MASTER

Indoor climate assessment of monumental and modern museum buildings
a case study for the Van Abbemuseum

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Indoor Climate Assessment of Monumental and Modern Museum Buildings:

A Case Study for the Van Abbemuseum

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Preface

This thesis is the result of my final graduation project, and is part of the PhD study of Ir. K. (Karin) Kompatscher in which the indoor climate of several museums are analyzed. In this study the current indoor climate of the Van Abbemuseum has been assessed, and research has been conducted to assess the impact of possible energy conserving measures on the indoor climate in terms of preservation of museum objects, thermal comfort, and building envelope. The museum for modern art exists of monumental and modern building parts, and is located in the Netherlands. This thesis is presented for the degree of Master of Science in Building Physics and Services of the Eindhoven University of Technology.

I would like to express my gratitude to several people for their help during the process. First of all I would like thank my supervisors Ir. K. (Karin) Kompatscher, Dr.ir. H.L. (Henk) Schellen, and Dr.ir. A.W.M. (Jos) van Schijndel for their guidance and critical reflections. They were always helpful and supportive, which worked very motivating. In addition, I would like to thank other staff members of the Eindhoven University of Technology: laboratory staff Ir.ing. M.A.P. (Marcel) van Aarle and W.J.M. (Wout) van Bommel for preparing the measurement devices and their instructions, and Dr.ir. M.H.J. (Marco) Martens for helping with the measurement data. Furthermore, I would like to say thanks to facility manager T. (Trudy) van den Meerakker of the Van Abbemuseum for facilitating my project at the museum and for answering my questions, contact person M. (Marc) Gijsman of the municipality of Eindhoven for providing information about the museum building and air handling units, and A. (Adrie) van Alebeek of Siemens for help with the building management system. Of course I would also like to thank the crew from the Van Abbemuseum for their support, in particular D. (Diederik) Koppelmans who was always available for technical help with the measurement devices. Finally I would like to say thanks to my family and friends for their endless support which kept me motivated.

I hope you will enjoy reading,

Eindhoven, November 22nd 2017
Elianne Paulussen

Abstract

The aim of the study in this thesis is to assess the current indoor climate of the monumental building part A and the modern building part B of the Van Abbemuseum (VAM), and to assess the impact of alternative energy conserving measures and their impact on the indoor climate in terms of preservation of museum objects, thermal comfort, and building envelope.

Currently, the VAM maintains very strict indoor climate requirements for temperature (T) and relative humidity (RH), which comes with a large energy consumption. Although both the air handling units in the monumental and modern building part are placed at the same time, the museum requirements for T and RH are not met in the exhibition rooms of the monumental building part during the summer. This has caused concerns for the museum staff regarding the degradation risks of museum objects. However, it is still unknown what the increased T and RH means for the museum objects as exhibited in the monumental building part. The museum board assumes that the increased T and RH in the rooms are caused by the plenums (space between the upper roof and lower separation ceiling of the exhibition room). This study focusses mainly on the indoor climate of the monumental building part because the indoor climate of the modern building parts seems to fit in the museum requirements according to the VAM.

In order to assess the current indoor climate of the VAM, instantaneous and continuous measurements have been conducted. Within the instantaneous measurements, the T and RH spread in both building parts have been measured, along with infrared thermography measurements to assess the microclimates. The ongoing continuous measurements include measurements of T and RH of the indoor and outdoor climate. In this thesis, 8.5 months of data results have been analyzed. A numerical model of the monumental building part has been modeled and calibrated in order to study the impact of different setpoint strategies of the Heating, Ventilation and Air Conditioning (HVAC) system on the energy savings and indoor climate.

The results for T and RH of the measured and simulated indoor climate have been analyzed with several tools. The data has been visualized in the Climate Evaluation Chart (CEC). The general and specific climate risk assessment have been used to estimate the degradation risks for objects exposed to the indoor climate. Of importance is that at least one full year of data is used to get 100% reliable results, if less data is used the results show an estimation. To be able to draw a full conclusion, one year of measured data derived from the building management system was analyzed as well. The thermal comfort has been analyzed by using the adaptive temperature guidelines for museums.

According to the CEC, the indoor climate of the exhibition rooms in the monumental building part do not fit into the museum requirements. The indoor climate of the rooms on the 1st floor of the modern building part fit to a large extent into the museum requirements. The T and RH in the rooms on the 2nd floor are a bit outside the museum requirements. For both building parts, the T_i is sometimes too high and the RH_i too low or too high according to the indoor climate requirements of the VAM.

The deviations between the indoor climate of the monumental and modern building part are due to the building structure types. The envelope of the monumental building part has a lower thermal resistance. As a result, the outdoor climate has a higher impact on indoor climate of the monumental building part. Mainly during the summer, the indoor climate (T and RH) of the monumental building part shows extremer fluctuations and is more often outside the museum requirements, in contrast to the more stable indoor climate of the modern building part. Due to solar radiation the T in the monumental plenum increases (up to 50.7°C), causing thermal radiation from the internal plenum structure to the rooms underneath. As a result, the T in the rooms increases. Since the HVAC systems have been installed in both building parts at the same time, it is expected that the capacities would fit for both building parts. However, the cooling capacity is too low in the monumental building part since the maximum T requirement of the VAM is exceeded during the summer. The HVAC system in the modern building part is able to cool the indoor climate to the desired T. During the winter, the indoor climate of both building parts are quite stable and show similar results. Thus, the current heating capacity is sufficient.

The results of the continuous measurements have shown that in both the monumental and modern building part (2^{nd} floor), the rooms without external walls have almost the highest mean T_i and lowest mean RH_i compared to the rooms with external walls. Near glass surfaces, higher T_i and lower RH_i have been measured during the summer than at locations without or further away from glass surfaces. The glass surfaces have a lower thermal resistance and solar radiation as a larger impact on the indoor climate, resulting in higher daily and yearly T_i and RH_i fluctuations. During the summer (increased solar radiation) the T is lower in rooms without solar radiation on the façade than in the rooms with solar radiation on the façade.

The results of the instantaneous measurements, which have been conducted during a warm day in the monumental building part, have shown that the T_i is lower in exhibition rooms with a non-translucent plastic sheet and/or polycarbonate channel plates placed on the internal plenum structure. The additional layers significantly decrease the T_s at the bottom surfaces of the internal plenum structures. However, the T_i in the rooms are decreased to a less extent. To prevent the rooms from undesired thermal radiation from the plenums, the thermal resistance of the internal plenum structure should be increased or the T in the plenum should be decreased.

The results of the general climate risk assessment have shown that no higher class than ASHRAE class B is met 100% of the time in the monumental building part, due to the high thermal radiation from the plenums and malfunctioning of the HVAC systems (causing outliers in the T_i and RH_i). ASHRAE class B is granted for historic buildings and since the most vulnerable objects of the VAM are not placed in the monumental building part, there is no reason for concern regarding the risks to objects displayed in this building part. The malfunctioning of the HVAC systems also caused lower ASHRAE classes met 100% of the time in the modern building part of the VAM. If no malfunctioning of the HVAC systems occurred, ASHRAE class AA would be met 100% of the time in almost every room of the modern building part. Class AA is the highest ASHRAE class and expected for modern museum buildings, and comes with very low risks for the museum objects.

The results of the specific climate risk assessment have shown that the objects are safe for biological and mechanical degradation. Chemical degradation of objects is possible at almost all of the measured locations, due to T_{avg}>20°C and/or RH_{avg}>50%.

Thermal comfort of the current indoor climate is poor in most rooms. Many underheating hours have been detected, mainly in the monumental building part and at the 2^{nd} floor of the modern building part. Location dependent, the underheating hours have been detected during the whole year or during warmer summer periods. Some overheating hours have been detected as well, due to the effect of turning on/off works of art consisting out of heat emitted luminaires, which also increases the risks to objects placed in the same room.

The museum staff of the VAM has to decide which setpoint strategy is optimum for the monumental building part of the VAM. Each setpoint strategy has its own (dis)advantages regarding energy use, museum objects, thermal comfort, and building envelope. According to the results of numerical study, the most interesting setpoint strategies would be strategy 5 and 29. The T setpoint of strategy 5 is based on the running mean outdoor temperature and the RH setpoint is based on the limits of ASHRAE class As. The setpoints of strategy 29 are similar to those of strategy 5, however, the T setpoint is based on the limits of ASHRAE class As during the nighttime. These strategies show an energy decrease of 33% to 43% compared to the reference strategy. Both strategy 5 and 9 meet ASHRAE class B for 100% of the time, show less degradation risks for the museum objects compared to the reference strategy, and show a great improved thermal comfort.

Recommended is to collect one year of data with less data loss, to be able to draw a full conclusion of the indoor climate and to get 100% reliable results out of the general and specific climate risk assessment. The different setpoint strategies have been implemented in a calibrated model. To get more accurate predictions, validation of the reference model would be needed. For the validation more real data of the HVAC system should be collected. In this research a first perception is given of the potential effect on the indoor climate (T and RH) of several (structural) measures regarding the monumental plenum structures. Further research is needed in order to let the VAM make a well-considered decision before implementing any measure.

Symbol explanation

AC	Air Conditioning
AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATG	Adaptive Thermal Guideline
BMS	Building Management System
CEC	Climate Evaluation Chart
DDW	Dutch Design Week
HAMBase	Heat Air and Moisture model for Building and System Evaluation
HVAC	Heating, Ventilation and Air-Conditioning
IR	Infrared
IRT	Infrared thermography
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
LM	Lifetime Multiplier
RH	Relative Humidity [%]
RH_{avg}	Average Relative Humidity [%]
RH_e	Outdoor Relative Humidity [%]
RH_i	Indoor Relative Humidity [%]
RMOT	Running Mean Outdoor Temperature
T	Temperature [°C]
T_{avg}	Average Temperature [°C]
T_e	Outdoor Temperature [°C]
T_i	Indoor Temperature [°C]
T_s	Surface Temperature [°C]
VAM	Van Abbemuseum

Table of content

1 Introduction

This chapter introduces the motive of the conducted research. Paragraph 1.1 describes the background information about the indoor climate in museums. In Paragraph 1.2, the problem statement is given. The objectives and research question are described in Paragraph 1.3. Paragraph 1.4 provides the report outline.

1.1 Background

This paragraph describes the literature findings. Paragraph 1.1.1 discusses several (inter)national indoor climate guidelines for museums throughout the years. In Paragraph 1.1.2 and Paragraph 1.1.3 the consequences of static and dynamic requirements are given, followed by information about thermal comfort in museums in Paragraph 1.1.4, and studies about decreasing the energy use in museums in Paragraph 1.1.5. Paragraph 1.1.6 describes previous conducted studies about the case study of this research: the Van Abbemuseum (VAM).

1.1.1 Indoor climate guidelines museums

The development of international guidelines for the indoor climate of museums expanded mainly in the 1940's along with the development of technology, although the ambition to learn about degradation of objects initiated in the 1920's and 1930's (Plenderleith, 1934; Brown & Rose, 1996; Kramer, 2017). Air conditioning (AC) became more common in Europe during the 1950's, in addition to the USA where AC became widely available (Brown & Rose, 1996). Plenderleith published in 1956 'Conservation of Antiquities and Works of Art' in which a temperature (T) of 10-24°C and relative humidity (RH) of 50-60% were recommended (Plenderleith, 1956). Plenderleith's publication became the standard in Europe. These indoor climate conditions could not be maintained in many American museums during severe winters (Brown & Rose, 1996). Therefore, in 1964 Buck came up with a recommended RH value of 45-65% (Buck, 1964). In 1978, Thomson published 'The Museum Environment', in which he questioned the narrow limits for RH. However, Thomson continued recommending a RH value of 45-65% (Thomson, 1978). Thomson's publication became the new standard (Brown & Rose, 1996). Many museums were struggling maintaining the indoor climate requirements of Thomson, they often negate the shortcoming, afraid to lose important loans or grants (Ashley-Smith et al., 1994). In 1986, Thomson republished 'The Museum Environment' to make a distinction between new/important museum buildings (class 1: RH of 45-55% or 50-60%) and historic museum buildings (class 2: RH of 40-70%). Class 2 was proposed to prevent large risks for the building and objects while keeping the costs for energy use and alterations low (Thomson, 1986). However, many museums still wanted to be identified with class 1, despite the fact that the narrower indoor climate specifications came with large energy costs (Brown & Rose, 1996).

In addition to the international guidelines as described in the previous paragraph, in the Netherlands the Deltaplan (D'Ancona, 1990) was released in 1990 by the Ministry of Health and Culture to make Dutch heritage institutions (like museums) more conscious about collection preservation, including indoor climate conditions. As a result, Dutch museums have been paying more attention to collection preservation and controlling the indoor climate than before the Deltaplan was launched, by installing Heating, Ventilation and Air-Conditioning (HVAC) systems (Kramer et al., 2015). Although the Deltaplan has made museums more aware of the importance of collection preservation, the Deltaplan has not provided indoor climate specifications. Consequently, museums each had their individualistic approaches and narrowed their allowed climatic fluctuations utmost to achieve optimal conservation conditions. The Dutch museums were demanding for indoor climate specifications to reach a target to achieve optimal conservation (Martens, 2012). Therefore, strict guidelines were developed by Jütte (1994), based on Thomson (1986) and the maximum safety factor for very sensitive materials: T as constant as possible and a RH of 48-55%. The implementation of these guidelines has led to several problems in monumental buildings. A need has arisen for an integrated climate approach for the Dutch situation based on risk management. In order to fulfil this need, Ankersmit (2009) published 'Klimaatwerk', which is the current Dutch guideline (Martens, 2012).

In the 1990's more international research to object degradation processes was conducted, of importance was the work of Michalski, Mecklenburg, Erhardt, and Tumosa. Their knowledge on how RH fluctuations and levels affect different kind of objects resulted in the conclusion that a RH range around 50% is safer than extreme RH levels (Kramer, 2017). In 1996, design parameter specifications were published in the 'Handbook of the American Society of Heating Refrigeration and Air-conditioning Engineers' (ASHRAE) concerning museums, libraries, and archives for the first time (ASHRAE, 2011). The guidelines of ASHRAE (2011) are not associated with a group of materials but to the degradation risks. The degradation processes are mainly influenced by T and RH. There are three types of object degradation: biological, mechanical, and chemical degradation. Biological degradation (mould growth) occurs when the climate around an object is too humid. Mechanical degradation occurs when there are increased fluctuations of T and RH, RH to a larger extent than T. T and RH fluctuations can cause materials to shrink and expand, combined with internal and external restraint. Chemical degradation is associated with the reaction speed of chemical processes, influenced by T and RH. See Martens (2012) for more information about the degradation of museum objects.

The guidelines of ASHRAE include six climate classes: AA, As, A, B, C and D, see Appendix A. The climate classes allow different ranges of short and seasonal fluctuations of the indoor climate (T and RH). Short-fluctuations and space gradients include any fluctuation period less than a seasonal period. However, hourly fluctuations do not effect most museum objects, and many objects take days to respond. ASHRAE Climate class AA allows the smallest amount of T and RH fluctuations and should give the lowest risks to the objects, but also comes with the highest potential for energy use. Although the risk to objects is low within class AA, no protection to historic buildings in cold climates is included. In cold climates, a higher risk for monumental buildings exists because of damage due to increased RH or condensation at the inside of the building envelope. Climate class A reduces the energy use compared to class AA by allowing more short RH fluctuations and seasonal T fluctuations. This causes slightly more risk of mechanical damage to very vulnerable objects, but lower risk for historic buildings in cold climates because T can be reduced in the winter and fewer opportunities will exist for increased RH or condensation at the inside of the building envelope. In addition, class As allows the same short-fluctuations as class AA, but allows larger seasonal T and RH fluctuations than classes AA and A. Classes A and As are for most museums and galleries the optimum. Classes B and C are for many medium and small institutions useful and feasible options, which are also the best options for most historic buildings. Climate class D only controls dampness of the indoor climate (ASHRAE, 2011).

1.1.2 Static requirements

The guidelines for indoor climate became stricter together with the developing technology in the 20th century: the capability of the HVAC systems was decisive for the level of climate conditioning instead of the collection or building requirements. It became possible to influence the indoor climate such that the outdoor climate had little impact on the indoor climate (Brown & Rose, 1996; Ankersmit, 2009). Although the strict indoor climate specifications decreased the climate risks to objects, the climate risks to the building increased. The developed strict guidelines could not be implemented in monumental buildings because they were based on the optimal climate for the most sensitive object in each group of materials (Martens, 2012). Moisturized air condensed on cold surfaces of the building envelope, which were dry before, and the quality of the building decreased (Mecklenburg, 2007). Besides the occurred problems near the building envelope, large HVAC systems were needed to meet the strict indoor climate specifications for T and RH. The placement of the systems resulted in irreversible damage to the building, loss of space, and large exploitation costs. Besides the occurring of problems, the preferred indoor climate of the museums was still not reached. Especially in monumental buildings, with large heat losses, enormous amounts of energy are required to meet the strict indoor climate specifications. Consequently, energy efficient control of the indoor climate became an issue for many museums located in monumental buildings (Martens, 2012) (Ankersmit, 2009). Limiting the heat losses of monumental buildings due to the extra insulation of the façade is often not possible. Insulating the façade from the outside is often in conflict with the monumental values of the building, and insulating from the inside is hazardous because of condensation problems (Schellen, 2002). Due to increased risk on mould growth, RH near the surface of >80% should be prevented. For museums, RH near the surface of <70% is recommended to decrease the risks for mould growth on museum objects (Martens, 2012).

1.1.3 **Dynamic requirements**

A need has arisen for more real indoor climate data of museums to investigate the impact of building quality and type of climate system on the indoor climate and preservation risks. Martens (2012) has conducted a study to this question and concluded that the T and RH climate specification guidelines can be very useful when no knowledge about the behavior of objects due to the local climatic environment is present. However, the guidelines are on the safe side; often more fluctuations in T and RH can be tolerated without increasing the degradation risks. Therefore, less strict climate conditions could be maintained. In addition, very valuable objects can be placed in (display) cases. Martens (2012) revealed that in monumental museum buildings the degradation risks of objects is often independent of how simple or modern the HVAC installation is. Even with the use of full air conditioning of large HVAC systems, strict indoor climate conditions are very hard to maintain.

The study of Martens (2012) also concluded that only little differences in preservation risks for different kind of building types occur when considering the average air conditions. This is because the climate systems compensate the poor quality of the envelope of monumental buildings. However, the conditions near the building envelope will differ from the average conditions. Effects like increased RH near the surface and condensation are commonly observed, resulting in risks on mould growth. The differences between the average conditions and the microclimate near walls are larger in monumental buildings than in modern or renovated buildings with insulated walls. Because of the differences, increased risk appears to the building envelope and to objects which are placed near the envelope (Martens, 2012).

1.1.4 **Thermal comfort**

Due to the lack of thermal comfort guidelines specific for museums, Kramer et al. (2016) developed the Adaptive Thermal Guideline (ATG) for museums in which thermal comfort limits for air-conditioned museums in temperate climate regions can be assessed. The developed guidelines are based on a 1200+ survey study, measurements and an intervention study in a strictly conditioned renovated museum with insulated walls in the Netherlands. The guideline takes the adaptive behavior of humans into account and is based on the Running Mean Outdoor Temperature (RMOT) of the current day and on the preceding three days. The comfort acceptance limits according to the 90% acceptance class (excellent) are shown in Figure 1.1. Although the analysis method can only be used to determine the 90% acceptance class, the 80% class would also be good because of a higher energy saving potential and thermal comfort is not the main priority in museums. A drawback of the current ATG for museums guideline is the lack of data when T_e is below 0°C (Kramer et al., 2016).

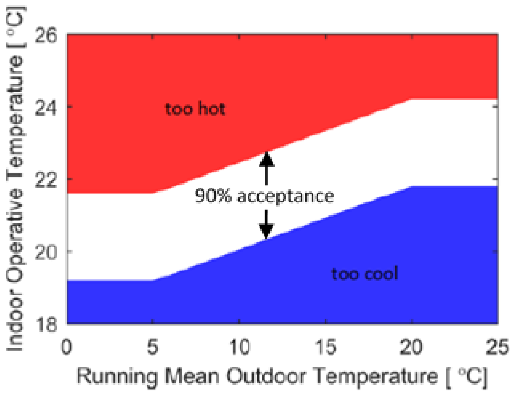

Figure 1.1: Adaptive Temperature Guideline for museums, according to the 90% acceptance class (Kramer et al., 2016).

1.1.5 **Energy consumption**

From 2005, attention for energy efficiency in monumental buildings and museums increased, and from 2010 more research was published. Mecklenburg et al. (1998) showed that an energy saving of 55% is possible by increasing the RH bandwidth from ±2% to ±7%. The study of Mecklenburg et al. is based on measurements conducted at nine museums at the West coast of the USA. The study of Artigas (2007) contained five museums at the East coast of the USA, and concluded that increasing the variance of the setpoint strategy decreases the energy use exponentially. Despite the fact that the five museums had different building types, HVAC systems, and outdoor climate conditions, the exponential relationship held true. A numerical study by Ascione et al. (2009) showed for an exhibition room in an Italian museum that a decrease in energy demand of 6-13% is possible by changing the T_i from constant 22°C to 22°C±1°C, and a decrease of 40% by increasing the RH_i bandwidth from 50%±2% to 50%±10%. Another numerical study for an Italian museum by Ascione et al. (2011) showed that changing the T_i setpoints from 22°C to 20°C in the winter and from 24°C to 26°C in the summer resulted in energy savings of 20% in the winter, 40% in spring/autumn, and 11% in the summer. The mentioned studies show that it is possible to decrease the energy consumption of museums enormous by using less strict indoor climate setpoint strategies for T and RH. Nevertheless, the results of the studies are hard to compare due to different research methodologies and case studies (building types and locations). The results are very dependent on the used HVAC system (Kramer et al., 2015).

While the previous studies from Mecklenburg et al. (1998), Artigas (2007), and Ascione et al. (2009, 2011) about energy efficiency have only focused on energy consumption, Kramer et al. (2015) also assessed the collection preservation quality and thermal comfort. This research was conducted by modelling and simulating the indoor climate of a state-of-the-art museum housed in a well-insulated renovated monumental building in the Netherlands. The research has shown that the T requirements are mostly dependent on the thermal comfort, and the RH is mostly dependent on the collection preservation. The thermal comfort was evaluated with the ATG of Linden et al. (2006). The collection preservation quality was evaluated with the specific climate risk assessment method of Martens (2012). From simulating several setpoint strategies for T_i and RH_i, one strategy came out as the best option: the former energy consumption decreased with 77%, and also improved the thermal comfort and collection preservation. For monumental uninsulated buildings, it may be necessary to apply seasonal changes to the RH limits to prevent high RH and condensation at the inside of the building envelope (Kramer et al., 2015). Another study by Kramer et al. (2016) has shown with full-scale measurements in the same museum that an energy saving of 63% is possible without significantly changing the degradation risks to objects. Within this study, the setpoint strategy was changed every week from the museums used setpoints (reference) to ASHRAE classes AA and A. Kramer et al. (2015) concluded from the numerical study that adapting less strict setpoint strategies will relatively save the most energy in modern museum buildings, while in monumental museum buildings the absolute savings will be the highest. In addition, Kramer et al. (2017) developed a seven-step algorithm for calculating the hourly setpoints of T_i and RH_i for museums. The lower and upper T limits are calculated based on the thermal comfort requirements according to the ATG for museums (Kramer et al., 2016), see Paragraph 1.1.4, and on the collection requirements according to the ASHRAE climate classes (ASHRAE, 2011). The calculated T limits are compared for each hourly value; during opening hours the most stringent limits are chosen and during closing hours the limits based on the collection requirements are chosen. The lower and upper RH limits are calculated based on the collection requirements (Kramer et al., 2017).

While Kramer has mainly focused on decreasing the energy consumption of one well-insulated building by conducting an experimental and numerical study to the indoor climate (T and RH) and energy use, PhD candidate Kompatscher studies the effect of developed energy conservation measures on the behavior of the indoor climate and museum objects. In contrast to Kramer, who conducted a lumped parameter study in the museum room, Kompatscher will conduct research to the effects of dynamic indoor climate specifications (T and RH) on local climates.

1.1.6 Van Abbemuseum

This study is part of the PhD study of Kompatscher and has assessed the current indoor climate of the Van Abbemuseum (VAM), located in the Netherlands. The building of the VAM exists of different buildings parts, see Figure 1.2.

Part A is the monumental building part, part B, C, and D are the modern building parts, and part E is housing offices in monumental townhouses. One of the houses is also a national monument (Rijksdienst voor het Cultureel Erfgoed). During this research, there is focused on the monumental building part A and the modern building part B, in which most of the exhibition rooms are located. Previous measurements during the summer period have shown that higher T and RH than preferred by the museum are measured in the exhibition rooms of the monumental building part A. This has caused concerns for the museum staff regarding the degradation risks to museum objects. The museum board assumes that the increased T_i and RH_i are caused by the plenums (space between the upper roof and lower separation ceiling of the exhibition room), see Figure 1.3. The plenums have a low thermal resistance, are not conditioned (Engelen, 2006), and no thermal resistant layer is added. Currently, it is impossible to open the outer structure of the plenums (roof surface) to cool or ventilate the plenums.

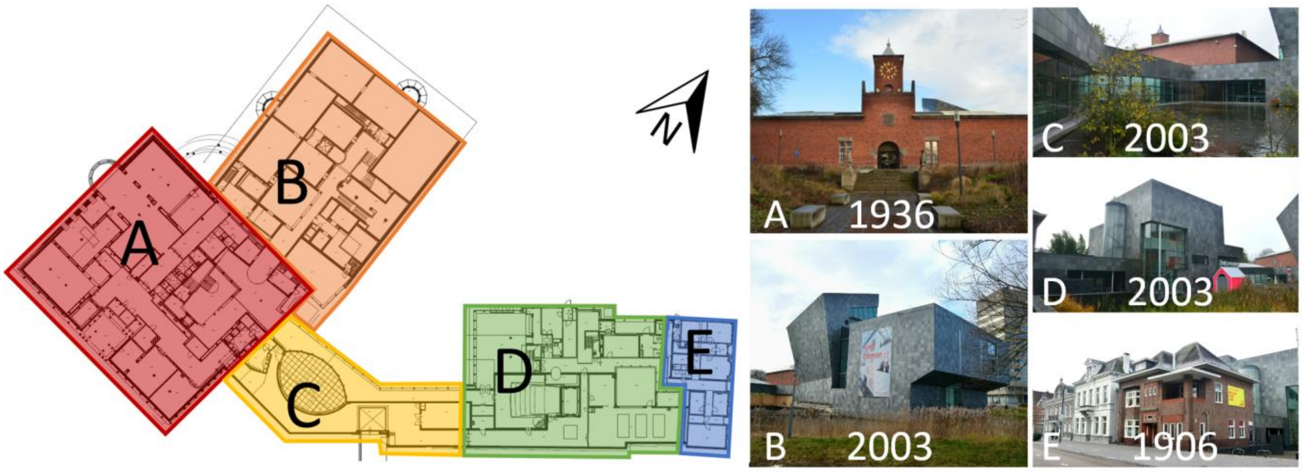

Figure 1.2: Overview building parts Van Abbemuseum, floor drawing by Cahen (2003), and façades and year of construction.

Figure 1.3: Plenum, lamellae detail which can regulate the light transmission into the exhibition rooms, and exhibition room.

During July 3rd, 2015, a surface temperature (T_s) of 41°C is measured with an infrared (IR) camera at the bottom surface of the plenum separation structure (Kompatscher, 2015). During this measurement moment, T_e was about 30.4°C (KNMI, 2017). Another study by Engelen (2006) showed that temperatures above 55°C were measured in the summer of 2006 in the plenum. Engelen (2006) concluded that the HVAC system in the monumental building part is unable to cool the exhibition rooms enough to reach the preferred indoor climate (T and RH). In addition, Engelen (2006) states that changing the current HVAC installations for larger installations with more power is impossible since they do not fit in the current installation spaces. Since the museum assumes that the increased T_i and RH_i are the effects of the heated up plenums in the summer, the most manageable option would be to mechanical cool down the plenums. Engelen (2006) recommends to integrate mechanical ventilation of the plenums into the current HVAC system, based on the measured T_i and T_e. The T in the plenum should be close to T_e. Another recommendation by Engelen (2006) is to insulate the retour ventilation pipes to minimize the effect of the plenum on the mixed air. This should have a positive effect in both summer and winter periods. However, using mechanical ventilation comes with high investment and maintenance bills. Instead of mechanical ventilation, it is also possible to make use of natural ventilation for the plenums by opening skylights in the roof. This will not cost extra electric energy, but the air flow is hard to control (Engelen, 2006). The museum does not want to place ventilators due to the large amount of noise. Engelen (2006) has also concluded that the plenum can function as a heating buffer when T in the plenum is below 26°C. When T is higher than 26°C, the plenum has a negative effect on the T_i and so on the RH_i in the exhibition room.

Besides ventilating the plenums, the museum also considered to place insulating glass in the roof structure. However, the current roof structure cannot support the weight of the glass. In addition, the wired glass of the internal plenum structures have been replaced with polycarbonate channel plates. Nevertheless, the conservators thought this was unacceptable due to the drastic change of light. Potential foils should provide maximum daylight and minimum sunlight. Another option that has been considered is to place a structure of polycarbonate channel plates with a layer of non-translucent plastic sheets on the shutters of the plenum, which deducts both light and heat (Meerakker & Gijsman, 2016).

The indoor climate (T_i and RH_i) in the modern building parts is manageable according to the museum. However, moisture problems in the basement and former depots have been detected, the moisture is located at the bottom of the walls. The surface of the walls is very wet. Moreover, water has been detected in the elevator shaft. Since three years, a too high RH_i has being detected in the depots, which are controlled by free cooling. The indoor climate in the tower does not meet the expectations of the museum, it feels draughty for the attendees. The inlet air rate in the top of the tower is set for more attendees than present, therefore the inlet air rate is too high to get a comfortable climate (Meerakker & Gijsman, 2016). Because the indoor climate (T_i and RH_i) of the VAM is conditioned by only a few HVAC systems, it is impossible to control the indoor climate of a single room.

Because of the differences in indoor climate conditions (T and RH) between the monumental and modern building part, visitors can experience discomfort while changing from building part in the museum.

1.2 Problem statement

The problem in the VAM is the very strict indoor climate requirements (T and RH), see Table 2.1, which comes with a large energy consumption. Although both the HVAC systems in the monumental building part A and modern building part B are placed at the same time, the museum requirements for T and RH are not met in the exhibition rooms of the monumental building part during the summer. This has caused concerns for the museum staff regarding the degradation risks of museum objects. However, it is still unknown what the increased T and RH means for the museum objects as exhibited in the monumental building part. Another problem is the very uncomfortable thermal climate for the employees of the VAM during the summer in the plenums of the monumental building part.

1.3 Objectives and research question

The main objectives of this research are:

- Assessing the current indoor climate of the monumental and modern building part of the VAM.
- Assessing possible energy conserving measures, such as setpoint strategies, and their impact on the indoor climate in terms of preservation of museum objects, thermal comfort, and building envelope.

The aim is to provide advice to the VAM while mainly focusing on the monumental building part because the indoor climate of the modern building part seems to be manageable. However, the indoor climate of the modern building part has also been assessed. Within this research, there is focused on the preservation of the museum objects and the building envelope.

The main research question is: 'What causes the differences in the current indoor climate between the monumental and modern building part of the Van Abbemuseum, and how can the current indoor climate be improved with respect to the museum objects, comfort, and building envelope?' The main research question is answered by literature, and experimental and numerical studies during the research.

1.4 Outline

The case study Van Abbemuseum is described in Chapter 2. Chapter 3 explains the methodology including the experimental and numerical studies, and the analysis tools. Chapter 4 shows the results of the several studies. The discussion and conclusion are described in Chapter 5 and 6. Chapter 7 describes the recommendations for the museum staff and for further research.

2 Case study: Van Abbemuseum

The Van Abbemuseum (VAM) is founded in 1936 and located in Eindhoven, the Netherlands. The museum exists of five different building parts, see Figure 1.2 in Paragraph 1.1.6, and the total gross floor surface is 9651m^2. The museum is open every day from 11AM till 5PM for visitors, except on Mondays when the museum is closed, and on Thursdays when the museum is open till 9PM. The museum counted 95,000 visitors in 2016.

This chapter describes the history and location, the different building parts, the indoor climate control system, and the art collection of the VAM.

2.1 History and location

The VAM is founded in 1936 by Henri van Abbe, who was the director of a cigar company and supporter of modern art. In 1932 Van Abbe came up with a proposal to the municipality of Eindhoven to build the museum for modern art. He wanted to provide 410,000 guilders ('gulden' or 'florijn' in Dutch) for the construction of the museum, the purchase of art, and maintenance of the museum for five years. The municipality accepted the offer in 1933 and gave away the area at the corner of the Bilderdijklaan, near the river the Dommel. In 1934 the construction of the museum began, and in 1936 the museum was opened under the name 'Stedelijk Van Abbe Museum' (Brouwers, 2003), see Figure 2.1 for an impression of the museum in 1936. In 2003 the national monument of architect A.J. Kropholler was renovated and modern building parts were added, designed by architect Abel Cahen. With the modern building parts, the museum increased its floor area by five times. With the coming of the modern building parts, the river has been widened and an ecological shore is constructed. The landscape changes have created a lake between the modern building parts, see Figure 2.1. The museum belongs to a group of museums for fine arts, and both collection and architectural design have a contemporary feeling (Van Abbemuseum, 2016).

Figure 2.1: Left: front façade of the Van Abbemuseum in 1936 (Kropholler, 1936), right: bird's eye view (Bing Maps).

2.2 Monumental building parts

The gross floor surface of the monumental building part A is 3179m^2, the gross floor surface of the offices (building part E) is 700m^2. See Appendix B for the floor plans. The monumental museum building part A exists of three building layers, including the plenums. The facades of the monumental building part exists of a trachyte plinth below and two dark red half brick walls on top with a cavity between them. The south façade has a thickness of 630mm, the other three facades have a thickness of 400mm. The inner walls are also made of bricks. All the walls of the exhibition rooms have a non insulated double wall at the inside surface. Fire protection doors are located at room 1, 6, and 10, see Figure 9.9 in Appendix D, to separate the exhibition rooms from the entry hall. The fire protection doors are opened every day from 9AM till 6PM. Since the building is designed as a museum, nearly no daylight is entering the spaces through the walls, only rooms 3 and 8 have a window. The glass of the windows is provided with ultraviolet filters to protect the art from harmful radiation. Sometimes the windows are covered by a (semi-)closed sheet.

Almost all the exhibitions rooms have external walls, only room 6 is completely surrounded by other rooms. Room 6 has a new floor and new upper roof. Room 7 has partly a new floor as well. The floors are made of concrete. The roofs exist of a steel structure and transparent polycarbonate channel plates (including ultraviolet filters). All the exhibition rooms have internal plenum separation structures, from which daylight can enter the exhibition room through the plenum. The light through the plenum separation structures can be managed with maintainable shutters, see Figure 1.3 in Paragraph 1.1.6. No heat resistant foils are added because such foils decrease the daylight entering the exhibition rooms. A library and the corridor to the modern building parts are located in the two former patios. See Appendix D for more specifications of the structures in the monumental building part. Appendix C shows impressions of the VAM.

2.3 Modern building parts

The gross floor surface of the modern buildings parts B, C, and D is 5772m^2. See Appendix B for the floor plans. The modern building part B exists of five building layers. All floors, facades and inner walls are made of concrete. The floors also exist out of a layer of screed, and the total building envelope is insulated. The facades are clad with natural stone: grey slate Flammet coming from Lapland (Van Abbemuseum, 2016). Some parts of the facades and roofs are made of a steel structure with glass plates. During cold days, condensation occurs at these structures. All exhibition rooms have double walls. Fire protection doors are located at several locations, and are opened every day from 9AM till 6PM. Just as the monumental building part A, the roofs of the exhibition rooms have plenum ceilings to let daylight enter the exhibition rooms. In contrast to building part A where the lamellae are located right above the plenum ceiling, the upper plenums in building part B have lamellae right under the glass surface of the roof structure. All translucent surfaces are provided with UV-filters, but without heat resistant foils. The roofs are made of a steel structure, (aerated) concrete, insulation and bitumen. See Appendix E for more specifications of the structures in the modern building part B. Building part B also consists of a 27m high tower with slanting walls. Every floor has an own structure, from high and spatially to modest or a surprising shape. The building is made to feel like a labyrinth (Van Abbemuseum, 2016). The museum has many spaces with several functions: exhibition rooms, rooms for presentations, library, museum café, museum shop, depots, offices, and installation rooms. Appendix C shows impressions of the VAM.

2.4 Indoor climate control system

The exhibition rooms, depots, restaurant, auditorium, and library are conditioned by several Air Handling Units (AHUs). These AHUs are controlled by the obtained data of the sensors in the building parts. This means that the spaces are heated, cooled and ventilated by the air handling system based on the setpoints and real average indoor temperature (T_i) and relative humidity (RH_i). The indoor climate requirements are shown in Table 2.1, the RH_i is decisive (Meerakker & Gijsman, 2016). The requirements of the museum are stricter than those of ASHRAE class AA, see Appendix A, which comes with the lowest risks to the objects, but also comes with the highest potential for energy use. Although the allowed short-fluctuations for T (±2K) are the same for both the museum requirements and ASHRAE class AA, ASHRAE class AA allows wider short RH fluctuations (±5%RH) than the museum (±3.5%RH).

Table 2.1: Indoor climate requirements Van Abbemuseum (Meerakker & Gijsman, 2016).

Parameter	Max. fluctuation per hour	Max. fluctuation per 24 hours
Temperature: 18-22°C	0.5°C	2.0°C
Relative humidity: 48-55%	0.5%	2.0%

The heating is produced by a CV-installation, the cooling in building parts A and B by an air-cooled compression chiller and the cooling in building parts D and E by an air-cooled scroll chiller. Radiators and/or floor heating are present in some non-exhibition spaces (Nelissen, 2000). See Appendix F for the ventilation schemes of building parts A and B. In the monumental building part A, inlets and outlet are located at the ceiling. In the modern building part B, the inlets are at the top of the walls, the outlets are located at the bottom, see Figure 2.2. Dust coming from visitors is visible around the vents in the monumental building part A and is periodically removed by vacuuming. The lights in the museum are turned on from approximately 9AM till 6PM. On Mondays, the lights are turned off as much as possible.

Figure 2.2: Inlets and outlets. Left: monumental building part A, right: modern building part B.

Although the total energy consumption (electricity and natural gas) is known by the VAM, see, these values are quite unusable since they also include other energy use, such as lighting. Therefore, information about the energy use for controlling the indoor climate, and the T and RH measured by the museum, should be extracted from the BMS. Plans are made to install a new control system in the summer of 2018, with the coming of a new executive company.

2.5 Art collection

The VAM exhibits and stores modern art objects, made in the period 1904 till now. In the monumental building part A temporary collections are shown, which changes about every 4 till 6 months. Sometimes the collection changes even more due to special events, such as 'Dutch Design Week' or 'GLOW Eindhoven'. In the modern building parts B and C the permanent collection is exhibited. The museum owns, among others, work of Pablo Picasso and Piet Mondriaan. The collection consists of the following type of objects: paintings on canvas, drawings on paper, cardboard, porcelain, jute, photo's, films, fabrics, plastics, wall drawings, sculptures of wood, stone, bronze or metal, books (in the library), and luminaires, see Figure 2.3 (Van Abbemuseum, 2016). At the official website www.vanabbemuseum.nl of the VAM, more works of art can be found.

Figure 2.3: Museum objects consisting luminaires: LED lamps, tubular fluorescent lamps, halogen lamps, incandescent lamps, and several art objects consisting lamps during 'Glow Eindhoven 2016'.

It is possible for other museums and institutions to get works of art on loan for temporary exhibitions. Among other conditions, the temporary exhibition room should have a stable T_i of 18-20 °C and a stable RH_i of 50-55% (with a marge of ±2%) (Van Abbemuseum, 2016). In addition, the VAM also lends works of art from other museums and institutions for temporary exhibitions in the VAM.

3 Methodology

The aim of this research is to assess the current indoor climate of the monumental and modern building part of the Van Abbemuseum (VAM), and to assess the impact of possible energy conserving measures on the indoor climate in terms of preservation of museum objects, thermal comfort, and building envelope. Therefore, the museums indoor climate (T and RH) has been analyzed based on measurements, data provided by the Building Management System (BMS) of the VAM, and numerical study.

