

Technische Specificatie

Projektnaam : Amsterdams Historisch Museum te Amsterdam — Software versie: E4.0 (2-5-2007)/A
Offertenummer : 1581-07-o / 001

MENG					
Luchtweerstand	Pa	0			

FILTER					
Filter type		Zakken (Synthetisch)	Uitnemen via		Zijkant (inschuif)
Filterklasse		F7	Testmethode		0.4 µm vlgs. EN 779
Aanvangsweerstand	Pa	70			
Ontwerpweerstand	Pa	111			
Eindweerstand	Pa	152			
			Filterlengte	mm	500
Materiaal filterframes		RVS 316			
Lekbak		RVS 316			

TOEGANG

Toegang via		Luik	Toegangskant		Rechts

TOEBEHOREN
1 x Montage toegeleverde drukverschilschakelaar
1 x Drukverschilmeter opbouw, Minihelic 5000 (0-250 Pa)

VERWARMER	(water)		Aantal elementen		1
Luchthoeveelheid	m3/s	0.72	Medium	100%	Water
Capaciteit	kW	18.33	Medium hoeveelheid	l/s	0.22
Intrede temp.	°C	15.0	Medium intrede	°C	90.0
Uittrede temp.	°C	36.0	Medium uittrede	°C	70.0
Luchtweerstand	Pa	18	Mediumweerstand	kPa	7
Pijpen/vinnen/aansl.		Cu / AlPP / Cu	Aansluitingen		Gasdraad (Rechts)
Frame element		Standaard	Aansluitdiameter		1"
Wanddikte pijpen	mm	0.35	Vinafstand	mm	3.0
Tube diameter	mm	12.45	Vindikte	mm	0.12
Luchtsnelheid	m/s	2.33			

MEETSECTIE					
Luchtweerstand	Pa	0			

TOEBEHOREN
1 x Meetsok, 6mm

KOELER			Aantal elementen		1
Luchthoeveelheid	m3/s	0.72	Medium	100%	Water
Capaciteit	kW	31.94	Medium hoeveelheid	l/s	1.53
Intrede temp. db	°C	26.0	Medium intrede	°C	5.0
Intrede temp. nb/RV	°C/%	21.8 / 70	Medium uittrede	°C	10.0
Uittrede temp. db	°C	9.0	Mediumweerstand	kPa	31
Uittrede temp. nb/RV	°C/%	9.0 / 100			
Luchtweerstand Element	Pa	348	Luchtweerstand Druppelv.	Pa	18
Pijpen/vinnen/aansl.		Cu / AlPP / Cu	Aansluitingen		Gasdraad (Rechts)
Frame element		Standaard	Aansluitdiameter		1 1/4"
Wanddikte pijpen	mm	0.35	Vinafstand	mm	2.0
Tube diameter	mm	12.45	Vindikte	mm	0.12
Luchtsnelheid	m/s	2.39	Druppelvanger		Kunststof
Lekbak, uitvoering		Standaard (Vlak)	Materiaal lekbak		RVS 304

Airovision

Carrier holland heating

Datum: 11/1/2008

Technische Specificatie

Projektnaam : Amsterdams Historisch Museum te Amsterdam Software versie: E4.0 (2-5-2007)/A
Offertenummer : 1581-07-o / 001

VENTILATOR

Ventilator type		Achterover gebogen			
Aantal ventilatoren		1	Motorvermogen	kW	1.50
Luchthoeveelheid	m3/s	0.72	Motor		Run
Uitblaassnelheid	m/s	7.03	Motor rendementsklasse		EFF2
Systeemeffect	Pa	60	Motortoerental	t/min	3000
Externe statische druk	Pa	250	Aansluitspanning	V	230/400
Totale statische druk	Pa	979	Stroom	A	3.3
Dynamische druk	Pa	30	Vermogen uit het net	kW	1.48
Totale druk	Pa	1009	Specific FanPower (SFPv)	kJ/m3	2.06
Ventilatortoerental	t/min	3152			
Rendement	%	71			
Asvermogen	kW	1.02			

Geluidsvermogen (dB)	Hz	63	125	250	500	1k	2k	4k	8k
Total	In dB	71	79	78	80	79	73	68	60
	Uit dB	74	78	77	79	77	75	68	57

TOEGANG

Toegang via	Luik	Kijkglas	Inclusief
Toegangskant	Rechts		

TOEBEHOREN
1 x Werkschakelaar, 3P 16A tbv stuurstroom circuit
1 x Montage toegeleverde drukverschilschakelaar
1 x Lichtarmatuur, Bulleye 40 Watt, incl. bekabeling
1 x Lichtschakelaar, incl. bekabeling naar lichtpunt

EXPANSIE

Luchtverdeelscherm		Inclusief	Materiaal verdeelscherm	Sendzimir
Luchtweerstand	Pa	11		

TOEGANG

Toegang via	Luik	Toegangskant	Rechts

INFRASOON BEVOCHTIGER

Luchtweerstand	Pa	70	Intredecondieties	°C / g/kg	36.0 / 1.0
Uittredecondieties	°C / g/kg	15.2 / 9.3	Capaciteit	kg/h	24.6
Luchtweerstand	Pa	70	Sectielengte	mm	1600
Benodigde waterhoeveelheid	kg/h	57.0			

TOEGANG

Toegang via	Luik	Toegangskant	Rechts

TOEBEHOREN
1x Infrasone bevochtiger KGM-3/3
1x Console (losse levering), inclusief pompset en frequentieregeling
Incl. het in bedrijf stellen van deze bevochtiger ter plaatse na installatie

VERWARMER	(water)		Aantal elementen		1
Luchthoeveelheid	m3/s	0.72	Medium	100%	Water
Capaciteit	kW	12.22	Medium hoeveelheid	l/s	0.15
Intrede temp.	°C	16.0	Medium intrede	°C	90.0
Uittrede temp.	°C	30.0	Medium uittrede	°C	70.0
Luchtweerstand	Pa	16	Mediumweerstand	kPa	5
Pijpen/vinnen/aansl.		Cu / AlPP / Cu	Aansluitingen		Gasdraad (Rechts)
Frame element		Standaard	Aansluitdiameter		1"
Wanddikte pijpen	mm	0.35	Vinafstand	mm	2.0
Tube diameter	mm	12.45	Vindikte	mm	0.12
Luchtsnelheid	m/s	2.33			

Datum: 11/1/2008

Technische Specificatie

Projektnaam : Amsterdams Historisch Museum te Amsterdam	Software versie: E4.0 (2-5-2007)/A
Offertenummer : 1581-07-o / 001	

GELUIDDEMPER

Lengte	mm	1120							
Luchtweerstand	Pa	22			Geluidsgegevens volgens			ISO 7235	
Dempingswaarden	Hz	63	125	250	500	1k	2k	4k	8k
	dB	3	8	15	29	40	39	25	16

UITBLAAS

Opening, breedte x hoogte	mm	738 x 578	Voorzien van:	
Luchtweerstand	Pa	0	Produkt op opening	Flexibele verbinding
				Enkelwandig

Honeywell

H7015A,B

DUCT HUMIDITY SENSOR/ COMBINED HUMIDITY/TEMPERATURE SENSOR

PRODUCT DATA

GENERAL

The H7015A Duct Humidity Sensor is a capacitance-type relative humidity sensor for duct mounting.

The H7015B Combined Humidity / Temperature Duct Sensor combines a capacitance type relative humidity sensor with a Pt 1000, BALCO 500 or 20kΩ NTC temperature sensor in one housing.

These sensors can be used
- for discharge, outside or return air control
- as high limit sensor e.g. for steam humidification

Models

OS-No.	Temperature Sensor Type
H7015A1006	-
H7015B1004	Pt 1000
H7015B1012	BALCO 500
H7015B1020	20kΩ NTC

FEATURES

- **Pt 1000, BALCO 500, or 20kΩ NTC temperature sensing element**
- **Wide sensing range**
- **Capacitance type sensing element for relative humidity**

SPECIFICATION

Power supply	24 Vac, ±20% (SELV) 15…30 Vdc
Current consumption	15 mA at 24 V
Ambient Limits	
Operating temperature	
- Terminal box	0...50 °C (32...122 °F)
Transport and storage temperature	-25...+60 °C (-31...+158 °F)
Humidity	5...95% rh, non-condensing
Safety	
Protection class	III as per EN60730-1
Protection standard	
- Terminal box	IP54 as per EN60529
Flame retardant terminal box	V1 as per UL94 plastic (ABS)
Dimensions	see Fig. 2
Weight	300 g
Mounting	duct
Temperature Sensor	
Temperature sensing range	-30...+70 °C (-22...+158 °F)
Nominal value	
- Pt 1000	1000 Ω at 0 °C
- BALCO 500	500 Ω at 23.3 °C
- NTC	20 kΩ at 25 °C
Accuracy	
- Pt 1000	$\Delta T/K = \pm(0.3 + 0.005 \cdot \lvert t \rvert)$ [t in °C] as per DIN IEC 751 Class B
- BALCO 500	±0.4 K at 23.3 °C
- NTC	±0.3 K at 25 °C
Sensitivity	
- Pt 1000	≈3.85 Ω/K
- BALCO 500	2 Ω/K
Characteristic	see EN0B-0476GE51
Response time at air velocity 5 m/s	
$\tau_{0.5\ Pt\ 1000}$	< 60 s
$\tau_{0.5\ Balco\ 500}$	< 45 s
$\tau_{0.5\ NTC}$	< 85 s

CE

Appendix D. Measurement plan

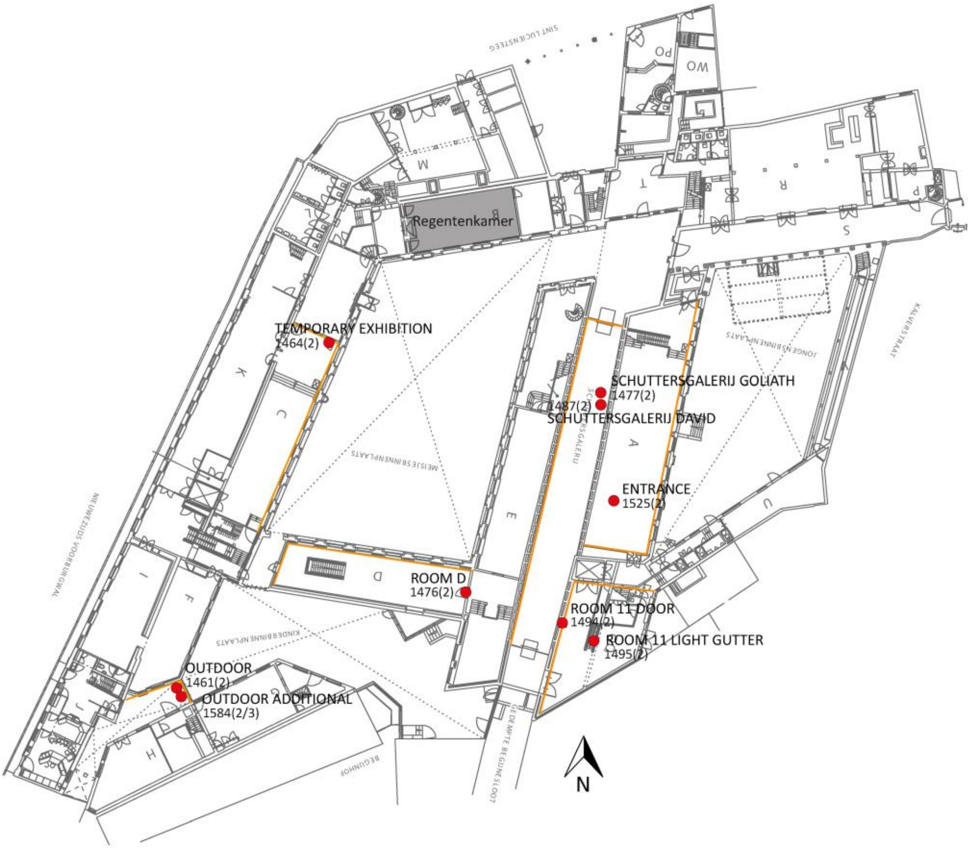

Figure D.1 Measurement setup on building level

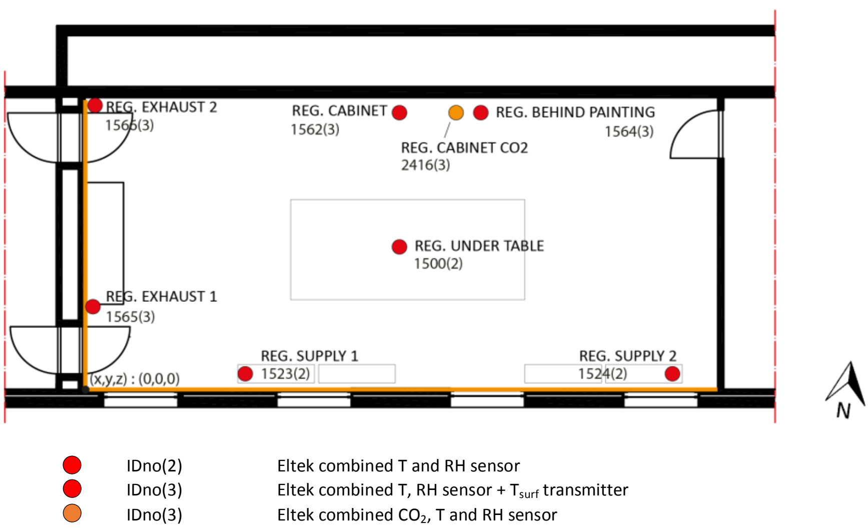

Figure D.2 Measurement setup of the Regentenkamer

Table D.1 Sensor specifications of the measurement setup on building and room level

Eltek, Squirrel 1000 series - Receiver ID 0934 serial number El8199, type RX250AL, gsm ID 1170 Number 06-53776798, Repeater ID 2902, T- 27 July - ?

Channel ID0934	Channel ID2902	ID	T	Transm. Channel	para-meter	Unit	Device	Type	Range	Accuracy	Location	x	y	z
1	M01	1500	6798	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Regentenkamer_under_table	5.514	3.150	0.124
2	M02			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
3	M03	1523	6822	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Regentenkamer_supply1	3.087	0.450	0.000
4	M04			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
5	M05	1524	6823	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Regentenkamer_supply2	11.757	0.453	0.000
6	M06			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
7	M07	1525	6824	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	entrance	5.300	5.686	2.835
8	M08			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
9	M09	1562	6901	C	T	˚C	Eltek - Sensirion sensor	GC-14E*	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Regentenkamer_cabinet	5.964	5.278	2.102
10	M010			D	RH	%	Eltek - Sensirion sensor	GC-14E*	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
11	M011			A	Tsurf	˚C	Elktek - U type thermistor	GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)		5.330		
12	M012	1564	6903	C	T	˚C	Eltek - Sensirion sensor	GC-14E*	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Regentenkamer_behind_painting	7.122	5.453	2.126
13	M013			D	RH	%	Eltek - Sensirion sensor	GC-14E*	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
14	M014			A	Tsurf	˚C	Elktek - U type thermistor	GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)				2.329
15	M015	1565	6904	C	T	˚C	Eltek - Sensirion sensor	GC-14E*	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Regentenkamer_exhaust1	0.347	1.307	2.305
16	M016			D	RH	%	Eltek - Sensirion sensor	GC-14E*	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
17	M017			A	Tsurf	˚C	Elktek - U type thermistor	GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)				
18	M018	1566	6905	C	T	˚C	Eltek - Sensirion sensor	GC-14E*	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Regentenkamer_exhaust2	0.201	5.426	2.402
19	M019			D	RH	%	Eltek - Sensirion sensor	GC-14E*	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
20	M020			A	Tsurf	˚C	Elktek - U type thermistor	GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)				2.252
21	M021	1578	6917	C	T	˚C	Eltek - Sensirion sensor	GC-14E*	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Regentenkamer_supply_to_LBK115	1.556	4.430	0.970
22	M022			D	RH	%	Eltek - Sensirion sensor	GC-14E*	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
23	M023			A	Tsurf	˚C	Elktek - U type thermistor	GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)				
24	M024	1584	6923	C	T	˚C	Eltek - Sensirion sensor	GC-14E*	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Outdoor_additional	6.557	0.448	0.230
25	M025			D	RH	%	Eltek - Sensirion sensor	GC-14E*	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
26	M026			A	Tsurf	˚C	Elktek - U type thermistor	GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)				
27	M027	1464	4667	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Temporary_exhibition	0.534	0.000	2.739
28	M028			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
29	M029	1476	4679	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Room_D	21.429	2.365	2.535
30	M030			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
31	M031	1477	4680	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Schuttersgalerij_goliath	3.093	6.920	2.642
32	M032			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
33	M033	1487	6785	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Schuttersgalerij_david	4.464	9.428	0.548
34	M034			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
35	M035	1494	6792	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Room_11_door	0.270	6.187	2.584
36	M036			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
37	M037	1495	6793	A	T	˚C	Eltek - Sensirion sensor	GC-13E	-40.0 - 120.0˚C	± 0.4˚C (5-40˚C)	Room_11_light_gutter	3.765	7.582	4.861
38	M038			B	RH	%	Eltek - Sensirion sensor	GC-13E	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
39	M039	1461	7029	A	Tex	˚C	Eltek - Sensirion sensor	GC-13R	-40.0 - 85.0˚C	± 0.4˚C (5-40˚C)*	Outdoor	6.557	0.448	1.450
40	M040			B	Rhex	%	Eltek - Sensirion sensor	GC-13R	0 - 100%	± 2% (10-90%), ± 4% (0-100%)*				
41	M041													
42	M042	2416	19158	A	T	˚C	Eltek	GW-47	-30.0 - 65.0˚C	± 0.5˚C (5-45˚C)	Regentenkamer_CO2	6.772	5.278	2.100
43	M043			B	RH	%	Eltek	GW-47	0 - 100%	± 2% (10-90%), ± 4% (0-100%)				
44	M044			C	CO2	ppm	Eltek	GW-47	0-5000 ppm	± 50ppm + 3% of measured value				
45	M045			C	CO2	V	Eltek	GW-47	0 - 1 V	-				