Paragraph 3.1 describes the experimental study, including instantaneous and continuous measurements. Paragraph 3.2 includes the numerical study using HAMBase, calibrated with the results of the continuous measurements. In Paragraph 3.3 multiple analyzing methods are described which have been used to assess the measured and simulated indoor climate data.

3.1 Experimental study

Paragraph 3.1.1 describes the instantaneous measurements regarding infrared thermography (IRT) and measurements of the indoor temperature (T_i) and relative humidity (RH_i) spread in the museum. Paragraph 3.1.2 describes the continuous measurements related to T, RH, and surface temperatures (T_s), and includes information about the measured data of the BMS.

3.1.1 Instantaneous measurements

In the next paragraphs, the IRT and the instantaneous measurements regarding T_i and RH_i are explained.

Infrared thermography

To indicate the microclimates in the VAM, infrared (IR) thermographs have been conducted with an IR camera of the structures of the museum. Microclimates are local deviations in which T_i and RH_i significantly differ from the average indoor climate. The principle of IR thermography is shown in Figure 3.1. To get accurate and reliable thermograms, large differences between T_i and T_e are required. Therefore, IR thermograms have been conducted during the winter (T_e<5 °C) on February 17th 2016 and in the summer (T_e>30°C) on July 20th 2016. Before measuring, a measurement plan has been designed. The IR thermograms have been mostly taken at the same locations, for the comparison between the seasonal climate situations. In addition, on July 20th 2016 IR thermograms have been made of the bottom surface of every internal plenum structure, see Figure 3.2, to compare the T_s of the different plenum separation structures. For every IR thermogram, the T and RH at that location have been noted, including the time and the location of the picture, and an extra visual picture was made. The IR results were of great importance for determining the locations of the T_s sensors, see Paragraph 3.1.2 for more information. Appendix G provides more information about the IR measurements, including the used devices, difficulties, outdoor climate conditions, and measurement locations.

Figure 3.1: Principle of IR thermography. IR camera (Flir systems, 2004) detects the IR energy (heat) that a surface emits (the higher T, the higher the emitted IR radiation) and transforms it into electronic signals. These signals are converted to a thermal image (Flir, 2016)

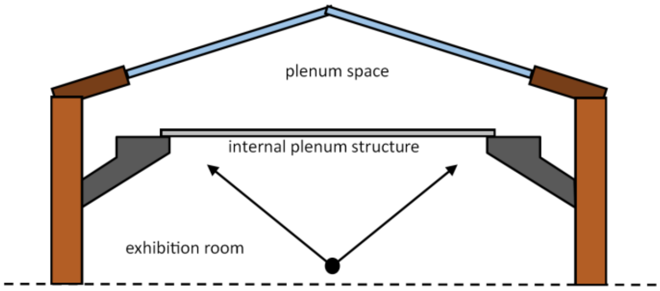

Figure 3.2: Schematic section view of an exhibition room and a plenum, showing the measurement set up of the IR thermograms taken at the bottom surface of the internal plenum structures in the monumental building part.

With the software program 'ThermaCAM Researcher Professional 2.8 SR-1' the IR thermograms can be edited later, for example changing the plotted T range, the room T and RH, and the emission factor of the surfaces looked at. The IR thermograms can be exported in the ThermaCAM software program to Matlab-files, which can be used to make a hygrogram ('relative humidity near the surface'-plot). The RH is of importance for the preservation of the objects and the building envelope. The hygrograms can be created by using a Matlab-tool developed by Schellen (2002). In this tool the IR thermograms (Matlab-files) have to be imported, the measured room T and RH have to be given and the preferred T and RH ranges have to be provided. The output is a composition of a 'surface temperature'-plot and a 'relative humidity near the surface'-plot. The Matlab-tool makes use of a few equations, see Appendix G.

Instantaneous measurements indoor temperature T_i and relative humidity RH_i

During the IRT measurements, as discussed in the previous paragraph, the T_i and RH_i have been measured in many rooms using a handheld device. By creating a color plot of the T_i and RH_i spread in the museum, a first conclusion of the current indoor climate could be drawn. In addition, the differences in T_i and RH_i during the winter and summer could be seen because the measurements were conducted during a cold and during a warm day. Since the handheld device is not very accurate and the instantaneous measurements represent only a fraction of time, no hard conclusions could be drawn. Appendix G provides more information about the used measurement devices, the outdoor conditions during the measurements and the rooms in which is measured.

3.1.2 Continuous measurements

Continuous measurements of the outdoor climate (T_e and RH_e) and indoor climate (T_i, RH_i, and T_s) in the monumental building part A and modern building part B were conducted from July 7th 2016 and are still ongoing, according to the measurement plan as shown in Appendix H. This measurement plan contains the locations and types of sensors that have been placed, taken limited data points into account. The sensors have been placed – by the staff of the museum – to be able to evaluate the current indoor climate (T_i, RH_i, and T_s) based on the results of the measurements. Thus, realistic values for the rooms should be obtained. Although the best location to observe the room T_i and RH_i would be in the middle of the room (Ankersmit, 2010), the sensors have been placed near the walls due to aesthetic considerations of the museum. Outliers require extra attention, such as thermal bridges, since they are often influenced by external factors, for example the outdoor climate and air inlets.

The measured indoor climate has been compared to the requirements set by the VAM, the outdoor climate, and data measured by the own sensors of VAM, which has been derived from the BMS. In addition, the differences between the monumental and modern building part have been assessed. Furthermore, a research has been conducted to what factor, such as the outdoor climate, visitors, and system malfunctions, influences the current indoor climate of the VAM the most and what the current indoor climate means for the museum objects, thermal comfort, and building envelope.

Although at least one year of measurements is needed to draw a complete conclusion of the indoor climate (Ankersmit, 2010), only 8.5 months of measured indoor climate data has been analyzed for the experimental study part of this research (July 7th 2016 till March 21st 2017). PhD candidate Kompatscher and the VAM continue the measurements. Despite the fact that not a whole year of own measurement data has been taken into account, the measurement includes 257 days: 76 in the summer, 91 in the autumn, and 90 in the winter. Hence, the extreme weather conditions have been included in this research. To be able to draw a full conclusion of the current indoor climate in this research, the BMS data has been compared and validated with 8.5 months of own measurement data, using the climate risk assessment analysis method as described in Paragraph 3.3.1. Since the BMS data is representative for the indoor climate, see Appendix P, one year of this data has been used for the climate risk assessment as well (March 21st 2016 till March 21st 2017).

In the next paragraphs, the measured parameters are explained.

Indoor temperature T_i, relative humidity RH_i, and surface temperature T_s

To measure the T_i and the RH_i, 23 'Eltek Wireless Data Logging Systems' sensors have been placed in the museum, see Figure 3.3 for the measurement principle. The Eltek sensors have been calibrated by the 'TU/e Building Physics and Services Laboratory'. The data obtained by the T/RH Eltek sensors are transmitted through repeaters to a central data logger receiver, from where the data are sent to the website 'Physics of Monuments' (Eindhoven University of Technology & Building Physics and Services, 2016) to analyze the measurements. A measurement interval of 10 minutes is applied. On July 7th 2016 the last Eltek sensors have been placed and on February 6th 2017 the last repeater has been placed.

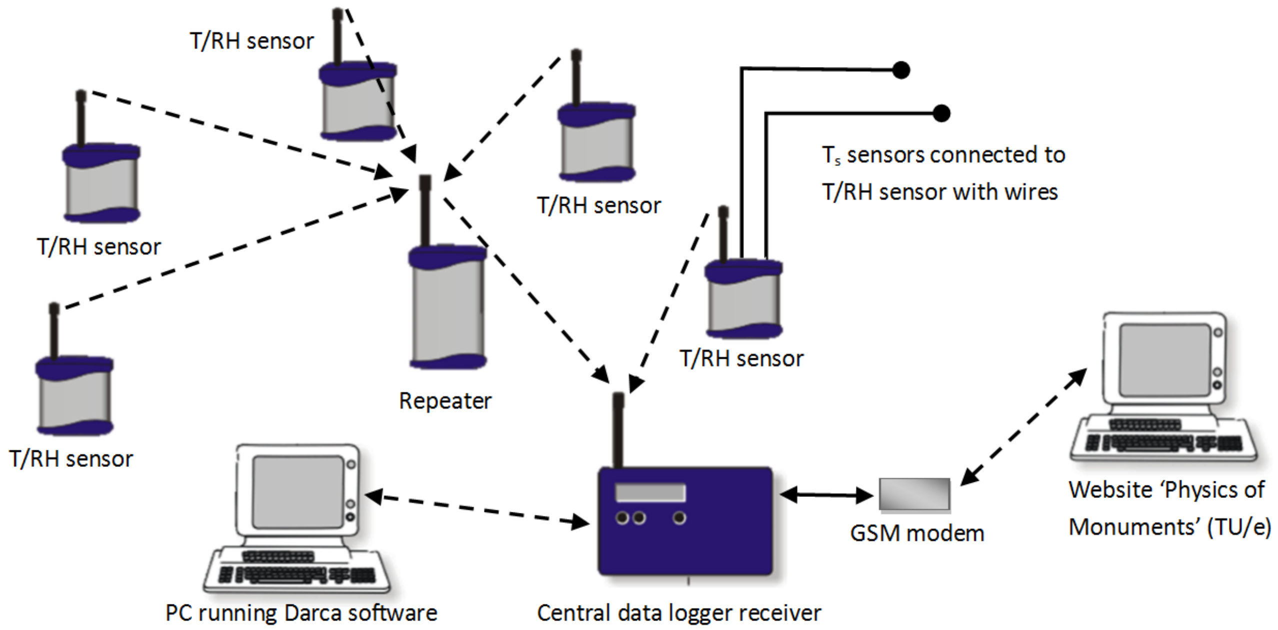

Figure 3.3: Principle of measurement setup continuous measurements Eltek sensors.

10 Eltek T/RH sensors have been placed in the monumental building part A, and 13 in the modern building part B. Appendix H shows all locations and types of sensors that have been placed. The locations of the sensors represent the locations from which deviations in T_i and RH_i in the museum could be detected, see Figure 9.24 in Appendix H. In addition, the data measured by the BMS sensors has been used for the analysis as well. The VAM has 3 T_i/RH_i sensors in building part A, and 6 T_i/RH_i sensors in building part B, see also Appendix H.

To measure the T_s, 5 T_s sensors have been placed in the monumental building part A and 6 in the modern building part B, see Appendix H for the locations. The sensors are attached to the Eltek T/RH sensors with white wires, see Figure 3.3 for the principle. The locations of the sensors represent the locations from which deviations in T_s in the museum could be detected, see Figure 9.30 in Appendix H. The IR thermograms taken on February 17th 2016 have played an important factor for choosing the locations of the T_s sensors. Figure 3.4 shows one example of an IR thermogram, from which the locations of the T_s sensors have been determined.

IR location 22, February 17th 2016 10:44, T_i = 19.6°C and RH_i = 46.5%

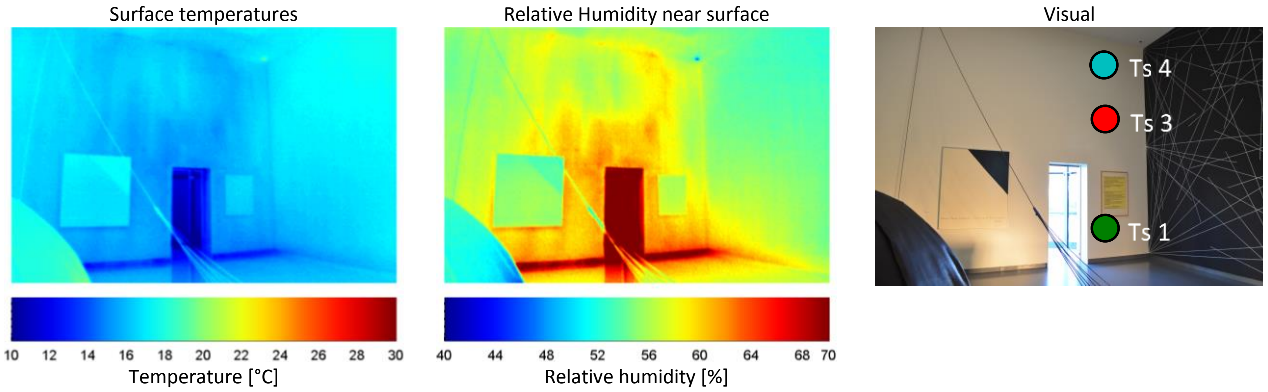

Figure 3.4: Measurement locations T_s sensors 1, 3, and 4. Locations have been determined with help of the IR thermogram of IR measurement location 22, conducted on February 17th 2016. Appendix G shows the locations of the conducted IR measurements.

Outdoor temperature T_e and relative humidity RH_e

The outdoor climate (T_e and RH_e) has been measured by 4 different sensors, see Figure 3.5: with an own Eltek sensor, 2 sensors owned by the VAM (BMS sensors), and by KNMI station Eindhoven (KNMI, 2017). The Eltek, BMS, and KNMI sensor data were in good agreement, see Appendix K for the comparison of the measured data. The KNMI data was used during this research due to data loss at the VAM location.

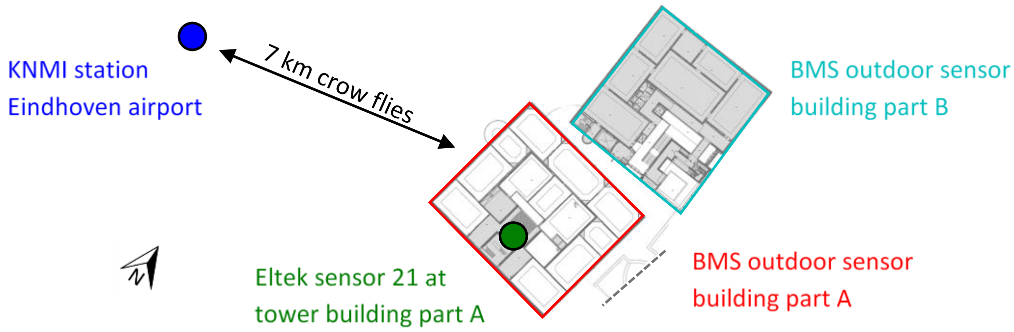

Figure 3.5: Locations of the 4 outdoor climate (T_e and RH_e) sensors. Floor plan under layer by Cahen (2003).

3.2 Numerical study

Paragraph 3.2.1 describes the multizone model with the software program 'Heat Air and Moisture model for Building and System Evaluation' (HAMBase). Paragraph 3.2.2 describes the simulations of adapted situations using different setpoint strategies modeled in HAMBase, based on the calibrated model of the current situation (reference model).

3.2.1 Current situation, model input

The current situation (reference model) was modeled in HAMBase version 2013 (Matlab) (Wit, 2006; Schijndel, 2007). In HAMBase, heat and vapour flows in a building can be simulated. The reference model has been used for assessing several setpoint strategies to improve the indoor climate and decrease the energy consumption of the VAM. In HAMBase, the building, building profiles and installations per zone have to be defined in order to simulate the indoor climate (T_i and RH_i) and the energy use per zone. Building profiles distinguish daily and weekly profiles, based on hourly shifts of the HVAC control and the amounts of visitors. Only the monumental building part A was modeled, because the indoor climate (T_i and RH_i) of the modern building part B fits better in the indoor climate requirements set by the VAM. See Table 2.1 for the requirements and Paragraph 4.1 for the results of the indoor climate measurements. In addition, it is assumed different (more dynamic) setpoint strategies in the modern building part would have a positive impact on decreasing the energy consumption and increasing the thermal comfort without significantly increasing the degradation risks of museum objects, based on the research of Kramer et al. (2016).

The monumental building part A is modeled using 16 zones, 8 zones represent the exhibition rooms and 8 zones represent the plenums. Figure 3.6 shows the zone boundaries and the corresponding Eltek sensors to which the simulation results can be compared. Appendix M shows the model input of the building, building profiles and the installations. The information for the model input is derived from the case study as described in Paragraph 2.2 and 2.4, and specific information about the HVAC system and the requirements regarding the indoor climate for the VAM have been withdrawn from the museum staff and the BMS. Appendix D shows the structure and materials of the monumental building part. Unknown values of the structures have been assumed based on personnel's knowledge. In addition, the visitors' profiles have been matched to reality as good as possible by using the number of visitors as registered at the reception desk. The visitors' profile of September 2016 has been used since this is a reference month (no vacation periods or special events), see Appendix L. The outdoor data (T_e and RH_e) used in HAMBase, has been derived from the KNMI (2017) and has been shifted with a delay of 1 hour, as explained in Appendix K.

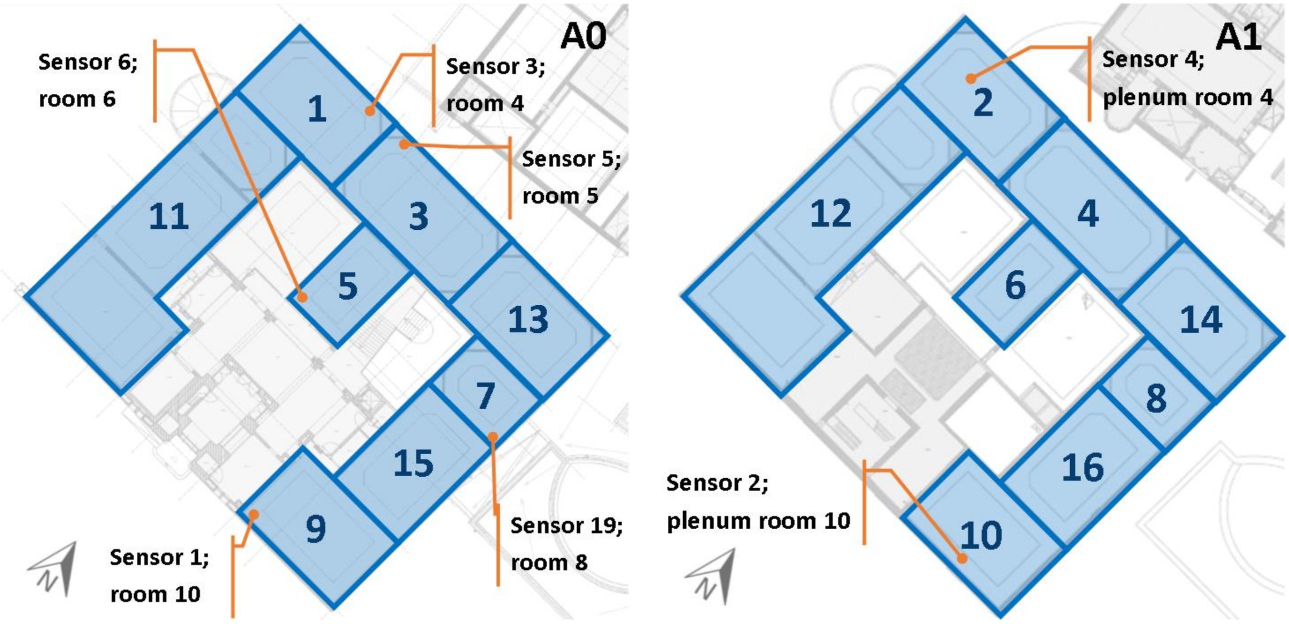

Figure 3.6: Zone numbers HAMBase model (blue) and corresponding Eltek sensor numbers (orange), monumental building part A. Floor plan under layers by Cahen (2003).

The model has been calibrated with the results of the continuous measurements, based on 8.5 months of measurement data, containing a summer to winter period. There has been focused on calibrating HAMBase zones 1 and 2, since sufficient measured data is available by Eltek sensors 3 (room 4) and 4 (plenum room 4). It is impossible to match the data of the simulation and measurements exactly because the simulation model is a simplified model of the complex reality. However, the average yearly T, RH, and humidity ratio should match and the shorter changes in time should be in accordance with the measurements (Martens, 2012). Besides comparing the T, RH, and humidity ratio, the (estimated) energy use of zone 1 and room 4 has also been compared. Appendix N provides more information about the calculation of the energy use. In addition, the results of the measurement data of Eltek sensors 3 and 4 and the simulation zones 1 and 2 have been compared using the climate risk assessment developed by Martens (2012) and the ATG for museums developed by Kramer et al. (2016), which are described in Paragraph 3.3.1 and 3.3.2.

3.2.2 **Adapted situations**

The reference model has been used to model possible future situations. This has been done by adding different setpoint strategies, with the aim to optimize the indoor climate (T and RH) and to decrease the energy conservation with respect to the museum objects, thermal comfort, and building envelope. The different setpoint strategies are based on variating the T_i and RH_i setpoints, making use of the setpoints of the reference model, CO_2 controlled ventilation, Running Mean Outdoor Temperature (RMOT), night setback (free floating (FF)), and limits of the ASHRAE classes.

For the CO_2 controlled ventilation, it is assumed that the day ventilation rate according to Table 9.18 in Appendix M is only operating when there are three or more visitors in one room, based on the visitors' profile as shown in Table 9.21 in Appendix M. When less or no visitors are present, the lower night ventilation rate is operating. For the setpoint strategies based on the RMOT, the lower and upper T limit of ATG for museums is applied, see Figure 3.7. The 90% thermal comfort acceptance class of the original ATG for museums (Kramer et al., 2016) has a bandwidth of ±1.2°C. However, a bandwidth of ±1.5°C has been implemented as well. Since the RMOT strategy is to complement the thermal comfort, some strategies are only based on the RMOT during opening hours. In these strategies, the RMOT is applied from two hours before opening until the museum is closed. During the closed hours, FF and the limits of the ASHRAE classes are applied. FF means that no setpoint is given for T and 100% recirculation is applied during the night, however, the ventilation rate due to infiltration is not diminished. The limits of the ASHRAE classes, as shown in Appendix A, have been implemented in several setpoint strategies. The T and RH limits of the same classes have been implemented, as well in combination with the CO_2 controlled ventilation, RMOT and FF setpoints.

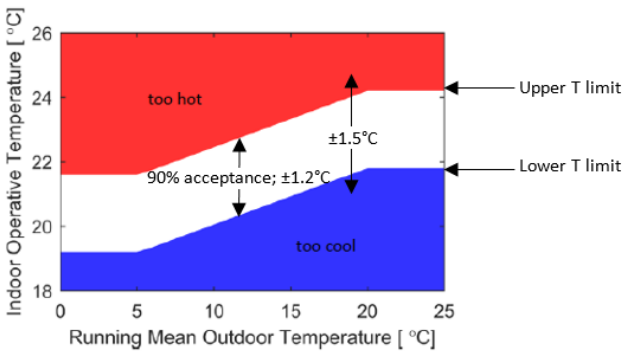

Figure 3.7: Adaptive Temperature Guideline for museums, showing the ±1.2°C bandwidth (90% acceptance class) and ±1.5°C bandwidth (Kramer et al., 2016).

The climate risk assessment method of Martens (2012) and the Adaptive Thermal Guideline for museums of Kramer et al. (2016) have been used to determine whether a measure has a positive or negative impact on the indoor climate. These analysis tools are further discussed in Paragraph 3.3.

3.3 Analysis tools

The results from the experimental and numerical study have been analyzed with the analysis methods as discussed in the following paragraphs. With these analysis methods, the impact of the indoor climate on the museum objects, thermal comfort, and building envelope has been estimated. The decrease in energy consumption has been estimated as well with the results of the HAMBase simulation model. In addition, measured data of T and RH have been used to describe the indoor climate, like averages, and short time (hourly, daily and weekly) and seasonal fluctuations. The data from the website 'Physics of Monuments', the BMS and the HAMBase simulation model, have been analyzed by importing the data in Matlab, prescribed files are available by the TU/e.

Paragraph 3.3.1 describes the climate risk assessment method of Martens (2012), including the climate evaluation chart, and general and specific climate risk assessment methods. In Paragraph 3.3.2 the Adaptive Thermal Guideline for museums of Kramer et al. (2016) is described.

3.3.1 Climate risk assessment method

The climate risk assessment method is developed within Martens' PhD study (2012) and includes the Climate Evaluation Chart (CEC), general climate risk assessment, and specific climate risk assessment methods. The climate risk assessment method has been used to analyze the indoor climate measurements (T and RH) and to determine whether a measure has a positive or negative impact on the indoor climate.

The CEC is a psychometric chart in which the T and RH data is plotted, see Figure 3.8 for an example. In the CEC only guidelines with fixed T and RH boundaries can be used, seasonal changes can only be taken into account when a separate CEC is created for each season.

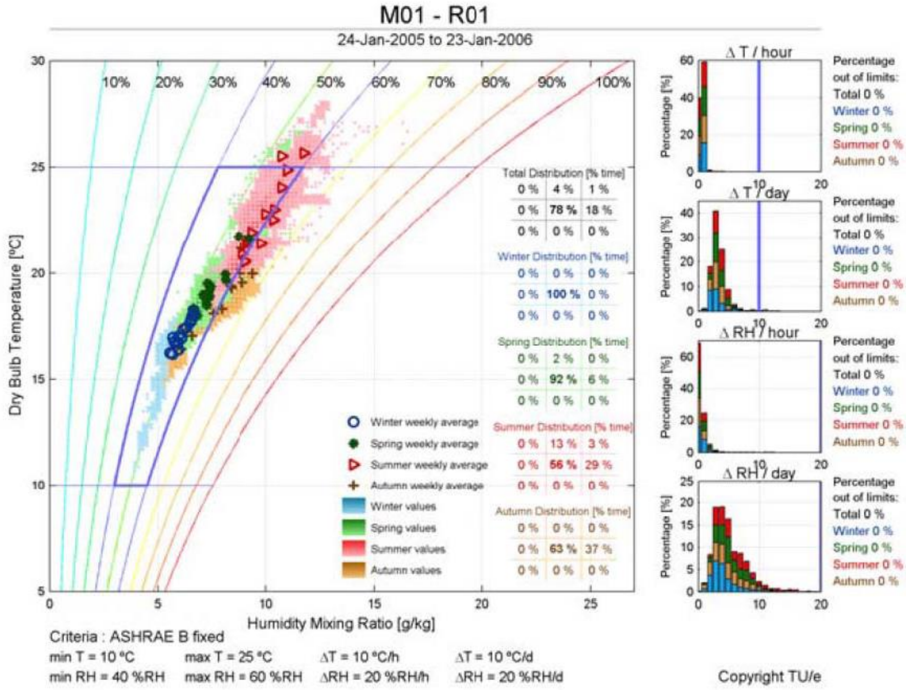

Figure 3.8: Example of a Climate Evaluation Chart (Martens, 2012).

In the general climate risk assessment, the climate data has been analyzed by determining the percentage of data that fits into each ASHRAE (2011) climate class: AA, As, A, B, C and D. See Appendix A for the climate classes and see Figure 3.9 for the tolerated short-fluctuations over a year for a few climate classes.

In the specific climate risk assessment the three degradation risks for four typical museum objects (paper, panel paintings, furniture and wooden sculptures) have been estimated. See Figure 3.9 for an example of the results of the specific climate risk assessment. The mould growth (Mould) is a risk parameter regarding the biological degradation. The Lifetime Multiplier (LM) is a risk parameter regarding the chemical degradation. The base material (Base) and pictorial layer (Pict) are risk parameters regarding the mechanical degradation. See Martens (2012) for more information about these analysis tools.

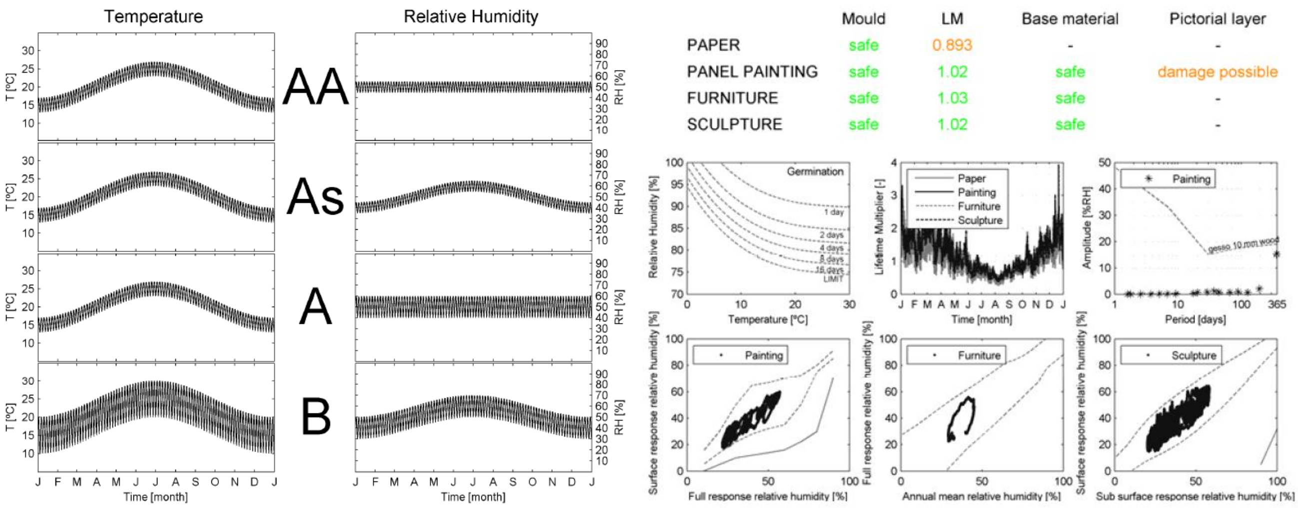

Figure 3.9: Left: tolerated short-fluctuations of temperature and relative humidity over a year according to the ASHRAE climate classes (Martens, 2012), right: example result risk overview specific risk assessment method (Martens, 2012).

Of importance is the fact that the results of the general and specific climate risk assessment methods are only 100% reliable when at least one full year of data is used (Martens, 2012). When data of less than a year is used, in this research 8.5 months, the results show an estimation. As mentioned in Paragraph 3.1.2, one year of measured data by the VAM, as derived from the BMS, has been analyzed as well to be able to draw a full conclusion.

3.3.2 **Adaptive Thermal Guideline for museums**

To assess the thermal comfort of the indoor climate (T_i), as obtained from the experimental study and extracted from the numerical study, the 'Adaptive Thermal Guideline for museums' analysis tool developed by Kramer et al. (2016) has been used, see also Paragraph 1.1.4. The tool requires some input parameters: the opening hours (for which the thermal comfort will be assessed), if the visitors have influence on the indoor climate control or not (e.g. operable windows), and the T_i and T_e. With the T_e the RMOT can be determined, see Equation 1, which has been proposed by van der Linden et al. (2006). The average T_e is the arithmetic mean of $T_{e,min}$ and $T_{e,max}$ of the given day. The bandwidth of the 90% acceptance class is ±1.2°C, see Figure 1.1 in Paragraph 1.1.4.

$$T_{e,ref} \frac{T_{e,i} + 0.8T_{e,i-1} + 0.4T_{e,i-2} + 0.2T_{e,i-3}}{2.4} \qquad \text{Equation 1}$$

With:

$T_{e,ref}$ = Reference outdoor temperature.

$T_{e,i}$ = Average outdoor temperature of the survey day.

$T_{e,i-n}$ = Average outdoor temperature of the day before the survey day, etc.

4 Research results

This chapter describes the results of the current indoor climate of the Van Abbemuseum (VAM) and the adaptive situations. Paragraph 4.1 shows the results of the current indoor climate measurements regarding temperature (T_i) and relative humidity (RH_i). Paragraph 4.2 visualizes some microclimates in the museum based on infrared thermography (IRT) and surface temperature (T_s) measurements. Paragraph 4.3 discusses the numerical study with the adapted setpoint strategies.

4.1 Current indoor climate

Paragraph 4.1.1 describes results of the instantaneous measurements. In paragraph 4.1.2 the results of the continuous measurements of the indoor climate are discussed, based on events happened during the measurement period and deviations by building physics, collection, and use. Most of the related graphs are shown in Appendix Q. Paragraph 4.1.3-4.1.6 show the results using the Climate Evaluation Chart (CEC), the general and specific climate risk assessment and the Adaptive Temperature Guideline (ATG) for museums analysis tools as explained in Paragraph 3.3.1 and 3.3.2. Before interpreting the results and analyses of the Eltek sensors in the next paragraphs, note there was some data loss. Thus, please be critical regarding the data results.

4.1.1 Instantaneous measurements

Instantaneous measurements on T_i and RH_i were conducted during the IRT measurements on February 17th 2016 and July 20th 2016. The outdoor conditions during the measurements were T_e=1.2°C and RH_e=75% on February 17th 2016, and T_e=33.6°C and RH_e=35% on July 20th 2016 (KNMI, 2017). The results of the T_i and RH_i spread over the museum are shown in color plots in Appendix O. During the measurement on February 17th 2016 the T_i and RH_i range were 18.7-20.7°C and 42.6-49.6%, on July 20th 2016 the spread was wider with respectively 19.5-26.5°C and 41.6-54.4%. On February 17th 2016, the T_i and RH_i measured in the monumental and modern building part were in the same range, while on July 20th 2016 the monumental building part clearly had a higher T_i and lower RH_i than the modern building part. The 2nd floor of the modern building part shows both during the winter and summer period slightly colder T_i than the 1st floor of the modern building part. The T_i at the 1st floor could be warmer due to heat emitting luminaires (works of art) in a few rooms. The instantaneous measurement results give a first impression of the indoor climate in the museum during two extreme outdoor climate days. However, because these measurements represent only a fraction of time and were measured by not very accurate handheld devices, no hard conclusions can be drawn.

4.1.2 Continuous measurements

Figure 4.1 shows the results for T_i and RH_i of two of the continuous measurement locations. Eltek sensor 5 is located in room 5 of the monumental building part, Eltek sensor 10 is located in a room at the 2nd floor of the modern building part, see Appendix H. Both rooms have a façade facing north (no solar radiation on the façade) and are directly underneath a plenum. The dashed boxes represent a typical summer and winter week, which close ups can been seen in Figure 4.3 and Figure 4.4. The numbers in Figure 4.1 represent some events during the measurement period. Events 1, 4, 6, 8, and 9 have caused outliers in the indoor climate of the VAM (T and RH) due to power failures and malfunctioning of the Heating, Ventilation, and Air Conditioning (HVAC) systems. During the power failure on November 14th 2016 (event 4), the Building Management System (BMS) showed unrealistic values for T and RH of the monumental building part A. The values have been corrected by using the measured values of the Eltek sensors. Appendix I shows how the data of the BMS has been corrected. The outliers are further explained in Appendix J. Events 2 and 3 were large events, namely Dutch Design Week (DDW, 22nd till 31st October 2016) and GLOW (12th till 20th November 2016), with extreme increased amounts of visitors compared to the reference amount of visitors during the year. At events 5 and 7, repeaters were placed in the VAM in order to reduce the data loss.

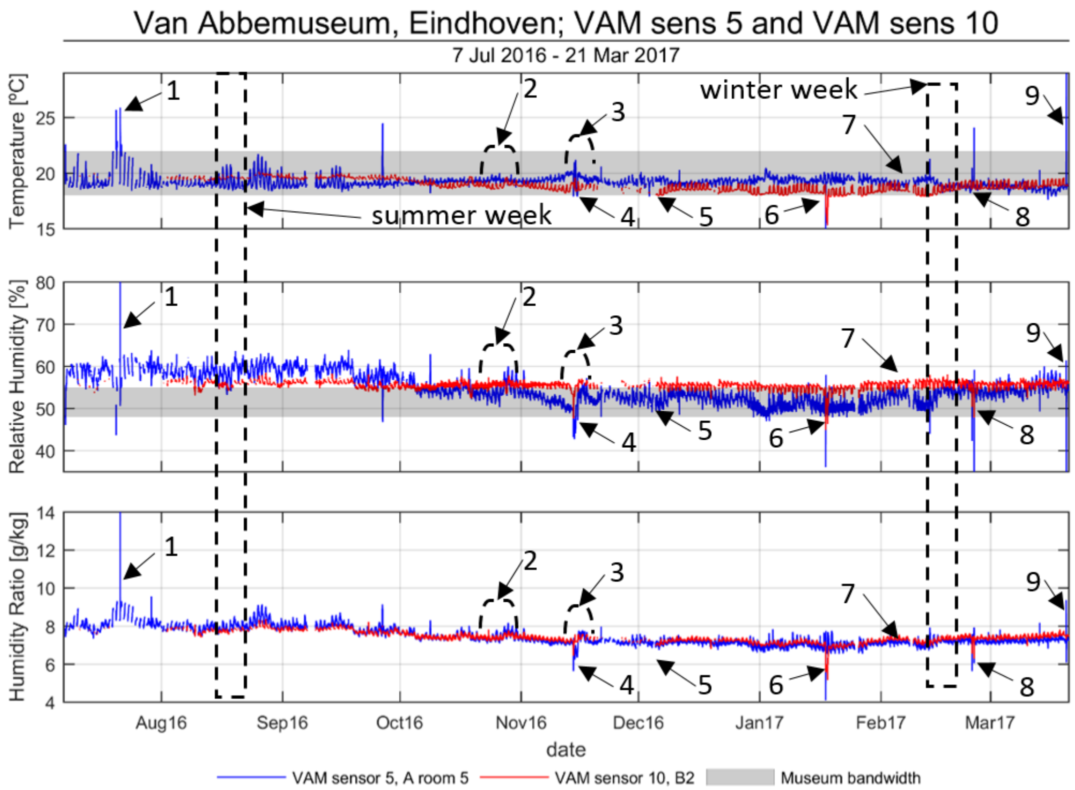

Figure 4.1: Measured T_i and RH_i for the measurement positions Eltek sensor 5 (monumental building part room 5) and Eltek sensor 10 (modern building part B2). Events during the measurement period: 1: open valves, 2: Dutch Design Week, 3: GLOW, 4: power failure, 5: placement 1st repeater, 6: fire alarm, 7: placement 2nd repeater, 8: fire alarm, 9: AHU test.

The results of the continuous measurements are discussed in the paragraphs below based on deviations of T_i and RH_i by building physics, collection, and use. The deviations by building physics are schematically shown in Figure 4.2. Deviations by the collection include works of art consisting out of heat emitting luminaires and deviations by use include the effect of large events.

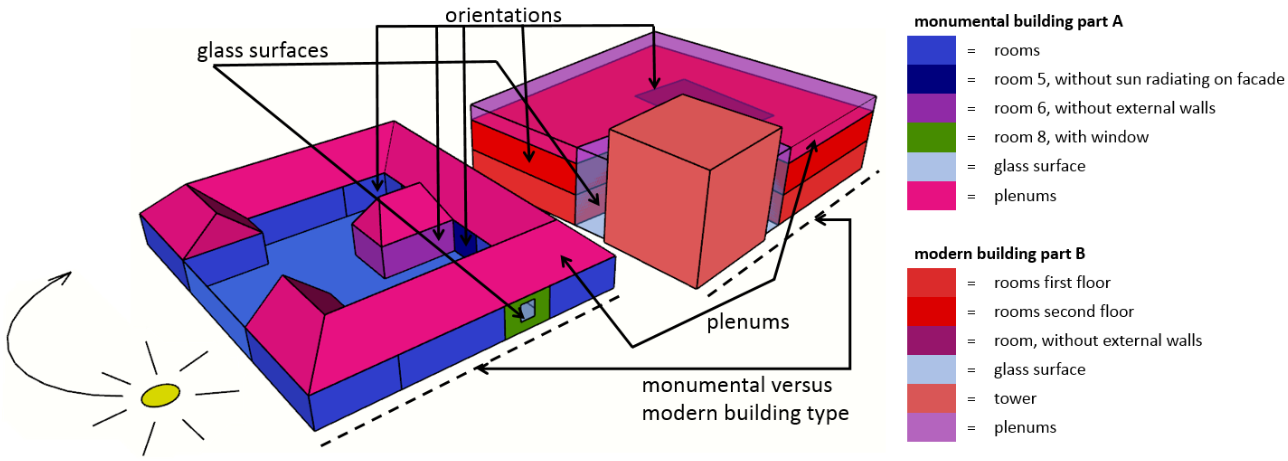

Figure 4.2: Schematic view of compared measurement data: deviations by building physics.

Building physics: monumental versus modern building type

Comparison of the exhibition rooms in the monumental building part and the exhibition rooms on the 2nd floor of the modern building part, shows that the outdoor climate has a larger impact on the indoor climate of the monumental building part, see Figure 4.1, Figure 9.70 and Figure 9.71, due to the low thermal resistance of the monumental building envelope. The measured data of the modern building part is much more stable. Moreover, in Figure 9.70 can also been seen that during the summer the T_i and RH_i in the monumental building part are more often outside the museum requirements than those of the modern building part. Figure 4.3 and Figure 9.72 show the close ups of a typical summer week. As can been seen in the figures, the outdoor climate has a larger impact on the data measured in the monumental building part and despite of some data loss during the summer in the modern building part, there still can be seen that the data measured in the modern building part is much more stable. Figure 4.4 shows the close up of a typical winter week. As can been seen in the figure, the T_i and RH_i in both the building parts are quite stable: the daily fluctuations are less extreme compared to those during the summer.