*specs assumed as GC-13E

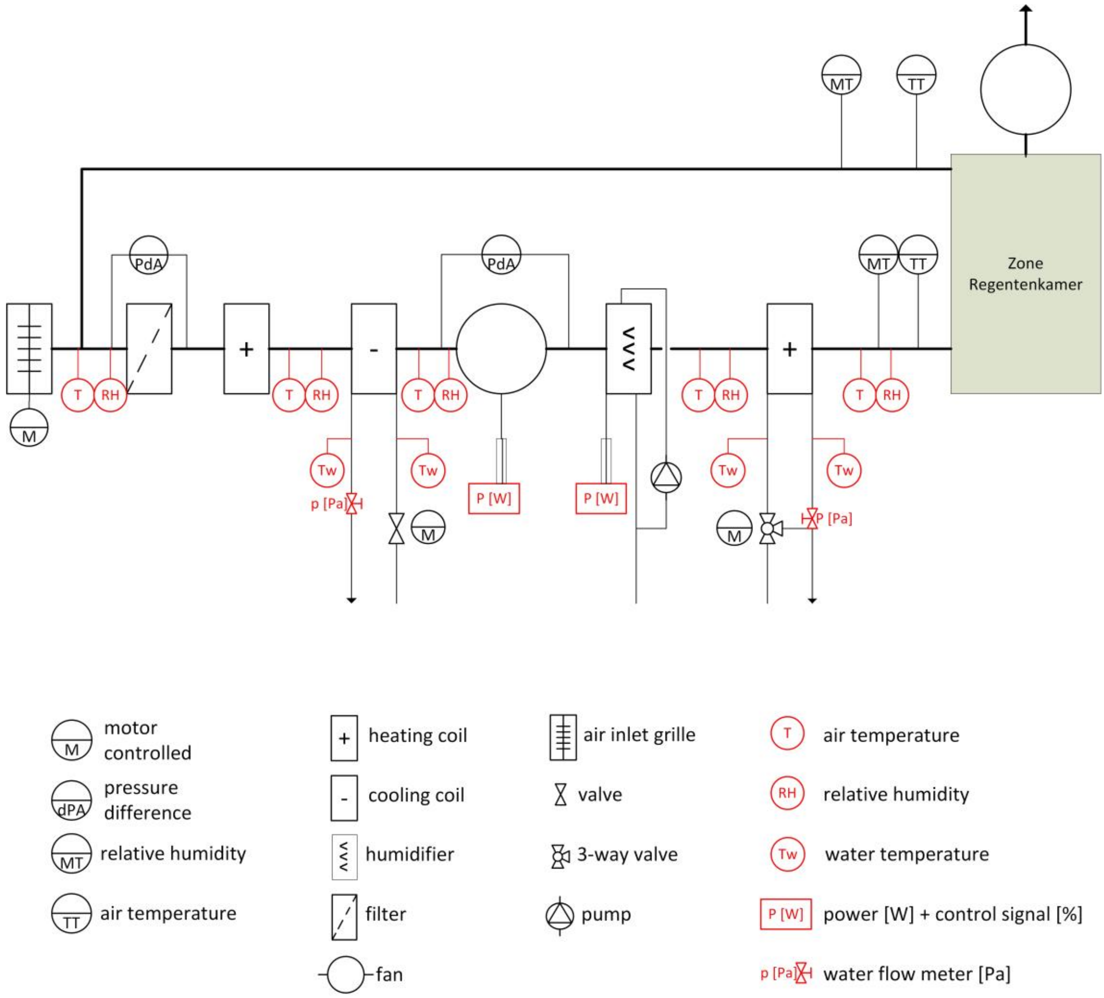

Figure D.3 Measurement setup of the HVAC system of the Regentenkamer: the components and sensors of the HVAC system in black and the additional measurement sensors in red

Table D.2 Sensor specifications of the measurement setup of the HVAC system

Datataker, DT85 Series 3 Data Logger, ID2927, mobile network ID 2817 — 13 January 2016 - ?

Channel ID2902	Connector	ID	Measured parameter	Unit	Desricption	Device/Type	Sensor	Article number	Range	Accuracy	Location
D01	1*	2014	Tsurf, water	˚C	surface temperature water	NTC	thermistor	-	-50-150˚C	± 0.2˚C, 0-70˚C	cold water, supply
D02	1+	2015	Tsurf, water	˚C	surface temperature water	NTC	thermistor	-	-50-150˚C	± 0.2˚C, 0-70˚C	cold water, return
D03	1-	2017	Tsurf, water	˚C	surface temperature water	NTC	thermistor	-	-50-150˚C	± 0.2˚C, 0-70˚C	warm water, supply
D04	2*	2018	Tsurf, water	˚C	surface temperature water	NTC	thermistor	-	-50-150˚C	± 0.2˚C, 0-70˚C	warm water, return
D035	12+	-	control signal	%	control signal fan	-	-	-	-	-	
D036	12-	-	control signal	%	control signal humidifier	-	-	-	-	-	
D037	13*	2935	flow (P)	Pa	flow, pressure difference	TA link	-	52 010-004	0-40 kPa	< ± 1.0 kPa	cooling
D038	13+	2934	flow (P)	Pa	flow, pressure difference	TA link	-	52 010-004	0-40 kPa	< ± 1.0 kPa	heating
D039	13-	2937	T	˚C	Air temperature	EE160, 004M	Pt1000	-	0-50˚C	± 0.3˚C at 20˚C	before the filter
D040	14*	2937	RH	% RH	Relative humidity	EE160	E+E sensor HCT01-00D	-	10 - 95%	± 2.5% RH at 20˚C	
D041	14+	2938	T	˚C	Air temperature	EE160, 004M	Pt1000	-	0-50˚C	± 0.3˚C at 20˚C	between preheater and cooling
D042	14-	2938	RH	% RH	Relative humidity	EE160	E+E sensor HCT01-00D	-	10 - 95%	± 2.5% RH at 20˚C	
D043	15*	2939	T	˚C	Air temperature	EE160, 004M	Pt1000	-	0-50˚C	± 0.3˚C at 20˚C	between cooling and fan
D044	15+	2939	RH	% RH	Relative humidity	EE160	E+E sensor HCT01-00D	-	10 - 95%	± 2.5% RH at 20˚C	
D045	15-	2940	T	˚C	Air temperature	EE160, 004M	Pt1000	-	0-50˚C	± 0.3˚C at 20˚C	between humidifier and heating
D046	16*	2940	RH	% RH	Relative humidity	EE160	E+E sensor HCT01-00D	-	10 - 95%	± 2.5% RH at 20˚C	
D047	16+	2941	T	˚C	Air temperature	EE160, 004M	Pt1000	-	0-50˚C	± 0.3˚C at 20˚C	in supply duct
D048	16-	2941	RH	% RH	Relative humidity	EE160	E+E sensor HCT01-00D	-	10 - 95%	± 2.5% RH at 20˚C	
1C	high speed	2978	KWh	KWh	Energy use fan	PRO380-s	-	0255 PRO380-s	0-99999999 pulse	B (= ± 1%)	fan
2C	high speed	2979	KWh	KWh	Energy use humidifier	PRO380-s	-	0255 PRO380-s	0-99999999 pulse	B (= ± 1%)	humidifier

Appendix E. Measurement data supplemented

A defect adapter of the logging system was the cause of data loss of the measurements on building and room level for about 1.5 months. BMS data was downloaded for all rooms equipped with Eltek T and RH sensors, so that the BMS data could be compared to measurement data. If the trends of both data sets were similar, measurement data was supplemented by BMS data.

The BMS and measurement data for T and RH were averaged before and after the period of missing data up to 1 Dec. At that moment, data was replaced. Differences between both data sets were calculated resulting in ΔT and ΔRH for the two periods (before and after data loss). Figure E.1 of Appendix E depicts this method for measurement position *room D*. Measurement data was supplemented by shifting BMS data by the best fitting ΔT and ΔRH of both periods.

BMS data for the *Regentenkamer* deviates excessively from the measurement data and was therefore not supplemented. Measurement positions for which data was supplemented are *room D, entrance, temporary exhibition, room 11 door, room 11 light gutter.*

For assessing general and specific risks to objects and for plotting CEC, the supplemented measurement data was uploaded separately on the website of physics of monuments (www.monumenten.bwk.tue.nl). The start date and measurement interval were entered. However, the measuring interval of TU measurements differed from the BMS measurement interval, resulting in a wrong distribution of data points over time. Therefore, supplemented BMS data was interpolated by using the *interp1* command in MATLAB. Figure E.2 of Appendix E depicts the result of interpolating supplemented data for *room D*, where the black dots are the measured data and the red dots the interpolated data. The procedure of supplementing and interpolating data can be found in the MATLAB script on the CD.

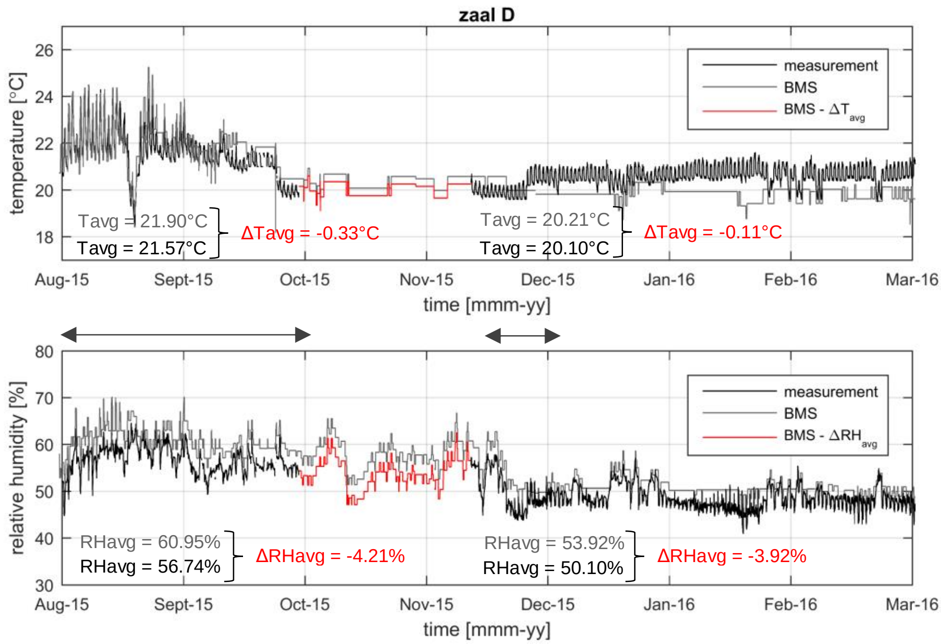

Figure E.1 Supplementation of measurement data

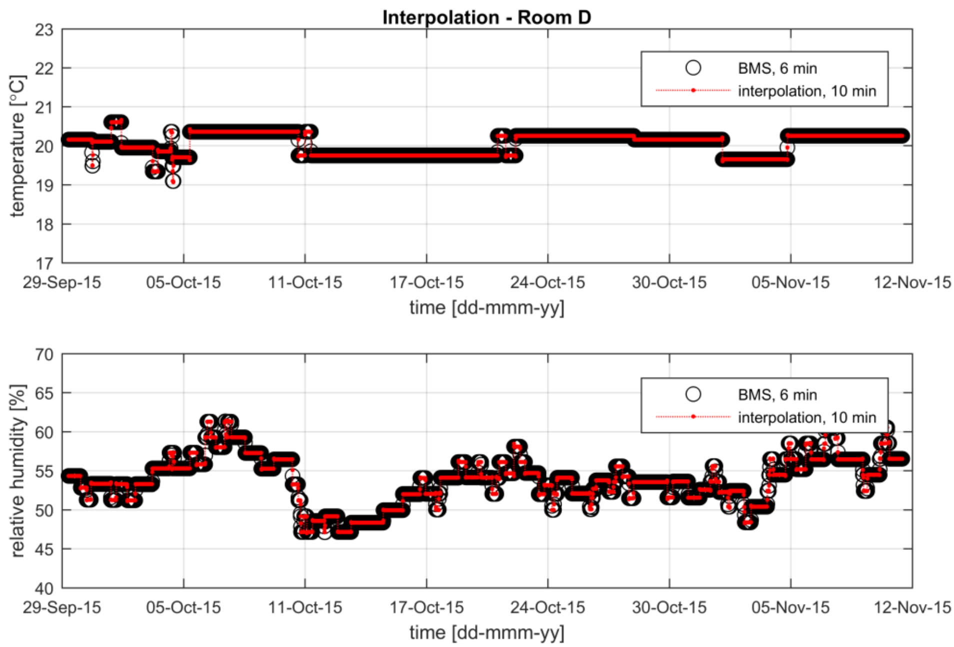

Figure E.2 Interpolation of supplemented measurement data

Appendix F. Model input

Building and structure specifications

Table F.1 General information on the building

parameter	description
building function type	historical building, museum exhibition room *Regentenkamer* (1 zone)
number of visitors per year	225.000
sort of visits	free tour and group tour

Table F.2 Volume of the zone

ID	description	vol [m³]
1	*Regentenkamer*	308.12

Table F.3 Structure materials

matID	material description
001	air
002	moderately ventilated cavity R_{cav} = 0.17 m²K/W
004	plenum R_{cav} = 0.15 m²K/W
238	brick
261	hard baked tiles
342	concrete
362	plaster (lime)
501	hardwood
508	plywood
518	timber flooring

Table F.4 Buildup of walls, floor and ceiling

ID	descript-tion	Ri [m²K/W]	d1 [m]	mat ID	d2 [m]	mat ID	d3 [m]	mat ID	d4 [m]	mat ID	d5 [m]	mat ID	Re [m²K/W]	ab [-]	eps [-]
1	south wall - plaster	0.13	0.010	362	0.100	238	0.50	002	0.100	238	0.100	238	0.04	0.7	0.9
2	south wall - wooden panel	0.13	0.030	501	0.100	238	0.50	002	0.100	238	0.100	238	0.04	0.7	0.9
3	west wall	0.13	0.030	501	0.100	238	0.323	001	0.100	238	0.010	362	0.13	0.6	0.9
4	west wall - door	0.13	0.044	501	0.475	001	0.044	501					0.13	0.8	0.9
5	north wall	0.13	0.010	362	0.210	238	1.000	002	0.100	238	0.100	238	0.13	0.4	0.9
6	east wall	0.13	0.010	362	0.100	238	0.010	362					0.13	0.4	0.9
7	east wall - door	0.13	0.080	501									0.13	0.6	0.9
8	floor	0.13	0.015	261	0.300	342							0.13	0.7	0.9
9	ceiling	0.13	0.030	501	0.200	004	0.010	508	0.010	518			0.13	0.6	0.9

Table F.5 Glazing type

ID	description	Uglas [W/m²K]	CFr [-]	ZTA [-]	ZTAw [-]	CFrw [-]	Uglasw [W/m²K]
1	glass – south wall	2.8	0.03	0.7	0.36	0.36	2.8

Table F.6 Building envelope

ID	description	volID	surface [m²]	wallID	glazing [%]	glasID	beta [°]	Gamma [°]	bridge
1	south wall - plaster	1	47.0	1	57	1	90	-8.45	0
2	south wall - wooden panel	1	6.7	2	0	1	90	-8.45	0

Table F.7 Adiabatic walls

ID	description	volID	surface [m²]	wallID
1	west wall	1	21.1	3
2	doors in west wall	1	3.8	4
3	north wall	1	53.7	5
4	east wall	1	23.1	6
5	door in east wall	1	1.8	7
6	floor	1	70.6	8
7	ceiling	1	70.6	9

Building profiles

Table F.8 Daily profile

period	vol ID	Ers [W/m²]	vvmin [h⁻¹]	vvmax [h⁻¹]	Tfc [°C]	Qint [W]	Gint [kg/s]	Tmin [°C]	Tmax [°C]	RHmin [%]	RHmax [%]
8am – 10am	1	1	0.97	0.97	10	706	0	18.5	21.5	40	60
10am – 5pm	1	1	0.97	0.97	10	1.2(706 + 180)	1.6×2.5e-5	18.5	21.5	40	60
5pm – 8am	1	1	0.1	0.1	10	0	0	18.5	21.5	40	60

Table F.9 Weekly profile

day	activating (HVAC)	opening (visitors)	closing (visitors) and deactivating (HVAC)	Staff & visitors	duration
Monday	8am	10am	5pm	2	continuous
Tuesday	8am	10am	5pm	2	continuous
Wednesday	8am	10am	5pm	2	continuous
Thursday	8am	10am	5pm	2	continuous
Friday	8am	10am	5pm	2	continuous
Saturday	8am	10am	5pm	2	continuous
Sunday	8am	10am	5pm	2	continuous

Heating, cooling and (de)humidification

Table F.10 Heating, cooling and (de)humidification

vol ID	description	heat [W]	cool [W]	hum [kg/s]	deh [kg/s]	CFh [-]	CFs [-]	CFi [-]	Etaww [-]	Twws [°C]	Twwc [°C]
1	*Regentenkamer*	12220	31940	0.0069	inf.	1	1	0.5	0	22	40

Appendix G. Model calibration

The results for the calibration of the room model of the *Regentenkamer* are displayed in Figure G.1. The model was calibrated over a dry winter period without dehumidification. Simulated data was compared to measurement data of the measurement position *Regentenkamer Exhaust 1*, because similar fluctuations in temperature were shown. The graph shows measured and simulated results for temperature, relative humidity, absolute humidity and power. Similar shapes and fluctuations for the measured and simulated data are displayed. However, measurement results show cooling power in this winter period, while the simulation results do not show power needed for cooling.

Figure G.2 displays the data of the winter week which is denoted by the dashed box in Figure G.1. At this scale, measurement data is comparable to simulated data as well: similar trends are displayed.

Deviations and mean deviations between measured and simulated data over the calibrated period are depicted in Figure G.3. For temperature, the mean and maximum deviation are 0.02°C and 2.7°C respectively. For relative humidity, these deviations are 1.34% and 12.97% respectively. The absolute humidity shows a mean deviation of 0.20 g/kg and a maximum deviation of 1.90 g/kg. For all parameters, simulation results are slightly higher than measurement results. From the small deviations between measurement and simulation results, it can be concluded that the model is calibrated.

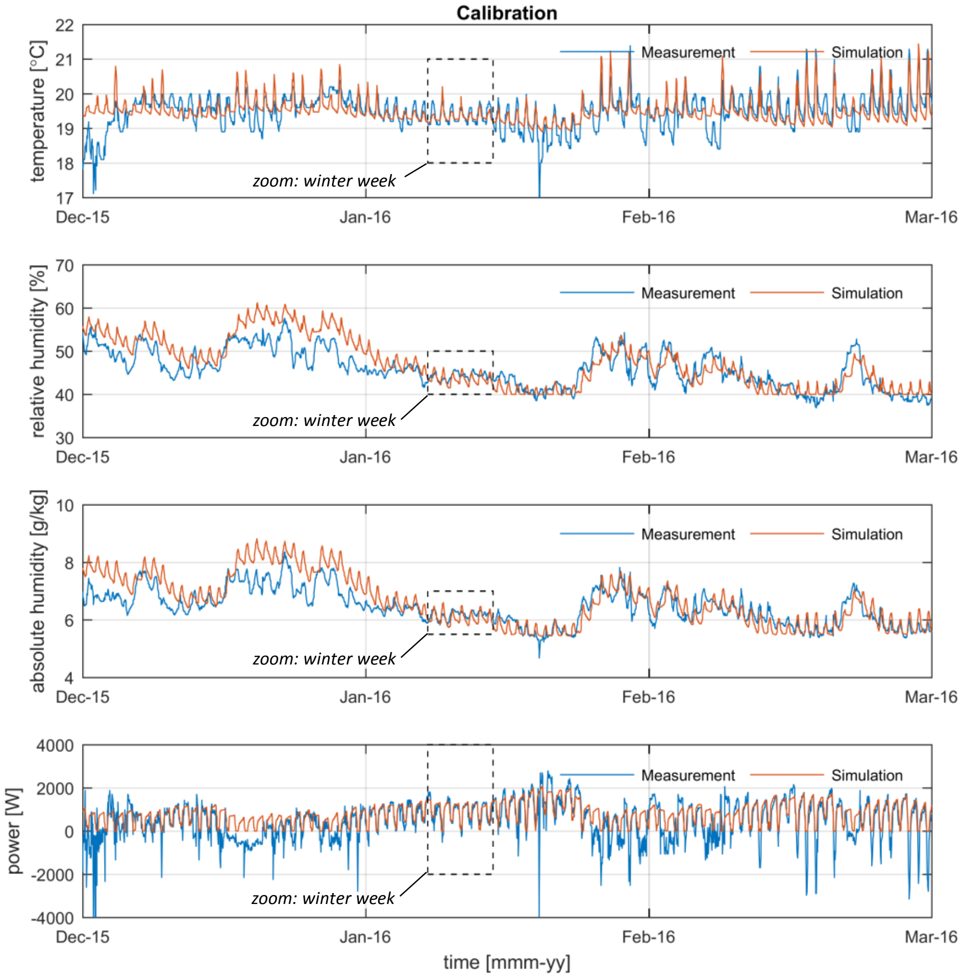

Figure G.1 Calibration of the room model of the Regentenkamer

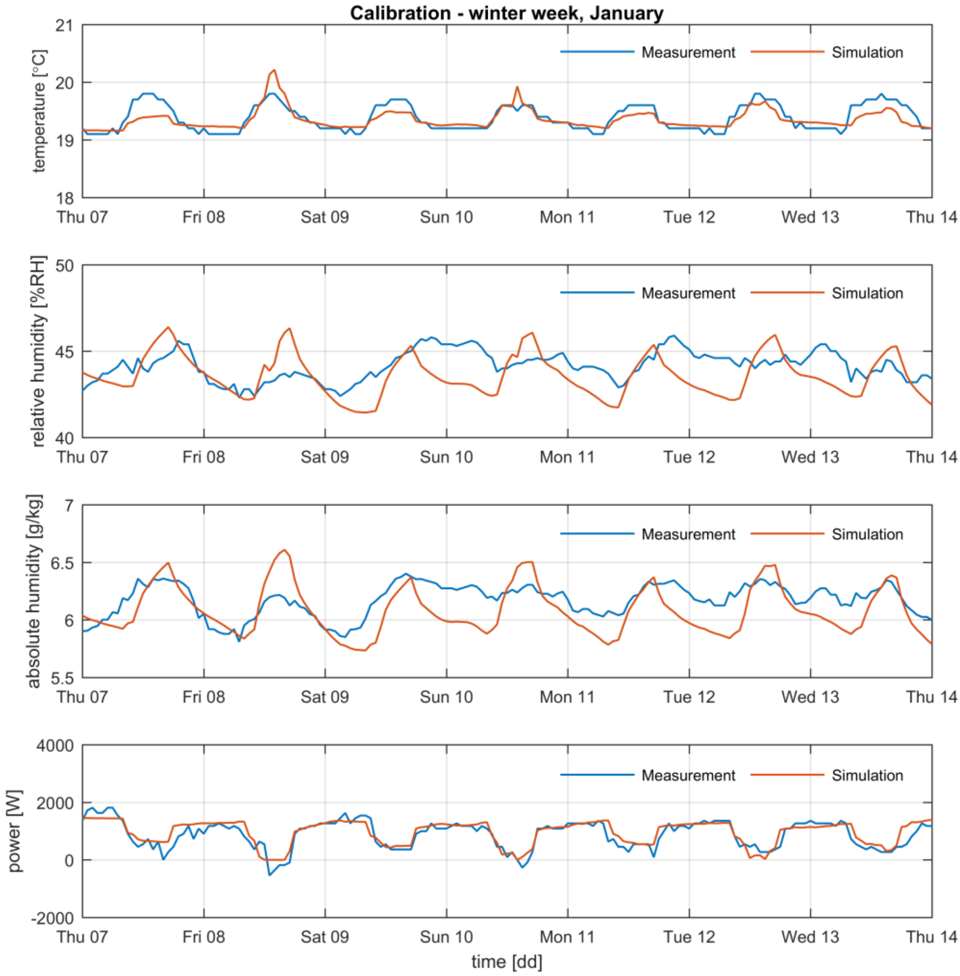

Figure G.2 Calibration of the room model of the Regentenkamer: zoom of a winter week in January

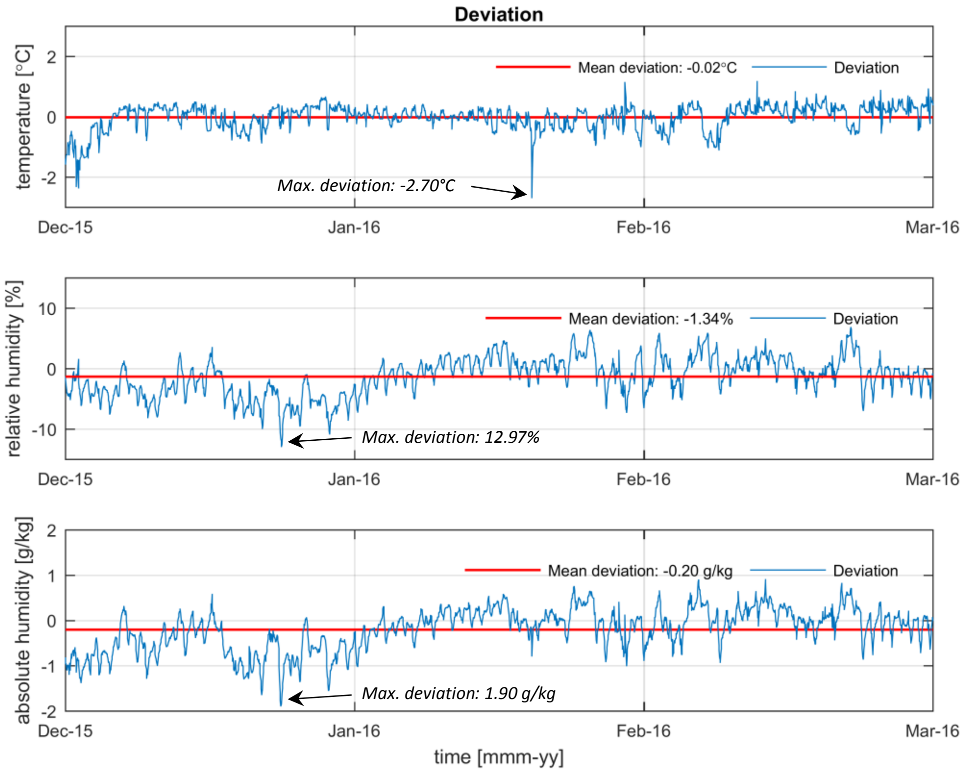

Figure G.3 Deviation between measured and simulated data

Appendix H. ASHRAE climate classes

Table H.1 Museum climate guidelines according to ASHRAE (2011)

Type	Set point or annual value	Maximum Fluctuations and Gradients in Controlled Spaces			Collection Risks and Benefits
		Class of control	**Short fluctuations & space gradients**	**Seasonal adjustments in system set points**	
General Museums, Art Galleries, Libraries and Archives All reading and retrieval rooms, rooms, for storing chemically stable collections, especially if mechanically medium to high vulnerability	50%RH (or historic annual average for permanent collections) Temperature set between 15 and 25°C *Note*: rooms intended for loan exhibitions must handle set point specified in loan agreement, typically 50%RH, 21°C, but sometimes 55 or 60%RH	**AA** Precision control; no seasonal RH changes	±5%RH, ±2K	Relative humidity no change, Up 5K; down 5K	No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50%RH exceeds a critical relative humidity. Chemically unstable objects unusable within decades.
		A Precision control; some gradients or seasonal changes, not both	**As** ±5%RH, ±2K	Up 10%RH; down 10%RH; Up 5K, down 10K	Small risk of mechanical damage to high vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs, and books. Chemically unstable objects unusable within decades.
			A ±10%RH, ±2K	RH no change; Up 5K, down 10K	
		B Precision control; some gradients plus winter temperature setback	±10%RH, ±5K	Up 10%RH, down 10%RH; Up 10K but not above 30°C, down as low as necessary to maintain RH control	Moderate risk of mechanical damage to high vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books. Chemically unstable objects unusable within decades less if routinely at 30°C, but cold winter periods double life.
		C Prevent all high risk extremes	Within 25 to 75%RH year-round Temperature rarely over 30°C, usually below 25°C		High risk of mechanical damage to high vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts, some books; tiny risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods double life.
		D Prevent dampness	Reliably below 75%RH		High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs. Mold growth and rapid corrosion avoided. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods double life.

Table H.2 Classification of climate control potential in buildings (ASHRAE, 2011)

Category of control	**Buil-ding class**	**Typical building construction**	**Typical type of building**	**Typical building use**	**System used**	**Practical limit of climate control**	**Class of control possible**
Uncon-trolled	I	Open structure	Privy, stocks, bridge, sawmill, well	No occupancy, open to viewers all year.	No system.	None	D (if benign climate)
	II	Sheathed post and beam	Cabins, barns, sheds, silos, icehouse	No occupancy. Special event access.	Exhaust fans, open windows, supply fans, attic venting. No heat.	Ventilation	C (if benign climate) D (unless damp climate)
Partial control	III	Uninsulated masonry, framed and sided walls, single glazed windows	Boat, train, lighthouse, rough frame house, forge	Summer tour use. Closed to public in winter. No occupancy.	Low-level heat, summer exhaust ventilation, humidistatic heating for winter control.	Heating, ventilation	C (if benign climate) D (unless hot, damp climate)
	IV	Heavy masonry or composite walls with plaster. Tight construction: storm windows	Finished house, church, meeting house, store, inn, some office buildings	Staff in isolated rooms, gift shop. Walk-through visitors only. Limited occupancy. No winter use.	Ducted low-level heat. Summer cooling, on/off control, DX cooling, some humidification. Reheat capability.	Basic HVAC	B (if benign climate) C (if mild winter) D
Climate control-led	V	Insulated structures, double glazing, vapor retardant, double doors	Purpose-built museums, research libraries, galleries, exhibits, storage rooms	Education groups. Good open public facility. Unlimited occupancy.	Ducted heat, cooling, reheat, and humidification with control dead band.	Climate control, often with seasonal drift	AA (if mild winters) A B
	VI	Metal wall construction, interior rooms with sealed walls and controlled occupancy	Vaults, storage rooms, cases	No occupancy. Access by appointment.	Special heating, cooling, and humidity control with precision constant stability control.	Special constant environment	AA A Cool Cold Dry

Appendix I. Analysis on the building (envelope)

Figure I.1 and Figure I.2 depict the analysis on the building and building envelope for the second and third floor.

The Figure shows the irradiated facades, the segments of the building envelope and a snapshot of the temperature and the relative humidity. For the first two figures the results are comparable to the results of the first floor. For the result description, see paragraph 4.1.

The last two figures show T and RH ranges in museum rooms at the second floor of 20.6-22.0°C and 40.7-51.6%. The lowest T was measured in room OQ and the highest T in room B, a south faced room. Room I shows the lowest RH and room A the highest RH. For the third floor, T and RH ranges are 22.0-22.2°C and 43.0-44.8%. At this floor measurements were only performed in two rooms.