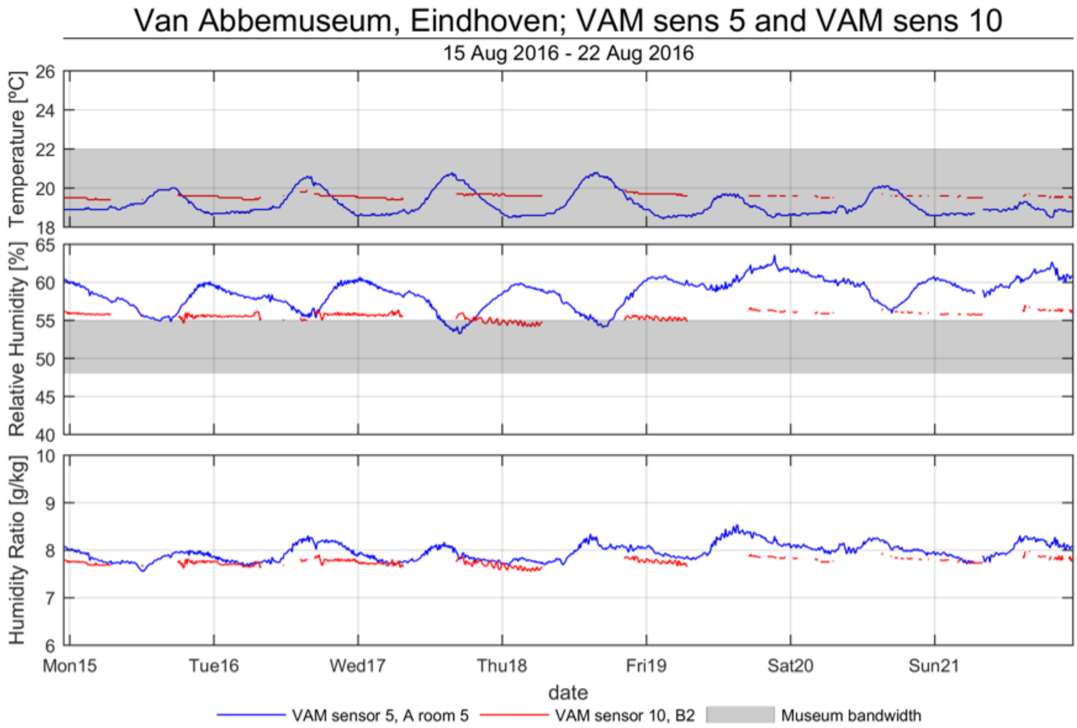

Figure 4.3: Measured T and RH for the measurement positions Eltek sensor 5 (monumental building part room 5) and Eltek sensor 10 (modern building part B2) during a typical summer week (August 15th 2016 till August 22nd 2016).

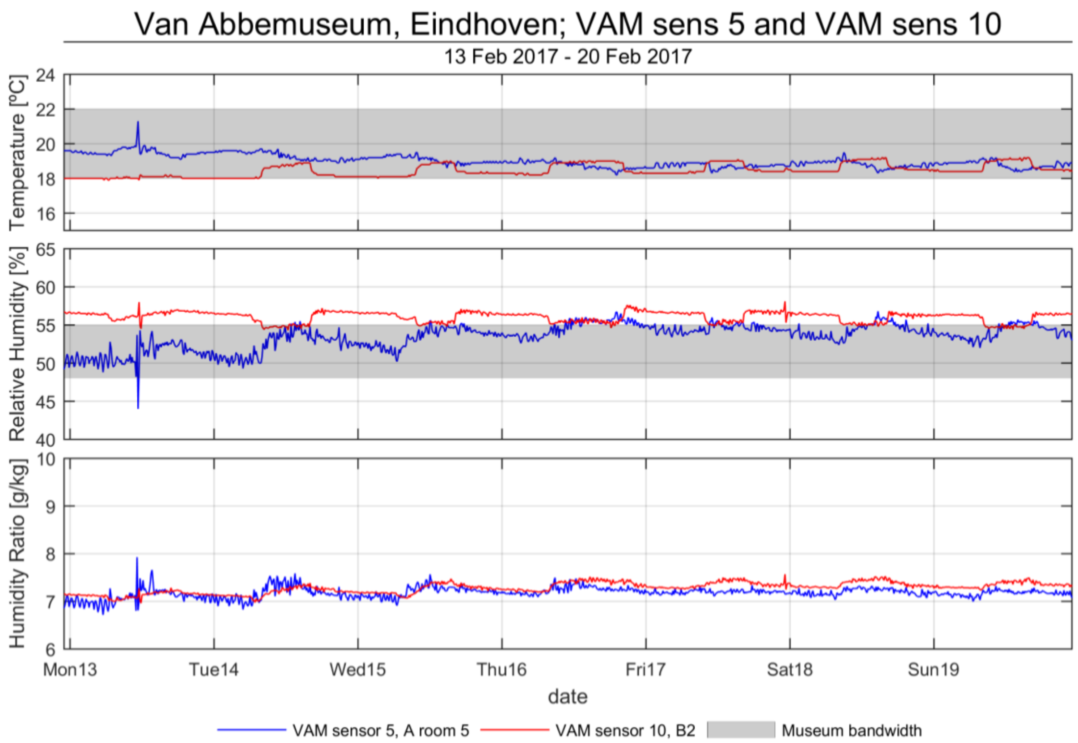

Figure 4.4: Measured T and RH for the measurement positions Eltek sensor 5 (monumental building part room 5) and Eltek sensor 10 (modern building part B2) during a typical winter week (February 13th 2017 till February 20th 2017).

Building physics: plenums

Figure 9.73 shows the outdoor climate data and the measured data of a room and plenum in the monumental building part and Figure 9.76 shows those of a room and plenum in the modern building part. As can been seen in the figures, the outdoor climate has a much larger impact on the T, RH, and humidity ratio in the monumental plenum than on those in the modern building part. Figure 9.74 shows an increased T and decreased RH in the summer. This causes an increased T_i in the rooms. Figure 9.75 shows that during the winter the outdoor climate still has an impact on the T and RH in the plenums. However, the values in the plenum are closer to the values in the room underneath than during the summer. The T in the plenums of the monumental building part fluctuates between the 8.4°C and 50.7°C, see Table 4.1. Figure 9.77 and Figure 9.78 show that the T and RH in the plenum in the modern building part are both during the summer and winter close to the indoor climate of the room underneath. Table 4.1 shows that the T in the plenums of the modern building part fluctuates between 13.4°C and 24.1°C, which is a smaller range than in the plenums of the monumental building part.

Table 4.1: Overview of T and RH for the measurement positions of the Eltek sensors (July 7th 2016 till March 21st 2017).

Sensor T/RH		Temperature [°C]						Relative humidity [%]					
		mean	drop	rise	min	max	range	mean	drop	rise	min	max	range
3	A0, room 4	18.7	0.9	1.4	16.7	23.6	6.9	55.9	0.5	0.5	49.2	59.8	10.6
4	A1, room 4, plenum	19.8	5.6	9.7	9.5	50.7	41.2	54.7	17.0	11.0	15.7	76.4	60.7
5	A0, room 5	19.2	0.3	0.1	18.0	22.9	4.9	54.8	3.0	4.3	44.2	62.6	18.4
6	A0, room 6	20.8	0.4	0.6	19.4	24.2	4.8	50.3	1.8	2.7	43.1	56.6	13.5
19	Ao, room 8	20.4	1.7	3.0	16.6	27.6	11.0	49.5	4.0	2.0	40.3	57.3	17.0
1	A0, room 10	19.7	1.3	1.7	16.4	24.7	8.3	54.1	1.7	1.5	45.4	59.1	13.7
2	A1, room 10, plenum	17.6	5.3	16.0	8.4	48.7	40.3	58.2	26.0	12.0	17.6	75.9	58.3
17	B-1, tower bottom	20.0	0.6	0.6	18.0	21.2	3.2	52.2	0.8	1.5	46.4	56.3	9.9
7A	B0	20.0	0.7	0.7	17.0	21.7	4.7	51.9	0.8	1.2	36.7	54.8	18.1
20	B0	20.3	0.6	2.0	16.6	23.3	6.7	49.7	1.9	0.7	34.8	54.0	19.2
8	B0, Picasso	20.2	0.2	0.2	18.8	21.2	2.4	50.6	1.5	2.2	40.6	58.5	17.9
15	B0, stairs bottom	19.7	0.8	1.0	17.2	21.3	4.1	52.7	0.2	0.2	47.4	54.5	7.1
16	B2, stairs top	20.2	1.0	1.4	17.3	23.3	6.0	52.1	1.1	0.7	46.5	54.0	7.5
9	B2	20.6	0.3	0.5	18.5	21.6	3.1	50.2	0.9	2.2	43.2	54.0	10.8
10	B2	18.9	0.4	0.8	15.9	20.0	4.1	55.5	0.3	0.5	50.6	57.8	7.2
11	B2	18.5	0.5	1.4	14.6	20.6	6.0	54.1	0.3	0.4	47.5	56.3	8.8
12	B3, plenum above 11	18.3	0.4	2.2	13.4	21.6	8.2	55.7	1.9	0.4	50.8	58.9	8.1
13	B2	19.8	0.6	0.8	16.4	21.9	5.5	53.5	0.4	0.8	48.7	58.3	9.6
14	B3, plenum above 13	18.9	1.2	1.7	14.0	24.1	10.1	55.6	2.3	1.4	45.9	61.0	15.1
18	B3, tower top	20.5	0.1	0.1	18.0	21.5	3.5	49.3	2.0	3.2	43.5	54.8	11.3

Table 4.2: Overview of T and RH for the measurement positions of the BMS sensors (March 21st 2016 till March 21st 2017).

Sensor T/RH	Temperature [°C]						Relative humidity [%]					
	mean	drop	rise	min	max	range	mean	drop	rise	min	max	range
A inlet	18.2	3.2	3.7	13.5	27.8	14.3	58.4	14.0	15.0	36.0	82.3	46.3
A0, room 1 / 2	20.9	1.2	0.9	18.4	26.0	7.6	50.9	0.7	1.0	45.6	54.4	8.8
A0, room 5 / 6	22.2	1.4	1.5	19.6	27.3	7.7	48.6	0.9	1.1	43.1	54.6	11.5
A0, room 9 / 10	20.6	0.7	0.6	18.3	25.2	6.9	50.5	1.4	1.6	46.1	54.4	8.3
B inlet AHU	22.2	1.0	0.8	19.5	43.2	23.7	45.3	1.6	0.9	13.1	48.8	35.7
B inlet rooms	20.4	0.8	1.0	18.1	24.8	6.7	48.3	5.3	5.0	36.2	60.4	24.2
B inlet tower	21.7	2.7	2.6	17.3	26.5	9.2	47.1	10.0	11.0	25.8	67.7	41.9
B outlet tower	20.7	1.6	1.7	17.6	25.2	7.6	48.9	1.8	2.0	41.0	52.9	11.9
B-1, sens 6	21.0	0.6	0.6	19.0	22.9	3.9	51.4	0.9	1.0	47.7	54.7	7.0
B0, sens 5	22.1	0.7	0.5	19.1	24.0	4.9	50.4	1.0	1.2	35.9	53.8	17.9
B1, sens 3	22.8	0.2	0.2	22.2	25.0	2.8	49.6	2.3	2.6	42.2	55.0	12.8
B1, sens 4	20.6	0.8	0.6	19.0	22.5	3.5	49.3	0.9	0.6	44.6	51.8	7.2
B2, sens 1	20.4	0.8	0.5	17.9	22.9	5.0	53.8	1.1	0.9	49.9	57.7	7.8
B2, sens 2	21.0	0.3	0.3	18.0	23.4	5.4	51.9	1.3	1.7	47.9	56.6	8.7

Building physics: orientation rooms and glass surfaces

Figure 9.79 shows the measured indoor climate of the exhibition rooms in the monumental building part. Table 4.1 and Table 4.2 show that T_{avg} in exhibition rooms of the monumental building part differs between 18.7-22.2°C and the RH_{avg} differs between 48.6-55.9%. Figure 9.79 and Table 4.1 show that the mean T_i is the highest in room 6 (Eltek sensor 6), and mean RH_i is one of the lowest for this room. Room 6 is the only room without external walls. The data measured by the three BMS sensors in the monumental building also show this, the highest mean T_i and lowest mean RH_i are reached at the BMS sensor between room 5 and 6, see Table 4.2 and Figure 9.81. Only the indoor climate of room 8 (Eltek sensor 19), which is the only room with a window in which is measured, shows a higher T_i and lower RH_i than those of room 6 during the summer period. Table 4.1 shows that in room 8 the highest T_i is measured of respectively 27.6°C, which was on a hot day (T_e was 36°C). Room 8 shows the widest T_i range with respectively 11°C. Due to the window, the thermal resistance of this room is lower than those of the other rooms in the monumental building part. Figure 9.79 and Figure 9.80 show that during the summer (high solar radiation) the T_i is lower in the room without solar radiation on the façade (room 5, Eltek sensor 5), than in the rooms with solar radiation on the façade (rooms 4, 8, and 10, Eltek sensors 3, 19, and 1).

Table 4.1 and Table 4.2 show that T_{avg} in the rooms of the modern building part differs between 18.5-22.8°C and the RH_{avg} differs between 48.9-55.5%. In addition to room 6 of the monumental building part, Figure 9.82 and Table 4.1 show that the room without external walls (Eltek sensor 9) on the 2nd floor of the modern building part also has the highest mean T_i and lowest mean RH_i compared to the other rooms in which are measured on the 2nd floor. Moreover, Figure 9.82 and Figure 9.83 show that during the summer the T_i in the room without solar radiation on the façade (Eltek sensor 10) is lower than in the rooms with solar radiation on the façade (Eltek sensors 11 and 13).

Figure 9.84-Figure 9.86 show the T_i and RH_i measured in the large corridor in the modern building part, which is surrounded by large glass surfaces with solar radiation on them. The T_i measured at the bottom of the corridor (Eltek sensor 15) is the whole year lower than at the top (Eltek sensor 16). During the summer the RH_i is slightly higher at the bottom than at the top, during the autumn and winter the RH_i of both locations are similar. In addition, the T_i and RH_i measured at the higher located sensor show extremer daily fluctuations. This is possible due to the location of Eltek sensor 16; the sensor is located closer to the large glass surfaces. Eltek sensor 15 is located further away from the glass surfaces.

Collection: works of art consisting out of heat emitting luminaires

During the measurement period, a few works of art consisting of luminaires have been present in the exhibition rooms of the VAM, see Figure 2.3 for an impression. These works of art emit heat, and as a result the T_i and RH_i of the surrounding air are fluctuating a lot when the luminaires are turned on/off. Figure 9.87 and Figure 9.88 show the impact of the luminaires on the indoor climate during opening hours. As can been seen, the daily fluctuations are much smaller on Mondays, when the museum is closed for visitors. The works of art near Eltek sensor 7A (halogen lamps, emitted approximately 1250W of heat) and Eltek sensor 20 (tubular fluorescent lamps, emitted approximately 650W of heat) have been present during the whole measurement period, the work of art near Eltek sensor 13 (extreme amount of incandescent lamps) has been present from September 2016 to February 2017. The tubular fluorescent lamps near Eltek sensor 20 have the highest impact on the indoor climate: when the luminaires are turned on, the T_i increases with 1.5°C and the RH_i decreases by 8%.

Use: large events

Figure 9.89 shows the measured T_i and RH_i of three rooms and the air inlet in the monumental building part from July 7th 2016 till March 21st 2017. Figure 9.90 shows the close up of the period around DDW. In the figure can been seen that during DDW the daily T_i fluctuations in the rooms are similar to the T_i fluctuations during the surrounding days. However, the inlet T is lower in the weekends of DDW compared to the other days. This could be due to the heat gains by visitors. Moreover, Figure 9.91 shows that during these weekends the T_e was warmer and therefore colder air could be blown in the rooms. As can been seen in Figure 9.90, the RH_i in the rooms was approximately 4% higher during the opening hours of the 2nd weekend of DDW, in addition to the increased RH of the inlet air. Figure 9.91 shows that during this weekend, the RH_e was lower. The increased

RH_i in the rooms could be the result of the moisture gains by visitors or the inlet air with an increased RH. The humidity ratio increased as well during the 2nd weekend, in addition to the outdoor humidity ratio.

Figure 9.92 and Figure 9.93 show the close ups of the period around GLOW. As shown in Figure 4.1 and discussed in Appendix J, malfunctioning of the HVAC system occurred during November 14th and 15th 2016, due to a power failure. The measured T_i in the rooms of the monumental building part was similar to the T_i during the surrounding days, with exception of the period around the power failure. The RH_i and the humidity ratio however show an increase from November 15th 2016. The moisture could come from visitors entering the museum with their wet coats on, due to a lot of rain during these days (KNMI, 2017), and because of a continuous open entrance door, which is usually closed.

Figure 9.94 shows the total energy use (electricity and gas) for the VAM. As can been seen in the figure, the electricity use during these large events was similar to the surrounding period. The gas use is in line with the T_e, see also Figure 9.47; the colder the T_e, the larger the gas use.

4.1.3 Climate Evaluation Chart

Table 4.3 and Table 4.4 show per measurement location the percentage of time the museum requirements are met for the total measurement period, according to the Climate Evaluation Chart (CEC), as explained in Paragraph 3.3.1. The museum requirements can be found in Table 2.1 in Paragraph 2.4. When some measured data fall out of the criteria, there is often no reason for concern. However, when weekly averages are not within the criteria, further research to the cause is recommended (Martens, 2012). In Appendix R the results are also shown, divided per season.

Table 4.3: Overview CEC results using the museum requirements for the measurement positions of the Eltek sensors, total period (July 7th 2016 till March 21st 2017).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	$\Delta T_{/h}$	$\Delta T_{/d}$	$\Delta RH_{/h}$	$\Delta RH_{/d}$
3 A0, room 4	18	1	0	56	24	1	0	0	0	1	10	28	62
5 A0, room 5	60	0	0	39	0	0	0	0	0	1	11	69	98
6 A0, room 6	84	5	0	0	0	0	0	11	0	1	12	25	85
19 Ao, room 8	69	0	0	0	0	1	0	4	25	3	23	40	78
1 A0, room 10	63	5	0	30	1	1	0	0	1	2	15	53	68
17 B-1, tower bottom	99	0	0	1	0	0	0	0	0	1	0	9	36
7A B0	100	0	0	0	0	0	0	0	0	2	1	14	75
20 B0	62	3	0	0	0	0	0	18	17	12	70	21	75
8 B0, Picasso	96	0	0	0	0	0	0	4	0	1	0	9	20
15 B0, stairs bottom	99	0	0	0	0	1	0	0	0	1	0	12	56
16 B2, stairs top	93	6	0	0	0	0	0	0	0	1	9	12	68
9 B2	99	0	0	0	0	0	0	1	0	0	0	5	11
10 B2	23	0	0	76	0	1	0	0	0	1	1	33	43
11 B2	77	0	0	8	0	15	0	0	0	0	1	31	25
13 B2	97	0	0	3	0	0	0	0	0	2	1	15	54
18 B3, tower top	66	0	0	0	0	0	0	33	0	1	1	40	79

Table 4.4: Overview CEC results using the museum requirements for the measurement positions of the BMS sensors, total period (March 21st 2016 till March 21st 2017).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	$\Delta T_{/h}$	$\Delta T_{/d}$	$\Delta RH_{/h}$	$\Delta RH_{/d}$
A0, room 1 / 2	87	12	0	0	0	0	0	0	1	1	12	18	60
A0, room 5 / 6	52	26	0	0	0	0	0	1	22	1	19	10	42
A0, room 9 / 10	93	5	0	0	0	0	0	1	0	1	13	16	45
B outlet tower	67	2	0	0	0	1	0	14	17	0	3	9	66
B-1, sens 6	98	2	0	0	0	0	0	0	0	0	2	5	15
B0, sens 5	47	48	0	0	0	0	0	1	5	5	2	13	82
B1, sens 3	0	76	0	0	0	0	0	0	24	0	0	13	31
B1, sens 4	92	1	0	0	0	0	0	7	0	1	0	9	28
B2, sens 1	91	0	0	9	0	0	0	0	0	0	0	25	31
B2, sens 2	99	1	0	1	0	0	0	0	0	0	1	13	16

Table 4.3 shows that at room 4, 5 and 10 in the monumental building part A it is 30 to 56% of the time too humid. In room 4, the RH_i is too high during the whole year, in room 5 during the summer, and in room 10 during the winter. At room 4 it is 24% of the time too humid and too cold, this is during the winter. At room 6 it is 11% of the time too dry (mainly during the winter) and at room 8 it is 25% of the time too dry and too hot (during the summer). The indoor climate of room 6 fits the best in the museum requirements, room 4 the least. The original CEC outputs of room 4 and 6 are shown in Figure 9.95 and Figure 9.96 in Appendix S. Table 4.4 shows that the indoor climate data measured by the BMS sensors in the monumental building part are 5 to 26% of the time too hot and/or a too dry. All the measured data of the measurement locations in the monumental building part show too large fluctuations of T and to a larger extent of RH. The tables in Appendix R show that during the spring and summer period the indoor climate in the monumental building part is often too hot and/or too humid/dry. During the autumn and winter period the indoor climate in the monumental building part is often too hot and/or too dry.

The CEC results of the modern building part have shown better results than those of the monumental building part. The indoor climate museum requirements are more percentage of the time met. However, Eltek sensors 20, 10, 11 and 18, and BMS sensors 3 and 5 meet the museum requirements 0% to 77% of the time. This is mainly due to a too humid and too dry and/or hot climate. However, the museum requirements are just a bit exceeded. In addition to the results of the monumental building part, the measured data of the modern building part also show too large fluctuations of T and to a larger extent of RH.

The tables in Appendix R show that during all seasons the indoor climate measured at Eltek sensor 20 is too dry and/or hot (22 to 56% of the time), see also the CEC output in Figure 9.99 in Appendix S. This is caused by the tubular and halogen lamps as shown in Figure 2.3 in Paragraph 2.5, which are turned on during opening hours. The measured RH at Eltek sensor 10 is during all seasons too humid (70 to 91% of the time), see also the CEC output in Figure 9.98 in Appendix S. At Eltek sensor 16 it is 21% of the time too hot during the summer. The data measured at Eltek sensor 11 shows that it is 16% too humid during autumn and 23% too cold during winter. Eltek sensor 18 shows a too dry indoor climate during autumn and winter (34 to 51% of the time). During all seasons, it is too dry and/or too hot at BMS sensor 3 (91 to 100% of the time), and too hot at BMS sensor 5 (17 to 92% of the time). BMS sensor 5 is located near Eltek sensor 20. At BMS sensor 1 it is 26% of the time too humid in the summer, and at BMS sensor 4 it is 25% of the time too dry during spring. Only the T and RH data measured at Eltek sensor 7A fits for 100% of the time into the museum requirements, see also the CEC output in Figure 9.97 in Appendix S.

4.1.4 General climate risk assessment

Table 4.5 and Table 4.6 show the result overviews of the general climate risk assessment, as explained in Paragraph 3.3.1. In contrast to the CEC analysis tool, the general climate risk assessment method does take seasonal changes into account. Please note that the results of the Eltek sensors of Table 4.5 are an estimation, due to the shorter measurement period. Table 4.6 does show reliable results since one full year of data measured by the BMS has been analyzed. Appendix A shows the features and risks of the ASHRAE classes. The risks are only valid when a class is met 100% of the time, since outliers determine whether damage occurs or not (Martens, 2012). Figure 9.100 in Appendix T shows in floorplans which ASHRAE class has been met 100% of the time at the Eltek measurement locations, according to the results in Table 4.5. Appendix H shows the exact locations of the sensors.

Table 4.5: Overview general climate risk assessment results for the measurement positions of the Eltek sensors (July 7th 2016 till March 21st 2017).

Sensor T/RH	ASHRAE climate classes					
	AA	As	A	B	C	D
3 A0, room 4	98.6	98.7	98.8	100	100	100
5 A0, room 5	85.6	99.0	99.3	100	100	100
6 A0, room 6	97.5	99.2	99.4	100	100	100
19 Ao, room 8	91.0	95.9	96.2	100	100	100
1 A0, room 10	96.8	97.5	97.8	100	100	100
17 B-1, tower bottom	100	100	100	100	100	100
7A B0	99.9	99.9	99.9	99.9	100	100
20 B0	90.2	89.8	90.5	99.8	100	100
8 B0, Picasso	99.7	99.8	100	100	100	100
15 B0, stairs bottom	100	100	100	100	100	100
16 B2, stairs top	100	99.9	100	100	100	100
9 B2	99.8	99.8	100	100	100	100
10 B2	99.9	99.9	100	100	100	100
11 B2	99.8	99.8	99.8	100	100	100
13 B2	99.9	99.9	99.9	100	100	100
18 B3, tower top	99.3	99.9	99.9	100	100	100

Table 4.6: Overview general climate risk assessment results for the measurement positions of the BMS sensors (March 21st 2016 till March 21st 2017).

Sensor T/RH	ASHRAE climate classes					
	AA	As	A	B	C	D
A0, room 1 / 2	98.1	98.1	98.1	100	100	100
A0, room 5 / 6	96.6	96.7	96.8	100	100	100
A0, room 9 / 10	98.8	98.8	98.8	100	100	100
B outlet tower	97.6	98.2	98.5	100	100	100
B-1, sens 6	100	100	100	100	100	100
B0, sens 5	99.9	100	100	100	100	100
B1, sens 3	99.8	99.9	99.9	100	100	100
B1, sens 4	100	100	100	100	100	100
B2, sens 1	100	100	100	100	100	100
B2, sens 2	99.9	99.9	99.9	100	100	100

As can be seen in Table 4.5 and Table 4.6, the data measured at the locations in the monumental building part A do fit 100% of the time in ASHRAE class B, which is a reasonable class for historic buildings (ASHRAE, 2011). The risks to objects within class B are described in Appendix A. The lowest values reached are 85.6% and 91.0% for ASHRAE class AA at Eltek sensor 5 (room 5) and 19 (room 8). Thus, most of the time the current indoor climate (T and RH) meets ASHRAE class AA. Appendix T shows the original general climate risk assessment output of the measured data by Eltek sensors 5 and 19. The fact that the measured data of Eltek sensor 5 only meets ASHRAE class AA 85.6% of the time, is mostly caused due to the RH, which is too high during the summer period and too low RH during the winter period. The measured data of Eltek sensor 19 only meets ASHRAE class AA 91.0% of the time, because of the too high T and too low RH during the summer period. In addition, all the indoor climates measured in the monumental building part have some outliers due to situations in which malfunctioning of the HVAC systems occurred, see also Appendix J.

Table 4.5 and Table 4.6 show that in the modern building part B the results differ per location. The ASHRAE classes met 100% of the time differ per location from class AA to C. Expected would be that the modern building part B of the VAM would reach ASHRAE classes between AA and A, and although this is not the case according to the results of this research, class AA has been met for at least 99.3% of the time. The reason for the lower ASHRAE classes is the same as the events appeared in the monumental building part; the fire alarms on January 17th 2017 and February 24th 2017, see also Appendix J. Appendix T shows the original general climate risk assessment output of the measured data by Eltek sensors 8 and 13 for an impression. In contrast to the other measurement locations in the modern building part, Eltek sensor 20 fits less percentage of time in ASHRAE class AA to A. Eltek sensor 20 is located at the 1st floor near the work of art consisting tubular fluorescent lamps, see Figure 2.3 in Paragraph 2.5. When the luminaires are turned on they emit much heat, approximately 650W, resulting in extreme daily fluctuations of T and RH. The original general climate risk assessment output of the measured data by Eltek sensor 20 is also shown in Appendix T.

Except for the measurement location of Eltek sensor 20, ASHRAE class AA would be met in the modern building part if the fire alarms would not be turned on during the measurement period. The measurements have shown that malfunctioning of the HVAC systems drastically influences the indoor climate (T and RH) of the museum by creating outliers. This immediately increases the risks for the museum objects (lower ASHRAE class met 100% of the time).

4.1.5 **Specific climate risk assessment**

Table 4.7 and Table 4.8 show the result overviews of the specific climate risk assessment, as explained in Paragraph 3.3.1. Please note that the results of the Eltek sensors of Table 4.7 are an estimation, due to the shorter measurement period. Table 4.8 does show reliable results since one full year of data measured by the BMS has been analyzed. Appendix H shows the exact locations of the sensors.

Table 4.7: Overview specific climate risk assessment results for the measurement positions of the Eltek sensors (July 7th 2016 till March 21st 2017).

Sensor T/RH	Paper		Panel painting				Furniture			Wooden sculpture		
	Mould	LM	Mould	LM	Base	Pict	Mould	LM	Base	Mould	LM	Base
3 A0, room 4		1.030		0.979				0.979			0.980	
5 A0, room 5		0.985		0.954				0.949			0.955	
6 A0, room 6		0.885		0.915				0.912			0.916	
19 Ao, room 8		0.945		0.974				0.980			0.974	
1 A0, room 10		0.931		0.926				0.929			0.927	
17 B-1, tower bottom		0.940		0.942				0.940			0.942	
7A B0		0.955		0.955				0.953			0.956	
20 B0		0.890		0.925				0.925			0.928	
8 B0, Picasso		0.952		0.961				0.958			0.961	
15 B0, stairs bottom		0.964		0.956				0.955			0.956	
16 B2, stairs top		0.916		0.927				0.929			0.928	
9 B2		0.896		0.923				0.920			0.923	
10 B2		1.000		0.962				0.962			0.962	
11 B2		1.070		1.020				1.020			1.020	
13 B2		0.945		0.937				0.936			0.938	
18 B3, tower top		0.945		0.966				0.961			0.966	

Table 4.8: Overview specific climate risk assessment results for the measurement positions of the BMS sensors (March 21st 2016 till March 21st 2017).

Sensor T/RH	Paper		Panel painting				Furniture			Wooden sculpture		
	Mould	LM	Mould	LM	Base	Pict	Mould	LM	Base	Mould	LM	Base
A0, room 1 / 2		0.849		0.888				0.888			0.888	
A0, room 5 / 6		0.755		0.833				0.833			0.834	
A0, room 9 / 10		0.899		0.926				0.926			0.926	
B outlet tower		0.925		0.959				0.959			0.959	
B-1, sens 6		0.832		0.870				0.870			0.870	
B0, sens 5		0.733		0.802				0.802			0.803	
B1, sens 3		0.686		0.771				0.771			0.771	
B1, sens 4		0.931		0.958				0.958			0.958	
B2, sens 1		0.857		0.873				0.873			0.873	
B2, sens 2		0.830		0.865				0.865			0.865	

All measurement locations show that the risks of mould growth (Mould), and possible damage of the base material (Base) and pictorial layer (Pict) are on the safe side. However, the Lifetime Multiplier (LM) is almost always <1 for all object types. This means that the objects have an increased risk regarding chemical degradation. Risks are caused by T_{avg} and RH_{avg} higher than the conditions of 20°C and 50%. The LM is in particular important for paper objects, other object are often provided with a protective layer such as varnish or paint. The protective layer can be removed and reapplied every few decades to extend the lifetime (Martens, 2012).

Eltek sensors 3 (monumental building part room 4) and 11 (modern building part 2nd floor), show the highest average LM values. BMS sensors 3 (modern building part between the 1st and 2nd floor) and 5 (modern building part 1st floor), show the lowest average LM values. Appendix U shows the original specific climate risk assessment output of the measured data by Eltek sensors 3 and 11 and BMS sensors 3 and 5. In addition the CECs with the T and RH boundaries of ASHRAE class AA are shown for an impression of the measured T and RH at those locations. Eltek sensors 3 and 11 show weekly averages of T and RH of approximately 20°C and 55%. BMS sensors 3 and 5 show weekly averages of T and RH of approximately 23°C and 50%.

4.1.6 Thermal comfort

The thermal comfort of the exhibition locations in the VAM have been assessed with the Adaptive Thermal Guideline (ATG) for museums tool from Kramer et. al (2016), as explained in Paragraphs 1.1.4 and 3.3.2. The opening hours have been set from 11AM to 5PM every day of the week. In the VAM the visitors have no influence on the indoor climate. The T_e data has been withdrawn from the KNMI (2017), and the T_i data has been taken from the measured data by the Eltek and BMS sensors.

Table 4.9 shows the result overview of the data measured by the Eltek sensors, and Table 4.10 shows the results of the data measured by the BMS sensors. The separate ATG for museums results are shown in Appendix V, and the exact locations of the sensors can be found in Appendix H. Because of data loss (in the period before the repeaters were placed), the total amount of assessed hours differs per room. In order to compare the different measurement locations, the discomfort hours are expressed in percentages.

Table 4.9: Overview ATG for museums results for the measurement positions of the Eltek sensors (July 7th 2016 till March 21st 2017).

Sensor T/RH	Overheating [% too hot]	Underheating [% too cold]	Total discomfort [%]	Total hours
3 A0, room 4	0.0	98.5	98.5	1516
5 A0, room 5	0.3	76.1	76.4	1476
6 A0, room 6	0.3	13.1	13.4	1507
19 Ao, room 8	8.8	63.1	71.9	1511
1 A0, room 10	0.7	83.4	84.1	863
17 B-1, tower bottom	0.0	68.4	68.4	1470
7A B0	0.0	46.0	46.0	1460
20 B0	19.2	17.6	36.8	1111
8 B0, Picasso	0.0	35.0	35.0	1518
15 B0, stairs bottom	0.0	64.6	64.6	1462
16 B2, stairs top	0.3	22.7	23.1	1456
9 B2	0.0	16.2	16.2	803
10 B2	0.0	99.8	99.8	1031
11 B2	0.0	99.9	99.9	1235
13 B2	0.0	56.7	56.7	1479
18 B3, tower top	0.0	33.5	33.5	1518

Table 4.10: Overview ATG for museums results for the measurement positions of the BMS sensors (March 21st 2016 till March 21st 2017).

Sensor T/RH	Overheating [% too hot]	Underheating [% too cold]	Total discomfort [%]	Total hours
A0, room 1 / 2	1.6	30.5	32.1	2140
A0, room 5 / 6	12.1	0.0	12.1	2184
A0, room 9 / 10	0.9	44.8	45.7	2163
B outlet tower	1.2	52.8	54.0	2161
B-1, sens 6	0.0	33.5	33.5	2172
B0, sens 5	11.0	1.5	12.5	2179
B1, sens 3	50.9	0.0	50.9	2184
B1, sens 4	0.2	39.8	40.0	2182
B2, sens 1	0.1	48.2	48.3	2166
B2, sens 2	0.5	37.5	38.0	2184

The results show that there is some overheating in the VAM. In the monumental building part, higher overheating percentages of time have been detected at Eltek sensor 19 (room 8) and the BMS sensor located at room 5/6, respectively 8.8% and 12.1%. The overheating hours have not only been detected at very high Running Mean Outdoor Temperature (RMOT) values, but also at lower RMOT values overheating hours are present. Overheating hours have also been detected at Eltek sensor 20 and BMS sensor 5, of respectively 19.2% and 11%. Both sensors are located at the 1st floor of the modern building part near the work of art cosist out of tubular fluorescent lamps, see Figure 2.3 in Paragraph 2.5. At BMS sensor 3 the overheating percentage is the largest with 50.9% of the time, caused in the winter period. This sensor is located in a corridor of the modern building part, which is not a location where visitors will be present for a longer period.

In contrast to the percentage of overheating hours, the percentage of underheating hours at many locations in the VAM are large, namely up to 99.9%. This is mainly the case in the monumental building part and at the 2nd floor of the modern building part. Dependent of the location, the underheating hours have been detected during the whole year or during summer periods (higher RMOT values).

The analysis method of Kramer et. al (2016) can only determine the 90% acceptance class (excellent). However, the 80% class would also be good since thermal comfort is not the main priority in museums and this class has a higher energy saving potential (Kramer et al., 2016). With wider comfort acceptance limits there would be less discomfort hours in the VAM according to the analysis tool, since some data points are right under or above the comfort acceptance limits of the 90% class.

4.2 Microclimates

The microclimates in the VAM near surfaces were investigated by using instantaneous (IRT) and continuous measurements (T_s). During the IRT measurements, many IR thermograms were taken, see Appendix G for the locations. Because many IR thermograms showed no sign of local climates, only a few IR thermograms are included in this thesis. Some microclimates of the VAM are discussed below, incorporating the IR thermograms, the T_s measurements and the T and RH measurements. A few other microclimates are discussed in Appendix W.

Wall without solar radiation, monumental and modern building part

The T graphs as shown in Figure 4.5 show the differences between the monumental and modern building part. Both T_s sensors are measured on walls without solar radiation on the façade. During the whole year, the T_i and T_s measured in the monumental building part A (T/RH sensor 5 and T_s sensor 6) show more deviations and larger differences than the temperatures measured in the modern building part B (T/RH sensor 11 and T_s sensor 9).

Wall with solar radiation, monumental and modern building part

The T graphs as shown in Figure 4.6 show the differences between the monumental and modern building part. Both T_s sensors are measured on walls with solar radiation on the façade. During the whole year, the T_i and T_s measured in the monumental building part A (T/RH sensor 1 and T_s sensor 7) show extremer fluctuations and differences than the temperatures measured in the modern building part B (T/RH sensor 13 and T_s sensor 11). During the summer the T is higher and during the winter the T is lower in the monumental building part.

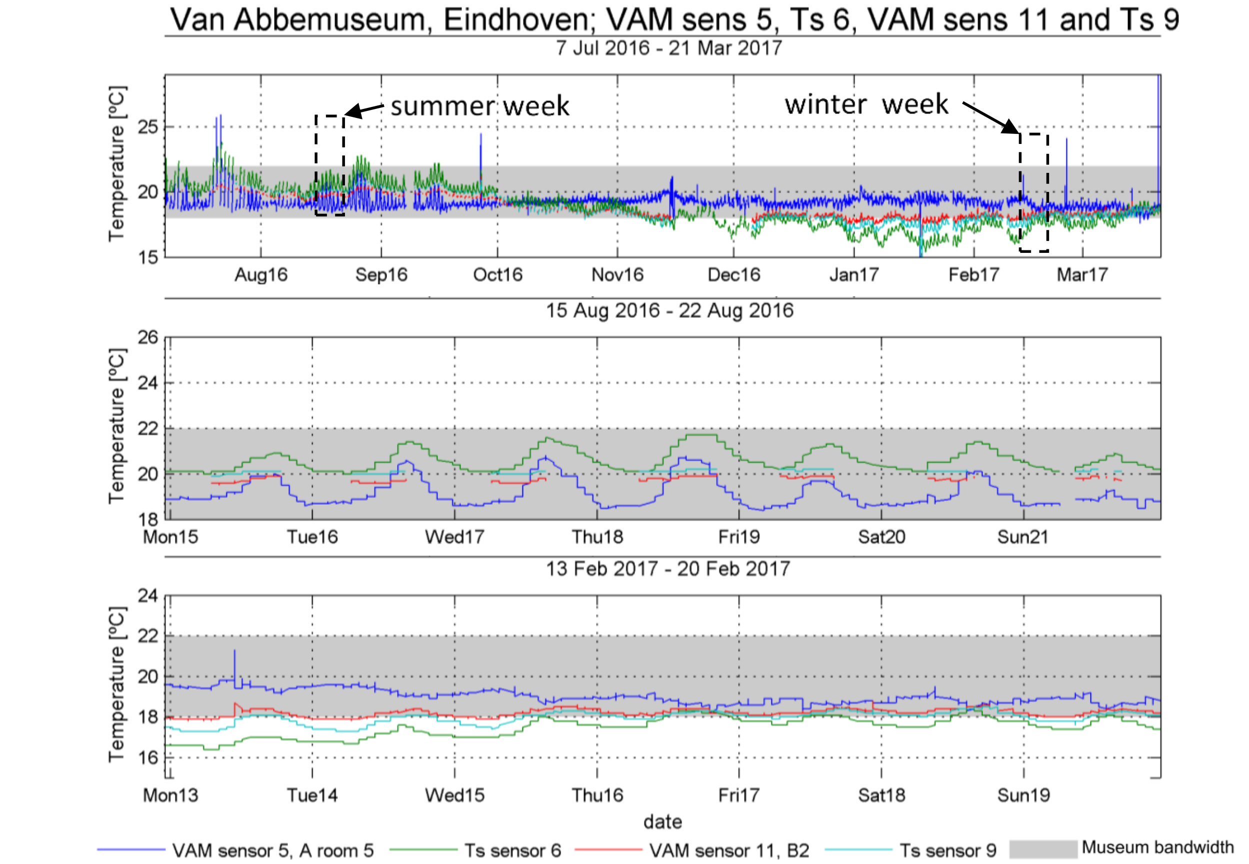

Figure 4.5: T_i and RH_i measured by Eltek sensors 5 and 11, and the T_s measured by T_s sensors 6 and 9.