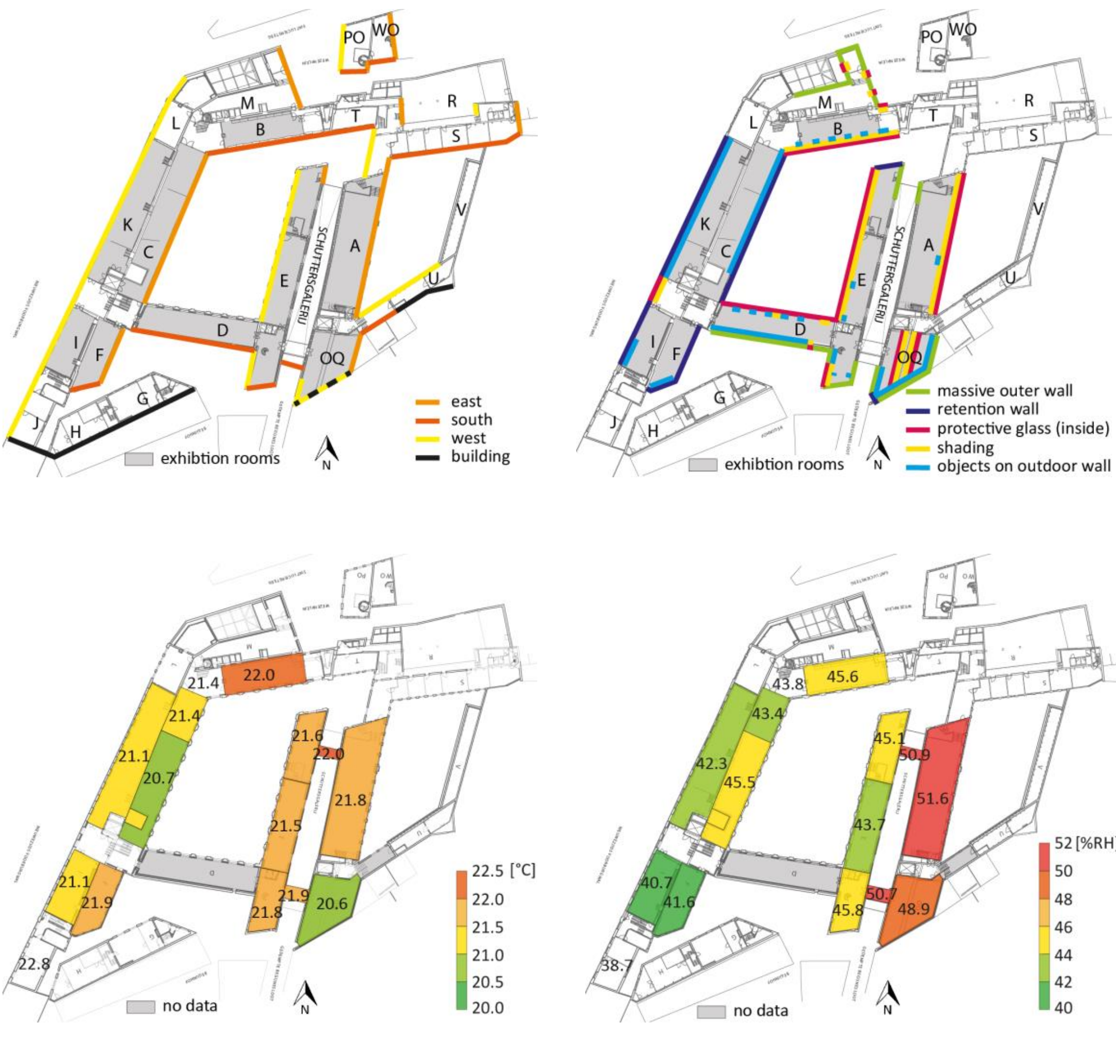

Figure I.1 Second floor analysis of: irradiated facades (top left), segments of the building envelope (top right), temperature (bottom left) and relative humidity (bottom right). June 10th, 2015, 2:00pm – 3:00pm

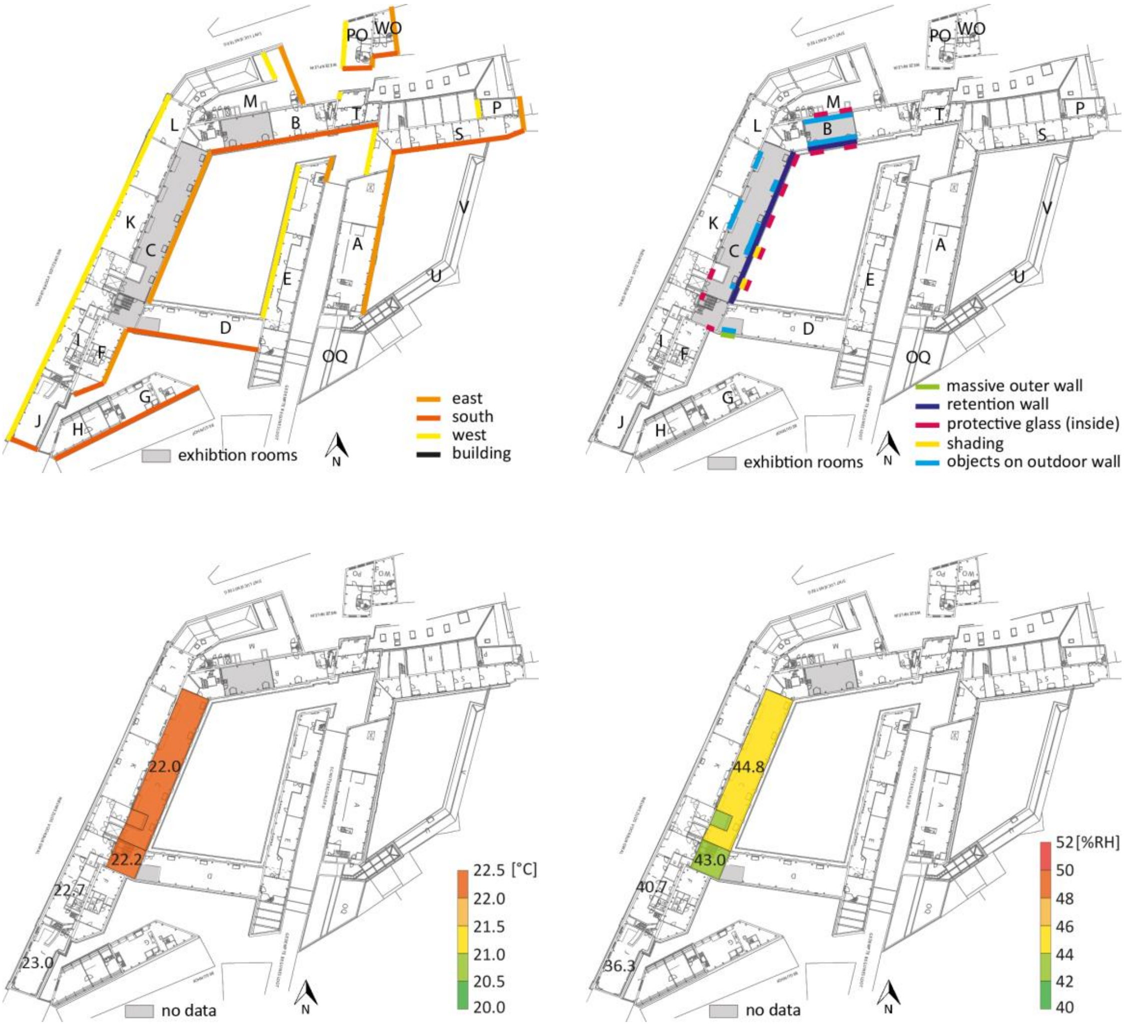

Figure I.2 Third floor analysis of: irradiated facades (top left), segments of the building envelope (top right), temperature (bottom left) and relative humidity (bottom right). June 10th, 2015, 3:00pm – 3:15pm

Appendix J. Outdoor climate

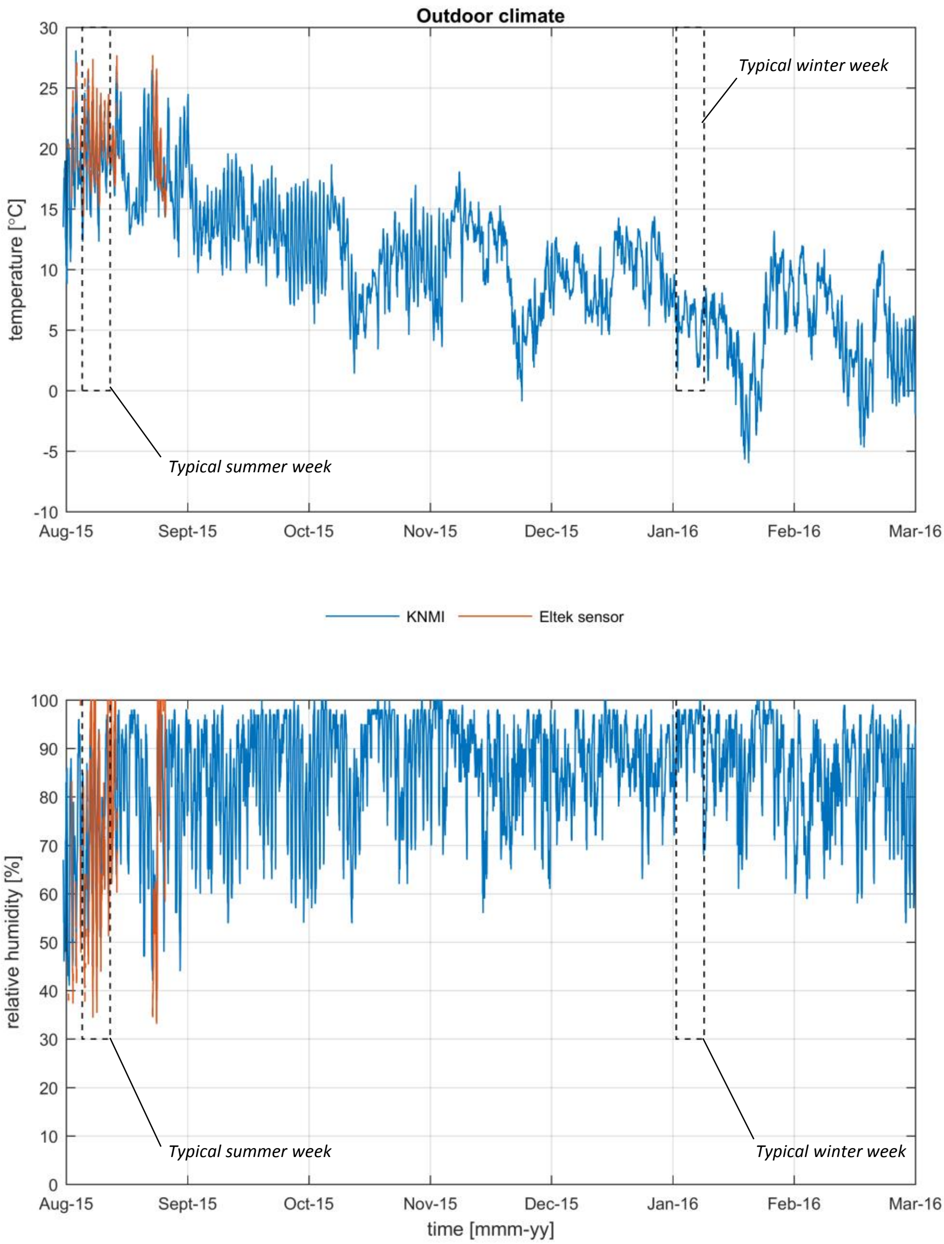

Figure J.1 Comparison of KNMI data and measurement data for the outdoor climate

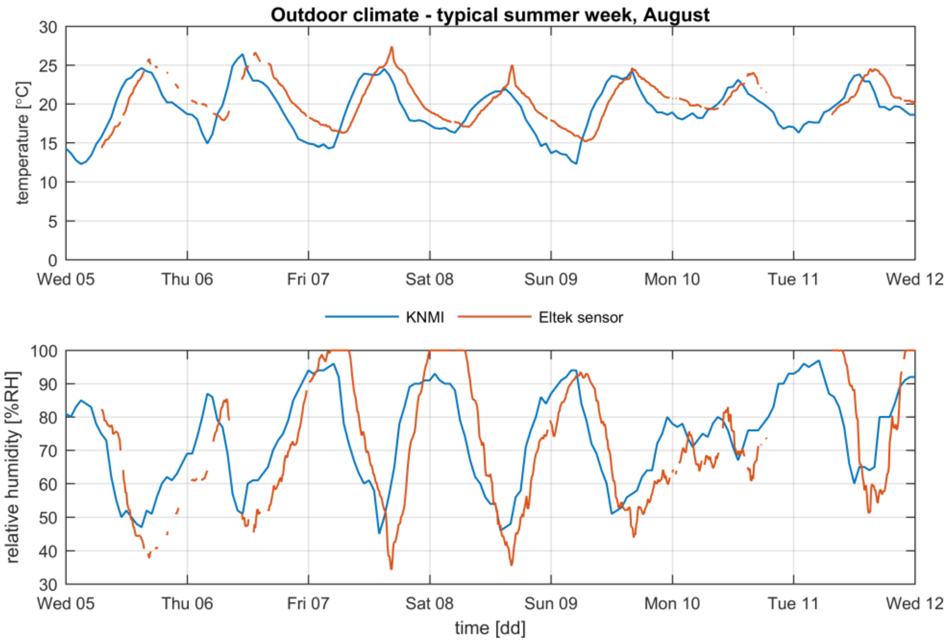

Figure J.2 Comparison of KNMI data and measurement data for the outdoor climate for a typical summer week in August

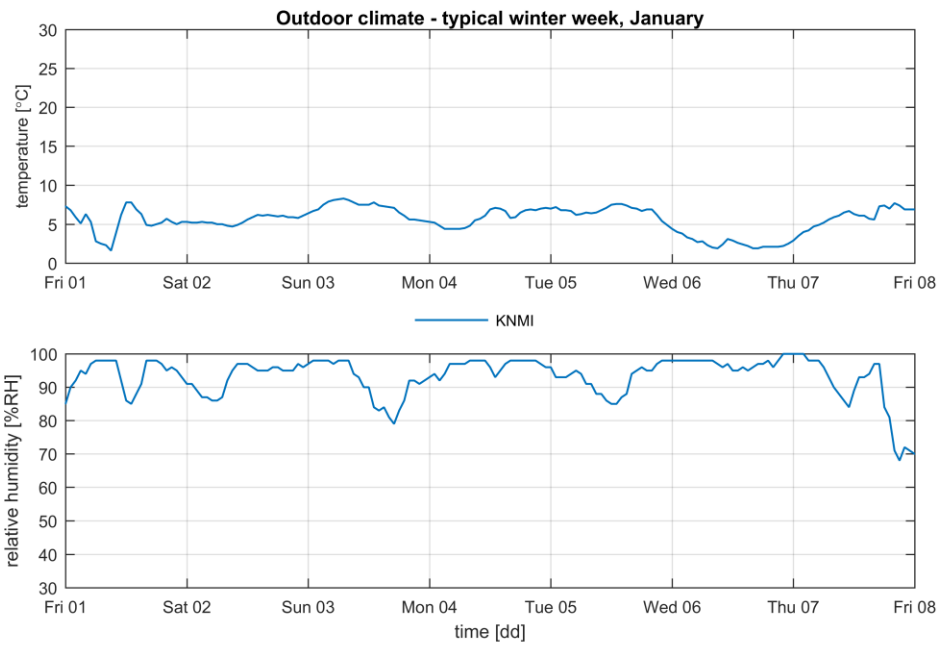

Figure J.3 Comparison of KNMI data and measurement data for the outdoor climate for a typical winter week in January

Appendix K. Graphs of the Regentenkamer

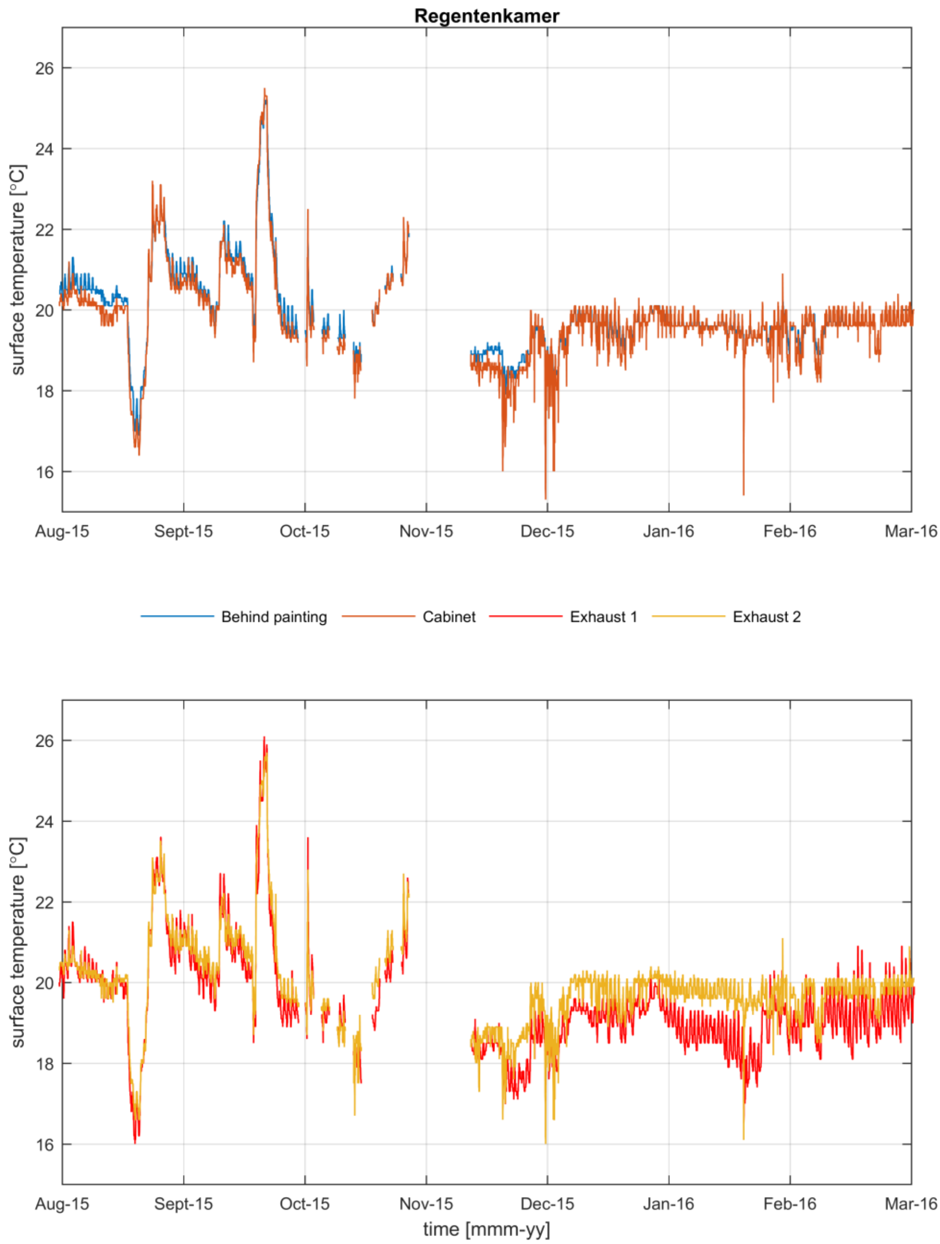

Figure K.1 Surface temperatures of the Regentenkamer for the measurement positions: Behind painting, Cabinet, Exhaust 1 and Exhaust 2

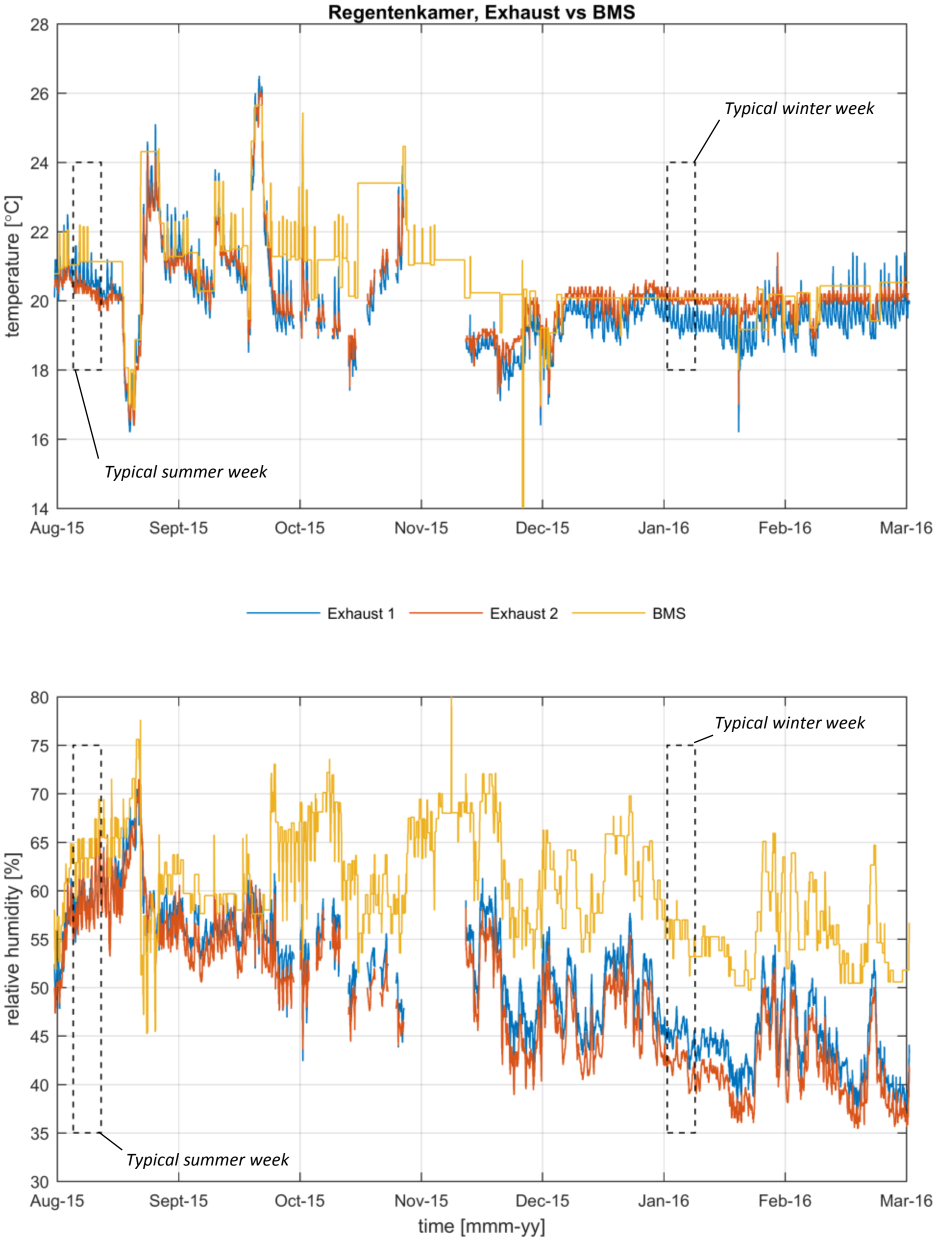

Figure K.2 Comparison of measurement data and BMS data for the exhaust

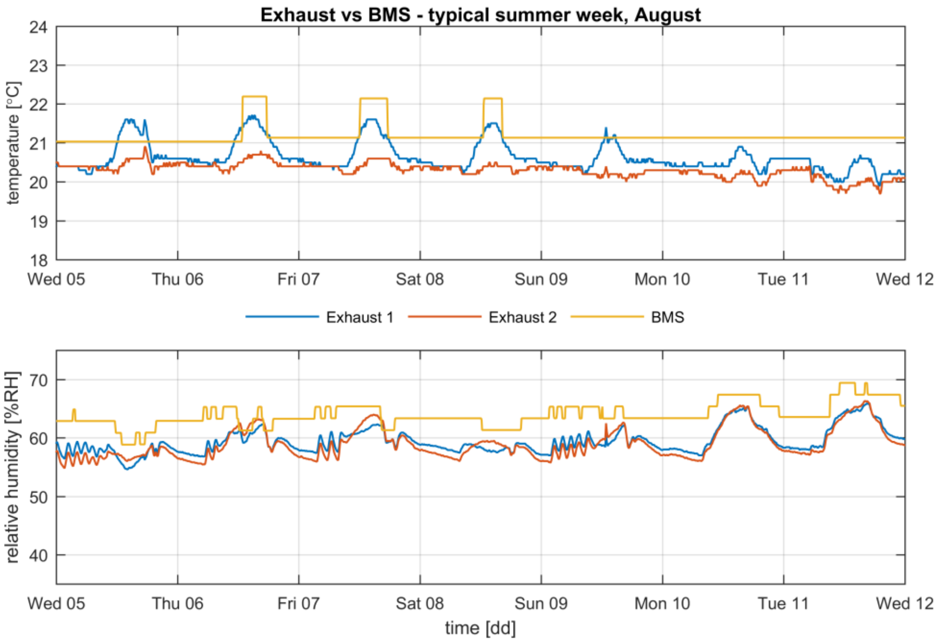

Figure K.3 Comparison of measurement data and BMS data for the exhaust for a typical summer week in August

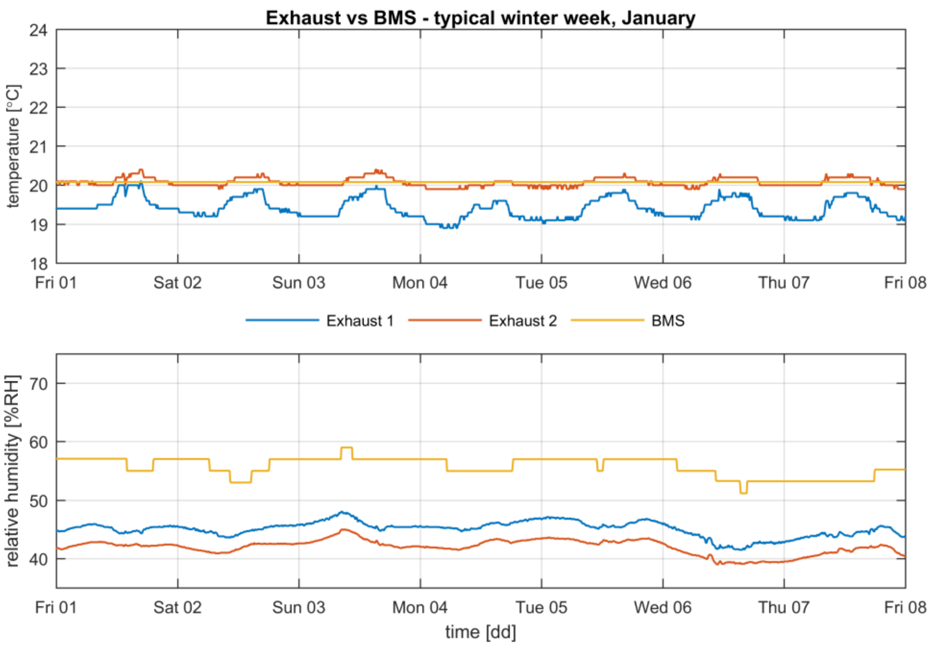

Figure K.4 Comparison of measurement data and BMS data for the exhaust for a typical winter week in January

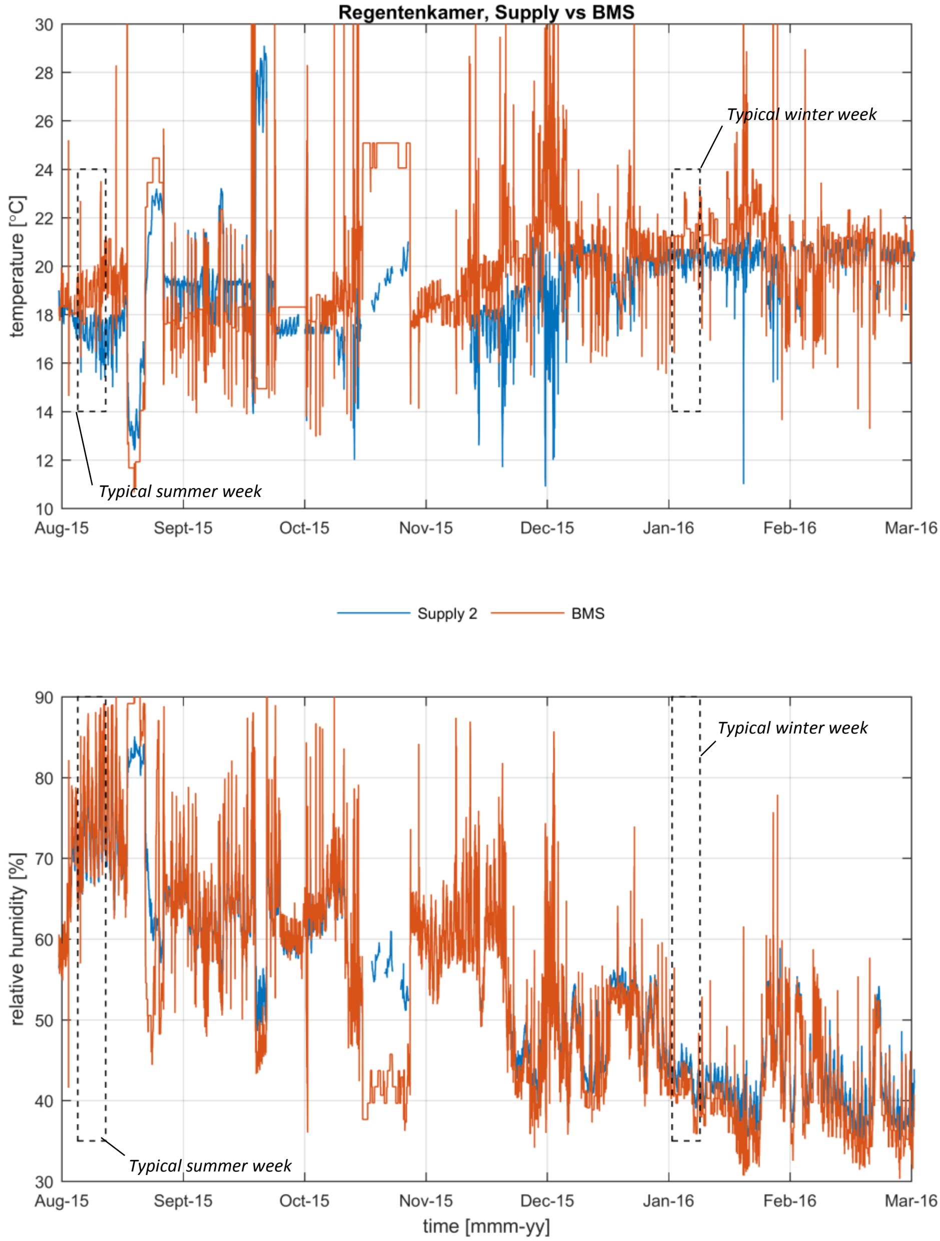

Figure K.5 Comparison of measurement data and BMS data for the supply

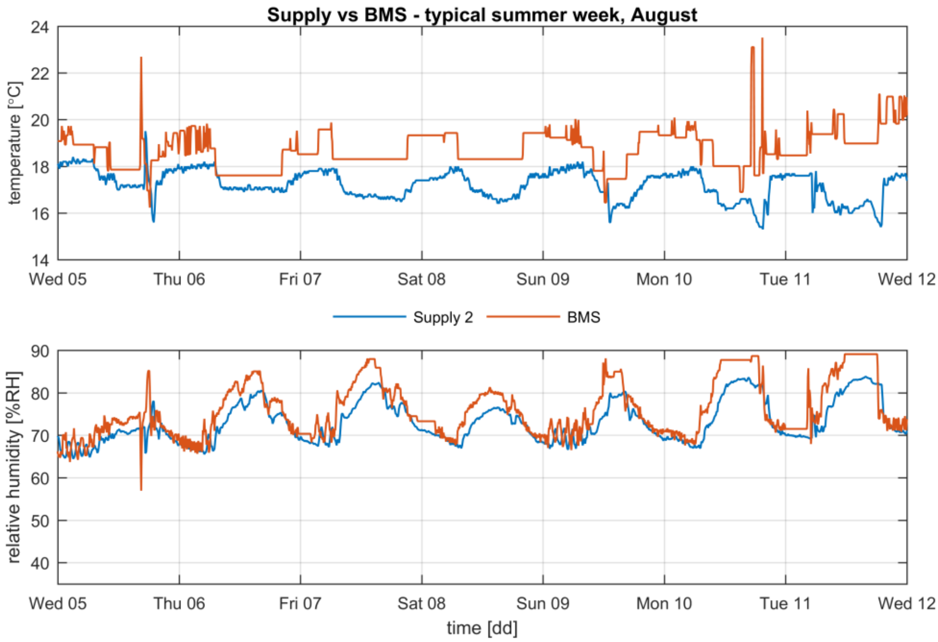

Figure K.6 Comparison of measurement data and BMS data for the supply for a typical summer week in August

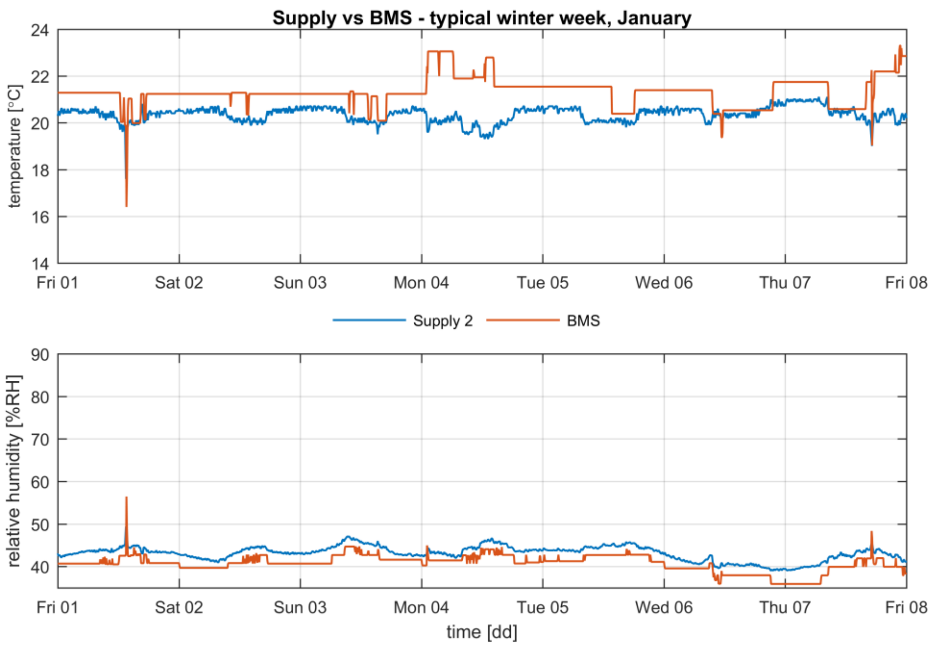

Figure K.7 Comparison of measurement data and BMS data for the supply for a typical winter week in January