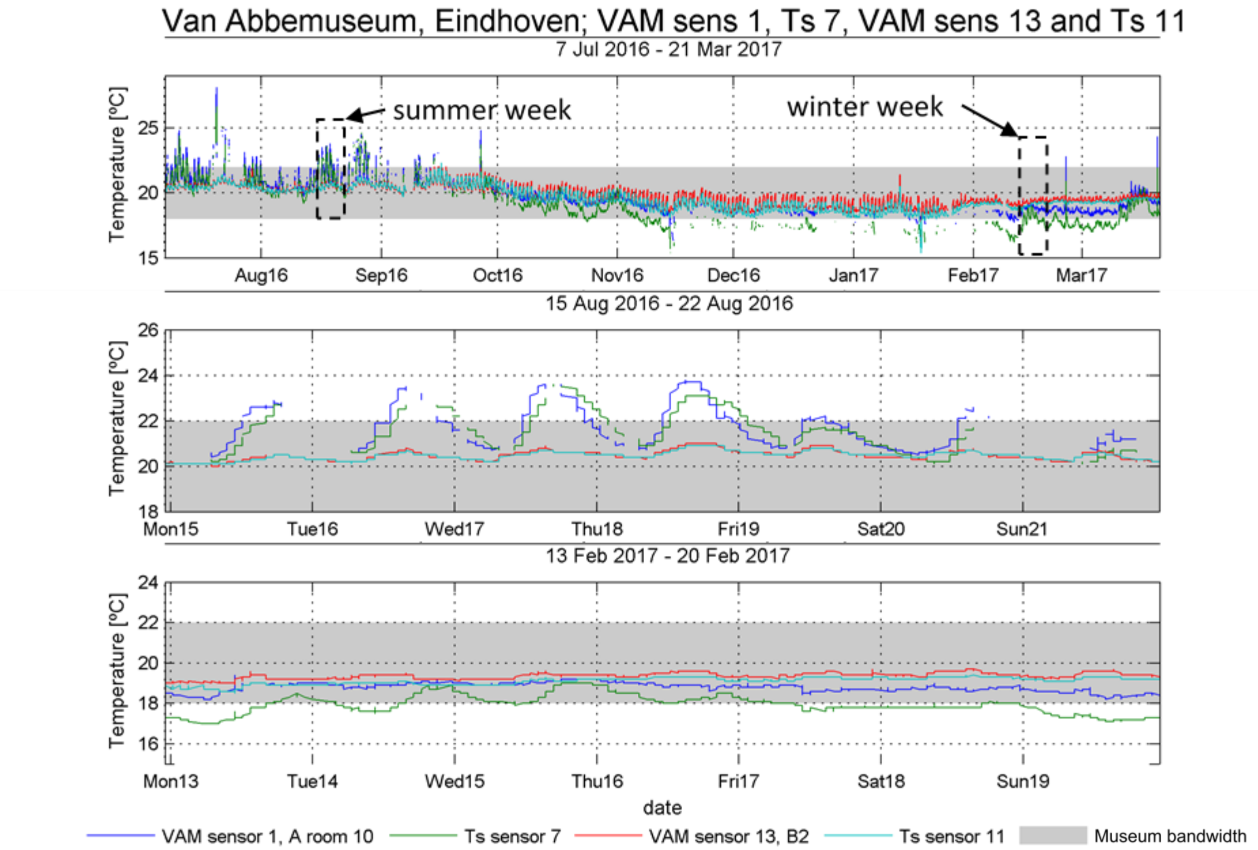

Figure 4.6: T_i and RH_i measured by Eltek sensors 1 and 13, and the T_s measured by T_s sensors 7 and 11.

(Non)covered internal plenum structures

During the summer of 2016, a room in the monumental building part without a covered internal plenum structure was room 10. Unlike room 10, room 4 had non-translucent plastic sheets on the internal plenum structure to eliminate daylight entering the room. Both rooms have the same orientations. Figure 4.7 shows that the bottom surface of the internal plenum structure in room 10 had a T_s of approximately 40°C during the IR measurements. The plenum in room 4 had a T_s of approximately 33°C at the bottom surface of the internal plenum structure, see Figure 4.8.

IR location 10, July 20th 2016 14:56, T_i = 26.0°C and RH_i = 42.8%

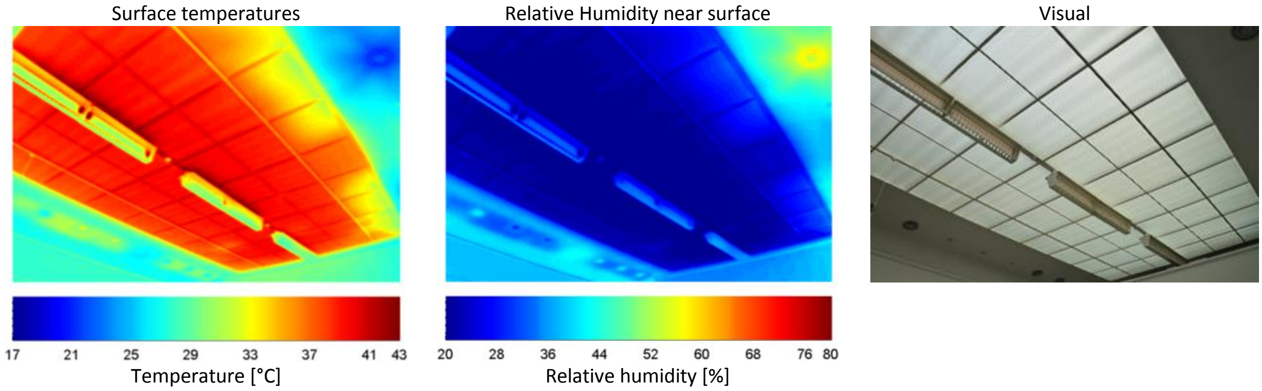

Figure 4.7: IR thermogram and hygrogram of IRT measurement plenum room 10, conducted on July 20th 2016. Daylight through internal plenum structure.

IR location 4, July 20th 2016 14:48, T_i = 24.3°C and RH_i = 48.2%

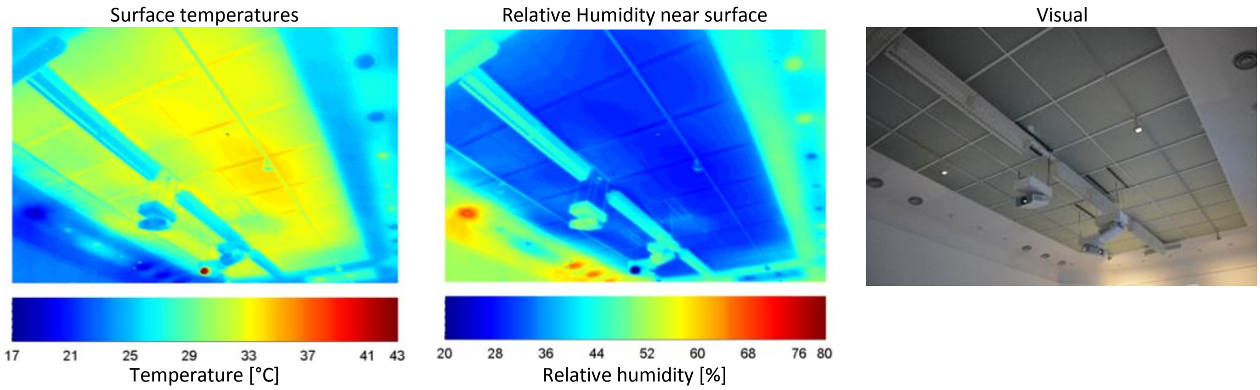

Figure 4.8: IR thermogram and hygrogram of IRT measurement plenum room 4, conducted on July 20th 2016. Internal plenum structure covered with non-translucent plastic sheets.

The T_i in the rooms did also differ during the summer, see Figure 9.137 in Appendix W: the T_i in room 4 is approximately 2°C lower than in room 10. Despite of much data loss in the plenums, the available data showed little difference in the measured T_i. The T_i measured in the plenum above room 4 was slightly higher than the T_i measured in the plenum above room 10. This is contradictory to the T_i measured in the underneath rooms.

The T_i difference in the rooms with different internal plenum structures has also been measured in the other rooms of the monumental building part, see Table 9.4 in Appendix G. The rooms with non-translucent plastic sheets covering the internal plenum structure had a T_i between 24.0-24.7°C (room 1, 2, 3, 4, 7, and 8). The T_i measured in the rooms without covered internal plenum structures was between 25.7-26.0°C (room 9 and 10). In room 6, which upper roof is renewed in 2003, the T_i was 23.4°C, and the T_i in room 5 with the polycarbonate channel plates and non-translucent plastic sheets was 23.8°C.

Internal plenum structures with(out) polycarbonate channel plates

During the summer of 2016, both room 4 and 5 in the monumental building part had an internal plenum structure covered by non-translucent plastic sheets. Both rooms have the same orientations. However, room 5 has an extra structure of polycarbonate channel plates build on the internal plenum structure. See Figure 9.11 in Appendix D for impressions of the polycarbonate channel plates placed on the plenum structure. Figure

4.9 shows that the bottom surface of the internal plenum structure in room 5 had a T_s of approximately 28°C during the IR measurements. This is approximately 5°C lower than the plenum of room 4, see Figure 4.8.

IR location 5, July 20th 2016 14:50, T_i = 23.8°C and RH_i = 49.0%

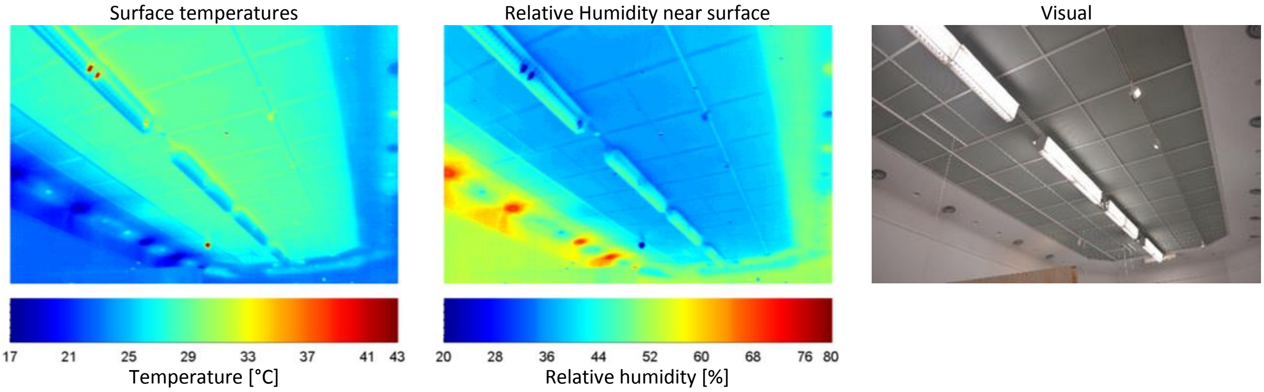

Figure 4.9: IR thermogram and hygrogram of IRT measurement plenum room 5, conducted on July 20th 2016. Internal plenum structure is covered with polycarbonate channel plates and non-translucent plastic sheets.

Although the T_s of the bottom surface of the internal plenum structure with the polycarbonate channel plate structures (room 5) is significantly lower than at plenums without these structures, the T_i in room 5 is only slightly decreased compared to the T_i in the other rooms in the monumental building part. Figure 9.137 in Appendix W shows that during the summer the T_i measured in room 5 is approximately 0.5-1.0°C lower than the T_i measured in room 4.

4.3 Numerical study

The next paragraphs describe the calibration of the numerical model of the monumental building part, the results of the reference strategy (current situation), and the different setpoint strategies. Table 4.11 shows an overview of all the setpoint strategies. T_i and RH_i graphs per strategy can be found in Figure 9.138-Figure 9.141 in Appendix X. Figure 4.10 shows the energy demand, and the thermal comfort is shown in Figure 4.11.

4.3.1 Calibration

HAMBase zones 1 and 2 have been calibrated with the measured data by Eltek sensors 3 (room 4) and 4 (plenum room 4). Comparisons have been made of the T, RH, humidity ratio, (estimated) energy use, and the results of the climate risk assessment analysis tools and ATG for museums tool. Since not all the setpoints were precisely known, some of the setpoints were varied to better match the measured and simulated data of zone 1/room 4 and zone 2/plenum room 4. These were setpoints concerning the ventilation rates, T and RH setpoints, internal heat and moisture gains, and installation capacities. The maintained values are shown in Appendix M.

Figure 9.54-Figure 9.57 in Appendix N show the comparison and deviation graphs of zone 1/room 4. For room 4 the mean deviations are 0.26°C for T, 0.32% for RH, and 0.16g/kg for the humidity ratio. Figure 9.58-Figure 9.61 in Appendix N show the comparison and deviation graphs of zone 2/plenum room 4. For the plenum above room 4 the mean deviations are 0.08°C for T, 2.39% for RH, and -0.10g/kg for the humidity ratio. The mean deviations have been considered as small mean deviations, concluding that the simulation model has been calibrated. Since exceptional situations during the measurement period are not included in the simulation model, such as malfunctioning of the HVAC systems during power failures and fire alarms, see also Appendix J, the deviation is actually lower than shown in the figures (peaks).

Table 9.25 in Appendix N shows the summary of the compared results (climate risk assessment tools and ATG for museums tool) of the data measured by Eltek sensor 3 and simulated data of zone 1. As can be seen in the table, the results of the analysis tools are similar, therefore the simulation model has been assumed to be calibrated.

4.3.2 **Reference – strategy 1**

The reference strategy describes the current situation of room 4 of the monumental building part. For the calibration, room 4 (HAMBase zone 1) and the plenum above room 4 (HAMBase zone 2) have been calibrated. The setpoints maintained during the calibration of HAMBase zone 1 were constantly 18-19°C for T and 55-56.5% for RH. The other input values are described in Appendix M. The results are shown in Table 4.11. According to the reference simulation model, the energy use is 352.2 kWh/m^2/year. The largest portion of the energy is used for cooling, followed by heating and to a lesser extent for (de)humidification, see Figure 4.10. ASHRAE class B is reached for 99.2% of the time, which is reasonable for historic buildings (ASHRAE, 2011), and the risks of mould growth, possible damage of the base material and pictorial layer are on the safe side for at least four object types (paper, panel painting, furniture, sculpture). However, since the average Lifetime Multiplier (LM) is <1, respectively 0.995, there is an increased risk regarding chemical degradation. The thermal comfort graph, see Figure 4.11, shows that the T_i is 93.1% of the time too cold and 2% of the time too hot to reach a 90% acceptance class.

4.3.3 **CO_2 control and T/RH setpoint based on RMOT and night setback – strategy 2-17**

The setpoints of strategy 2 are similar to those of the reference strategy 1. However, in strategy 2 CO_2 controlled ventilation has been used, as explained in Paragraph 3.2.2. The results are comparable to the results of strategy 1: the energy use is 15% less (slightly decrease for heating and (de)humidification and increase for cooling, see Figure 4.10), ASHRAE class B is reached for 99.3% of the time, the average LM is 0.990, and the T_i is 93.3% of the time too cold and 2.1% of the time too hot, see Figure 4.11.

In strategies 3 to 7 the reference T setpoints of 18-19°C have been replaced with the limits of the ATG for museums based on the running mean outdoor temperature (RMOT) as explained in Paragraph 3.2.2 (bandwidth ±1.2°C). The RH setpoints differ for strategies 3 to 7, from the reference setpoint to ASHRAE class B. The five strategies all show a decrease in energy demand compared to the reference strategy. Strategy 3 comes with an increased energy use for heating, see Figure 4.10, but the total use is still 11% lower than at the reference strategy. Strategies 4 to 7 show a comparable decrease in energy demand, respectively 32% to 35%. The heating and cooling demands are the same, but the (de)humidification demands show small differences. Strategies 3, 4, and 5 reach ASHRAE class B for 100% of the time, strategies 6 and 7 respectively 97.3% and 96.8% of the time. Although strategies 3 and 7 score a lower average LM value than the reference strategy, strategies 4, 5, and 6 show an average LM value >1, which means that the risks to objects regarding chemical degradation are small. All five strategies show a great improvement in thermal comfort, the T_i is 6.7% to 11.6% of the time too cold and 3.3% to 7.0% of the time too hot, see Figure 4.11.

The RH setpoints of strategies 8 to 12 are equal to those of strategy 3 to 7. The T setpoints however have been expanded with free floating (FF) during the nighttime, as explained in Paragraph 3.2.2. Although the energy use decreases drastically compared to the reference strategy, the risks to objects increases: ASHRAE class C is met 100% of the time and the average LM is in all strategies <1. In strategies 9 and 10 there is also an increased risk regarding mechanical degradation of the base material for sculpture objects. The thermal comfort increases: the T_i is 25.5% of the time too cold and 21.2% of the time too hot see Figure 4.11. Figure 9.139 in Appendix X shows that the T_i reaches values up to 41°C and down to 3°C.

The setpoints of strategies 13 to 17 are similar to the setpoint of strategies 8 to 12, in addition CO_2 controlled ventilation has been added. The results for the energy demand, risks to objects and the thermal comfort are very close to those of strategies 8 to 12. One worthy to mention difference is that in strategies 13 to 17 there is no increased risk regarding possible damage of the base material.

Table 4.11: Simulation results for zone 1 (March 21st 2016 to March 21st 2017) of different setpoint strategies. The energy use includes the energy required for heating, cooling, and (de)humidification. The risks to objects have been assessed according to the general and specific climate risk assessment. The specific climate risk assessment represents the average results for the four object types. Thermal comfort is expressed in the percentage of discomfort hours during opening hours, based on the ATG for museums.

Stra-tegy	Setpoint		Energy		General						Specific				Discom-fort
	T [°C]	RH [%]	Total [kWh/ m2/year]	Vs. ref [%]	AA	As	A	B	C	D	Mould	LM	Base layer	Pict. Layer	[%h]
1. Ref	18-19	55-56.5	352.2	0	92.4	92.4	92.4	99.2	100	100		0.995			95.1
2.	18-19 CO2	55-56.5	300.9	-15	93.1	93.1	93.1	99.3	100	100		0.990			95.4
3.	RMOT	55-56.5	312.1	-11	92.2	92.2	92.2	100	100	100		0.744			18.5
4.	RMOT	AA	239.5	-32	71.1	89.9	96.1	100	100	100		1.028			10.0
5.	RMOT	As	236.2	-33	45.5	87.6	96.0	100	100	100		1.012			10.0
6.	RMOT	A	230.2	-35	32.8	70.6	81.5	97.3	100	100		1.010			10.0
7.	RMOT	B	230.6	-35	35.2	73.0	80.8	96.8	100	100		0.991			10.0
8.	RMOT/FF	55-56.5	175.5	-50	33.0	37.9	39.1	80.5	100	100		0.587			46.7
9.	RMOT/FF	AA	149.6	-58	26.4	32.9	39.7	81.7	100	100		0.670			46.7
10.	RMOT/FF	As	147.5	-58	18.6	32.7	39.7	81.8	100	100		0.706			46.7
11.	RMOT/FF	A	135.2	-62	14.3	21.6	33.2	75.9	100	100		0.740			46.7
12.	RMOT/FF	B	132.6	-62	16.0	18.8	26.7	75.6	100	100		0.803			46.7
13.	RMOT/FF/CO2	55-56.5	171.9	-51	32.5	37.6	38.8	80.8	100	100		0.555			45.9
14.	RMOT/FF/CO2	AA	147.3	-58	24.7	32.5	39.4	81.9	100	100		0.617			45.9
15.	RMOT/FF/CO2	As	145.8	-59	18.2	32.2	39.4	81.9	100	100		0.646			45.9
16.	RMOT/FF/CO2	A	133.6	-62	13.5	21.4	33.0	75.3	100	100		0.677			45.9
17.	RMOT/FF/CO2	B	131.4	-63	15.6	19.1	26.2	75.0	100	100		0.741			45.9
18.	AA	AA	160.4	-54	43.8	63.3	77.6	98.6	100	100		0.947			93.9
19.	As	As	134.9	-62	10.1	38.0	41.4	98.6	100	100		0.992			93.9
20.	A	A	129.8	-63	7.2	33.3	32.8	92.7	100	100		0.980			93.9
21.	B	B	30.4	-91	4.0	11.6	8.2	78.8	100	100		0.866			95.7
22.	C	C	79.7	-77	3.5	7.8	7.2	47.9	100	100		0.930			94.6
23.	D	D	78.9	-78	3.5	7.7	7.2	47.8	97.0	100		0.937			94.6
24.	RMOT±1.5	AA	228.7	-35	71.5	88.2	94.9	100	100	100		1.017			88.5
25.	RMOT±1.5	As	225.8	-36	47.4	86.5	94.9	100	100	100		1.007			88.5
26.	RMOT±1.5	A	219.7	-38	34.0	68.9	81.7	97.4	100	100		1.000			88.5
27.	RMOT±1.5	B	220.3	-37	36.8	72.1	82.2	96.5	100	100		0.989			88.5
28.	RMOT/AA	AA	204.2	-42	72.6	82.8	93.7	100	100	100		1.020			15.1
29.	RMOT/As	As	201.6	-43	51.0	82.4	93.6	100	100	100		1.009			15.1
30.	RMOT/A	A	195.4	-45	38.4	55.6	82.6	96.1	100	100		0.999			15.1
31.	RMOT/B	B	147.9	-58	25.3	28.1	53.5	92.7	100	100		0.975			26.8

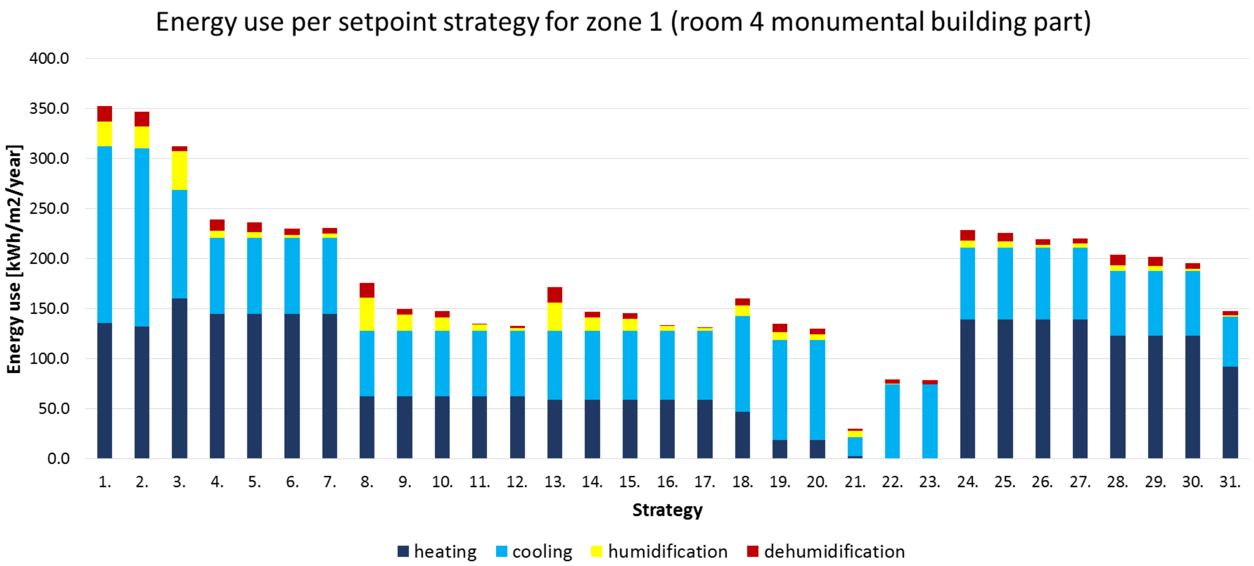

Figure 4.10: Simulated energy demand per setpoint strategy, divided in heating, cooling, and (de)humidification. The setpoints per strategy can be found in Table 4.11.

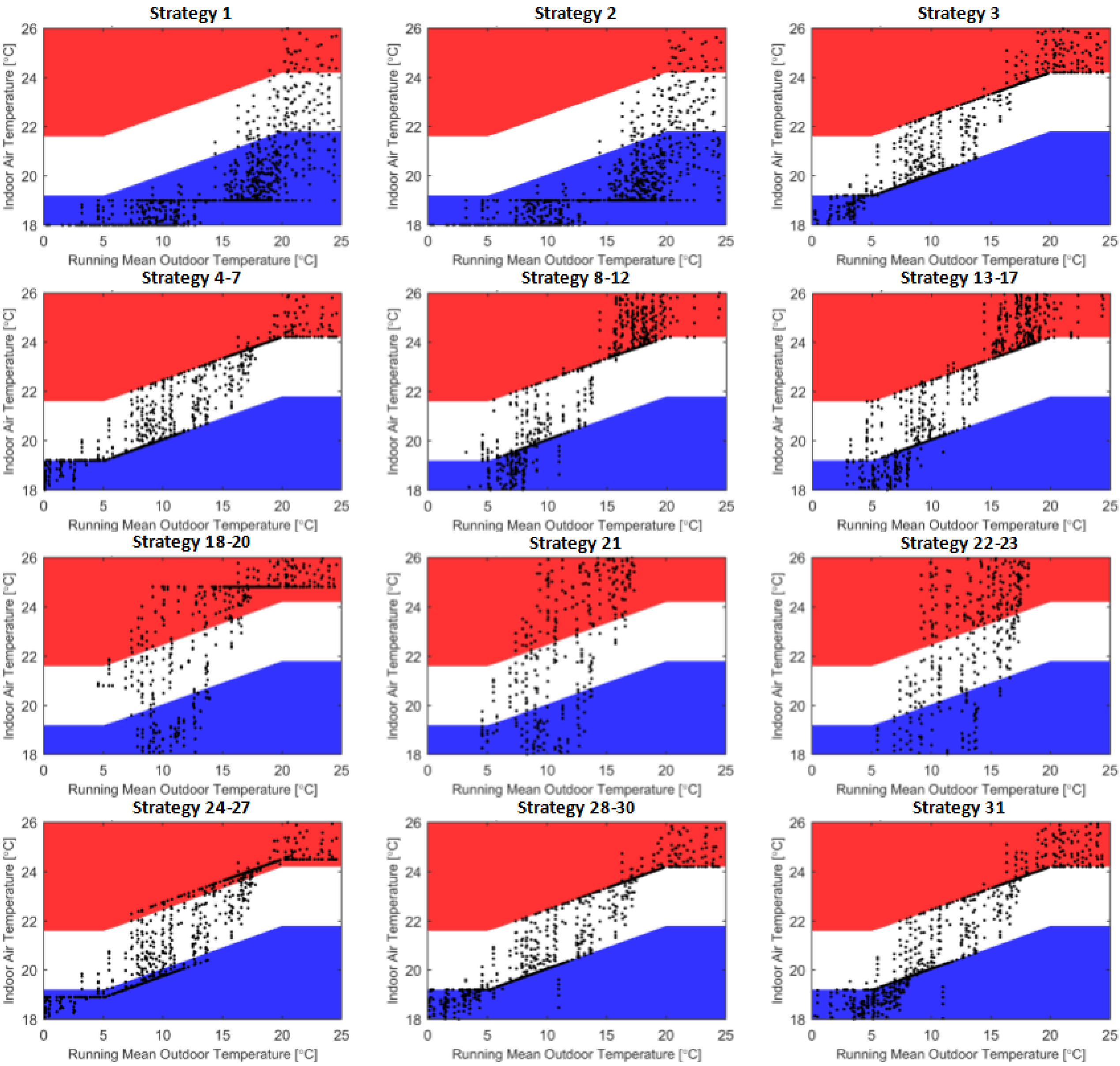

Figure 4.11: ATG for museums results of the setpoint strategies. The setpoints per strategy can be found in Table 4.11.

4.3.4 T/RH setpoint based on ASHRAE climate classes – strategy 18-23

In strategies 18 to 23 the T and RH setpoints are based on the six ASHRAE climate classes, as explained in Paragraph 3.2.2. All six strategies show a great decrease in energy demand compared to the reference strategy, respectively 54% to 91%. Strategies 22 and 23 are the only two strategies in this research were no demand for cooling has been used, see Figure 4.10. In addition, no energy for humidification has been used in strategy 23. The results of the general climate risk assessment tool differ a lot per strategy: ASHRAE class B is met 47.8% to 98.6% of the time. The average LM values are all <1, which means that these strategies all have an increased risk for the objects regarding chemical degradation. Moreover, strategies 21 to 23 have an increased risk regarding the mechanical degradation of the base material and pictorial layer. The total thermal discomfort hours is similar to those of the reference strategy, however, the ratios are different: the T_i is 51.2% to 54.8% of the time too cold and 39.8% to 44.2% of the time too hot, see Figure 4.11.

4.3.5 T/RH setpoint based on RMOT and ASHRAE climate classes – strategy 24-31

The setpoints for T and RH of strategies 24 to 27 are similar to the setpoints of strategies 4 to 7, except that the bandwidth of the 90% acceptance class (limits ATG for museums), is changed from ±1.2°C to ±1.5°C, see Figure 3.7 in Paragraph 3.2.2. The results for energy demand, and for the general and specific climate risk assessment of strategies 24 to 27 and strategies 4 to 7 are very similar, however, the thermal comfort hours of strategies 24 to 27 are poor, the T_i is 48.4% of the time too cold and 40.1% of the time too hot. A total thermal discomfort of 88.5% of the time seems high, nevertheless, in Figure 4.11 can been seen that many T_i points are 0.3°C below the lower limit and above the upper limit. As mentioned in Paragraph 1.1.4, the ATG for museums analysis method can only be used to determine the 90% acceptance class, however, the 80% class would also be good because thermal comfort is not the main priority in museums (Kramer et al., 2016).

The T setpoints for strategies 28 to 31 are based on limits of the ATG for museums (bandwidth ±1.2°C) in combination with the limits of ASHRAE classes AA to B during the nighttime. The RH setpoints differ from ASHRAE class AA to B. The four strategies all show a decrease in energy demand compared to the reference strategy, respectively 42% to 58%. Strategies 28 and 29 reach ASHRAE class B for 100% of the time, strategies 30 and 31 respectively 96.1% and 92.7% of the time. The risks to objects are very low within strategies 28 and 29, unlike strategies 30 and 31 which score an average LM value <1. All four strategies show a great improvement in thermal comfort, the T_i is 10.7% to 19.8% of the time too cold and 4.4% to 7.0% of the time too hot, see Figure 4.11.

4.3.6 Optimum setpoint strategy

The museum staff of the VAM has to decide which setpoint strategy is optimum for the monumental building part of the VAM. Each setpoint strategy has its own (dis)advantages regarding energy use, museum objects, thermal comfort, and building envelope. According to the results of the simulated setpoint strategies, using the calibrated model of room 4 of the monumental building part, the most interesting setpoint strategies would be strategy 5 and 29. Compared to the reference situation, both strategies show a good amount of energy decrease, less degradation risks for the museum objects, and an improved thermal comfort. However, the results of the general risk assessment are partly decreased; the percentage of time the indoor climate meets ASHRAE classes AA and As decreases, but increases for the rest of the classes. Both strategies meet ASHRAE class B for 100% of the time.

According to the results of the numerical study, strategies 4 and 28 would also be interesting setpoint strategies. However, since ASHRAE class As allows more seasonal fluctuations than ASHRAE class AA, potential outliers in the indoor climate (T and RH) would be less different from the average indoor climate. Based on the results of the experimental study, outliers occur sometimes in the VAM when malfunctioning of the AHUs occur (due to fire alarms and tests).

5 Discussion

This chapter discusses the results of the indoor climate assessment of the current situation of the Van Abbemuseum (VAM), see Paragraph 5.1, and the numerical study in which several setpoint strategies have been implemented in the calibrated simulation model, see Paragraph 5.2.

5.1 Current indoor climate

The indoor climate assessment regarding the continuous measurements in the VAM is based on the temperature (T_i) and relative humidity (RH_i) measured by two types of sensors: Eltek sensors owned by the Eindhoven University of Technology (TU/e), and Building Management System (BMS) sensors owned by the VAM. In the experimental study part of this research, 8.5 months of measured indoor climate data by the Eltek sensors has been analyzed. Despite the fact that at least one year of measurements is needed to draw a complete conclusion of the indoor climate and to get reliable results out of the general and specific climate risk assessment, the results based on the measurements by the Eltek sensors are still useful since the extreme weather conditions are included (summer to winter period). Although the best location to observe the room T_i and RH_i would be in the middle of the room, the Eltek sensors have been placed near the walls and often not in sight of the visitors due to aesthetic considerations of the museum. Therefore, some of the locations are not representative for the locations of the museum objects and visitors.

To be able to draw a full conclusion of the current indoor climate in this research, one year of measured data by the BMS sensors is included as well. The BMS sensor data has been compared with 8.5 months of measured data by the calibrated Eltek sensors. The BMS sensor data has been considered to be representative for the (local) indoor climate in which the sensors are located. The BMS sensors are located at eye height on the walls. However, many of the BMS sensors are placed in portals between exhibition rooms, which is also not very representative for the locations of museum objects. Due to the power failure on November 14^{th} 2016, the data measured by the BMS sensors in the monumental building part was unrealistic. The values have been corrected by using the measured values of the Eltek sensors, they were - in contrast to the BMS sensors - not connected to the power grid.

Since only 8.5 months of measured data by the Eltek sensors has been used in the general and specific climate risk assessment, the results of the Eltek measurement positions are an approximation. The analysis of the BMS measurement positions are based on a full year of measurements and are therefore more reliable. Because 8.5 months and one year of measured BMS data have been analyzed separately and their results do not differ that much, it is estimated that the analysis of one year of measured Eltek data will be similar to the analysis containing 8.5 months. Moreover, similar results are expected since the 8.5 months of measured Eltek data already include the extreme weather conditions, only a spring period is missing.

Although the results of the general climate risk assessment are reasonable for the different building parts of the VAM, higher ASHRAE classes would be met 100% of the time if no malfunctioning of the Heating, Ventilation, and Air Conditioning (HVAC) systems occurred in case of false fire alarms and tests of the HVAC installation consultancy. The malfunctioning has a drastic impact on the inlet air (HVAC control based on incorrect values provided by the BMS sensors) and therefor influences the indoor climate by creating outliers. This increases the risks to museum objects (lower ASHRAE class met 100% of the time). The extreme outliers show how dependent the indoor climate is on the HVAC installations.

The results of the specific climate risk assessment show that the lifetime multiplier (LM) is <1 for the different object types at most measurement locations, meaning that there is an increased risk regarding chemical degradation. Risks are caused by T_{avg}>20°C and RH_{avg}>50% (Martens, 2012). However, these values are based on reference values and do not consider the climate in which an object is stored previously. Due to the easy use of the specific climate risk assessment tool, it would be worth to add more object types. This is especially the case for museums showing modern art, such as the VAM, in which some objects are made from modern materials, for example plastics, metals, and luminaires.

The thermal comfort has been analyzed by using the Adaptive Temperature Guideline (ATG) for museums analysis tool. These guidelines however are based on surveys, measurements and an intervention study in a renovated museum with insulated walls. Although the envelope of the modern building part of the VAM could be similar, the envelope of the monumental building part is very different. The ATG for museums guidelines could be too strict for the monumental building part. In addition, an 80% acceptance class instead of a 90% acceptance class could be reasonable since thermal comfort is not the main priority in museums. Since many data points fell just out of the thermal comfort limits of the 90% acceptance class, an 80% acceptance class would have less considered discomfort hours in the VAM.

5.2 Numerical study

A numerical model of the monumental building part of the VAM is created, including the exhibition rooms and the plenums. Although the model is divided in sixteen zones, only one exhibition room zone and one corresponding plenum zone have been calibrated and further analyzed. Due to the lack of information of some characteristics of the museum building and the HVAC system, some assumptions have been made. There are some differences between the results of the measured data and the simulated data. The RH show different fluctuations, but are in the same range. Smaller fluctuations are not shown in the simulation results (setpoints are reached). Different T and RH setpoints and lower installation capacities have been used in the numerical model than have been found in the available (old) documents of the VAM. The real T and RH setpoints for the total monumental building part could be 20-22°C and 51%. If these real T and RH setpoints would have been used in the numerical model, zone 1 could not has been calibrated due to the differences between the measured and simulated results. The capacity of the CV installation could be 173kW and the capacity of the cooling system could be 102 kW according to (old) documents of Nelissen (2000). In addition, estimated heat and moisture gains have been added to the plenum zones, representing heat coming from installations and some water puddles as have been observed in the plenums.

Besides comparing the T, RH and humidity ratio, the (estimated) energy use of the real and simulated exhibition rooms have also been compared. The mass flow for estimating the real energy use has been variated until the estimated and simulated energy use corresponded. However, the mass flow in the estimation has been probably considered too high according to found ventilation scheme's (Nelissen, 2000). In addition, the supply T in the estimation has not been measured at the air inlets of the exhibition room, but has been extracted from the BMS: the supply T has been measured at only one location for the whole monumental building part and it is unknown where exactly the sensor is located (probably near the air handling unit outlet).

The deviation overview of the measured and simulated T of the plenum, see Figure 9.61, shows that the deviation is still quite large (max. deviation of -13.3°C) in the months with larger solar radiation. This could partly be due to the used outdoor climate data derived from the KNMI. The solar radiation could be different at the KNMI station Eindhoven than at the VAM. Since is it very hard to match the simulated T to the measured T of the plenum, it could be that in reality the roof structure has more impact on the indoor climate of the plenum than expected according to the simulation. The RH and humidity ratio deviations show larger differences between the measured and simulated results as well. However, in contrast to the T in the plenum, the RH and humidity ratio in the plenum do not directly influence the indoor climate of the exhibition rooms because of no air exchange between the plenums and the exhibition rooms. The lower installation capacities and different T and RH setpoints of the exhibition room simulation could be partly explained by the fact that the simulated indoor climate of the plenum is different from reality. Despite the fact that altering the plenum would cost extra money, further research into conditioning or insulating the plenums is recommended, since the plenums seems to have more impact (thermal radiation effects) on the exhibition rooms than currently simulated. Appendix Y provides a first perception of the potential effect of possible (structural) measures on the indoor climate (T and RH) of the exhibition rooms and the plenums.

Because of the differences between the real situation and the calibrated numerical model, deviations should be considered in the simulation results of the reference model and the results of the different setpoint strategy simulations.

Since the plenum is not conditioned by the HVAC installation, the results of the different setpoint strategies have only been analyzed for exhibition room 4 of the monumental building part (HAMBase zone 1). Expected has been that the setpoint strategies based on the Running Mean Outdoor Temperature (RMOT) should have no discomfort hours, however, due to the smaller capacities in the numerical model, the limits of the ATG for museums could not always be met. Since the installation capacities are larger in reality, the ATG for museums limits could be possibly met in reality, resulting in less discomfort hours. The simulated T_i and RH_i results of the setpoint strategies based on the ASHRAE climate classes have been expected to meet their corresponding climate classes 100% of the time. Instead, lower ASHRAE classes have been met 100% of the time. Since the limits of the ASHRAE classes have been used as the setpoints and not as the requirements, the T_i and RH_i fluctuate right under and above the limits of the ASHRAE classes, resulting in lower percentages of time the ASHRAE class has been met. When the T and RH setpoints would be a bit narrower, the corresponding ASHRAE class is more likely to be met. This would also be the case in reality if the museum requirements of T=18-22°C and RH=48-55% would be used as the setpoints instead of more narrow values, for example T=19-21°C and RH=50-53%. The BMS starts reacting to the indoor climate when the T and/or RH setpoints are already exceeded, which results in lower percentages of the time the museum requirements are met.

6 Conclusion

This chapter describes the conclusions regarding the objectives of this research. The conclusions of the current indoor climate assessments of the monumental and modern building part are described in Paragraph 6.1. Paragraph 6.2 concludes the results of the adapted situations.

6.1 Current situation

The measurement results of the current indoor climate of the Van Abbemuseum (VAM) have been compared for different locations, see Table 6.1. In the paragraphs below, the conclusions of the results are described based on deviations by building physics, Heating, Ventilation, and Air Conditioning (HVAC) systems, collection, and use.

6.1.1 Building physics: monumental versus modern building type

The results in Table 6.1 show that the indoor climate of the exhibition rooms in the monumental building part do not fit into the museum requirements. The indoor climate of the rooms on the 1st floor of the modern building part fit to a large extent in the museum requirements. The temperature (T) and relative humidity (RH) in the rooms on the 2nd floor are a bit outside the museum requirements, but do not result in lower ASHRAE classes met 100% of the time or in larger risks to objects compared to the indoor climate of the 1st floor. For both building parts applies that sometimes the T_i is too high and the RH_i too low or too high according to the indoor climate requirements of the VAM.

The deviations between the indoor climate of the monumental and modern building part are due to the building structure types. The envelope of the monumental building part has a lower thermal resistance. As a result, the outdoor climate has a higher impact on indoor climate of the monumental building part than on the indoor climate of the modern building part. This is mainly the case during the summer, see Figure 6.1, when the increased T in the plenums cause thermal radiation to the rooms underneath. As a result, the T_i in the rooms increases and the HVAC system cannot compensate this due to the too low cooling capacity, see for more information Paragraphs 6.1.2 and 6.1.5.

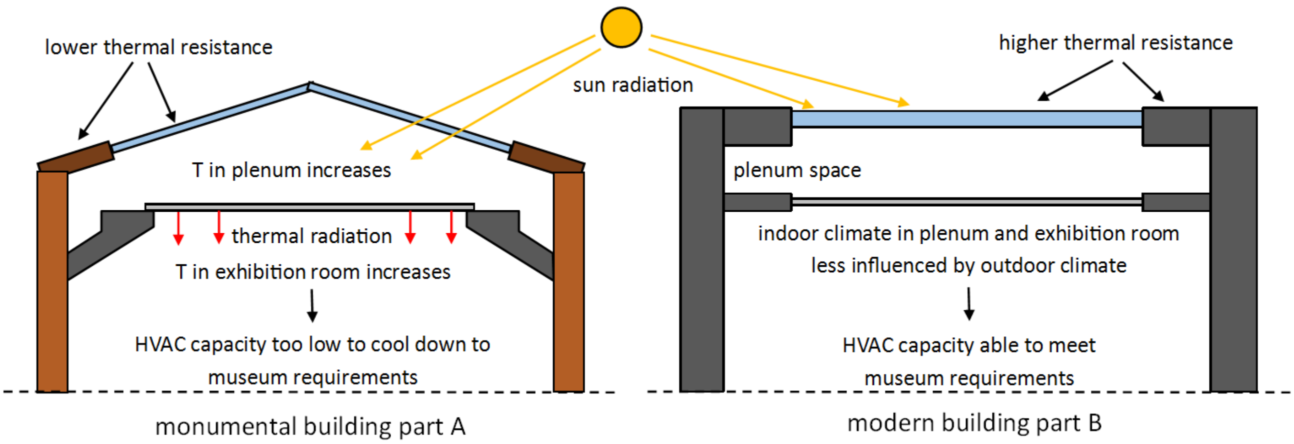

Figure 6.1: Schematic section view of the monumental and modern building part and the impact of the outdoor climate on the indoor climate during the summer.

The lower thermal resistance of the monumental building envelope and the higher thermal resistance of the modern building envelope have also impact on the microclimates near the external walls of the building parts. The results of the infrared thermography (IRT) and surface temperature (T_s) measurements have shown that the T_i and T_s in the monumental building part have more deviations and larger differences mutually than the T_i and T_s in the modern building part. T_e has a larger impact on the T_s at the inside of the monumental building envelope than on the T_s at the inside of the modern building envelope. This applies for both facades with and without solar radiation on the façade. Due to the differences between the average conditions and the microclimates near the walls, the risks for the building envelope and objects placed near external walls are larger in the monumental building part than in the modern building part.

Table 6.1: Summary of the results of the data measured by the Eltek sensors (July 7th 2016 till March 21st 2017) and BMS sensors (March 21st 2016 till March 21st 2017). The current indoor climate conditions are described by T_{avg} and RH_{avg}, and by the CEC assessed according to the museum requirements (T_i=18-22°C and RH_i=48-55%, max. Δ/h=0.5 and max. Δ/d=2.0). The risks to objects have been assessed according to the general and specific climate risk assessment. The letter in the general climate risk assessment indicates the best ASHRAE class which is met 100% of time, the letter between the brackets is the class which is met 98% or 99% of time. The specific climate risk assessment represents the average results for the four object types. Thermal comfort is expressed in the percentage of discomfort hours during opening hours, based on the ATG for museums.

VAM Sensors T/RH	Averages		CEC [%]											Risks to objects					Discom-fort
	Tavg [°C]	RHavg [%]	OK	too hot	too humid	too humid/ cold	too cold	too dry	too dry/hot	ΔT/h	ΔT/d	ΔRH/h	ΔRH/d	General	Specific				[%h]
															Mould	LM	Base layer	Pict. Layer	
3 A0, room 4	18.7	55.9	18	1	56	24	1	0	0	1	10	28	62	B (AA)		0.992			98.5
5 A0, room 5	19.2	54.8	60	0	39	0	0	0	0	1	11	69	98	B (A)		0.961			76.4
6 A0, room 6	20.8	50.3	84	5	0	0	0	11	0	1	12	25	85	B (As)		0.907			13.4
19 Ao, room 8	20.4	49.5	69	0	0	0	1	4	25	3	23	40	78	B		0.968			71.9
1 A0, room 10	19.7	54.1	63	5	30	1	1	0	1	2	15	53	68	B		0.928			84.1
17 B-1, tower bottom	20.0	52.2	99	0	1	0	0	0	0	1	0	9	36	AA		0.941			68.4
7A B0	20.0	51.9	100	0	0	0	0	0	0	2	1	14	75	C (AA)		0.955			46.0
20 B0	20.3	49.7	62	3	0	0	0	18	17	12	70	21	75	C (B)		0.917			36.8
8 B0, Picasso	20.2	50.6	96	0	0	0	0	4	0	1	0	9	20	A (AA)		0.958			35.0
15 B0, stairs bottom	19.7	52.7	99	0	0	0	1	0	0	1	0	12	56	AA		0.958			64.6
16 B2, stairs top	20.2	52.1	93	6	0	0	0	0	0	1	9	12	68	AA		0.925			23.1
9 B2	20.6	50.2	99	0	0	0	0	1	0	0	0	5	11	A (AA)		0.916			16.2
10 B2	18.9	55.5	23	0	76	0	1	0	0	1	1	33	43	A (AA)		0.972			99.8
11 B2	18.5	54.1	77	0	8	0	15	0	0	0	1	31	25	B (AA)		1.033			99.9
13 B2	19.8	53.5	97	0	3	0	0	0	0	2	1	15	54	B (AA)		0.939			56.7
18 B3, tower top	20.5	49.3	66	0	0	0	0	33	0	1	1	40	79	B (As)		0.960			33.5

BMS Sensors T/RH	Averages		CEC [%]											Risks to objects					Discom-fort
	Tavg [°C]	RHavg [%]	OK	too hot	too humid	too humid/ cold	too cold	too dry	too dry/hot	ΔT/h	ΔT/d	ΔRH/h	ΔRH/d	General	Specific				[%h]
															Mould	LM	Base layer	Pict. Layer	
A0, room 1 / 2	20.9	50.9	87	12	0	0	0	0	1	1	12	18	60	B (AA)		0.878			32.1
A0, room 5 / 6	22.2	48.6	52	26	0	0	0	1	22	1	19	10	42	B		0.814			12.1
A0, room 9 / 10	20.6	50.5	93	5	0	0	0	1	0	1	13	16	45	B (AA)		0.919			45.7
B outlet tower	20.7	48.9	67	2	0	0	1	14	17	0	3	9	66	(As)		0.951			54.0
B-1, sens 6	21.0	51.4	98	2	0	0	0	0	0	0	2	5	15	AA		0.861			33.5
B0, sens 5	22.1	50.4	47	48	0	0	0	1	5	5	2	13	82	As (AA)		0.785			12.5
B1, sens 3	22.8	49.6	0	76	0	0	0	0	24	0	0	13	31	B (AA)		0.750			50.9
B1, sens 4	20.6	49.3	92	1	0	0	0	7	0	1	0	9	28	AA		0.951			40.0
B2, sens 1	20.4	53.8	91	0	9	0	0	0	0	0	0	25	31	AA		0.869			48.3
B2, sens 2	21.0	51.9	99	1	1	0	0	0	0	0	1	13	16	B (AA)		0.856			38.0

6.1.2 **Building physics: plenums**

The outdoor climate has a large impact on the indoor climate of the monumental plenums. During the measurements, the T in the monumental plenums fluctuated between 8.4°C and 50.7°C, which causes increased T in the rooms during the summer and much discomfort for the museum staff while working in the plenum. Due to the high thermal radiation from the plenums during the summer (and malfunctioning of the HVAC systems), no higher class than ASHRAE class B is met 100% of the time in the rooms of the monumental building part, see Table 6.1. However, ASHRAE class B is granted for historic buildings and since the most vulnerable objects of the VAM are not placed in the monumental building part, there is no reason for concern regarding the risks to objects displayed in this building part. Nevertheless, if the VAM decides to place high-vulnerable artifacts in the monumental building part under the current indoor climate conditions (ASHRAE class B met 100% of the time), there would be moderate risks of mechanical damage to these objects (ASHRAE, 2011).

The results of the instantaneous measurements of the T_i in the monumental building part have shown that on a warm day (T_e =33.6°C) the T_i was lower in exhibition rooms which internal plenum structures were covered with a non-translucent plastic sheet to exclude daylight in the exhibition room. One of the exhibition rooms, room 5, has a structure of polycarbonate channel plates build on the internal plenum structure. This additional structure decreases the T_s at the bottom surface of the internal plenum structure. However, the T_i in the room is decreased to a less extent. To prevent the rooms from undesired thermal radiation from the plenums, the thermal resistance of the internal plenum structure should be increased or the T in the plenum should be decreased.

While the outdoor climate has a large impact on the indoor climate of the monumental plenums, the outdoor climate has a lower impact on the indoor climate of the modern plenums due to the higher thermal resistance. Therefor the negative impact of the modern plenums on the exhibition rooms is less than in the monumental building part. During the measurements, the T in the modern plenums fluctuated between 13.4°C and 24.1°C, which is a much smaller range than measured in the monumental plenums and much more comfortable for the museum staff.

6.1.3 **Building physics: orientation rooms and glass surfaces**

The continuous measurements results have shown that the rooms without external walls have almost the highest mean T_i and lowest mean RH_i compared to the rooms with external walls, in both the monumental and modern building part (2nd floor), see Eltek sensors 6 (room 6) and 9 in Table 6.1.

The measurement results of the only room with a window in the monumental building part (Eltek sensor 19, room 8), in which is measured, have shown higher T_i and lower RH_i during the summer than the measurement results of the room without external walls (Eltek sensor 6, room 6). Also, the T_i and RH_i ranges over the year are the largest in room 8. Due to the window, the room has a lower thermal resistance, and solar radiation has a larger impact on the indoor climate of this room compared to the other rooms. The same results have been shown in the large corridor of the modern building part: near the large glass surfaces (Eltek sensor 16) increased T_i, decreased RH_i, and extremer daily fluctuations have been detected than further away from the glass surfaces (Eltek sensor 15).

The measurement results of the rooms without solar radiation on the façade (Eltek sensors 5 and 10), in both the monumental and modern building part (2nd floor), have shown that during the summer (increased solar radiation) the T_i is lower in these rooms than in the rooms with solar radiation on the façade.

The results of the specific climate risk assessment, see Table 6.1, have shown that the objects in both the monumental and modern building part are safe for biological and mechanical degradation. However, the lifetime multiplier (LM) is almost always < 1, meaning that chemical degradation is possible. Risks are caused by T_{avg}>20°C and RH_{avg}>50% (Martens, 2012). The rooms with the best indoor climate for the objects are located at the 2nd floor of the modern building part, where T_{avg} and RH_{avg} are approximately 20°C and 55%. The lowest values are reached at the 1st floor of the modern building part, where T_{avg} and RH_{avg} are approximately 23°C and 50%. From these results can be concluded that T_{avg} has a more negative impact on the LM than RH_{avg}.

The thermal comfort of the current indoor climate in the VAM is poor in most rooms, see Table 6.1. In contrast to some overheating hours in the exhibition rooms, see also Paragraph 6.1.7, many underheating hours have been detected, mainly in the monumental building part and at the 2nd floor of the modern building part. Location dependent, the underheating hours have been detected during the whole year or during warmer summer periods.

6.1.4 HVAC: setpoints

The current indoor climate requirements set by the VAM (T=18-22°C and RH=48-55%) are not met. The current setpoints in the Building Management System (BMS) are different from the requirements, respectively T=20-22°C and RH=51% in the monumental building part, and T=20-23°C and RH=51% in the modern building part. If the VAM would adjust the current setpoints in the BMS to their indoor climate requirements, the indoor climate requirements are less likely to be met than in the current situation, due to the wider range of the requirements.

6.1.5 HVAC: capacity

As concluded in Paragraph 6.1.2, the increased T in the monumental plenums cause an increased T in the exhibition rooms during the summer. The indoor climate (T_i and RH_i) of the monumental building part shows extremer fluctuations and is more often outside the museum requirements, in contrast to the more stable climate in the modern building part. Since the HVAC systems have been installed in both building parts at the same time, it is expected that the capacities would fit for both building parts. However, the cooling capacity is too low in the monumental building part since the maximum T requirement of the VAM is exceeded during the summer. The HVAC system in the modern building part is able to cool the indoor climate to the desired T. During the winter, the indoor climate of both building parts are quite stable and show similar results. Thus, the current heating capacity is sufficient.

6.1.6 HVAC: malfunctioning

Due to malfunctioning of the HVAC systems, some outliers have occurred in the indoor climate (T_i and RH_i) of the VAM. In addition to the thermal radiation from the plenums into the exhibition rooms of the monumental building part, the outliers have caused that lower ASHRAE classes are met 100% of the time in the monumental building part, see Table 6.1, coming with an increased risk to objects compared to higher ASHRAE classes. Moreover, the occurred outliers have also caused lower ASHRAE classes met 100% of the time in the modern building part of the VAM, see Table 6.1. Expected would be that the modern building part would met ASHRAE classes of AA or A 100% of the time. If no malfunctioning of the HVAC systems would have occurred, ASHRAE class AA would have met 100% of the time in every room of the modern building part (except for the room with the heat emitting luminaires, near Eltek sensor 20). Class AA is the highest ASHRAE class and comes with very low risks to the museum objects.

6.1.7 Collection: works of art consisting out of heat emitting luminaires

Some works of art consist out of heat emitting luminaires. As a result, the T_i and RH_i of the surrounding air extremely fluctuate when the luminaires are turned on and off daily. The tubular fluorescent lamps near Eltek sensor 20 have the highest impact on the indoor climate: when the luminaires are turned on, approximately 650W of heat is emitted and the T_i increases with 1.5°C and the RH_i decreases by 8%. As a result, the indoor climate requirements are met to a lesser extent and the expected ASHRAE classes AA to A met 100% of the time are not met: the risks to objects placed in the same room as the heat emitting luminaires increases. Besides an increased risk to objects, the works of art consisting heat emitting luminaires also lower the thermal comfort hours by creating overheating hours in the exhibition rooms.

6.1.8 Use: large events

During 'Dutch Design Week' (DDW) and 'GLOW Eindhoven 2016', which were events with extreme increased amount of visitors, the T_i in the rooms of the monumental building part was similar to the T_i during the surrounding days. During the weekend of DDW, the inlet T was lower compared to the other days. This could have been due to the heat gains by visitors and/or because the T_e was warmer and therefore colder air could be blew in the rooms. During the opening hours of the 2nd weekend of DDW, the RH_i in the rooms increased with approximately 4% compared to the surrounding days, in addition to the increased RH of the inlet air, while the RH_e was lower. The increased RH_i in the rooms could have been the result of the moisture gains by visitors or the increased RH of the inlet air. During GLOW the RH_i also increased. The moisture could have come from visitors entering the museum with wet coats on and due to a continuous open entrance door (which is usually closed).

6.2 Adapted situations

The museum staff of the VAM has to decide which setpoint strategy is optimum for the monumental building part of the VAM. Each setpoint strategy has its own (dis)advantages regarding energy use, museum objects, thermal comfort, and building envelope. According to the results of the simulated setpoint strategies, the most interesting setpoint strategies would be strategy 5 and 29, see Table 6.2. The T setpoint of strategy 5 is based on the Running Mean Outdoor Temperature (RMOT) and the RH setpoint is based on the limits of ASHRAE class As. This strategy shows an energy decrease of 33% compared to the reference strategy. The setpoints of strategy 29 are similar to those of strategy 5, however, the T setpoint is based on the limits of ASHRAE class As during the nighttime. This strategy shows an energy decrease of 43% compared to the reference strategy. Both strategy 5 and 9 meet ASHRAE class B for 100% of the time and show less degradation risks for the museum objects compared to the reference strategy. ASHRAE class B is a reasonable class for historic buildings. In addition, both strategies show a great improved thermal comfort: strategy 5 shows a discomfort of 10% of the time and strategy 29 15.1% of the time. Although the thermal comfort is less compared to strategy 5, strategy 29 would be a good option since thermal comfort is not the main priority in museums and the thermal comfort analysis has been based on a 90% acceptance class (excellent) while an 80% acceptance class would also be good.

According to the numerical study, it would also be interesting to use the limits based on the RMOT in combination with the limits of ASHRAE class AA for the T and RH setpoints (strategies 4 and 28), see Table 4.11 in Paragraph 4.3.3. However, since ASHRAE class As allows more seasonal fluctuations than ASHRAE class AA, potential outliers in the indoor climate (T and RH) would be less different from the average indoor climate. Based on the results of the experimental study, outliers occur sometimes in the VAM when malfunctioning of the HVAC systems occur (due to fire alarms and tests).

Table 6.2: Optimum setpoint strategies according to the simulated setpoint strategies. Results are based on the simulated data of one year (March 21st 2016 till March 21st 2017) for the indoor climate of room 4 of the monumental building (zone 1). The energy use includes the energy required for heating, cooling, and (de)humidification. The risks to objects have been assessed according to the general and specific climate risk assessment. The specific climate risk assessment represents the average results for the four object types. Thermal comfort is expressed in the percentage of discomfort hours during opening hours, based on the ATG for museums.

Strategy	Setpoint		Energy		General						Specific				Discomfort
	T [°C]	RH [%]	Total [kWh/m2/year]	Vs. ref [%]	AA	As	A	B	C	D	Mould	LM	Base layer	Pict. Layer	[%h]
1. Ref	18-19	55-56.5	352.2	0	92.4	92.4	92.4	99.2	100	100		**0.995**			95.1
5.	RMOT	As	236.2	-33	45.5	87.6	96.0	100	100	100		**1.012**			10.0
29.	RMOT/As	As	201.6	-43	51.0	82.4	93.6	100	100	100		**1.009**			15.1

7 Recommendations

This chapter describes the recommendations for the museum staff of the Van Abbemuseum (VAM), see Paragraph 7.1, and for further research, see Paragraph 7.2.

7.1 Museum staff

The current indoor climate requirements of the VAM are stricter than ASHRAE class AA. Especially for the modern building part, it is recommended to make the bandwidth wider, since the AHU is able to cool down to their setpoints, in contrast to the AHU of the monumental building part. This causes underheating hours during the summer. According to the study of Kramer et al. (2016), it is assumed different (more dynamic) setpoint strategies in the modern building part would have a positive impact on decreasing the energy consumption and increasing the thermal comfort without significantly increasing the degradation risks of museum objects.

If the VAM decides to place high-vulnerable objects in the monumental building part, under the current indoor climate conditions (ASHRAE class B met 100% of the time), it is recommended to place them in microclimate cases (Martens, 2012). If high-vulnerable objects are placed in the monumental building part without a microclimate case, there would be moderate risks of mechanical damage to these objects (ASHRAE, 2011).

The indoor climate results have shown that at works of art consisting out of heat emitting luminaires, the T_i and RH_i of surrounding air fluctuate drastically when the luminaires are turned on/off. Recommended is to not place vulnerable objects near these works of art. The best locations in the museum for vulnerable objects are in the modern building part (not in rooms with façade openings), due to the more stable climate.

During GLOW, an increased amount of visitors enter the VAM and the main entrance door is directly opened. As a result, moisture from the outdoor climate easily infiltrates into the museum. It is recommended to internally separate the monumental building part (GLOW exhibition) from the modern building part, in order to not increase the RH_i in the modern building part as well.

The measurements have shown that malfunctioning of the HVAC systems cause drastic outliers in T_i and RH_i. Recommended is to shut down all components of the HVAC systems in case of malfunctioning, in order to stop the HVAC control based on incorrect values provided by the BMS sensors. Another suggestion is to replace the plasterboards, since the current plasterboards are repeatedly painted. Due to the layers of paint, the plasterboards are less able to adopt and release moisture, so fluctuations cannot be diminished.

The polycarbonate channel plates placed in the monumental building part on the internal plenum structure decrease the T_s at the bottom surface of the plenum structure. However, the T_i in the room is decreased to a much less extent. It is up to the museum staff to decide if the investment in polycarbonate channel plate structures is profitable. Further research into other possible measures could provide more interesting options to improve the indoor climate in the rooms and plenums, see Paragraph 7.2 and Appendix Y.

Although the T and RH sensors owned by the VAM (BMS sensors) are located at eye height on the walls, many of the BMS sensors are placed in portals between exhibition rooms, which is not representative for the locations of museum objects. The sensors could be placed on locations which are more representative for the museum objects, so the HVAC system can control to their climate instead to the climate of portals.

The museum staff of the VAM has to decide which setpoint strategy is optimum for their museum, with respect to the energy use, museum objects, thermal comfort, and building envelope. According to numerical study, the most interesting setpoint strategies would be strategy 5 and 29. Compared to the reference situation, both strategies show a good amount of energy decrease, less degradation risks for the museum objects, and a great improved thermal comfort. Both strategy 5 and 9 meet ASHRAE class B for 100% of the time, which is a reasonable class for historic buildings. Compared to strategy 5, strategy 29 comes with 10% more energy decrease and 5.1% less thermal comfort hours. Although the thermal comfort is less, strategy 29 would be a good option because of the higher energy savings and thermal comfort is not the main priority in museums.

7.2 Further research

To decrease the amount of data loss and to collect one year of data measured by the Eltek sensors, it is recommend to measure at least till February 6th 2018 since the last repeater is placed on February 6th 2017. From this date, nearly no data loss occurred, except for Eltek sensor 9 (bad battery). With one year of data with less data loss, a full and more reliable conclusion of the indoor climate can be drawn. Also, the general and specific climate risk assessment require one year of data to get 100% reliable results. Since the outdoor climate data measured by the KNMI is used during this research, the Eltek outdoor sensor can be removed.

The results of the specific climate risk assessment have shown that the LM is <1 for the different object types at most measurement locations, thus there is an increased risk regarding chemical degradation. Risks are caused by T_{avg}>20°C and RH_{avg}>50% (Martens, 2012). However, these values are based on reference values and do not consider the climate in which an object is stored previously. It would be interesting to conduct more research into this. In addition, it would also be interesting to add more (modern) object types into the specific climate risk assessment tool, since the type of collection differs per museum and therefore different indoor climate specifications would be optimal for different museums.

The guidelines of the ATG for museums tool were developed in a state-of-the-art museum. The ATG guidelines could be too strict for the monumental building part of the VAM due to the different building envelope structure. Further research is needed to create thermal comfort guidelines for museums with a monumental envelope. In addition, it would be useful to include an 80% acceptance class in the guidelines since thermal comfort is not the main priority in museums.

In the numerical study of this research, setpoint strategies have been implemented in a calibrated numerical model. To get more accurate predictions, validation of the reference simulation model would be needed. The real setpoints should be included (which are T=20-22°C and RH=51% in the monumental building part). Also the real air inlet velocity in the exhibition room should be measured to be able to calculate the mass flow. The mass flow is needed for determining the power use. The power use could be imported in HAMBase to better match the capacities of the HVAC systems. When the new building management system is implemented in the VAM (summer 2018), it could be possible to save more data parameters due to the larger saving capacity of the computer system, such as the percentages of recirculation and the power use of the HVAC system itself.

In addition to changing the T and RH setpoints, (structural) measures can be implemented in the numerical reference model to research their impact on the indoor climate (T and RH) of the monumental building part. Some possible measures are: 1) changing the current roof structures for structures with a higher thermal resistance, 2) increasing the thermal resistance of the internal plenum structures, 3) natural ventilation of the plenum with outdoor air when the T in the plenum is above 26°C (Engelen, 2006). Appendix Y provides a first perception of the potential effect of these three measures on the indoor climate (T and RH) of the exhibition rooms and the plenums. The study concludes that the third measure is the most interesting option considering to improve the indoor climate (T and RH) of both the exhibition rooms and the plenums. In addition to the numerical setpoint strategy study, the measures have been implemented in a calibrated numerical model. To get more accurate predictions, validation of the reference simulation model would be needed. Besides the potential effects on the indoor climate (T and RH), other aspects such as the monumental value, the constructional implementation, investment costs, and quality of (day)light, should be considered as well in future research in order to let the VAM make a well-considered decision before implementing any measure.

The results of the three simulated measures have shown that plenum related measures have a significant impact on the indoor climate (T and RH) of the exhibition rooms, due to the thermal radiation effects of the internal plenum structures. To further study the thermal radiation effects of the internal plenum structures, the plenums and exhibition rooms should modeled in COMSOL, since it is impossible to extract the radiation temperature of a single surface from HAMBase.

Some other problems in the VAM related to the indoor climate (T and RH) are not examined in this research, but do require further research. These problems are moisture problems in the basement and former depots, the high inlet rate in the tower, and the lack of controlling the indoor climate of a single room (DIY room).

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9 Appendices

Appendix A. ASHRAE climate classes

Table 9.1: ASHRAE climate classes; Temperature and Relative Humidity Specifications for Collections (ASHRAE, 2011).

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Set Point or Annual Average</th><th colspan="3">Maximum Fluctuations and Gradients in Controlled Spaces</th><th rowspan="2">Collection Risks and Benefits</th></tr>
<tr><th>Class of Control</th><th>Short Fluctuations plus Space Gradients</th><th>Seasonal Adjustments in System Set Point</th></tr>
<tr><td rowspan="6">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</td><td rowspan="6">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</td><td>AA
Precision control, no seasonal changes, with system failure fallback</td><td>±5% RH, ±2K</td><td>Relative humidity no change
Up 5K;
down 5K</td><td>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.</td></tr>
<tr><td rowspan="2">A
Precision control, some gradients or seasonal changes, not both, with system failure fallback</td><td>As
±5% RH, ±2K</td><td>Up 10% RH,
down 10% RH
Up 5K;
down 10K</td><td rowspan="2">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.</td></tr>
<tr><td>A
±10% RH, ±2K</td><td>RH no change
Up 5K;
down 10K</td></tr>
<tr><td>B
Precision control, some gradients plus winter temperature setback</td><td>±10% RH, ±5K</td><td>Up 10% RH,
down 10% RH
Up 10K but not above 30°C</td><td>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.</td></tr>
<tr><td>C
Prevent all high-risk extremes</td><td colspan="2">Within 25 to 75% RH year-round
Temperature rarely over 30°C, usually below 25°C</td><td>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.</td></tr>
<tr><td>D
Prevent dampness</td><td colspan="2">Reliably below 75% RH</td><td>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.</td></tr>
</table>

Appendix B. Floor plans Van Abbemuseum

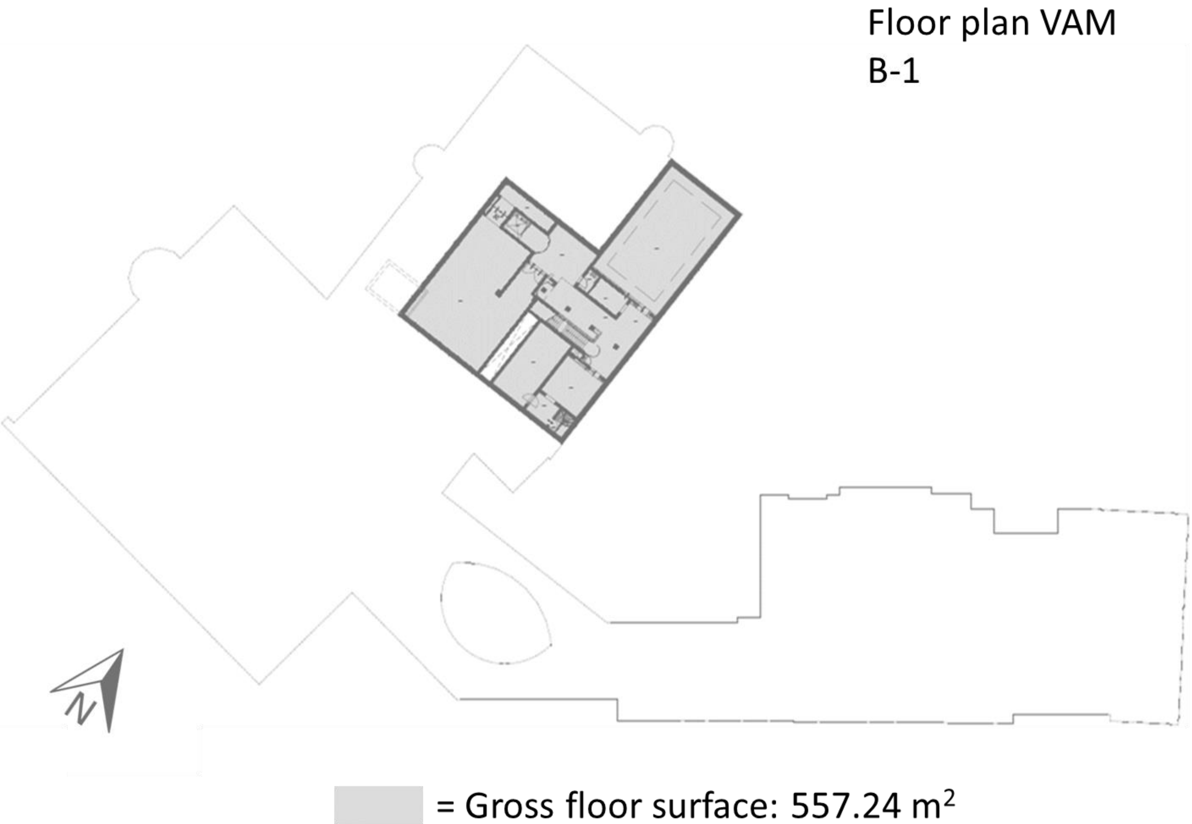


Figure 9.1: Floor plan B-1, floor plan under layer by Cahen (2003).

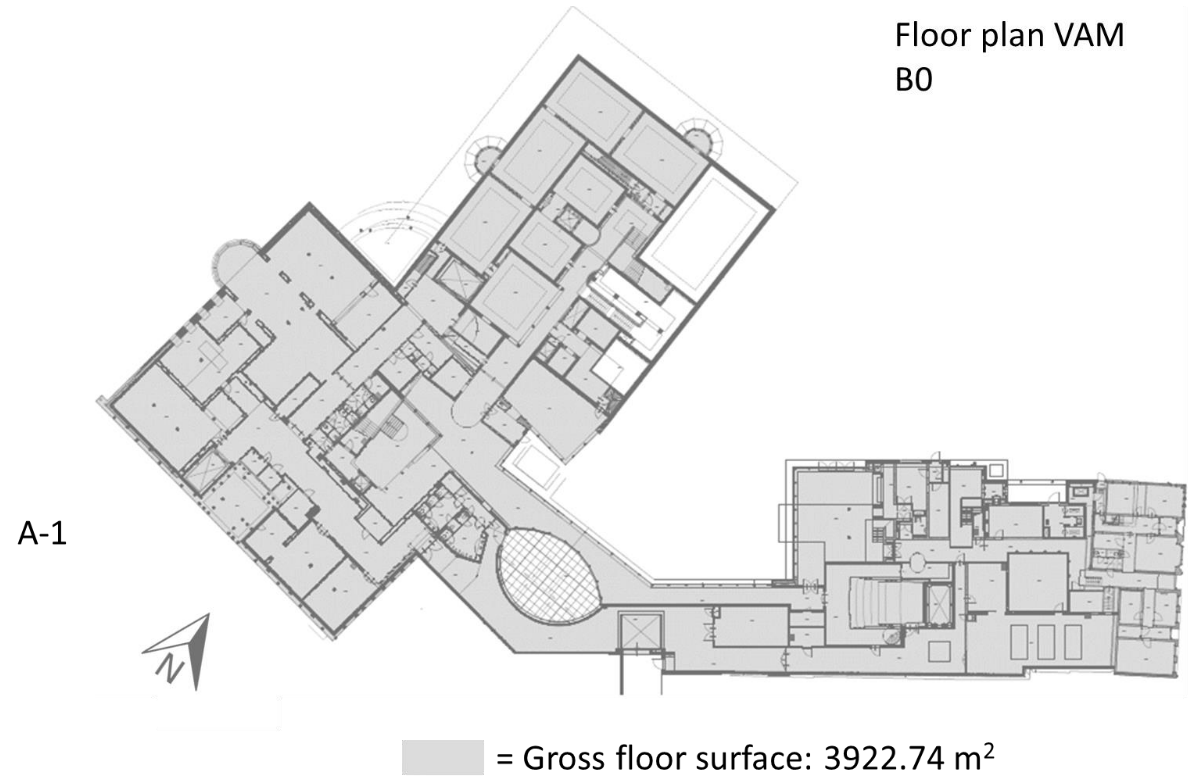


Figure 9.2: Floor plan A-1 and B0, floor plan under layer by Cahen (2003).

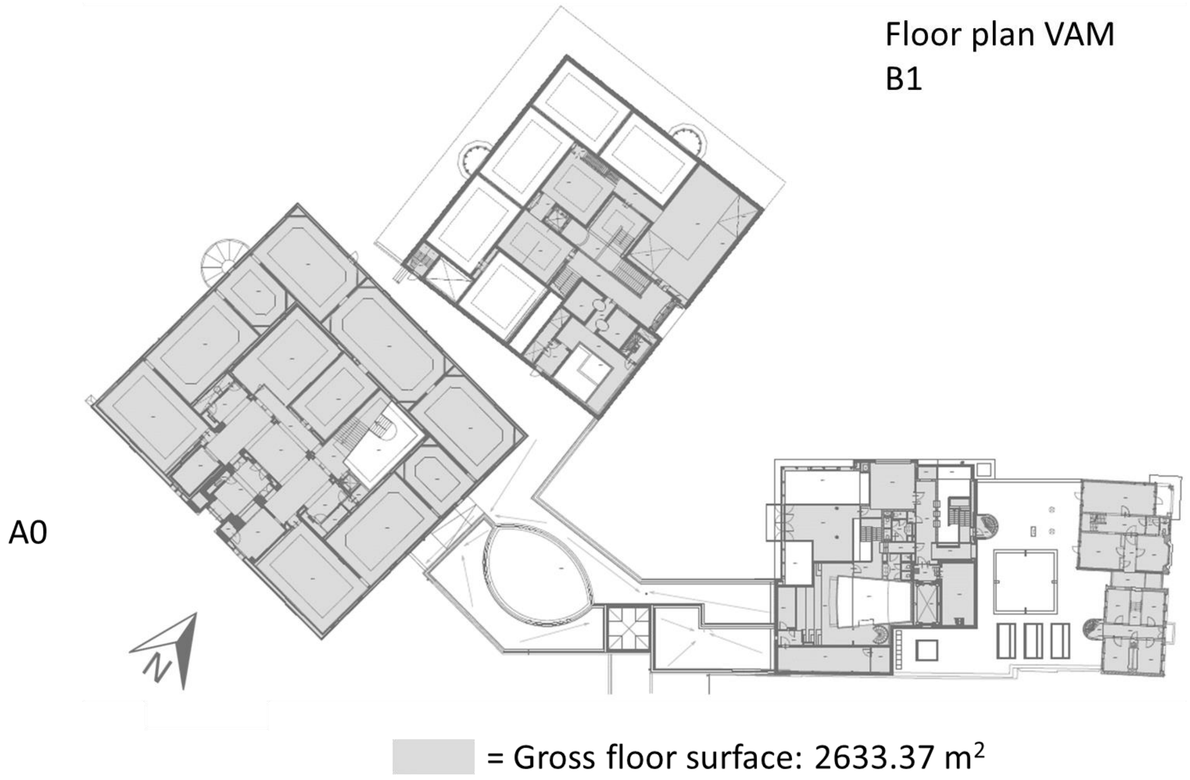


Figure 9.3: Floor plan A0 and B1, floor plan under layer by Cahen (2003).

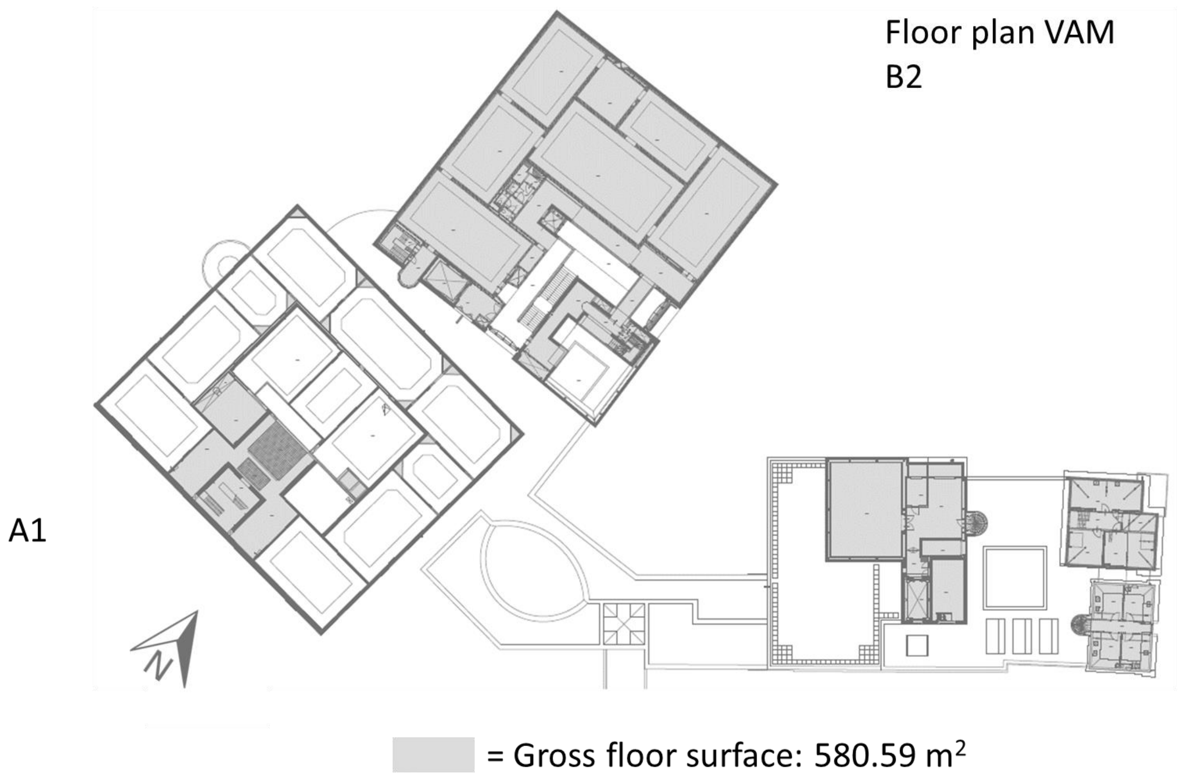


Figure 9.4: Floor plan A1 and B2, floor plan under layer by Cahen (2003).