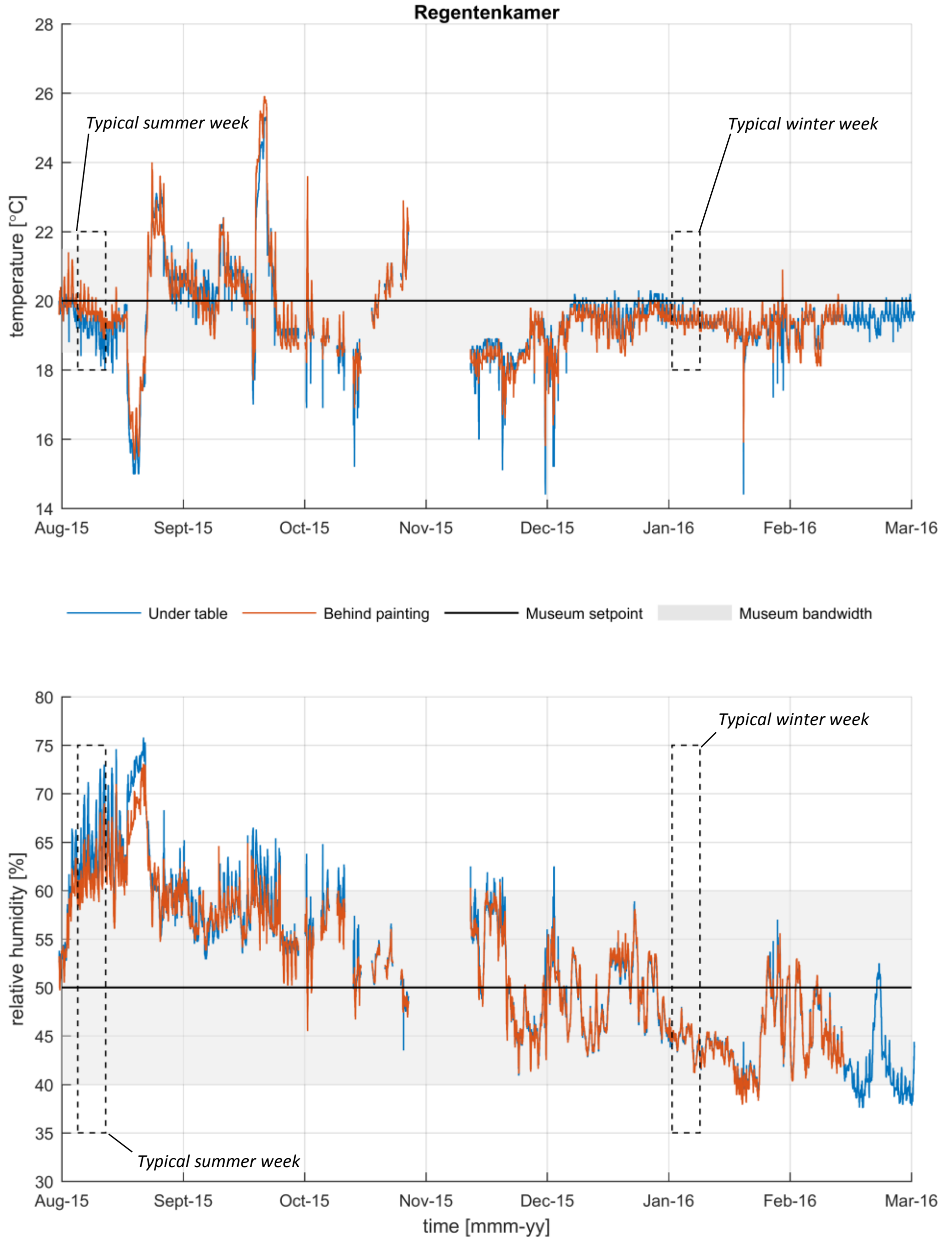

Figure K.8 Measured temperature and relative humidity for the measurement positions of the Regentenkamer: Under table and Behind painting

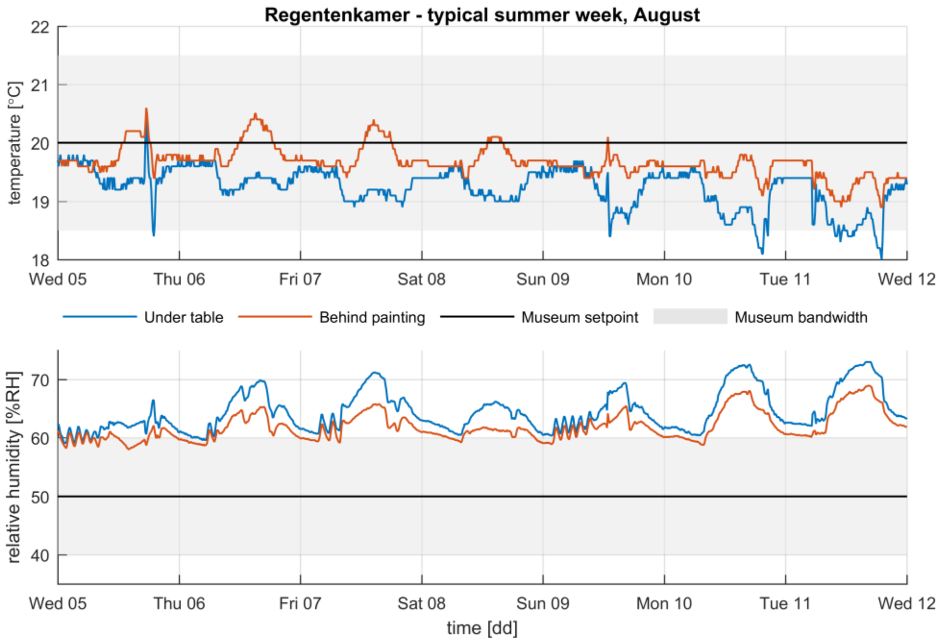

Figure K.9 Measured temperature and relative humidity for a typical summer week in August for the measurement positions of the Regentenkamer: Under table and Behind Painting

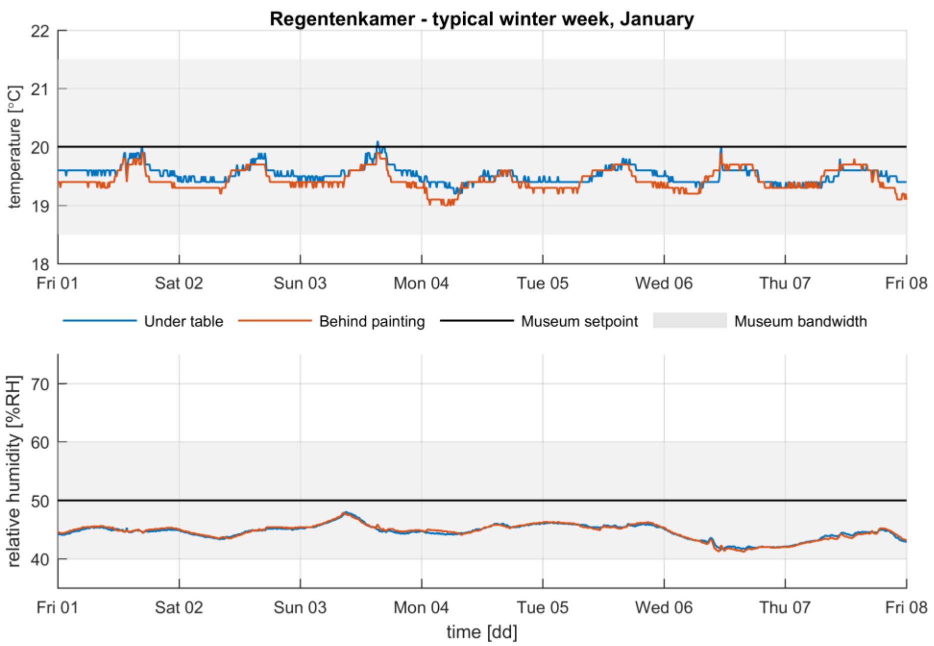

Figure K.10 Measured temperature and relative humidity for a typical winter week in January for the measurement positions of the Regentenkamer: Under table and Behind Painting

Appendix L. Graphs of other exhibition rooms

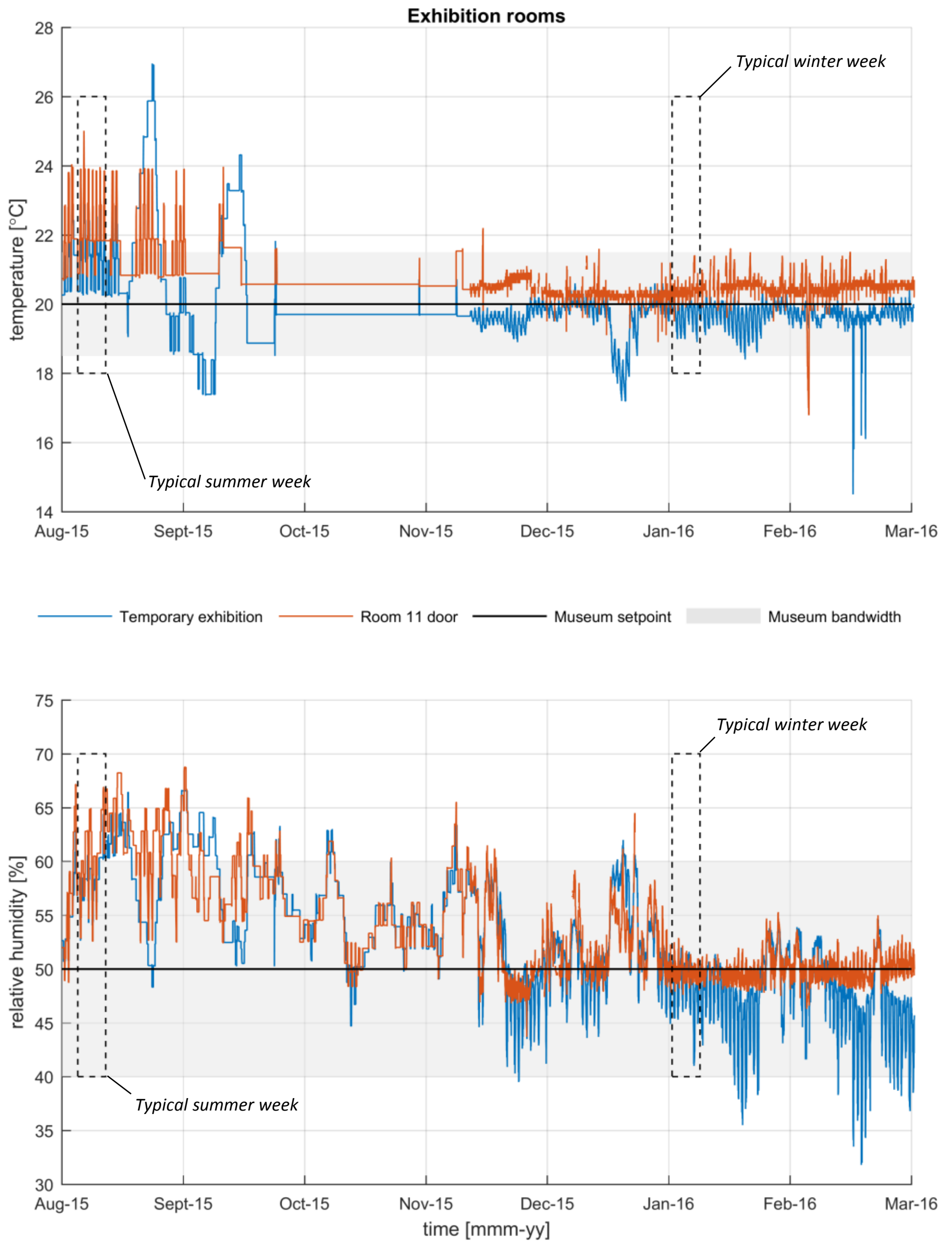

Figure L.1 Measured temperature and relative humidity for the measurement positions Temporary exhibition and Room 11

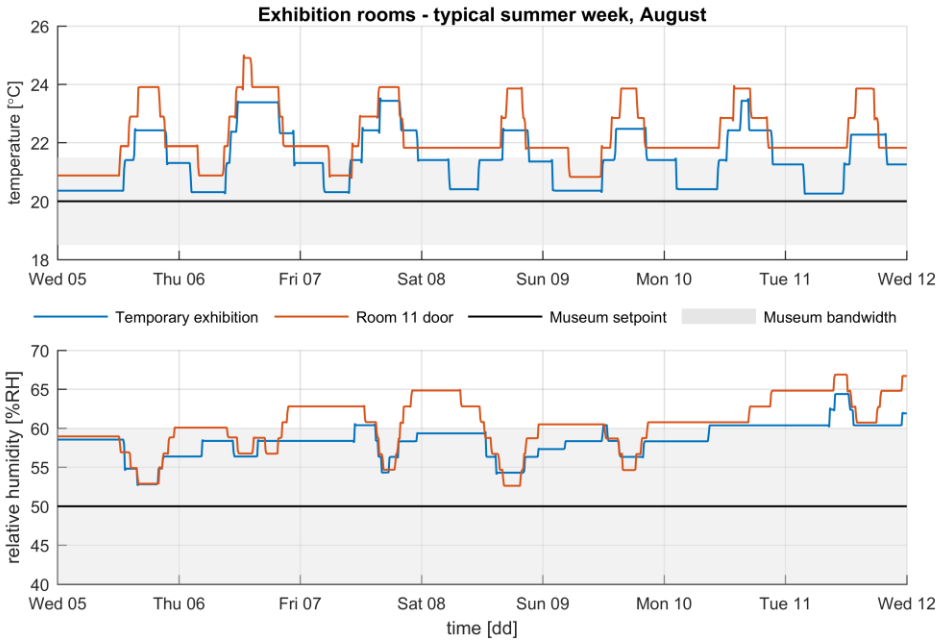

Figure L.2 Measured temperature and relative humidity for a typical summer week in August for the measurement positions Temporary exhibition and Room 11 door

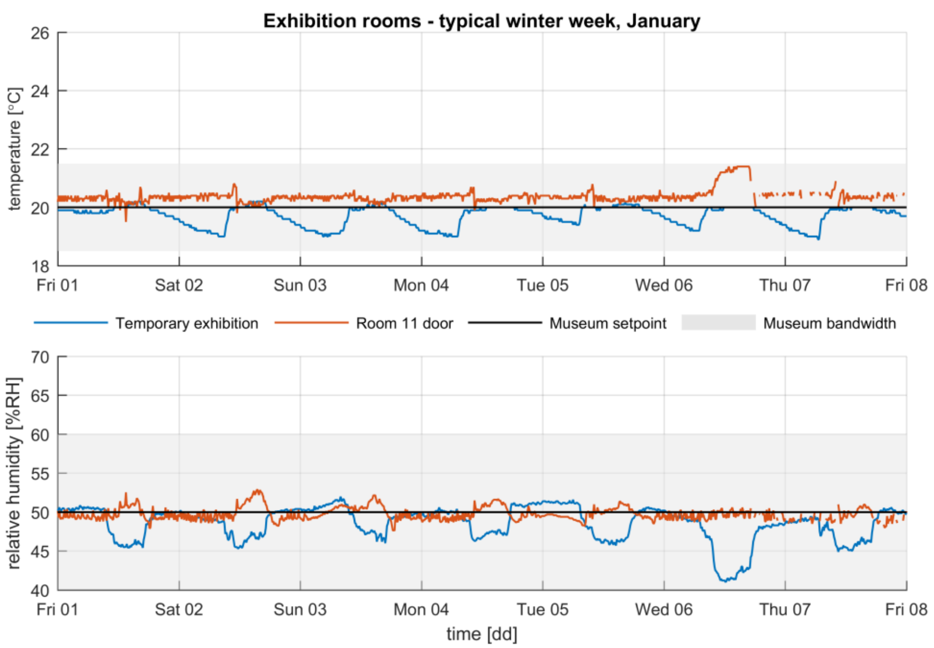

Figure L.3 Measured temperature and relative humidity for a typical winter week in January for the measurement positions Temporary exhibition and Room 11 door