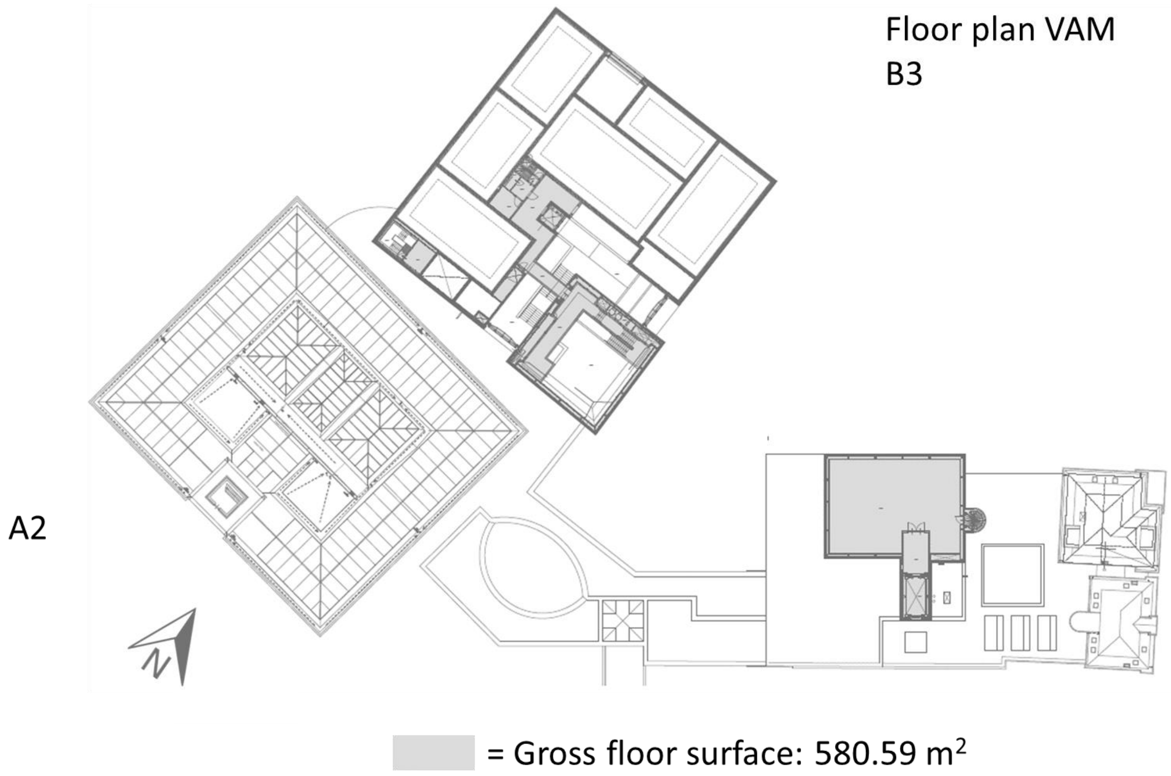


Figure 9.5: Floor plan A2 and B3, floor plan under layer by Cahen (2003).

Appendix C. Overview building Van Abbemuseum

Figure 9.6: Exterior VAM.

Figure 9.7: Interior, monumental building part A.

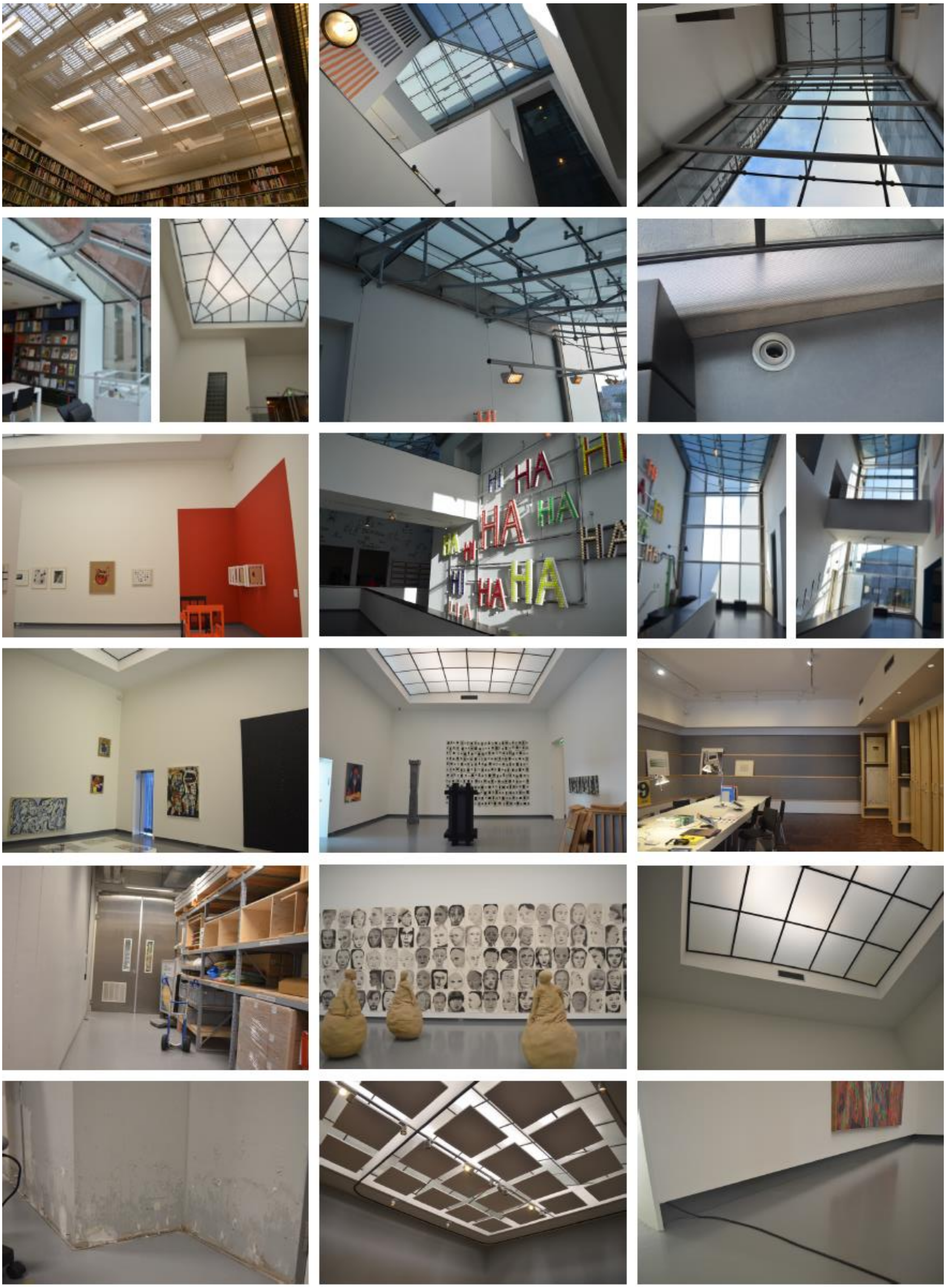


Figure 9.8: Interior, modern building part B.

Appendix D. Structure types monumental building part A, exhibition rooms

Figure 9.9: Structure types monumental building part A, floor plan under layer by Cahen (2003). All the walls of exhibition rooms have an extra double wall with a layer of multiplex and plasterboard.

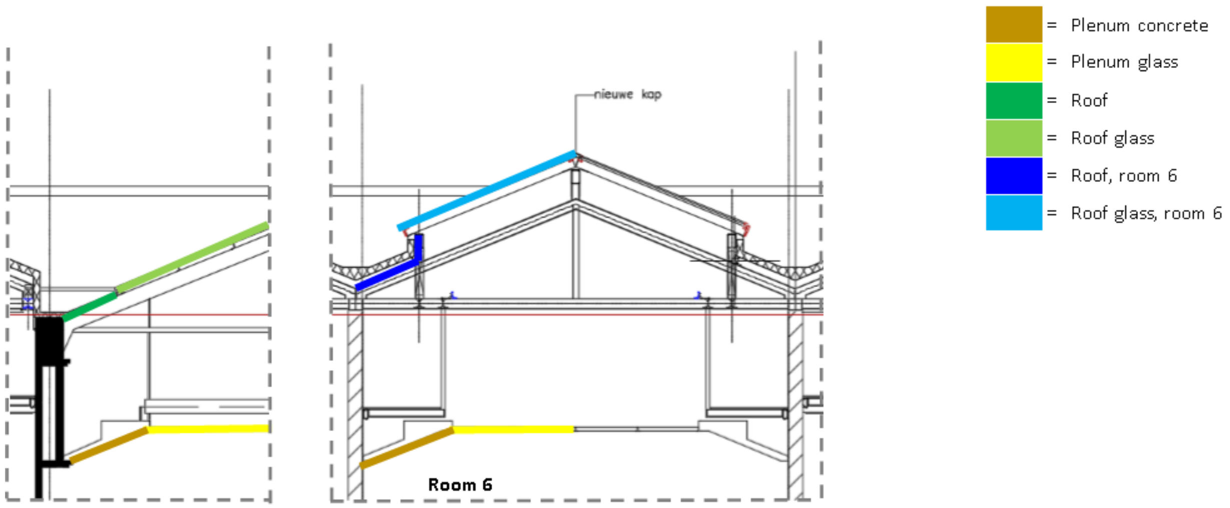


Figure 9.10: Structure types monumental building part A. Sections under layer by Cahen (2003).

An overview of the materials per structure type are shown below. All the walls of the exhibition rooms have an extra double wall (meranti multiplex 18mm + plasterboard 12mm, see Figure 9.11). Walls with a fire protection door (room 1, 6 and 10) have an extra double wall: structure of wood.

Facades:

Double wall	85mm
Brickwork	100mm
Cavity	170-400mm
Brickwork	130mm

Façade openings:

Frame of steel	
Double glass	
Door of wood	40mm

Inner walls 1:

Brickwork	220mm

Inner walls 2:

Brickwork	100mm
Cavity	200mm
Brickwork	100mm

Inner walls 3:

Brickwork	100mm

Inner walls 4:

Brickwork	100mm
Cavity	200mm
Brickwork	100mm
Cavity	80mm
Brickwork	150mm

Floor 150mm

Screed	30mm
Concrete	120mm

Floor 180mm

Concrete	180mm

Floor 150mm

Concrete	150mm

Plenum concrete:

Concrete	150mm

Plenum glass:

Steel structure	
Blasted wired safety glass	

Roof:

Steel structure	
Wood	37mm
Bitumen	4mm

Roof glass:

Steel structure	
Polycarbonate channel plates	20mm

Roof, room 6:

Steel structure	
Insulation	100mm
Bitumen	4mm

Roof glass, room 6:

Steel structure	
Polycarbonate channel plates	20mm

Figure 9.11: Structure types monumental building part A. South façade, interior exhibition room, double wall, plenum concrete, polycarbonate channel plate, roof view, plenums, polycarbonate channel plate structure covered with non-translucent plastic sheets above room 5.

Appendix E. Structure types modern building part B, exhibition rooms

An overview of the materials per structure type are shown below. All the walls of exhibition rooms have an extra double wall with a thickness of 85mm.

Basement walls:

Concrete	350mm
Insulation	100mm

Facades:

Concrete	150mm
Insulation	100mm
Flammet natural stone	40mm

Glass surfaces (façade and roof):

Frame of steel/RVS
HR++ glass

Fire protection doors:

Steel	50mm

Inner walls:

Concrete	200mm-250mm

Basement floor:

Screed	50mm
Concrete	350mm
Insulation	100mm

Floors:

Screed	50mm
Concrete	200mm-400mm

Plenum structure:

Plasterboard	12mm
Steel structure	

Plenum glass:

Steel structure
Double layered safety glass

Roof:

Steel structure	
Concrete/aerated concrete	200mm
Insulation	100mm
Bitumen	4mm
Lamellae + polycarbonate channel plates	20mm

Figure 9.12: Structure types modern building part B. North and east façade, glass surfaces, interior exhibition room, plenum between floors, plenum below upper roof.

Appendix F. AHU ventilation schemes building part A and B

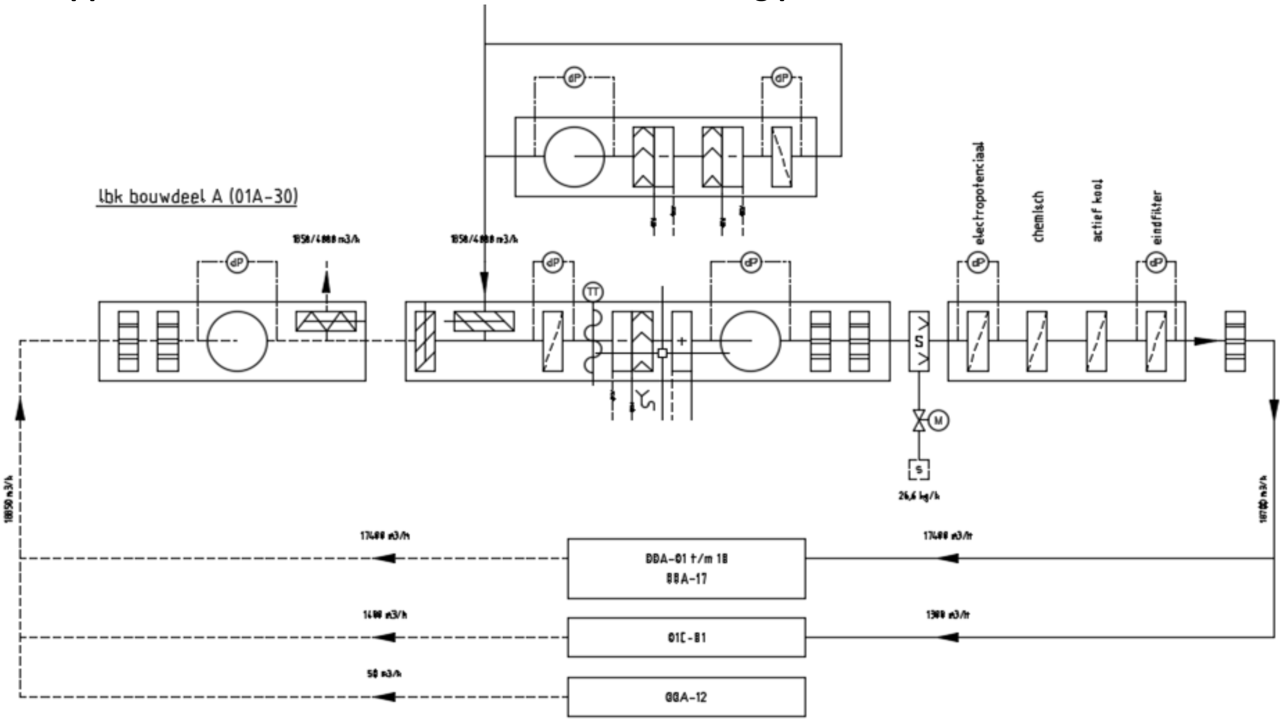


Figure 9.13: Air Handling Unit ventilation scheme of the monumental building part A (Nelissen, 2000).

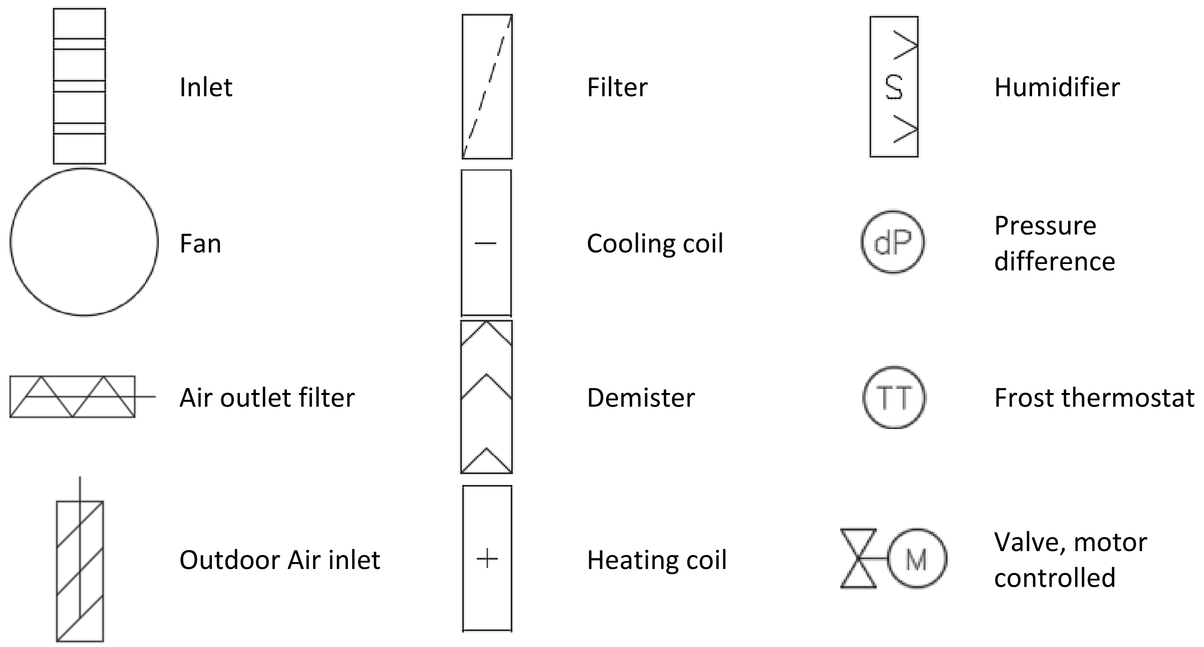


Figure 9.14: Air Handling Unit symbols.

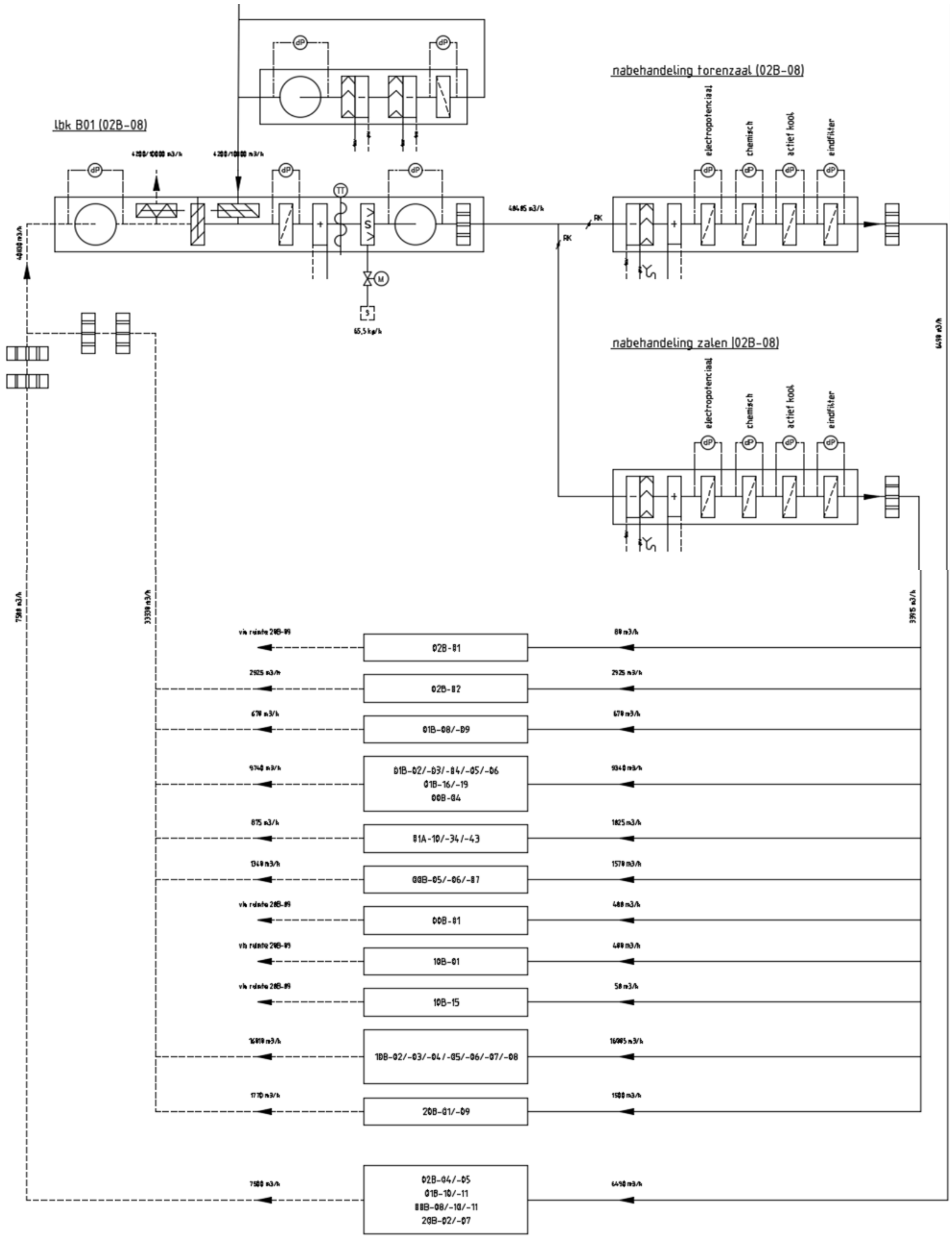


Figure 9.15: Air Handling Unit ventilation scheme of the modern building part B (Nelissen, 2000).

Appendix G. Measurement plan infrared thermography

The continuous measurements of the average T and RH in the rooms do not provide climate data for the entire indoor climate. An indoor climate is almost never uniform distributed, with local deviations as result. These local deviations can be determined with for instance, infrared (IR) thermograms. Infrared thermography (IRT) measurements are non-destructive testing (NDT) periodic measurements, and can be performed with an IR camera.

IR (wavelength band 780 – 1,000,000nm) has a longer wavelength than visible light (wavelength band 380 – 780nm), and is therefore invisible for the human eye (DIN 5031, 1982). Thermal imaging helps to “see” and “measure” thermal energy emitted from an object, heat is emitted from everything with a T above absolute zero. The higher the T of an object, the larger the emitted IR radiation. An IR camera detects IR energy (heat), and transforms it into electronic signals. These signals are converted to a thermal image (Flir, 2016). Thermal images can show the insulating features of the building envelope and the presence of thermal bridges and air leaks.

IR thermograms of the building have been conducted in both the monumental and modern building part of the Van Abbemuseum, part A and B, with the ‘FLIR systems ThermaCAM S65 HS’ IR camera, ID0835. For every IR thermogram, the T and RH at that moment have been noted, including the time and the location of the picture, and an extra visual picture was made. The thermograms give an overview of the T distribution over a relative wide surface area, in which the T differences can be determined by 0.08°C, with an accuracy of ±2°C (Flir systems, 2004). See Figure 9.16 for the technical specifications of the IR camera.

TECHNICAL SPECIFICATIONS

IMAGING PERFORMANCE	
Thermal:	
Field of view/min focus distance	24°x18° /0.3 m (with 35 mm lens)
Spatial resolution (IFOV)	1.3 mrad
Thermal sensitivity	0.08°C at 30°C
Image frequency	50/60 Hz non-interlaced
Focus	Automatic or manual
Electronic zoom function	2,4,8 interpolating
Detector type	Focal Plane Array (FPA), uncooled microbolometer 320 x 240 pixels
Spectral range	7.5 to 13μm
Digital image enhancement	Normal and enhanced
Visual:	
Built-in digital video	640 x 480 pixels, full color
IMAGE PRESENTATION	
Video output	RS170 EIA/NTSC or CCIR/PAL composite video and IEEE-1394 FireWire output (full radiometric data)
Viewfinder	Built-in, high-resolution color LCD (TFT)
External display	4" LCD with integrated remote control
MEASUREMENT	
Temperature range	-40°C to +1,500°C (-40°F to +2,732°F) Up to +2,000°C (3632°F), optional
Accuracy	±2°C, ±2% of reading
Measurement mode	Spot/manual (up to 10 movable), automatic placement and reading of max. and min. temperature within area. Area (circle or box, up to 10 movable), isotherm (2), line profile, Delta T
Atmospheric transmission correction	Automatic, based on inputs for distance, atmospheric temperature and relative humidity
Optics transmission correction	Automatic, based on signals from internal sensors
Emissivity correction	Variable from 0.1 to 1.0 or select from listings in pre-defined materials list
Reflected ambient temperature correction	Automatic, based on input of reflected temperature
External optics/window correction	Automatic, based on input of optics/window transmission and temperature
IMAGE STORAGE	
Type	Removable Flash-card (256 MB) - Built-in Flash memory (50 images) Built-in RAM memory for AVI and burst recording
File formats - Thermal	Standard JPEG, 14 bit measurement data included
File formats - Visual	Standard JPEG (including movable marker) linked with corresponding thermal image
Voice annotation of images	30 sec. of digital voice "clip" stored together with the image Bluetooth wireless headset
Text annotation of images	Predefined text selected and stored together with the image
LENSES (OPTIONAL)	
Field of view/min focus distance	7°x5.3°/4 m (with 122 mm lens) 12°x 9°/1.2 m (with 71 mm lens) 45°x 34°/0.1 m (with 18 mm lens) 80°x 60°/0.1 m (with 9 mm lens) 200μm close-up (64 mm x 48 mm/150 mm) 100μm close-up (34 mm x 25 mm/80 mm) 50μm close-up (15 mm x 11 mm/19mm) 18μm close-up (6 mm x 4 mm/7mm)
Lens identification	Automatic
SYSTEM STATUS INDICATOR	
LCD Display	Shows status of battery and storage media. Indication of power, communication and storage modes

LASER LOCATIR™	
Classification	Class 2
Type	Semiconductor AlGaInP Diode Laser: 1mW/635 nm red
BATTERY SYSTEM	
Type	Li-Ion, rechargeable, field replaceable
Operating time	2 hours continuous operation
Charging system	in camera (AC adapter or 12 V from car) or 2 bay intelligent charger
External power operation	AC adapter 110/220 V AC, 50/60 Hz or 12 V from car (cable with Std plug: optional)
Power saving	Automatic shutdown and sleep mode (user selectable)
ENVIRONMENTAL SPECIFICATION	
Operating temperature range	-15°C to +50°C (5°F to 122°F)
Storage temperature range	-40°C to +70°C (-40°F to 158°F)
Humidity	Operating and storage 10% to 95%, non-condensing
Encapsulation	IP 54 IEC 529
Shock	Operational: 25G, IEC 68-2-29
Vibration	Operational: 2G, IEC 68-2-6
PHYSICAL CHARACTERISTICS	
Weight	2.0 kg incl. battery and top handle (includes remote control, LCD, video camera and laser) - 1,4 kg excluding battery and remote control with LCD
Size	100mm x 120mm x 220 mm (3.9"x4.7"x8.7") camera body
Tripod mounting	1/4" - 20
INTERFACES	
FireWire	IEEE-1394 FireWire output (standard, full radiometric data)
USB / RS-232	Image (thermal and visual), measurement, voice and text transfer to PC
IrDA	Wireless communication
Remote control	Top carrying handle with video camera, Laser LocatIR and LCD

Figure 9.16: Technical specifications FLIR systems ThermaCAM S65 HS: Infrared camera for scientific applications (Flir systems, 2004).

To get useful IR thermograms, in which the effect of thermal bridges is visible, there should be a large T difference between the indoor and outdoor climate. When the sun radiates on the façade, even during a very cold day, the solar radiation should be taken into account since the solar radiation has a large impact on T_s.

During the IRT measurements, extra attention should be given to reflecting materials, for example glass of showcases or windows of the building. Reflecting materials reflect a part of the radiation from the surrounding areas, this can lead to an unreal, inaccurate and confusing IR thermograms.

IR thermograms are made on February 17th 2016 in the morning and on July 20th 2016 in the afternoon, to get a good representation of the local T deviations in a winter and a summer situation. During both measurement moments, the sun shone on the south and east facades. The outdoor conditions during the measurements are shown in Table 9.2.

Table 9.2: Outdoor conditions during IRT measurements, values from (KNMI, 2017).

Variable	Temperature [°C]		Relative humidity [%]	
	February 17th 2016	July 20th 2016	February 17th 2016	July 20th 2016
Min	-4.8	20.2	61	35
Max	5.1	33.9	93	90
Average	-0.3	26.4	80	59
During IR measurement	1.2, 10AM-11AM	33.6, 2PM-3PM	75, 10AM-11AM	35, 2PM-3PM

The IR thermograms have been mostly conducted at the same locations, for the comparison between the seasonal climate situations. In addition, IR thermograms have been conducted of the bottom surface of every internal plenum structure on July 20th 2016 to compare the T_s of the different internal plenum structures. Figure 9.17 and Figure 9.18 show the locations, Table 9.3 and Table 9.4 show the T and RH of the locations during the IR thermogram moment. The T and RH on February 17th 2016 are measured with a handheld device: 'IAQ-Calc Indoor Air Quality Meter Model 7545', ID2196. The T and RH on July 20th 2016 are measured with another handheld device: 'Rotronic HygroPalm 21 Humidity & Temperature Meter', ID2854.

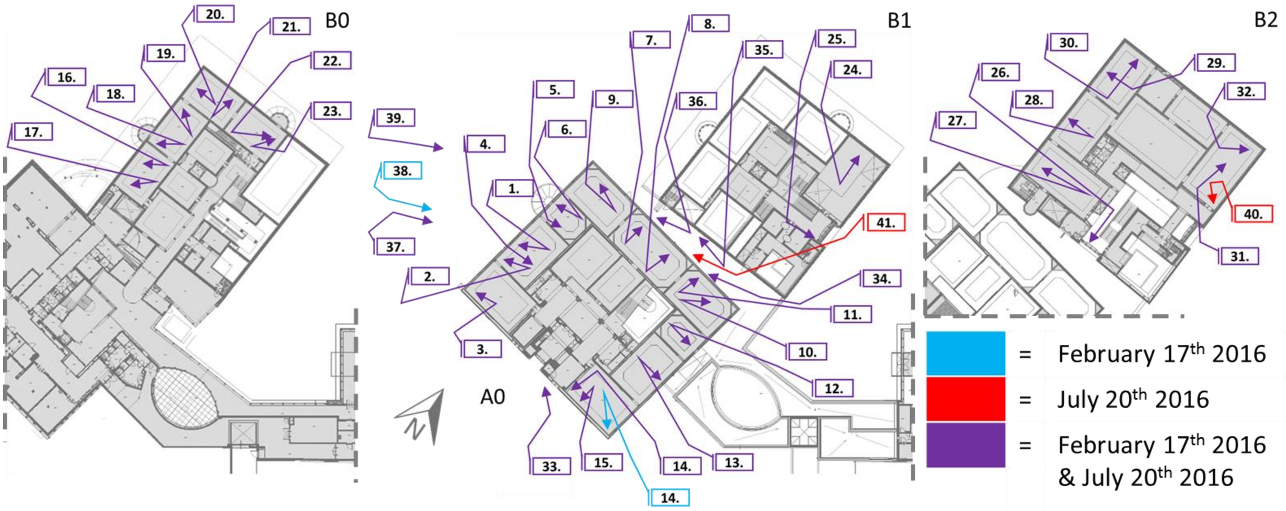


Figure 9.17: IRT, measurement locations B0, A0, B1, and B2, floor plan under layer by Cahen (2003).

Table 9.3: Additional information IR thermograms taken at February 17th 2016 and July 20th 2016.

Image number	Location	February 17th 2016			July 20th 2016		
		Time [hh:mm]	T [°C]	RH [%]	Time [hh:mm]	T [°C]	RH [%]
0	A0, entrance hall.	10:30	20.7	42.6	-	-	-
1	A0, room 2, upper corner, partly adjacent to outside.	09:52	19.5	48.4	13:54	19.5	48.4
2	A0, room 2, total corner, partly adjacent to outside.	09:55	19.5	48.4	13:55	19.5	48.4
3	A0, room 1, lower corner, fully adjacent to outside. Solar radiation on facade	09:58	19.4	48.0	13:56	24.2	47.6
4	A0, room 2, roof with open lamellae. Solar radiation on roof.	10:02	19.5	48.4	13:57	19.5	48.4
5	A0, room 3, roof with closed lamellae. Solar radiation on roof.	10:03	19.2	47.2	13:59	26.5	41.6
6	A0, room 3, screened window.	10:05	19.2	47.2	14:00	26.5	41.6
7	A0, room 5, wall adjacent to outside.	10:10	19.5	46.1	14:02	23.9	48.4
8	A0, room 5, wall adjacent to outside.	10:12	19.5	46.1	14:02	23.9	48.4
9	A0, room 4, total corner, fully adjacent to outside.	10:14	19.1	47.3	14:03	24.1	47.8
10	A0, room 7, total corner, fully adjacent to outside. Solar radiation on façade.	10:18	19.4	49.0	14:05	23.5	49.4
11	A0, room 7, total corner, partly adjacent to outside.	10:18	19.4	49.0	14:05	23.5	49.4
12	A0, room 8, window. Solar radiation on facade	10:21	19.3	48.4	14:07	24.6	46.8
13	A0, room 9, wall adjacent to outside. Solar radiation on façade.	10:23	19.7	48.2	14:08	25.7	43.8
14	A0, room 10, total corner, fully adjacent to outside. Solar radiation on façade.	10:25	19.8	47.3	14:10	26.3	41.6
15	A0, room 10, wall adjacent to outside. Solar radiation on façade.	10:25	19.8	47.3	14:12	26.3	41.6
16	B0, wall adjacent to outside.	10:36	20.1	44.7	14:17	21.5	52.7
17	B0, roof with open lamellae. Solar radiation on roof.	10:37	20.1	44.7	14:19	21.5	52.7
18	B0, wall/corner partly adjacent to outside, entrance to orangery.	10:40	19.9	45.5	14:21	21.0	52.7
19	B0, wall/corner partly adjacent to outside.	10:40	19.9	45.5	14:21	21.0	52.7
20	B0, wall adjacent to outside.	10:41	19.7	45.7	14:22	21.9	50.5
21	B0, wall adjacent to outside.	10:43	19.7	45.7	14:22	21.9	50.5
22	B0, wall/corner partly adjacent to outside, entrance to orangery.	10:44	19.6	46.5	14:24	21.9	50.5
23	B0, upper corner and roof, wall partly adjacent to outside.	10:44	19.6	46.5	14:24	21.9	50.5
24	B1, wall adjacent to outside.	10:50	20.2	46.0	14:26	20.5	54.4
25	B1, glass façade adjacent to outside. Solar radiation on facade	10:53	19.7	45.6	14:29	22.3	49.6
26	B2, glass façade adjacent to outside. Solar radiation on facade	10:54	19.3	47.3	14:30	22.6	48.0
27	B2, wall adjacent to outside.	10:59	18.8	47.8	14:31	21.4	51.4
28	B2, wall adjacent to outside.	11:01	18.8	49.4	14:32	20.8	53.6
29	B2, wall adjacent to outside.	11:02	18.7	49.6	14:33	20.8	53.6
30	B2, wall adjacent to outside.	11:03	18.7	49.6	14:34	20.8	53.6
31	B2, wall adjacent to outside.	11:05	19.2	49.4	14:37	21.2	52.5
32	B2, total corner fully adjacent to outside. Solar radiation on facade	11:07	19.2	49.4	14:37	21.2	52.5
33	Outside, monumental building part, entrance, south façade. Solar radiation on façade	11:12	5.0	46.8	13:07	33.0	41.7

34	Outside, monumental building part, north façade.	11:14	5.0	46.8	13:11	33.0	41.7
35	Outside, modern building part, south façade. Solar radiation partly on facade	11:15	5.0	46.8	13:15	33.0	41.7
36	Outside, monumental building part, north façade.	11:16	5.0	46.8	13:16	33.0	41.7
37	Outside, monumental building part, west façade.	11:18	1.9	56.6	13:20	33.0	41.7
38	Outside, monumental building part, west façade.	11:18	1.9	56.6	-	-	-
39	Outside, monumental and modern building part, west façade.	11:19	1.9	56.6	13:20	33.0	41.7
40	B2, total corner, one wall adjacent to outside. Solar radiation on facade	-	-	-	14:38	21.2	52.5
41	Outside, monumental and modern building part, west façade.	-	-	-	13:11	33.0	41.7

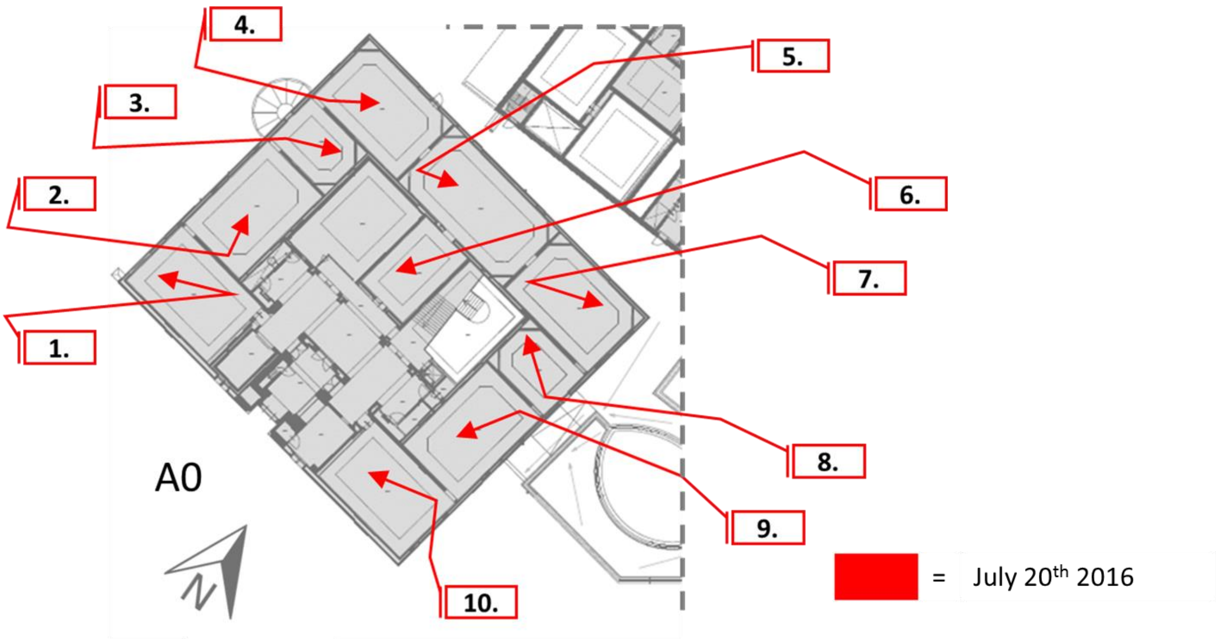


Figure 9.18: IRT bottom surface internal plenum structures, measurement locations A0, floor plan under layer by Cahen (2003).

Table 9.4: Additional information IR thermograms bottom surface internal plenum structures taken at July 20th 2016.

Image number	Location	Time [hh:mm]	T [°C]	RH [%]
1	Room 1, closed lamellae. Solar radiation.	14:43	24.0	48.7
2	Room 2, closed lamellae. Solar radiation.	14:46	24.7	47.4
3	Room 3, closed lamellae. Solar radiation.	14:48	24.5	48.1
4	Room 4, closed lamellae. Solar radiation.	14:48	24.3	48.2
5	Room 5, closed lamellae + polycarbonate channel plate. Solar radiation.	14:50	23.8	49.0
6	Room 6, open lamellae. Solar radiation.	14:50	23.4	51.4
7	Room 7, closed lamellae. Solar radiation.	14:53	24.0	48.6
8	Room 8, closed lamellae. Solar radiation.	14:53	24.5	47.0
9	Room 9, open lamellae. Solar radiation.	14:55	25.7	43.8
10	Room 10, open lamellae. Solar radiation.	14:56	26.0	42.8

With the software program 'ThermaCAM Researcher Professional 2.8 SR-1' the IR thermograms can be edited at a later moment, for example changing the plotted T range, the room T and RH, and the emission factor of the surfaces looked at. The IR thermograms can be exported in the ThermaCAM software program to Matlab-files, which can be used to make a hygrogram, showing the RH near the surface. The hygrogram can be made by using a Matlab-tool developed by (Schellen, 2002). In this tool the IR thermograms have to be imported, the room T and RH have to be given and the preferred T and RH ranges have to be provided. The output is a composition of a 'surface temperature'-plot and a 'relative humidity near the surface'-plot.