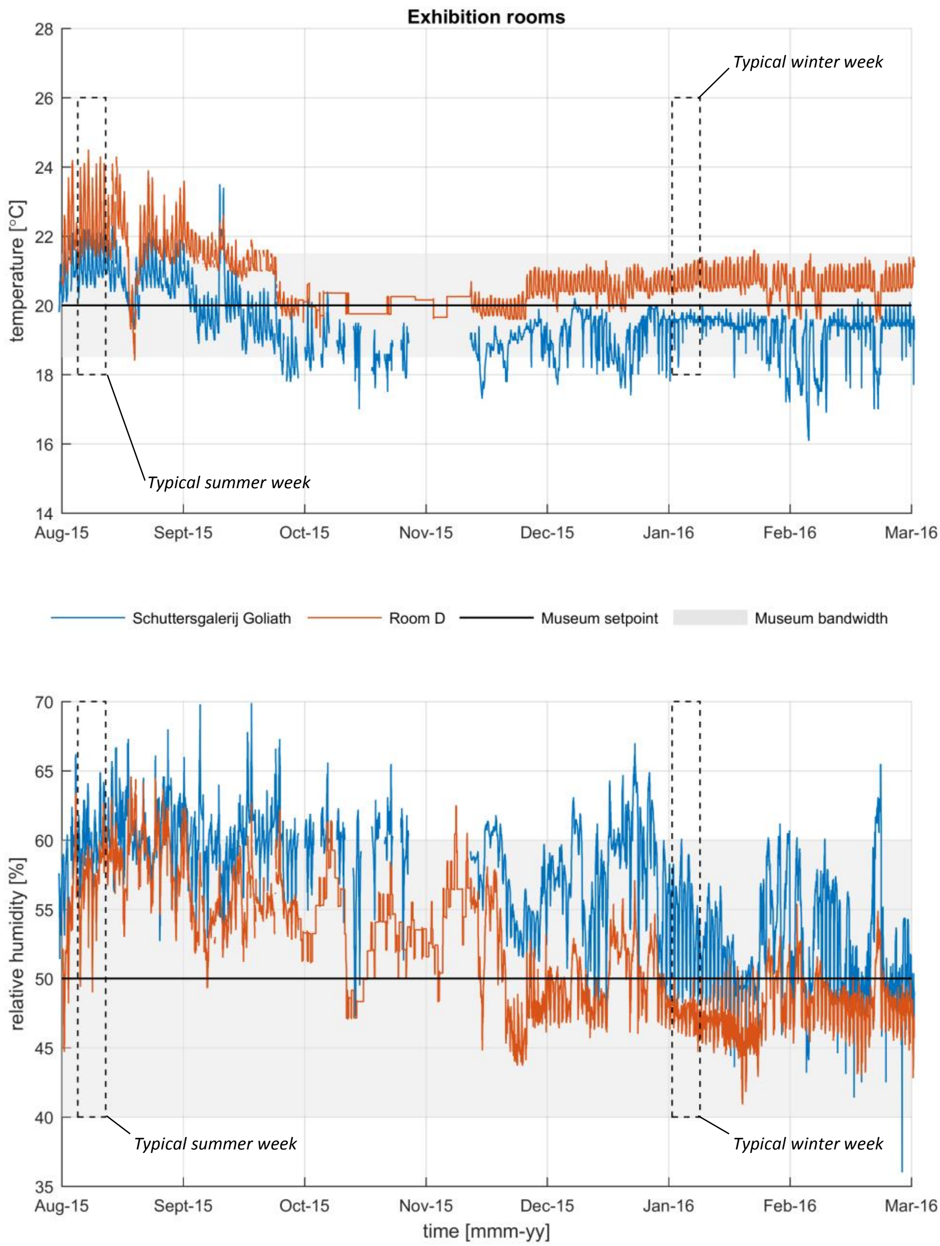

Figure L.4 Measured temperature and relative humidity for the measurement positions Schuttersgalerij Goliath and Room D

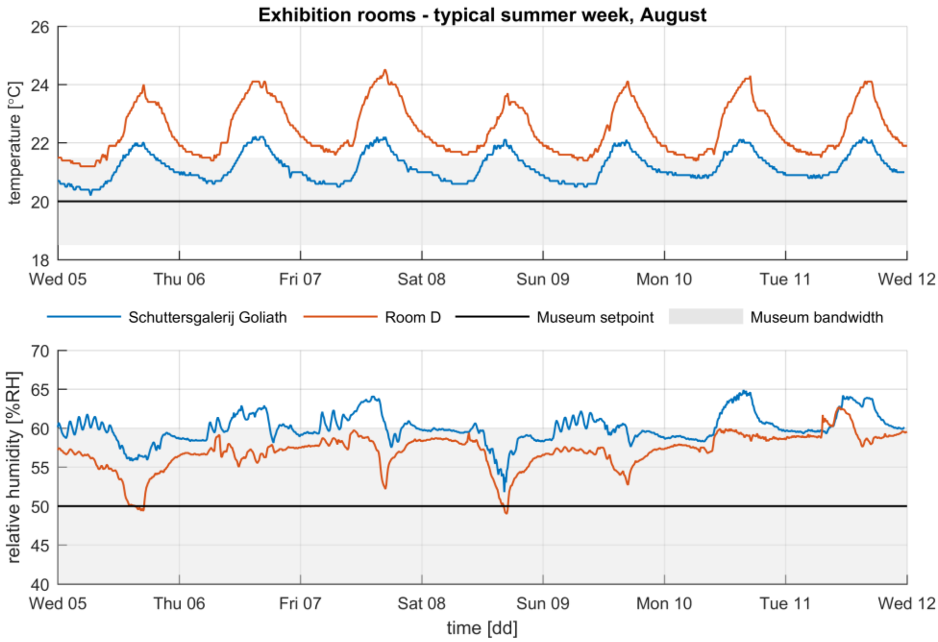

Figure L.5 Measured temperature and relative humidity for a typical summer week in August for the measurement positions Schuttersgalerij Goliath and Room D

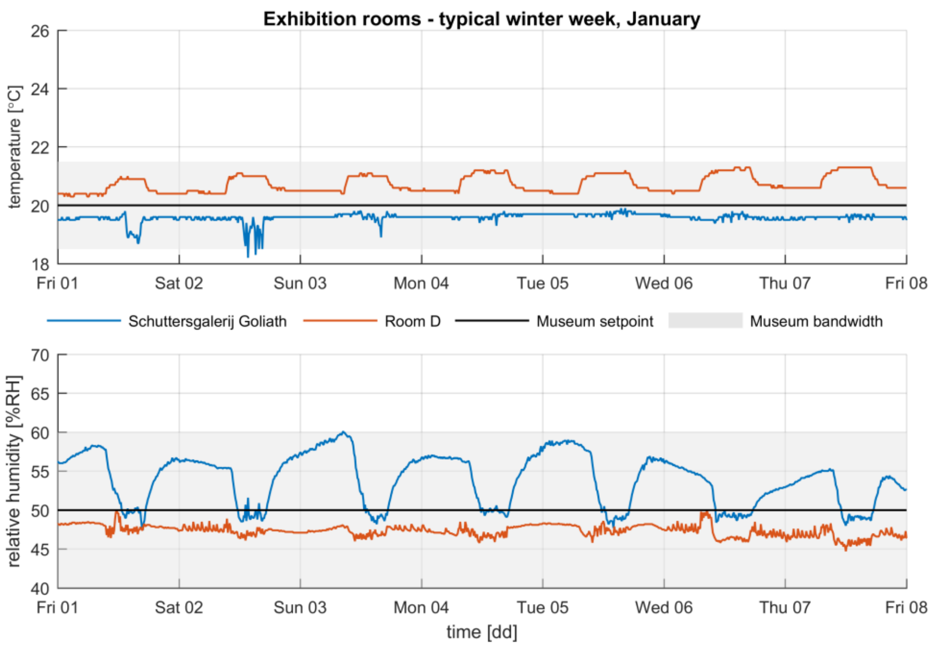

Figure L.6 Measured temperature and relative humidity for a typical winter week in January for the measurement positions Schuttersgalerij Goliath and Room D

Appendix M. Climate Evaluation Charts

Figure M.1 up to Figure M.4 display the CEC for the measurement positions *Schuttersgalerij Goliath*, *Temporary exhibition*, *Room 11 door* and *Room D*. ASHRAE climate class A has been set in the CEC's. Seasonal adjustments were excluded because the control stratgy of the museum is also set to constant values. Limits for this class are Tmin 15°C, Tmax 25°C, RHmin 40% and RHmax 60%. Hourly and daily fluctuations in T and RH may not exceed 2°C and 10%.

For the *Schuttersgalerij* 73% of the data is within the limits of ASHRAE climate class A. 27% of the data is too humid, especially in the summer and autumn. ΔT/day for this climate class is exceeded 8% of the time and ΔRH/day 15% of time, mostly in the winter. For the *Temporary exhibition* 84% of the data is OK, 1% too hot, 1% too dry and 13% too humid. High RH levels are mainly displayed in the sumer. ΔT/day is exceeded 11% of the time, mostly in the summer. The ΔRH/day limit is passed 9% of time. However, most of the these fluctuations are in the winter. *Room 11 door* is 84% OK and 16% too humid. ΔT/day is exceeded 12% of the time. 5% of the measurement data passes ΔRH/day limits. High RH levels and large fluctuations in T and RH are especially displayed in the summer. *Room D* shows that 96% of the data is within the set climate class. 4% of the data is too humid. ΔT/day is exceeded 8% of time in the summer. Only 1% of ΔRH/day is exceeded in this room. High RH levels and large fluctuations in T and RH are mostly measured in the summer. No rooms exceed the limits of ASHRAE climate A for hourly fluctuations in T and RH.