The Matlab-tool makes use of equations. Equation 2 calculates the absolute RH near the surface. The vapor saturation pressure (Psat) is dependent of the surface T, see Equation 3 and Equation 4. The partial vapor pressure (Pv) in the air depends on the T and RH in the room and is determined with Equation 5, Equation 6, and Equation 7.

$$RH_s = \frac{Pv}{Psat\ (T_s)} \qquad \text{Equation 2}$$

With:

RH_s	=	Relative humidity near a surface in %.
RH_i	=	Relative humidity air in %.
Psat	=	Saturated vapor pressure near a surface in Pa.
Pv	=	Partial vapor pressure in Pa.
T_s	=	Surface temperature in °C.
T_i	=	Air temperature in °C.

$$For\ \theta \geq 0\,°C: \quad Psat\ (T_s) = 611 * \exp\ (17.08 * T_s)/(234.18 + T_s) \qquad \text{Equation 3}$$

$$For\ \theta < 0\,°C: \quad Psat\ (T_s) = 611 * \exp\ (22.44 * T_s)/(272.44 + T_s) \qquad \text{Equation 4}$$

$$Pv = RH_i * \text{Psat}\ (T_i) \qquad \text{Equation 5}$$

$$For\ \theta \geq 0\,°C: \quad Psat\ (T_i) = 611 * \exp\ (17.08 * T_i)/(234.18 + T_i) \qquad \text{Equation 6}$$

$$For\ \theta < 0\,°C: \quad Psat\ (T_i) = 611 * \exp\ (22.44 * T_i)/(272.44 + T_i) \qquad \text{Equation 7}$$

Appendix H. Measurement plan continuous measurements

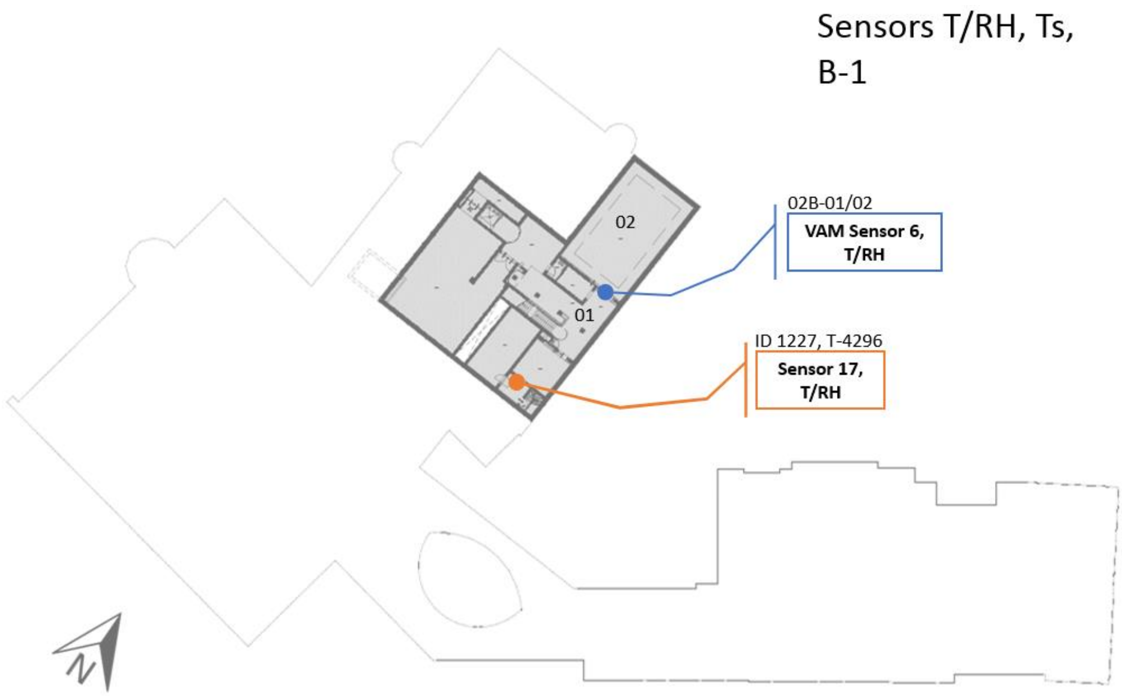


Figure 9.19: T/RH/T_s sensors, measurement locations B-1, floor plan under layer by Cahen (2003).

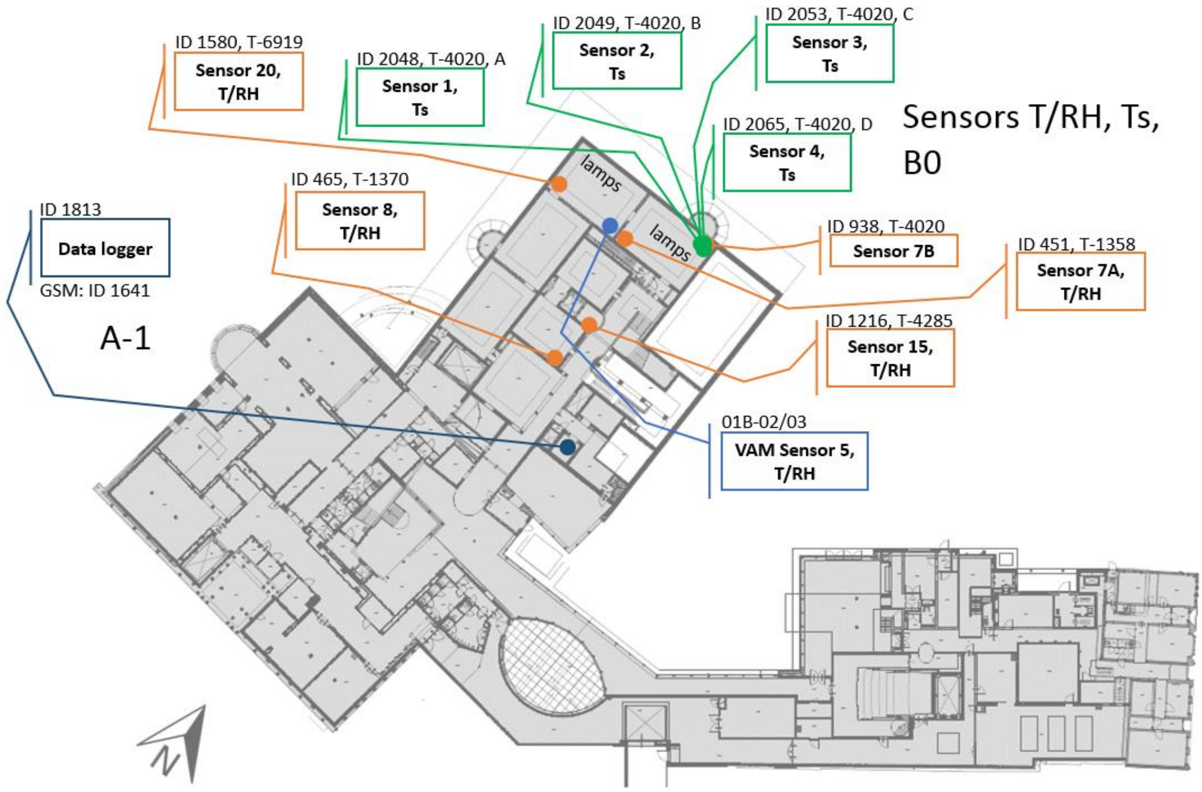


Figure 9.20: T/RH/T_s sensors, measurement locations B0, floor plan under layer by Cahen (2003).

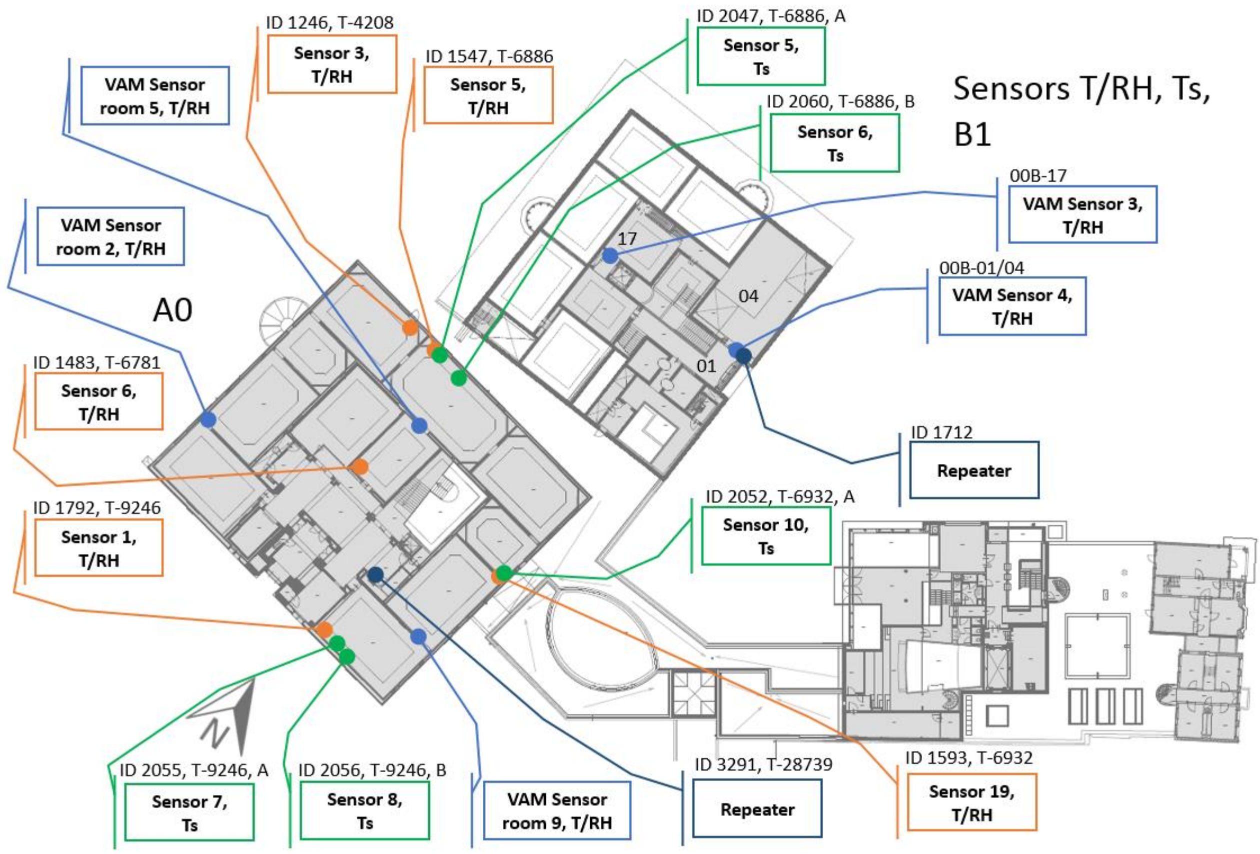


Figure 9.21: T/RH/T_s sensors, measurement locations A0 and B1, floor plan under layer by Cahen (2003).

Figure 9.22: T/RH/T_s sensors, measurement locations A1 and B2, floor plan under layer by Cahen (2003).

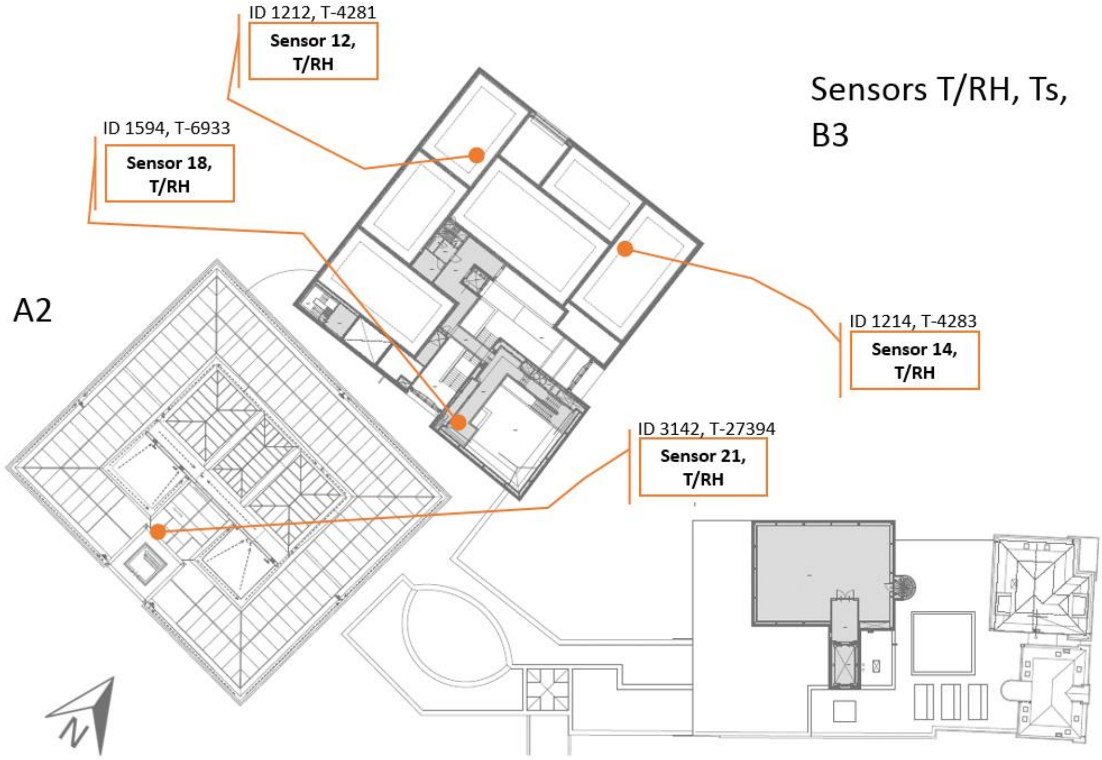


Figure 9.23: T/RH/T_s sensors, measurement locations A2 and B3, floor plan under layer by Cahen (2003).

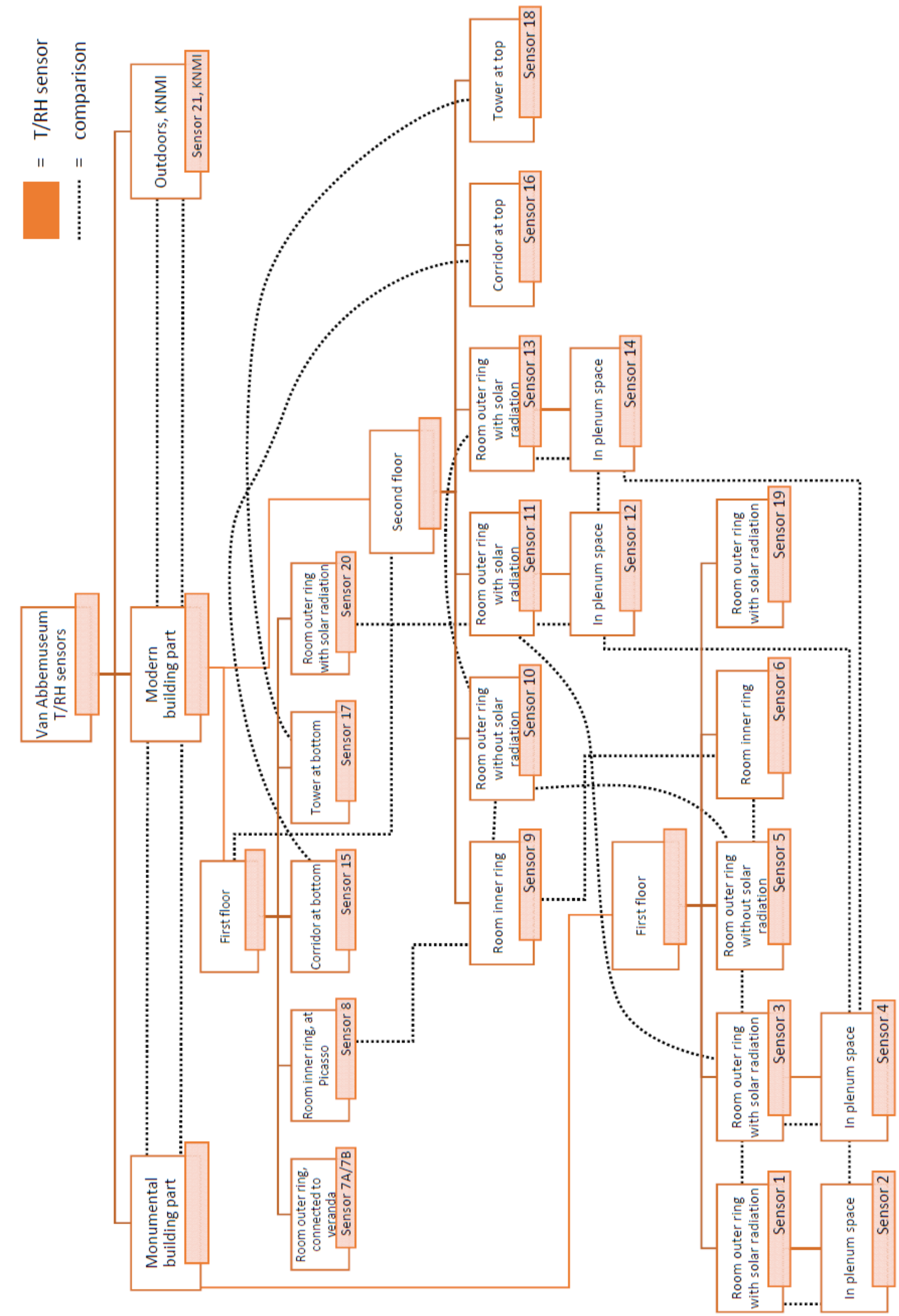


Figure 9.24: Possible comparisons of the data measured by the individual Eltek sensors, to detect differences in T_i and RH_i in the museum. It incorporates differences in the indoor climate by monumental/modern building part, 1st /2nd floor, room/plenum, rooms with/without external walls, room with/without solar radiation on the façade, corridor at bottom/top, and tower at bottom/top.

The figures below show measurement locations of the T_s sensors with the corresponding IR thermograms. Exact locations of IR thermograms can be found in Appendix G. The measurement locations of the T_s sensors are also shown in the floor plans above.

IR location 7, February 17th 2016 10:10, T_i = 19.5°C and RH_i = 46.1%

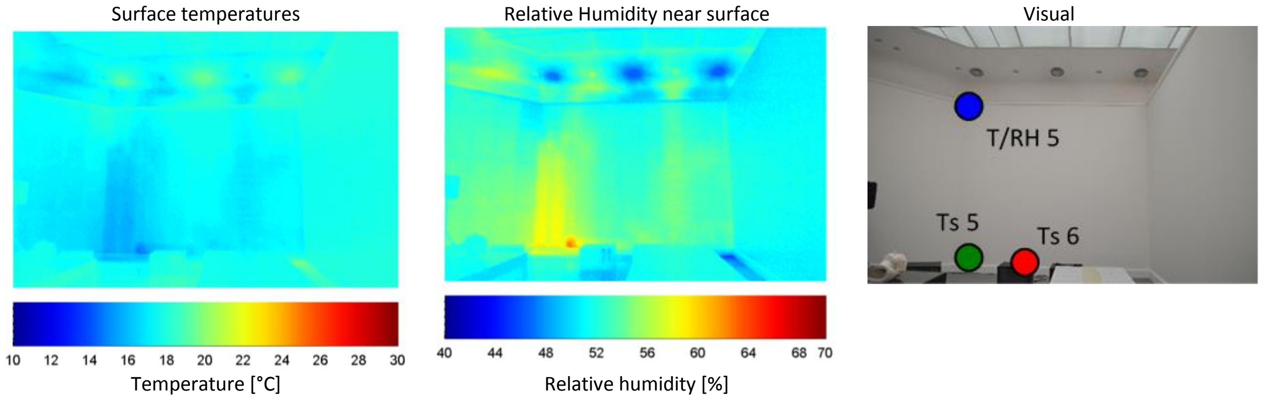


Figure 9.25: IR thermogram and hygrogram of IR measurement location 7, conducted on February 17th 2016.

IR location 15, February 17th 2016 10:25, T_i = 19.8°C and RH_i = 47.3%

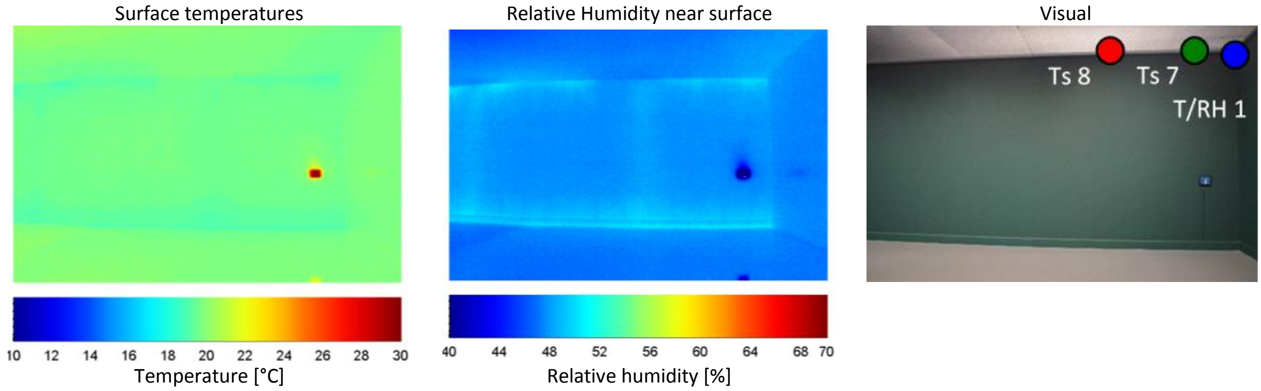


Figure 9.26: IR thermogram and hygrogram of IR measurement location 15, conducted on February 17th 2016.

IR location 30, February 17th 2016 11:03, T_i = 18.7°C and RH_i = 49.6%

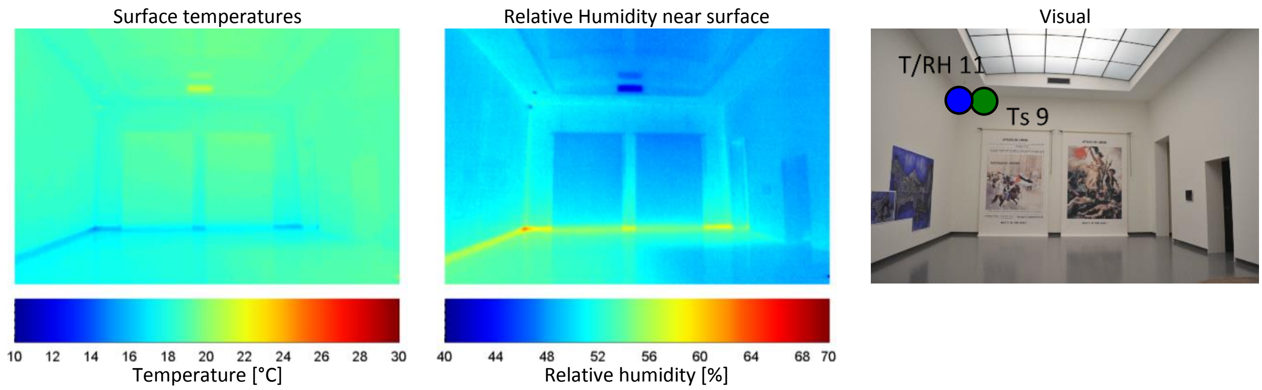


Figure 9.27: IR thermogram and hygrogram of IR measurement location 30, conducted on February 17th 2016.

IR location 12, February 17th 2016 10:21, T_i = 19.3°C and RH_i = 48.4%

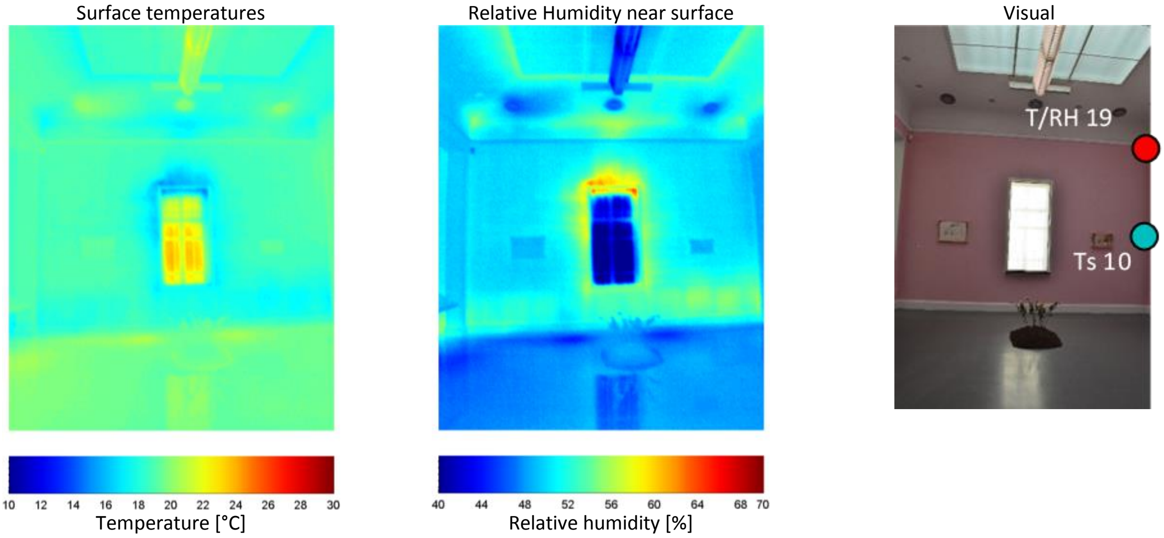


Figure 9.28: IR thermogram and hygrogram of IR measurement location 12, conducted on February 17th 2016.

IR location 40, July 20th 2016 14:38, T_i = 21.2°C and RH_i = 52.5%

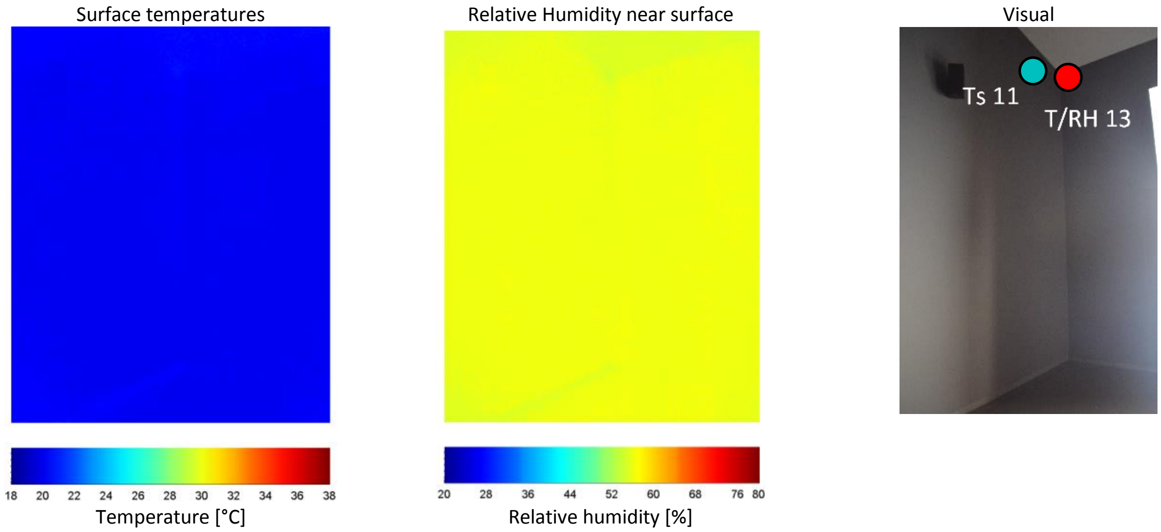


Figure 9.29: IR thermogram and hygrogram of IR measurement location 40, conducted on July 20th 2016.

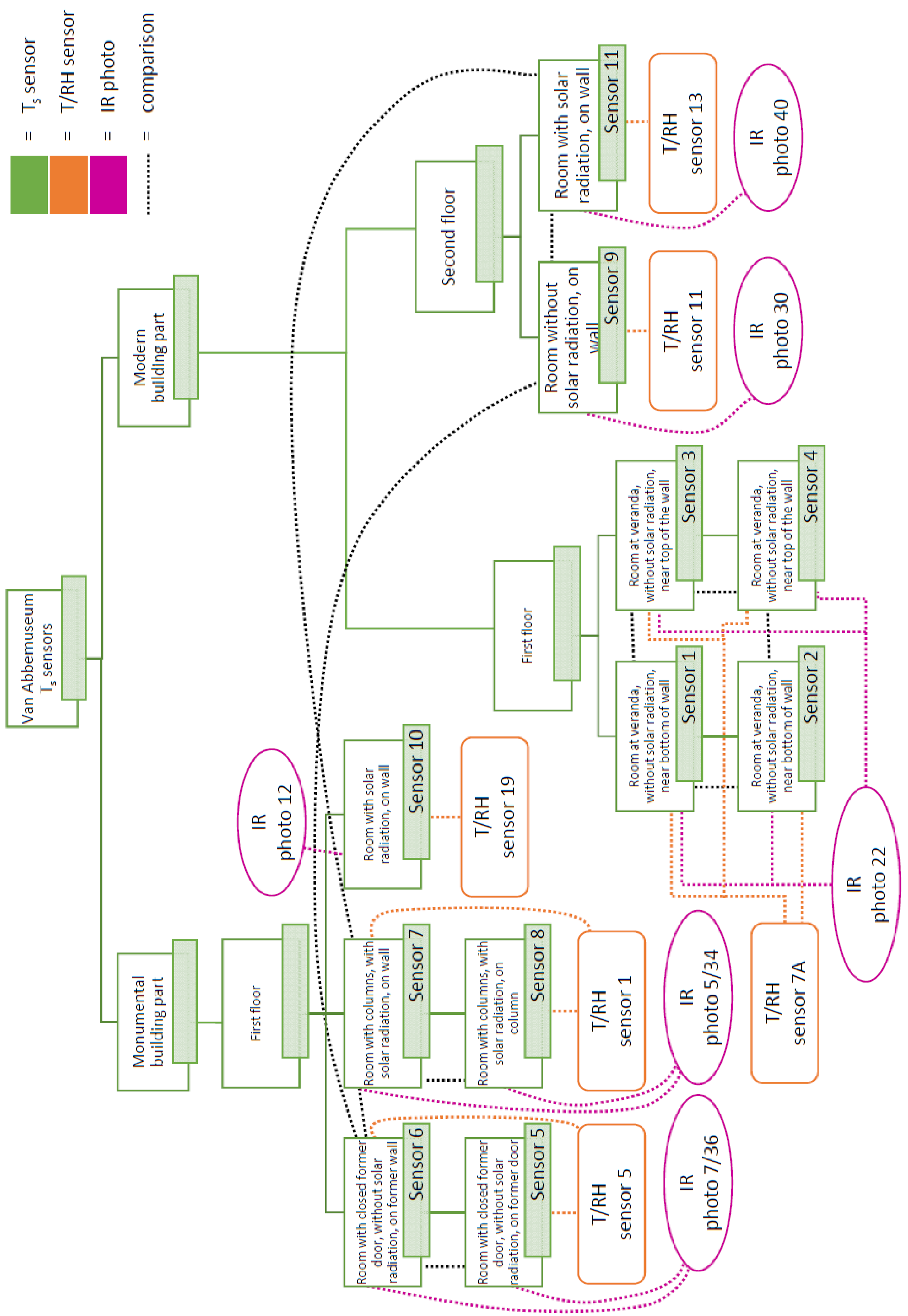


Figure 9.30: Possible comparisons of the data measured by the individual Eltek sensors, to detect differences in T_s in the museum. It incorporates differences in the indoor climate by monumental/modern building part, façade/bricked former door surface, façade/column in façade, façade with/without solar radiation, and on a façade adjacent to veranda on bottom/top.

Figure 9.31: Exact locations of the logger, repeaters and sensors. Orange circles represent T/RH sensors, green circles represent T_s sensors.

Table 9.5: Exact locations of the logger, repeaters and sensors.

Device	Location	Height [m]	Distance from corner [m]
Logger	B0 in storage room		
Repeater 1	B1 at DIY room, in closet. Left on a high shelf.		
Repeater 2	Location: A0 at reception deck. Under the white seat.		
T/RH 1		4.1, roof at 4.7	0 (placed on the double wall)
T/RH 1, Ts 7	A0, room 10	4.1	1 away from T/RH 1
T/RH 1, Ts 8	A0, room 10	4.1	3 away from T/RH 1
T/RH 2	A1, room 10, plenum		
T/RH 3	A0, room 4	3.8, roof at 4.7	0.4
T/RH 4	A1, room 4, plenum		
T/RH 5	A0, room 5	4.1, roof at 4.7	0 (placed on the double wall)
T/RH 5, Ts 5	A0, room 5	0.2	0.2
T/RH 5, Ts 6	A0, room 5	0.2	1.5
T/RH 6	A0, room 6	3.8, roof at 4.6	0.2
T/RH 7A	B0	4.9, roof at 5.3	0.4
T/RH 7B	B0	5.5 (above plenum), roof at 5.3	
T/RH 7B, Ts 1	B0	0.3	1.6
T/RH 7B, Ts 2	B0	1.9	1.6
T/RH 7B, Ts 3	B0	3.5	1.6
T/RH 7B, Ts 4	B0	5.2	1.6
T/RH 8	B0, Picasso	2.8, roof at 3.2	0.4
T/RH 9	B2	5.6, roof at 5.9	0.2
T/RH 10	B2	3.3, roof at 3.6 (above canvas)	0.2
T/RH 11	B2	5, roof at 5.3	0.2
T/RH 11, Ts 9	B2	5	0.2
T/RH 12	B3, plenum		
T/RH 13	B2	5.1, roof at 5.4	0.2
T/RH 13, Ts 11	B2	5.1	0.3
T/RH 14	B3, plenum		
T/RH 15	B0, stairs bottom	2.2 till floor B0, 6.2 till floor B-1, roof at 3.3 (bottom floor B1)	0.1
T/RH 16	B2, stairs top	0.4 till floor B2, 13.3 till floor B-1	0.1
T/RH 17	B-1, tower bottom	3.9	0.2
T/RH 18	B3, tower top	3.7	2
T/RH 19	A0, room 8	4.1, roof at 4.7	0 (placed on the double wall)
T/RH 19, Ts 10	A0, room 8	1.7	0
T/RH 20	B0	4.9, roof at 5.3	0.2
T/RH 21	A2, outside, at north façade tower		

Table 9.6: Logger and repeater specifications of the measurement setup.

Device	Type	ID	Start date	Location
Logger Eltek	Squirrel 1000 series, RX250AL PHEBE	1813	4-7-2016	B0 storage room
GSM modem	Fargo Maestro 100 , number 06-20628950	1641	4-7-2016	B0 storage room
Repeater Eltek	GenII RP250GD	1712	5-12-2016	B1 DIY room
Repeater Eltek	GenII RP250GD, T-28739	3291	6-2-2017	A0 reception deck

Table 9.7: Sensor specifications of the measurement setup, part 1 of 2.

Chan-nel	Sensor VAM	ID	Serie no.	Tra-ns	Para-meter	Unit	Device	Type	Range	Accuracy	Start date	Location
1	T/RH 1, Ts 7	2055	9246	A	Ts,i	°C	Eltek - U type Thermistor	GenII GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)	4-7-2016	A0, room 10
2	T/RH 1, Ts 8	2056	9246	B	Ts,i	°C	Eltek - U type Thermistor	GenII GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)	4-7-2016	A0, room 10
3	T/RH 1	1792	9246	C	Ti	°C	Eltek - Sensirion Temperature	GenII GC-14E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +65°C)	4-7-2016	A0, room 10
4	T/RH 1	1792	9246	D	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-14E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	A0, room 10
5	T/RH 2	1243	4205	A	Ti	°C	Eltek - Sensirion Temperature	Unkown	-30.0 - 65.0	Unkown	13-6-2016	A1, room 10, plenum
6	T/RH 2	1243	4205	B	RHi	% RH	Eltek - Sensirion Humidity	Unkown	0.0 - 100.0	Unkown	13-6-2016	A1, room 10, plenum
7	T/RH 3	1246	4208	A	Ti	°C	Eltek - Sensirion Temperature	GenII GC-10 Temp/RV - 30/65gr 0-100%	-30.0 - 65.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	4-7-2016	A0, room 4
8	T/RH 3	1246	4208	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-10 Temp/RV - 30/65gr 0-100%	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	A0, room 4
9	T/RH 4	1472	4675	A	Ti	°C	Eltek - Sensirion Temperature	GenII GC-13E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	13-6-2016	A1, room 4, plenum
10	T/RH 4	1472	4675	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-13E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	13-6-2016	A1, room 4, plenum
11	T/RH 5, Ts 5	2047	6886	A	Ts,i	°C	Eltek - U type Thermistor	GenII GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)	7-7-2016	A0, room 5
12	T/RH 5, Ts 6	2060	6886	B	Ts,i	°C	Eltek - U type Thermistor	GenII GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)	7-7-2016	A0, room 5
13	T/RH 5	1547	6886	C	Ti	°C	Eltek - Sensirion Temperature	GenII GC-14E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +65°C)	7-7-2016	A0, room 5
14	T/RH 5	1547	6886	D	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-14E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	7-7-2016	A0, room 5
15	T/RH 6	1483	6781	A	Ti	°C	Eltek - Sensirion Temperature	GenII GC-14E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	4-7-2016	A0, room 6
16	T/RH 6	1483	6781	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-13E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	A0, room 6
17	T/RH 7A	451	1358	A	Ti	°C	Eltek - Sensirion Temperature	GenII T/RV/ ext T	-40.0 - 120.0	Unkown	4-7-2016	B0
18	T/RH 7A	451	1358	B	RHi	% RH	Eltek - Sensirion Humidity	GenII T/RV/ ext T	0.0 - 100.0	Unkown	4-7-2016	B0
19	T/RH 7B, Ts 1	2048	4020	A	Ts,i	°C	Eltek - U type Thermistor	GenII GS-34 4xT(ntc)	-50.0 - 150.0	± 0.2˚C (-15-40˚C)	4-7-2016	B0
20	T/RH 7B, Ts 2	2049	4020	B	Ts,i	°C	Eltek - U type Thermistor	GenII GS-34 4xT(ntc)	-50.0 - 150.0	± 0.2˚C (-15-40˚C)	4-7-2016	B0
21	T/RH 7B, Ts 3	2053	4020	C	Ts,i	°C	Eltek - U type Thermistor	GenII GS-34 4xT(ntc)	-50.0 - 150.0	± 0.2˚C (-15-40˚C)	4-7-2016	B0
22	T/RH 7B, Ts 4	2065	4020	D	Ts,i	°C	Eltek - U type Thermistor	GenII GS-34 4xT(ntc)	-50.0 - 150.0	± 0.2˚C (-15-40˚C)	4-7-2016	B0
23	T/RH 8	465	1370	A	Ti	°C	Eltek - Sensirion Temperature	GenII T/RV/ ext T	-40.0 - 120.0	Unkown	13-6-2016	B0, Picasso
24	T/RH 8	465	1370	B	RHi	% RH	Eltek - Sensirion Humidity	GenII T/RV/ ext T	0.0 - 100.0	Unkown	13-6-2016	B0, Picasso
25	T/RH 9	967	1385	A	Ti	°C	Eltek - Sensirion Temperature	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	4-7-2016	B2
26	T/RH 9	967	1385	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B2
27	T/RH 10	973	4182	A	Ti	°C	Eltek - Sensirion Temperature	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	4-7-2016	B2
28	T/RH 10	973	4182	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B2
29	T/RH 11, Ts 9	2066	6900	A	Ts,i	°C	Eltek - U type Thermistor	GenII GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)	4-7-2016	B2

Table 9.8: Sensor specifications of the measurement setup, part 2 of 2.