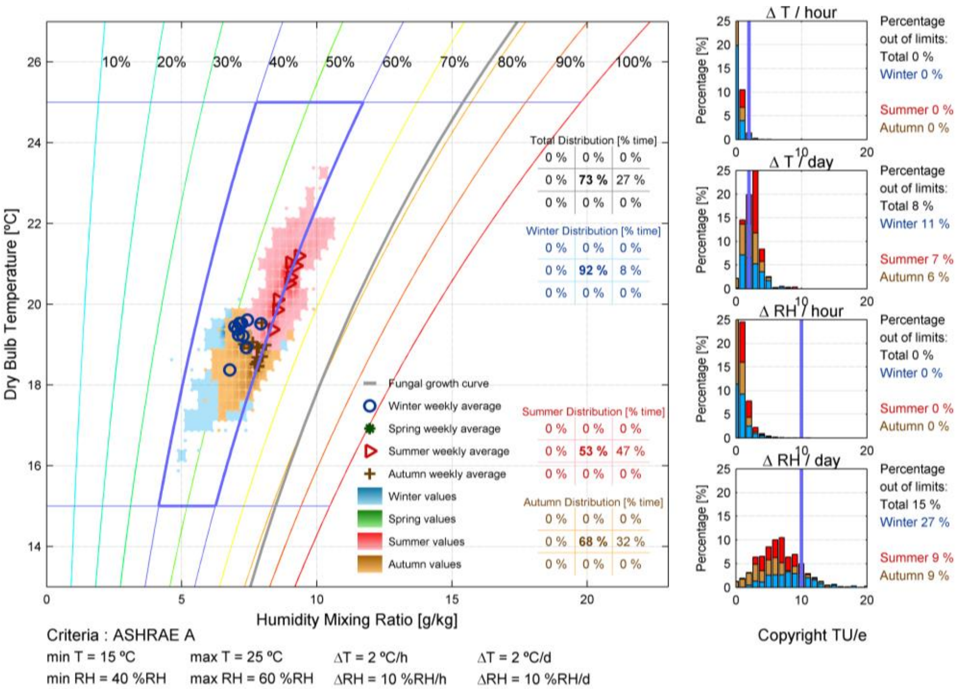

Figure M.1 CEC of the measurement position Schuttersgalerij Goliath

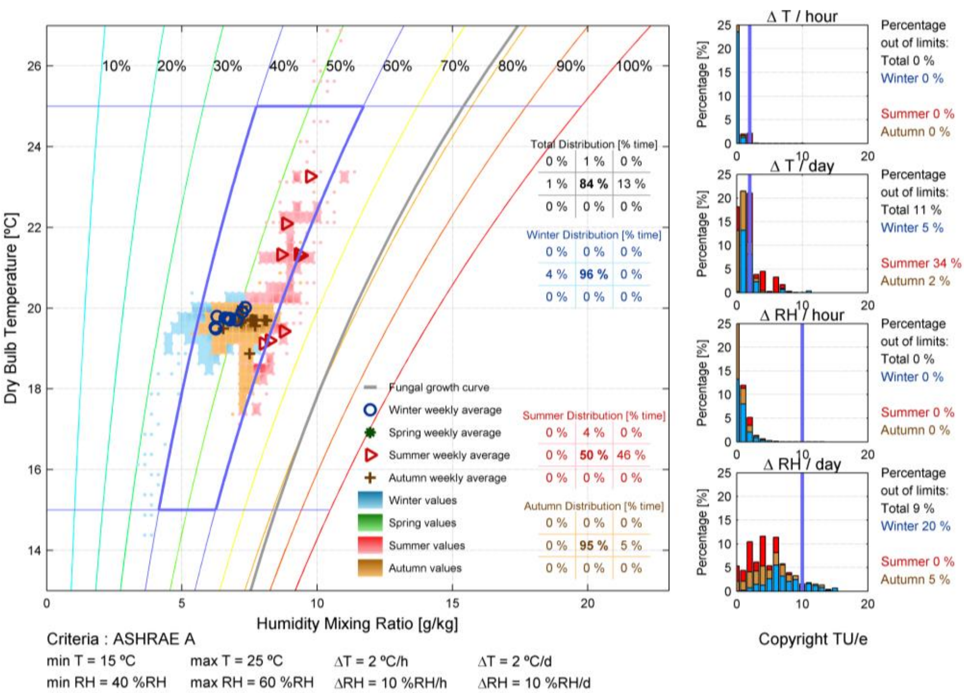

Figure M.2 CEC of the measurement position Temporary exhibition

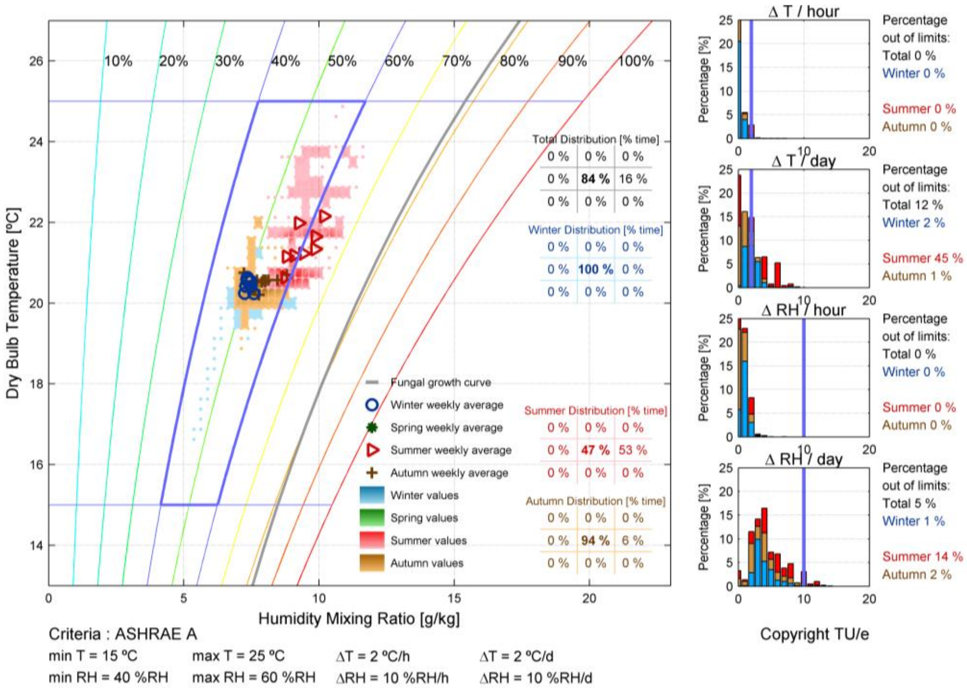

Figure M.3 CEC of the measurement position Room 11 door

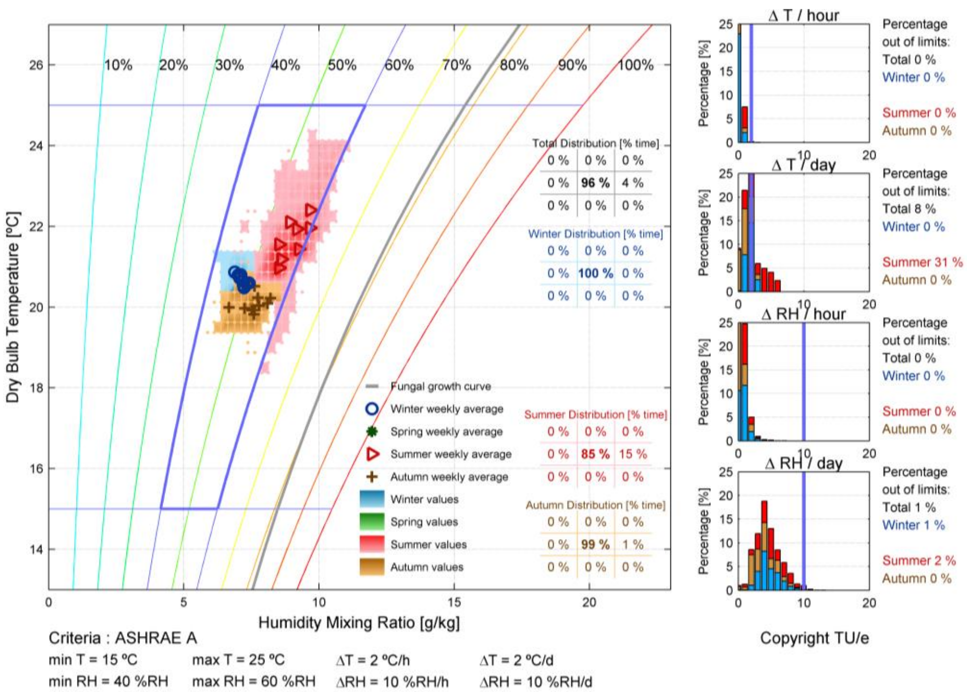

Figure M.4 CEC of the measurement position Room D

Appendix N. Building simulation

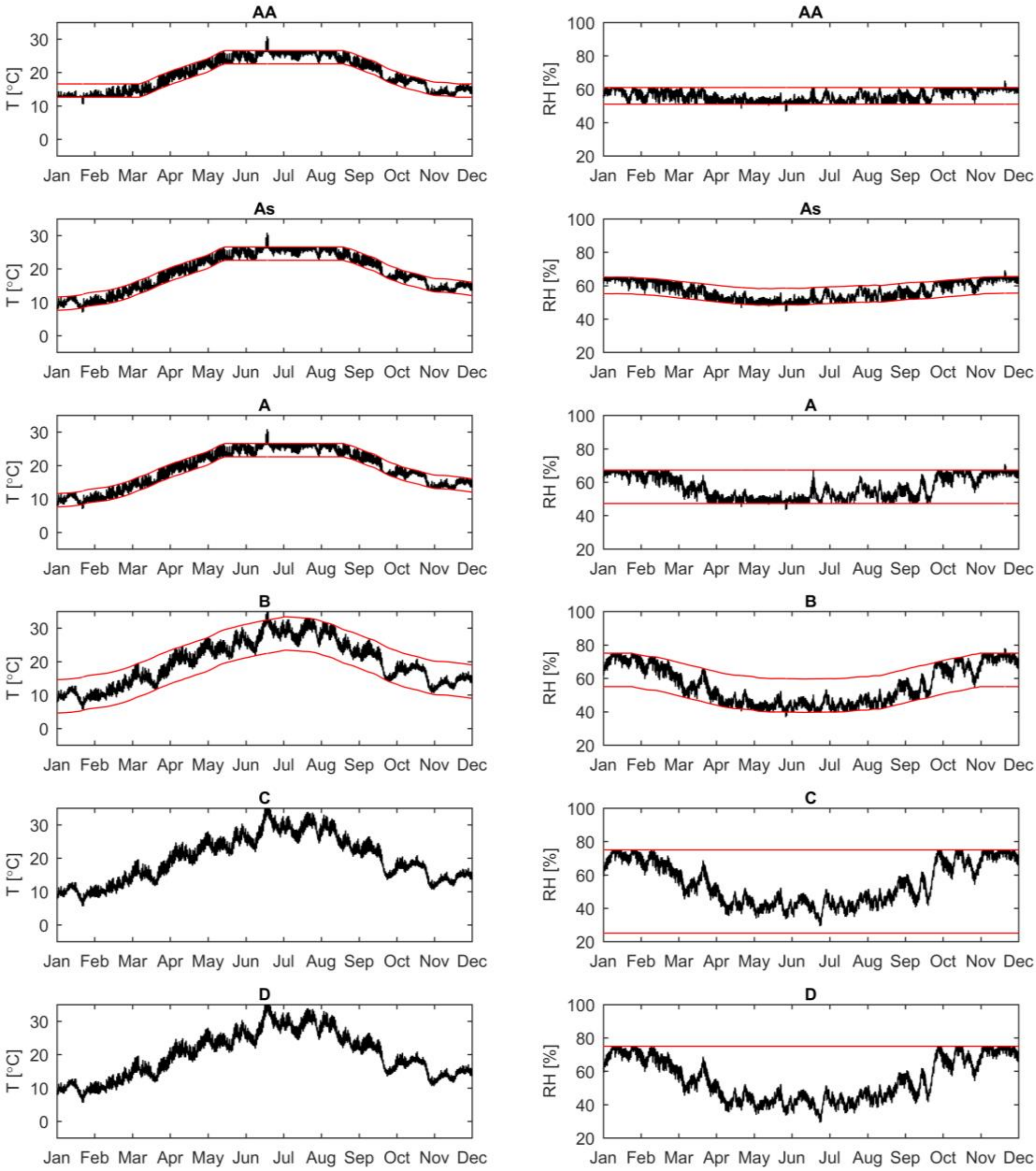

Figure N.1 Building simulation, T and RH setpoint based on ASHRAE climate classes

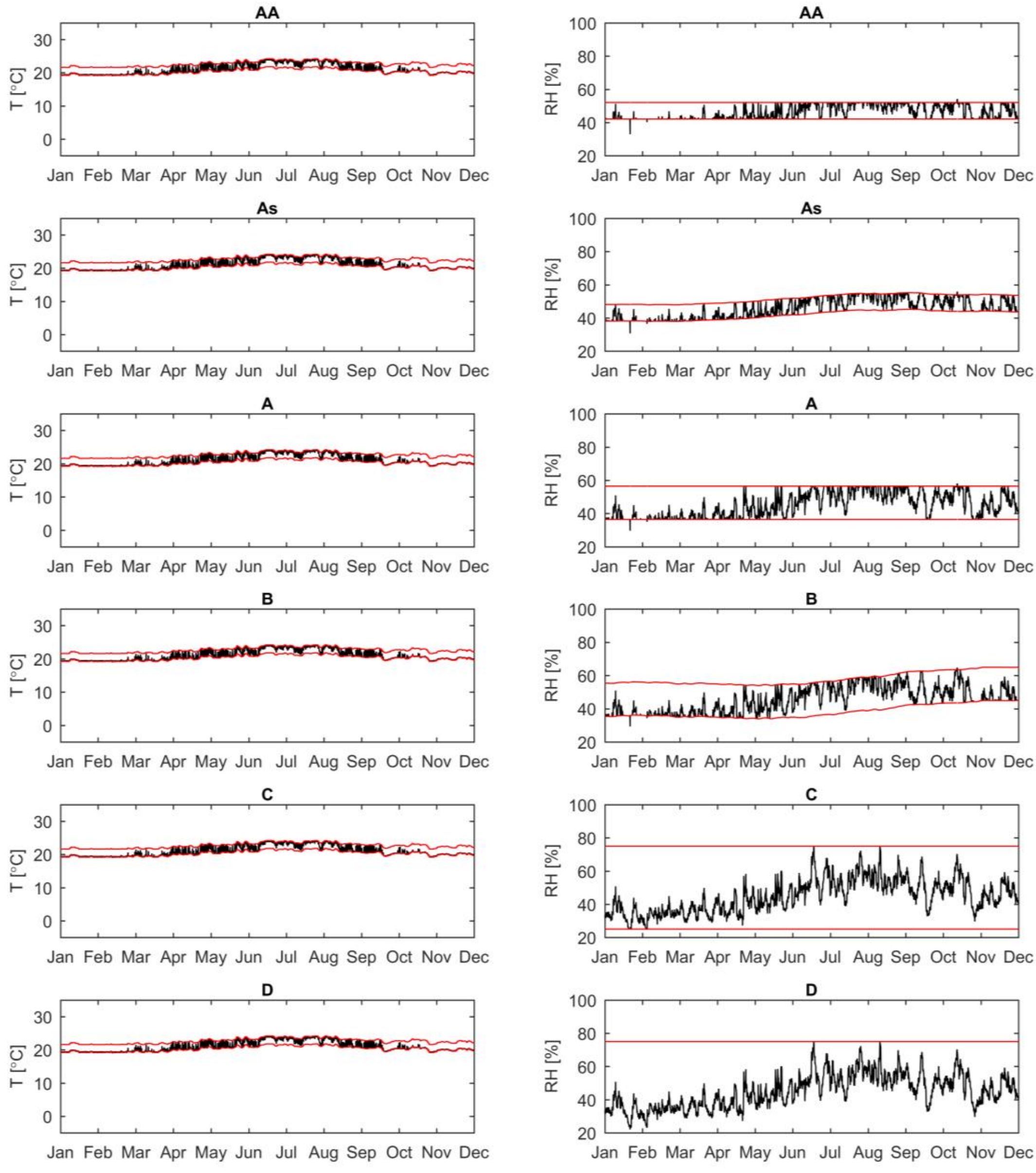

Figure N.2 Building simulation, T setpoint based on RMOT and RH setpoint based on ASHRAE climate classes

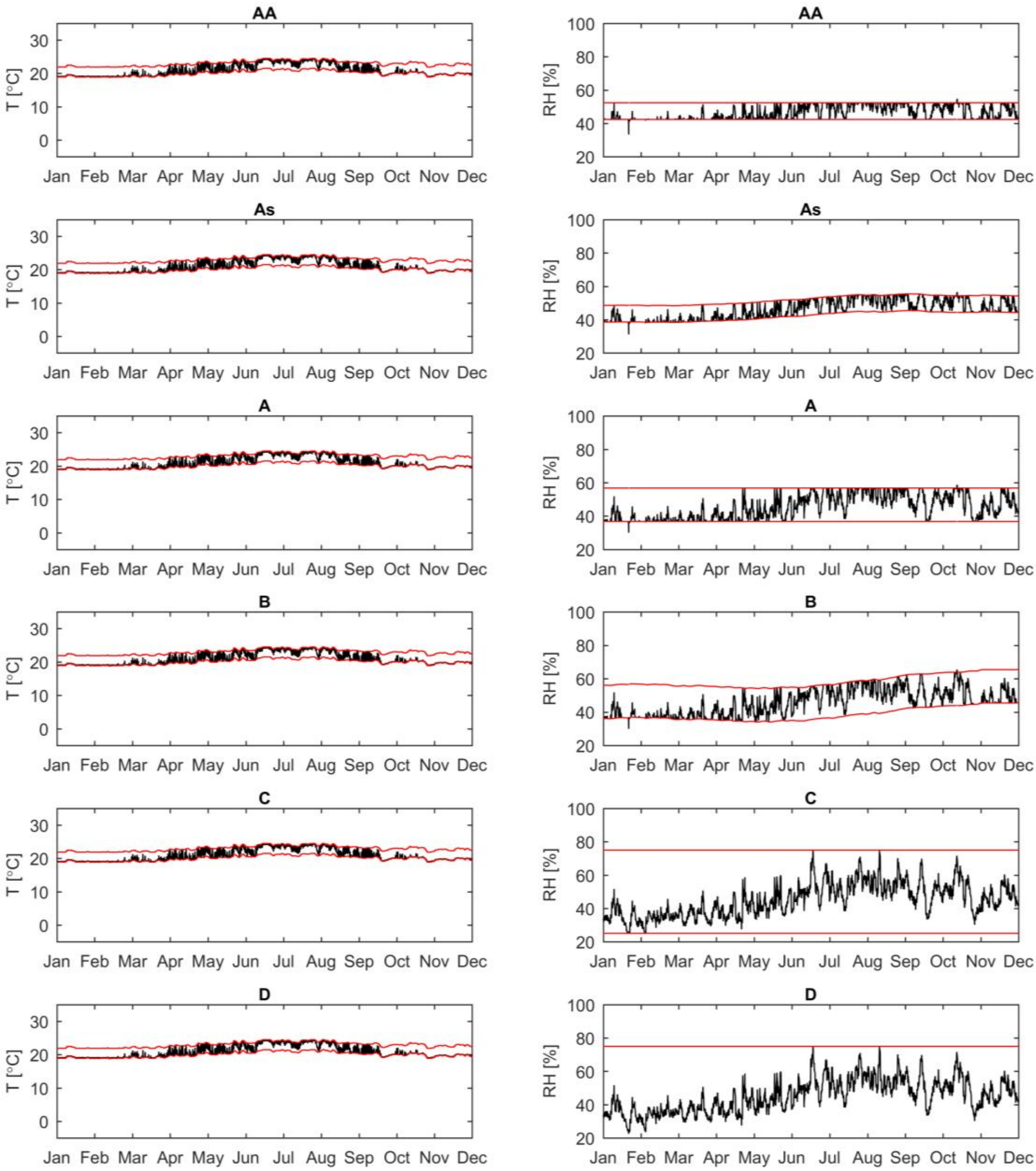

Figure N.3 Building simulation, T setpoint based on RMOT ±1.5°C and RH setpoint based on ASHRAE climate classes

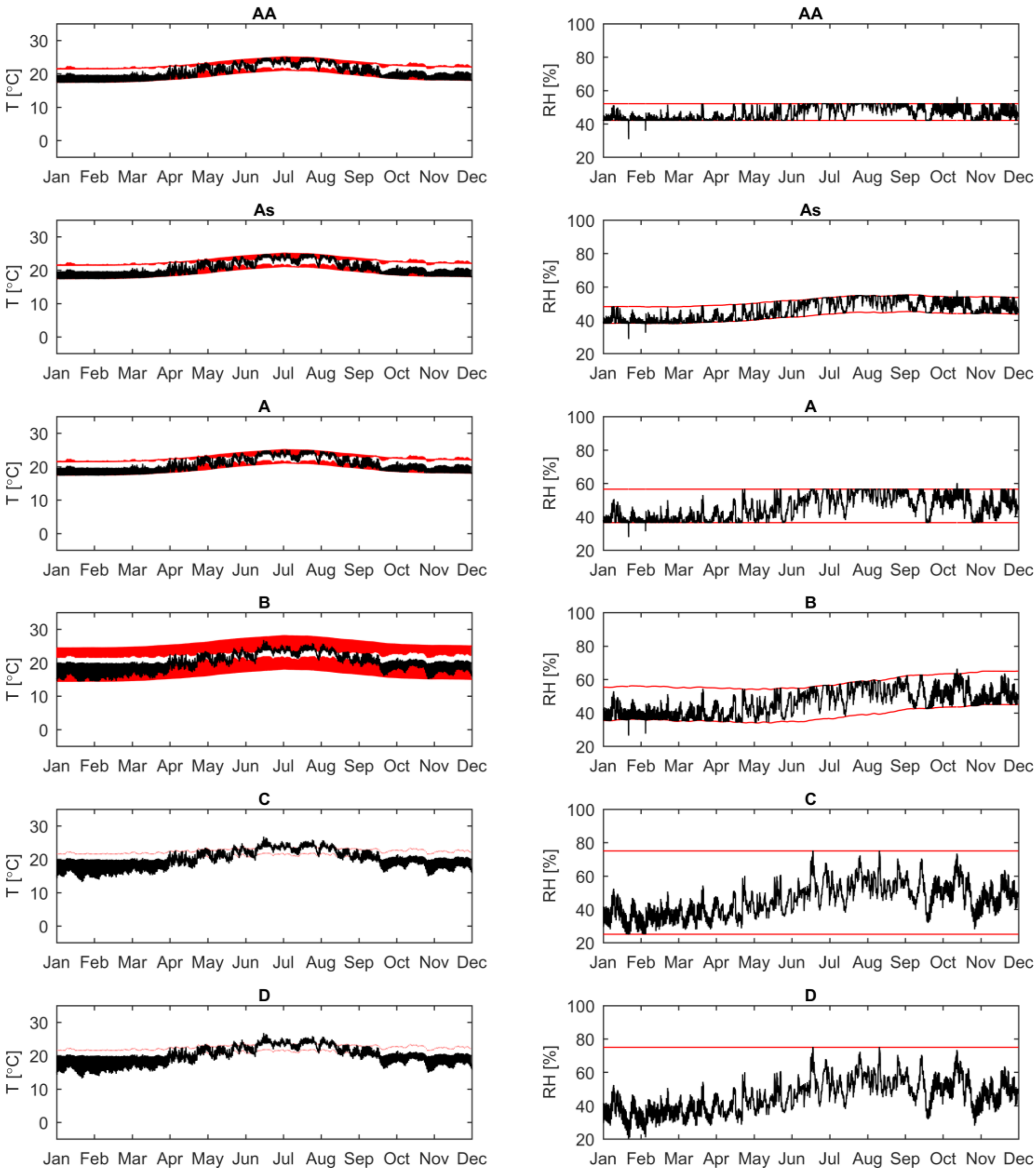

Figure N.4 Building simulation, T setpoint based on RMOT during opening hours and on ASHRAE climate classes during closing hours, RH setpoint based on ASHRAE climate classes