Channel	Sensor VAM	ID	Serie no.	Trans	Parameter	Unit	Device	Type	Range	Accuracy	Start date	Location
31	T/RH 11	1561	6900	C	Ti	°C	Eltek - Sensirion Temperature	GenII GC-14E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +65°C)	4-7-2016	B2
32	T/RH 11	1561	6900	D	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-14E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B2
33	T/RH 12	1212	4281	A	Ti	°C	Eltek - Sensirion Temperature	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	13-6-2016	B3, plenum
34	T/RH 12	1212	4281	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	13-6-2016	B3, plenum
35	T/RH 13, Ts 11	2062	6913	A	Ts,i	°C	Eltek - U type Thermistor	GenII GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)	4-7-2016	B2
37	T/RH 13	1574	6913	C	Ti	°C	Eltek - Sensirion Temperature	GenII GC-14E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +65°C)	4-7-2016	B2
38	T/RH 13	1574	6913	D	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-14E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B2
39	T/RH 14	1214	4283	A	Ti	°C	Eltek - Sensirion Temperature	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	13-6-2016	B3, plenum
40	T/RH 14	1214	4283	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	13-6-2016	B3, plenum
41	T/RH 15	1216	4285	A	Ti	°C	Eltek - Sensirion Temperature	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	4-7-2016	B0, stairs bottom
42	T/RH 15	1216	4285	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B0, stairs bottom
45	T/RH 17	1227	4296	A	Ti	°C	Eltek - Sensirion Temperature	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	4-7-2016	B-1, tower bottom
46	T/RH 17	1227	4296	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GS-11 T-40/120gr RVO-100% ext T-40/70gr	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B-1, tower bottom
47	T/RH 21	3142	27394	A	Te	°C	Eltek - Sensirion Temperature	T/RV GD-13Ecf	-40.0 - 120.0	Unkown	7-7-2016	A2, outside, at N-façade tower
48	T/RH 21	3142	27394	B	Rhe	% RH	Eltek - Sensirion Humidity	T/RV GD-13Ecf	0.0 - 100.0	Unkown	7-7-2016	A2, outside, at N-façade tower
49	T/RH 16	1484	6782	A	Ti	°C	Eltek - Sensirion Temperature	GenII GC-13E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +80°C)	4-7-2016	B2, stairs top
50	T/RH 16	1484	6782	B	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-13E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B2, stairs top
51	T/RH 18	1594	6933	C	Ti	°C	Eltek - Sensirion Temperature	GenII GC-14E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +65°C)	4-7-2016	B3, tower top
52	T/RH 18	1594	6933	D	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-14E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B3, tower top
53	T/RH 19, Ts 10	2052	6932	A	Ts,i	°C	Eltek - U type Thermistor	GenII GC-14E	-40.0 - 70.0	± 0.2˚C (-15-40˚C)	7-7-2016	A0, room 8
55	T/RH 19	1593	6932	C	Ti	°C	Eltek - Sensirion Temperature	GenII GC-14E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +65°C)	7-7-2016	A0, room 8
56	T/RH 19	1593	6932	D	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-14E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	7-7-2016	A0, room 8
59	T/RH 20	1580	6919	C	Ti	°C	Eltek - Sensirion Temperature	GenII GC-14E	-40.0 - 120.0	± 0.4°C (+5 to +40°C) ± 1.0°C (-20 to +65°C)	4-7-2016	B0
60	T/RH 20	1580	6919	D	RHi	% RH	Eltek - Sensirion Humidity	GenII GC-14E	0.0 - 100.0	± 2% (10 to 90% Rh) ± 4% (0 to 100% Rh)	4-7-2016	B0

Appendix I. Measurement data supplemented and adjusted

Power failure

Due to a power failure on November 14th 2016, the T_i and RH_i were not measured by the BMS sensors in the monumental building part. The BMS corrected the archived T_i and RH_i by extremely high T_i and RH_i values of respectively 50°C and 100%, which resulted in poor climate risk assessment results.

In contrast to the BMS sensors, the Eltek sensors did measure the T_i and RH_i during the power failure because the Eltek sensors are not connected to the electrical grid. Because the T_i and RH_i data measured by both sensor types at corresponding locations have been considered similar, see Appendix P, the data measured by the BMS sensors during the power failure have been replaced by the data measured by the Eltek sensors. This have been done for the BMS sensors located at rooms 1/2 and 9/10. The data measured at these sensors have been replaced for data measured by Eltek sensor 19. To better match the BMS data, the substituted data has also been shifted a little (T_i with +1.5 and RH_i with -3.5%). See Figure 9.32 for an example of the adjustment of the data measured by the BMS sensor. The exact locations of the sensors can be found in Appendix H.

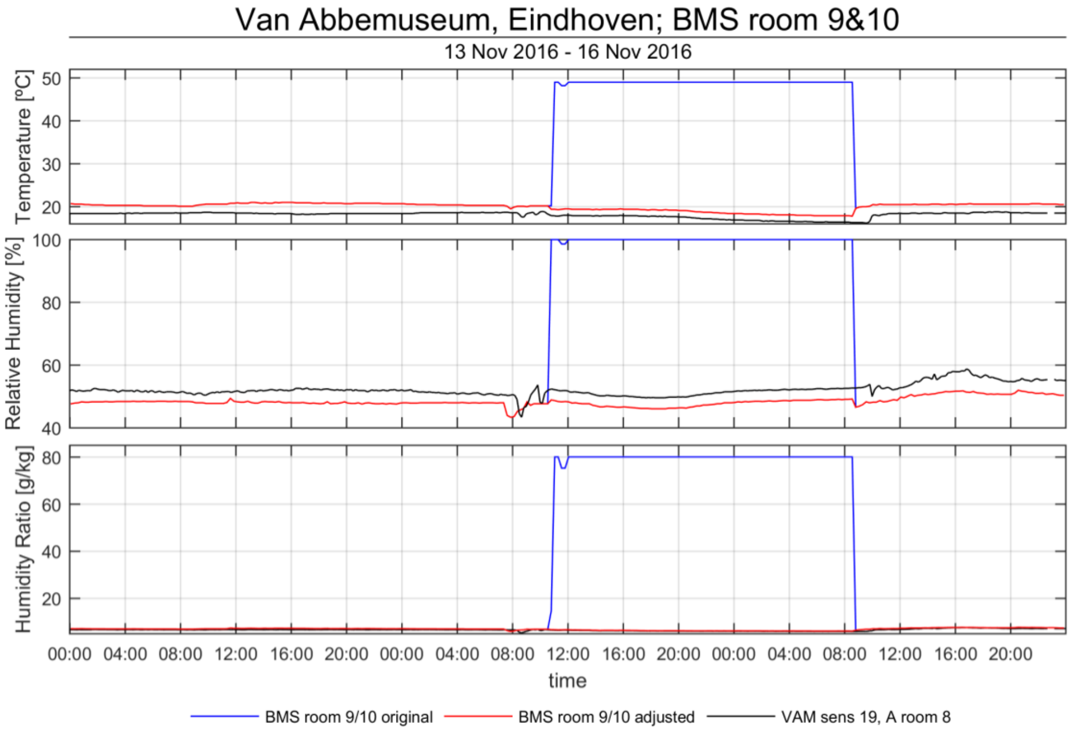


Figure 9.32: Original data measured by the BMS sensor located at room 9/10 versus Eltek sensor 19, and adjustment of the data measured by the BMS sensor during the period of the power failure on November 14th 2016.

Since the data measured during the power failure at Eltek sensor 6 did not show big differences compared to the previous days, the data measured during the power failure by the corresponding BMS sensor located at room 5/6 has been replaced by the data measured on November 13th 2016 by the same sensor. See Figure 9.33 for the adjustment of the data measured by the BMS sensor.

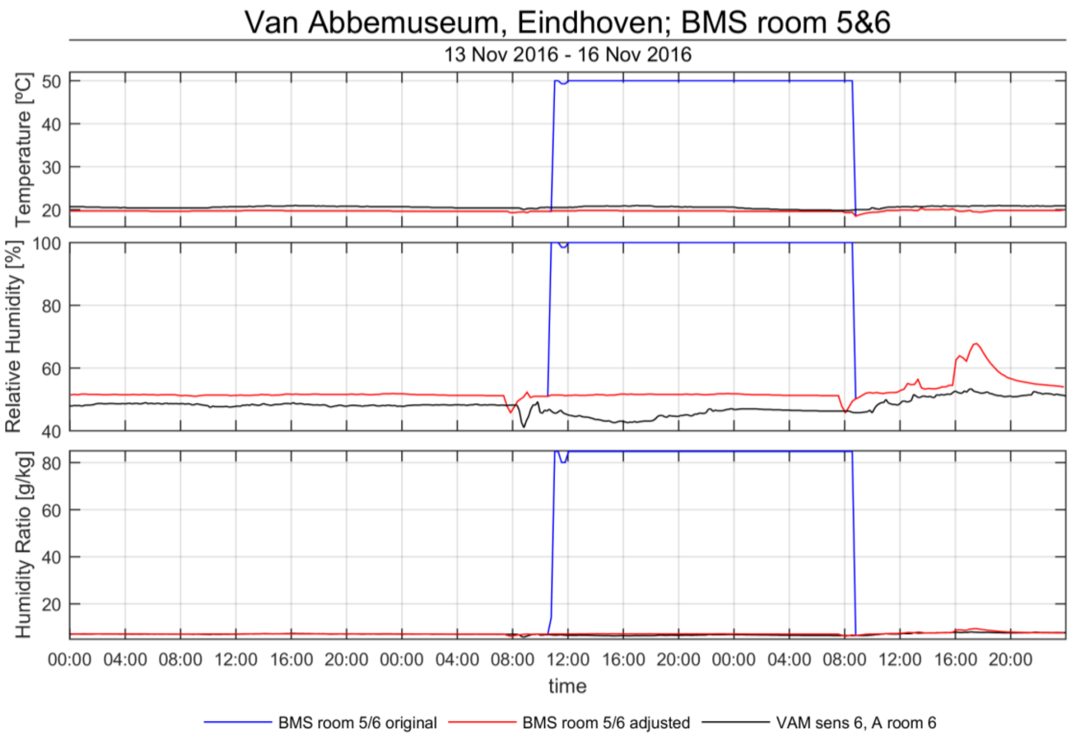


Figure 9.33: Original data measured by the BMS sensor located at room 5/6 versus Eltek sensor 6, and adjustment of the data measured by the BMS sensor during the period of the power failure on November 14th 2016.

Appendix J. Outliers measurement data, malfunctioning HVAC systems

Some of the outliers in the measured data (T and RH) in the Van Abbemuseum (VAM) can be explained by certain occurrences in the use of the museum and malfunctioning of the Heating, Ventilation, and Air Conditioning (HVAC) systems. The following paragraphs provide information about some of the outliers.

Maintenance – 18-21st April 2016

Due to maintenance in the museum, air with an increased T and decreased RH have been blown in the monumental building part, resulting in increased T_i in the rooms, while the RH_i remained similar to the past days, see Figure 9.34. Increased T and decreased RH have also been shown at the inlets of the tower and rooms of the modern building part, resulting in increased T_i and decreased RH_i in the rooms, see Figure 9.35.

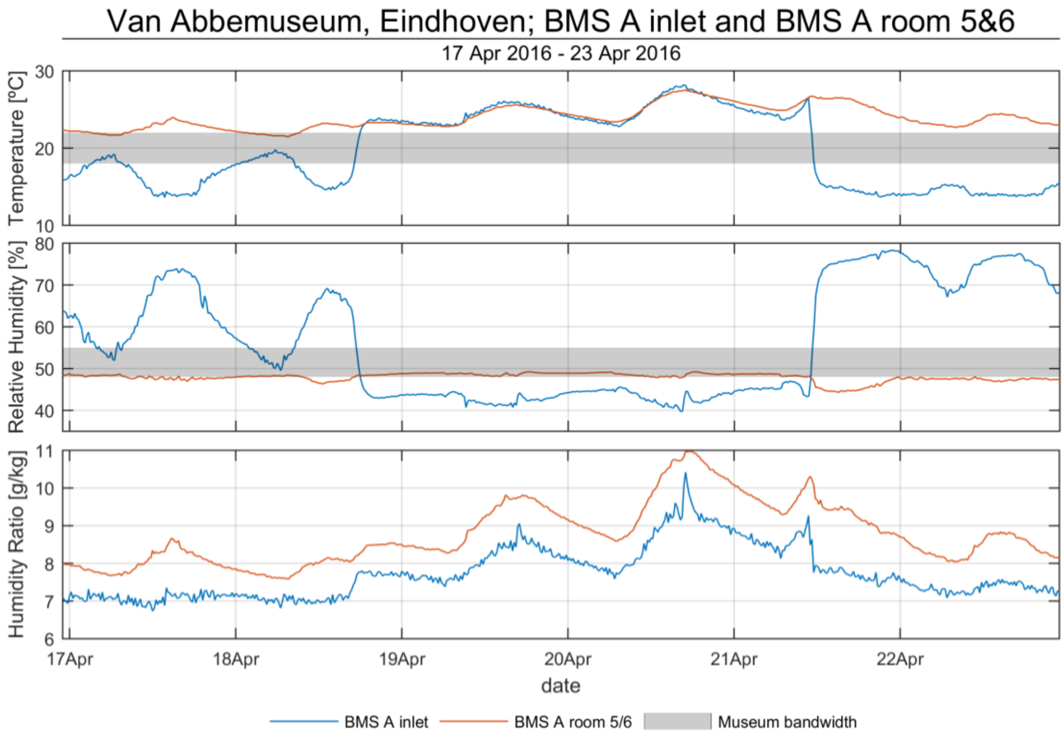


Figure 9.34: Measured T, RH, and humidity ratio for the measurement positions BMS inlet and BMS sensor room 5/6 (building part A) (April 17th 2016 till April 23rd 2016).

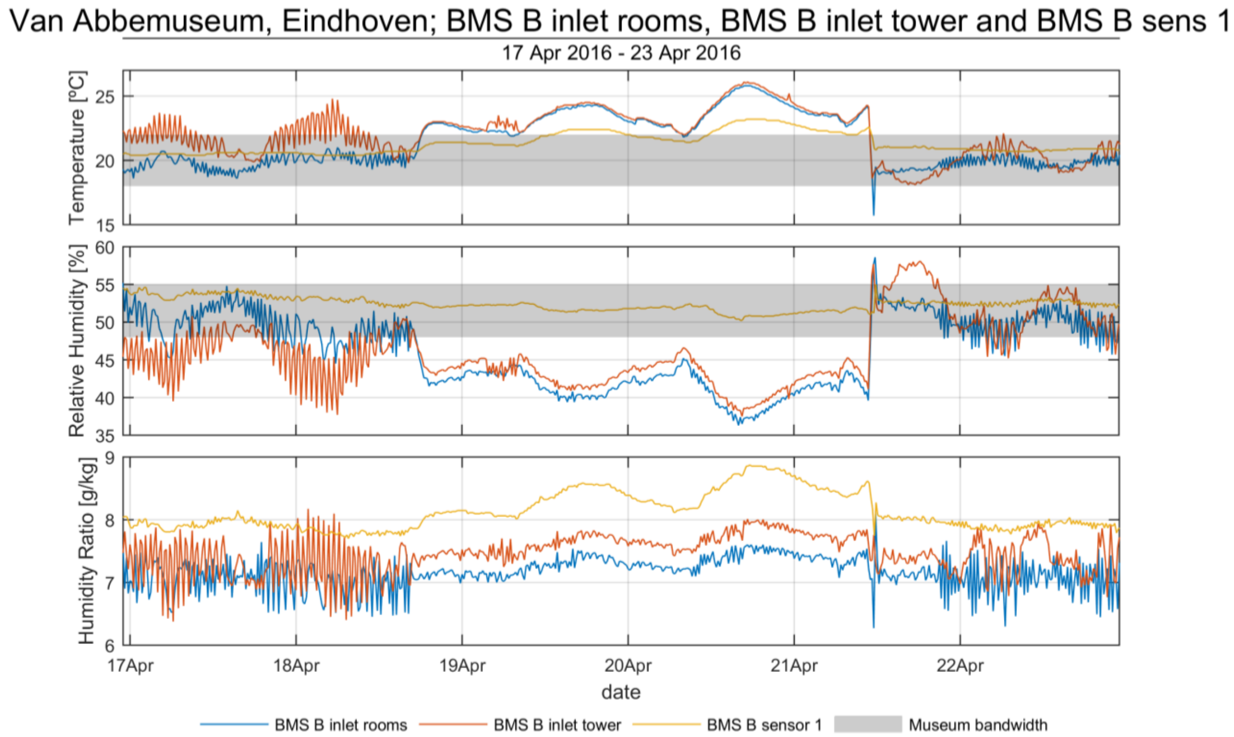


Figure 9.35: Measured T, RH, and humidity ratio for the measurement positions BMS inlet rooms, inlet tower and BMS sensor 1 (building part B) (April 17th 2016 till April 23rd 2016).

Open valves – 20-21st July 2016

It is assumed that on the 20th and 21st of July 2016 the valves of the HVAC systems of the monumental building part were opened three times. Because of that, an increased T and decreased RH were blown into the rooms. As a result, the RH_i in the rooms increased, see Figure 9.36.

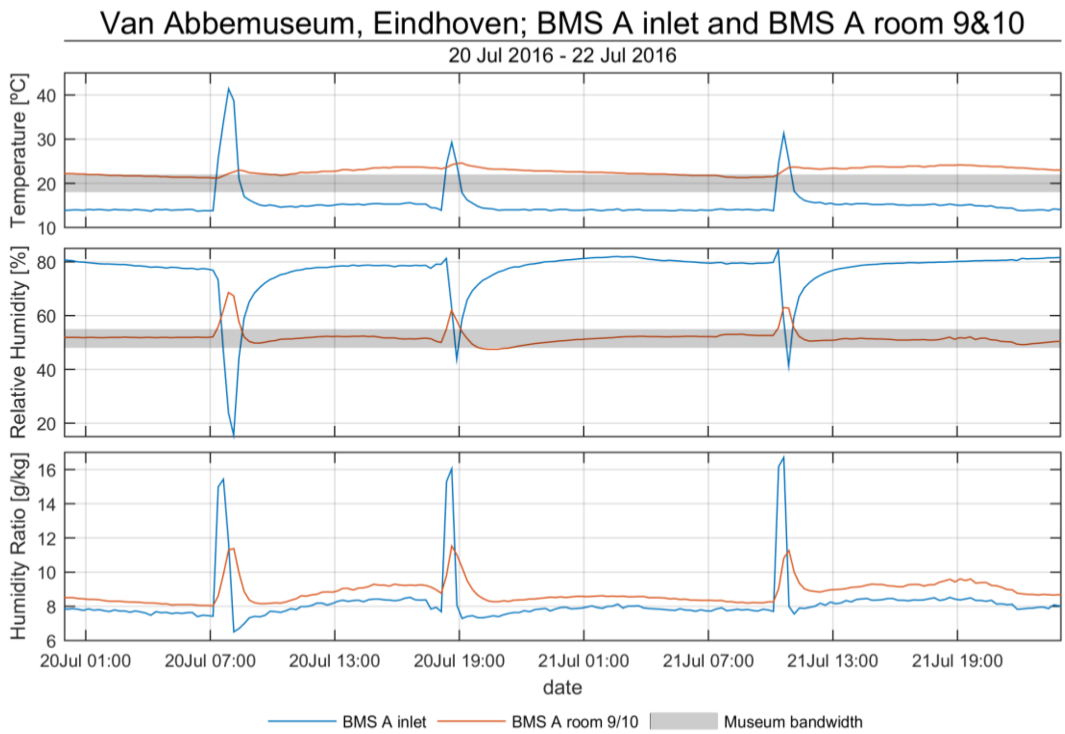


Figure 9.36: Measured T, RH, and humidity ratio for the measurement positions BMS inlet and BMS sensor room 9/10 (building part A) (July 20th 2016 till July 22nd 2016).

Power failure – November 14-15th 2016

Due to the power failure on November 14th 2016, the T_i and RH_i were not measured by the BMS sensors in the monumental building part. Since the Eltek sensors did measure during the power failure, the data of the BMS sensors could have been adjusted with the data measured by the Eltek sensors. See also Appendix I for the adjustment. The power failure resulted in T and RH fluctuations in both the monumental and modern building part, see Figure 9.37 and Figure 9.38.

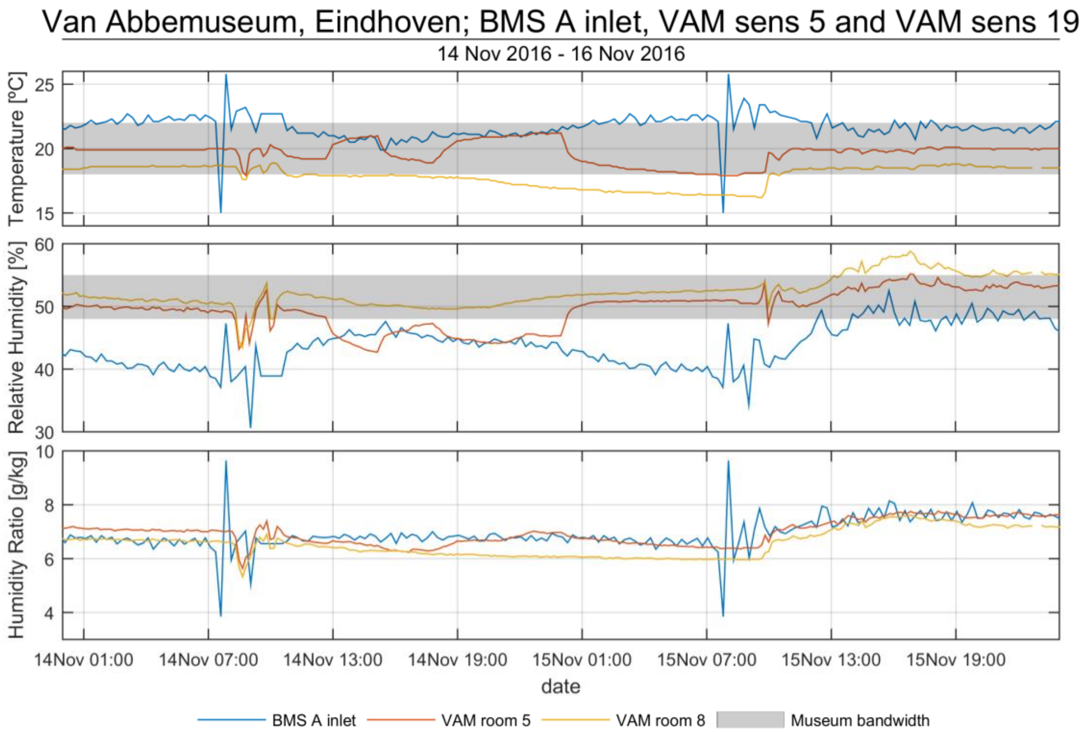


Figure 9.37: Measured T, RH, and humidity ratio for the measurement positions BMS inlet and the Eltek sensors 5 and 19 (building part A) (November 14th 2016 till November 16th 2016).

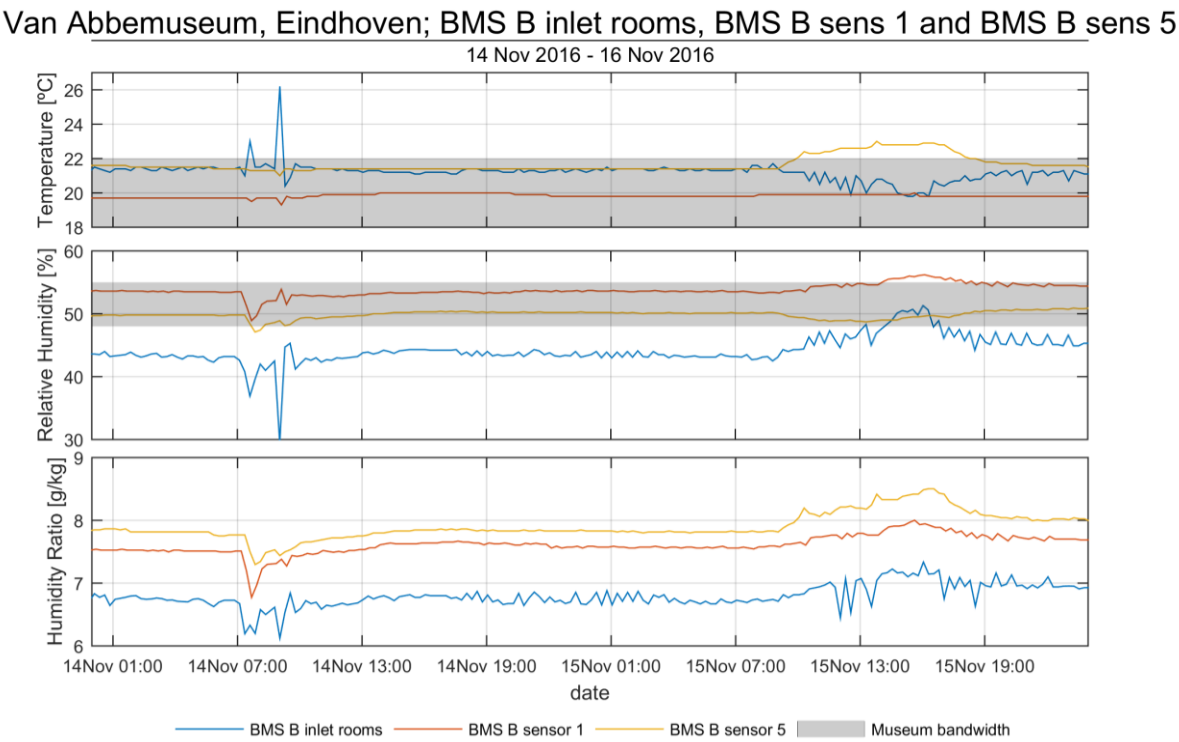


Figure 9.38: Measured T, RH, and humidity ratio for the measurement positions BMS inlet rooms and BMS sensors 1 and 5 (building part B) (November 14th 2016 till November 16th 2016).

Fire alarm – January 17-18th 2017

In the evening of January 17th 2017 the fire alarm turned on, and was turned off at 8.30PM on January 18th 2017. At 9PM a reset was conducted. In the morning, technical support has been watching at the indoor climate values. Malfunctioning of the HVAC systems did have impact on the RH_i in the monumental building part, and to a lesser extent on the T_i, see Figure 9.39. The impact on the T_i and RH_i in the modern building part was much larger and for a longer period, see Figure 9.40.

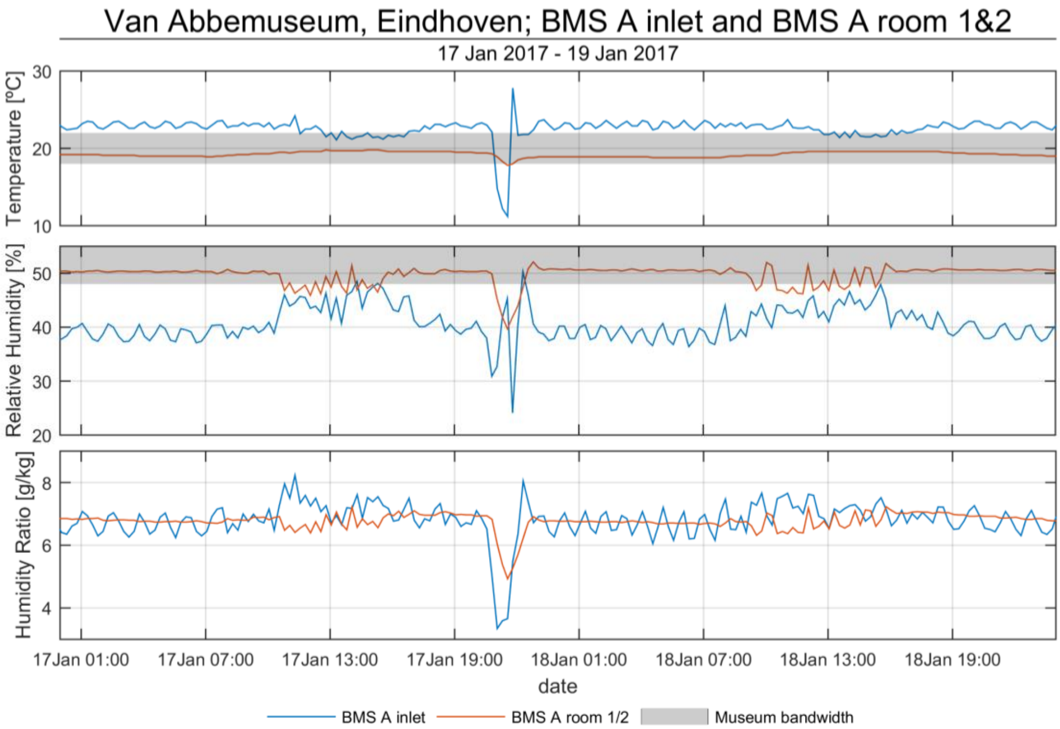


Figure 9.39: Measured T, RH, and humidity ratio for the measurement positions BMS inlet and sensor room 1/2 (building part A) (January 17th 2017 till January 19th 2017).

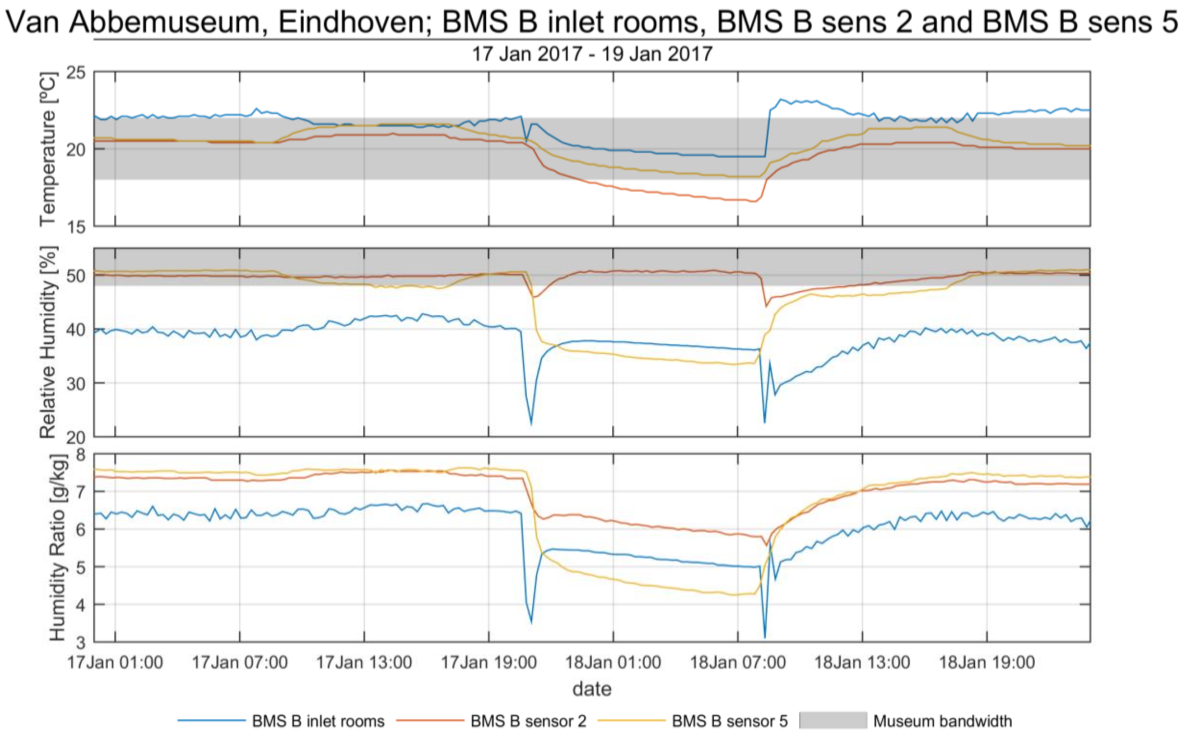


Figure 9.40: Measured T, RH, and humidity ratio for the measurement positions BMS inlet rooms and BMS sensors 2 and 5 (building part B) (January 17th 2017 till January 19th 2017).

Fire alarm – February 24th 2017

At 8AM on February 24th 2017 much steam was released due to a kettle in building part E (offices). As a result, the fire alarm went on and malfunctioning of the HVAC systems occurred. At 5PM the fire alarms were manually turned on as a test. In both the monumental and modern building part air with decreased RH was blown in the rooms during the malfunctioning period of the HVAC systems. In the monumental building part the blown in air had also an increased T. In both building parts the T_i remained nearly the same, but the RH_i showed a decrease, see Figure 9.41 and Figure 9.42.

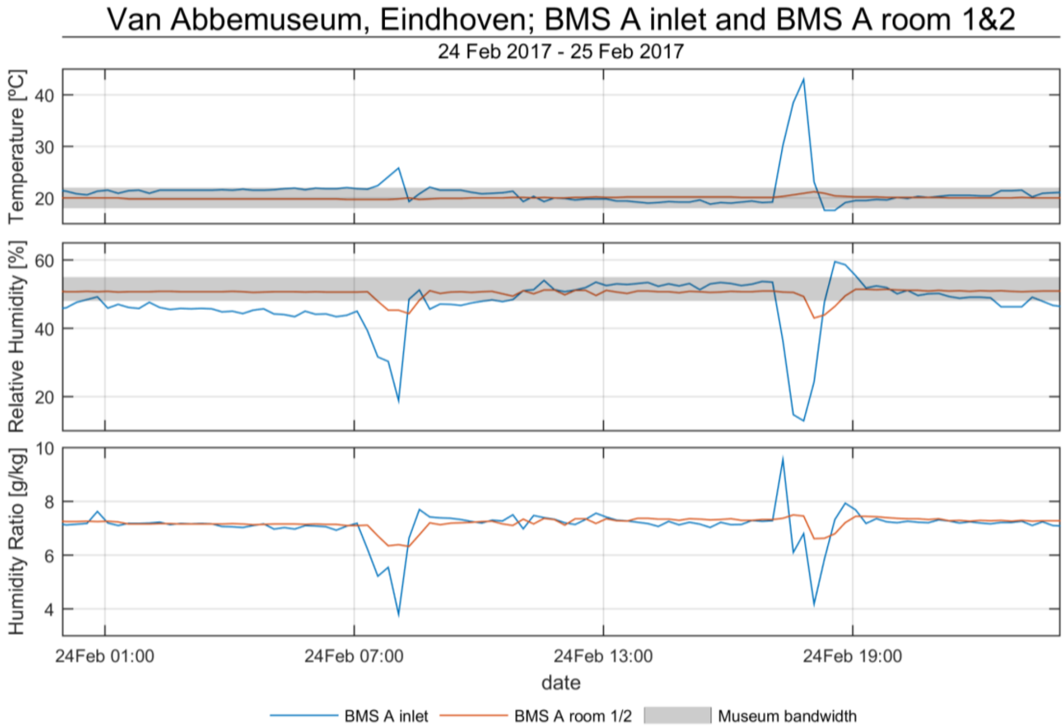


Figure 9.41: Measured T, RH, and humidity ratio for the measurement positions BMS inlet and BMS sensor room 1/2 (building part A) (February 24th 2017 till February 25th 2017).

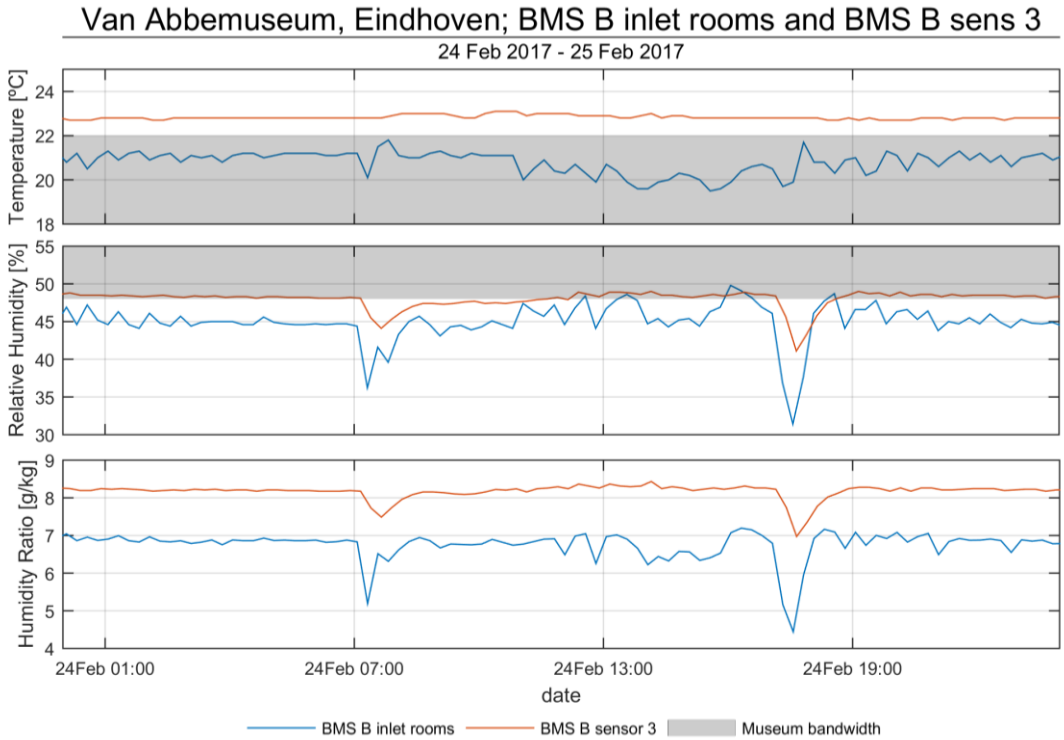


Figure 9.42: Measured T, RH, and humidity ratio for the measurement positions BMS inlet rooms and BMS sensor 3 (building part B) (February 24th 2017 till February 25th 2017).

HVAC system test – March 20th 2017

Due to a test on March 20th 2017, malfunctioning of the HVAC systems of the whole museum occurred between 7AM and 8AM. This resulted in the monumental building part in an extreme increased T_i and decreased RH_i, as a result of the blown in air with an increased T and decreased RH inlet, see Figure 9.43.

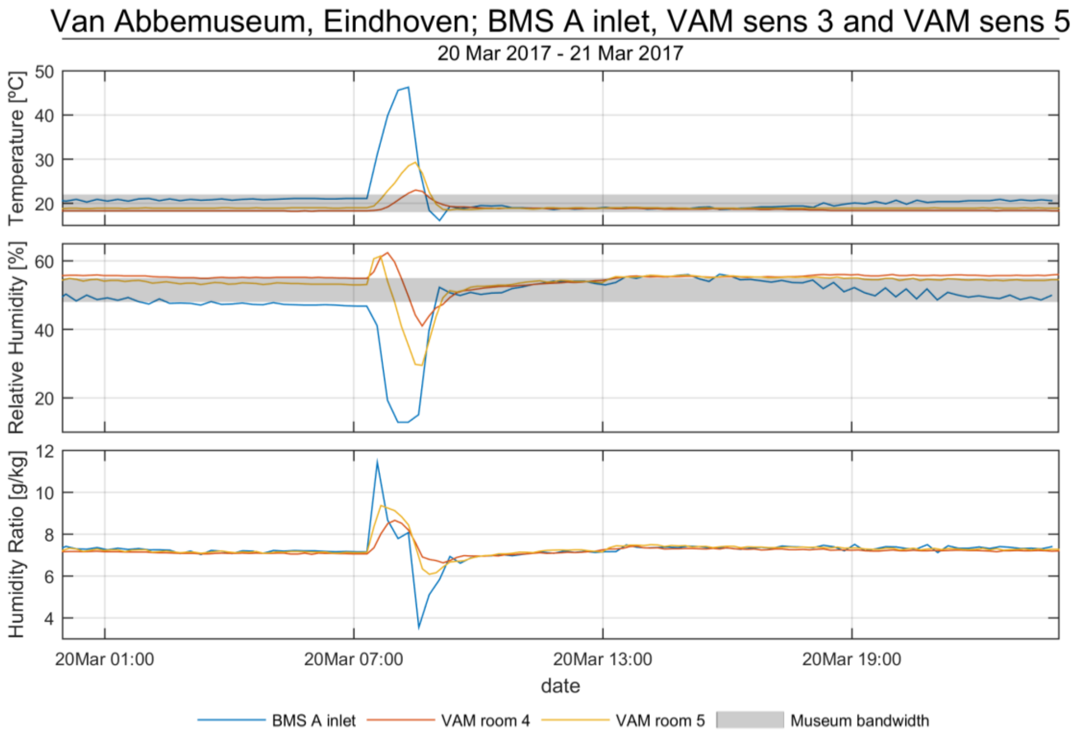


Figure 9.43: Measured T, RH, and humidity ratio for the measurement positions BMS inlet and the Eltek sensors 3 and 5 (building part A) (March 20th 2017 till March 21st 2017).

Appendix K. Outdoor climate

The figures below show the comparison of the outdoor climate (T_e and RH_e) measured by the own Eltek sensor, the two sensors of the VAM (BMS), and the data measured by the KNMI (KNMI, 2017). The first three figures, see Figure 9.44 to Figure 9.46, show the comparison with the original KNMI data. The data of the Eltek sensor and the BMS sensors have been nearly the same. The comparison between the data measured by the Eltek sensor and the KNMI show little differences in the T_e and RH_e. During the summer, see Figure 9.45, the data during the daytime has been very similar, during the nighttime the measured T_e by the KNMI has been lower and the RH_e has been higher. During the winter, see Figure 9.46, the measured data by the KNMI and the own sensors have been very similar. The data obtained by the Eltek sensor has a delay of approximately 1 hour and shows higher T_e and lower RH_e than the sensor of the KNMI. The difference between the two sensors is that the sensor of the KNMI is placed in a half open grassland at a height of 1.5 m, and the own sensor is placed on the museum in the city center of Eindhoven. Despite the little differences, the agreement was enough to use the weather data obtained by the KNMI. Moreover, the data of the KNMI has been delayed with 1 hour to better match with the measured data by the Eltek sensor, see Figure 9.47 to Figure 9.49.

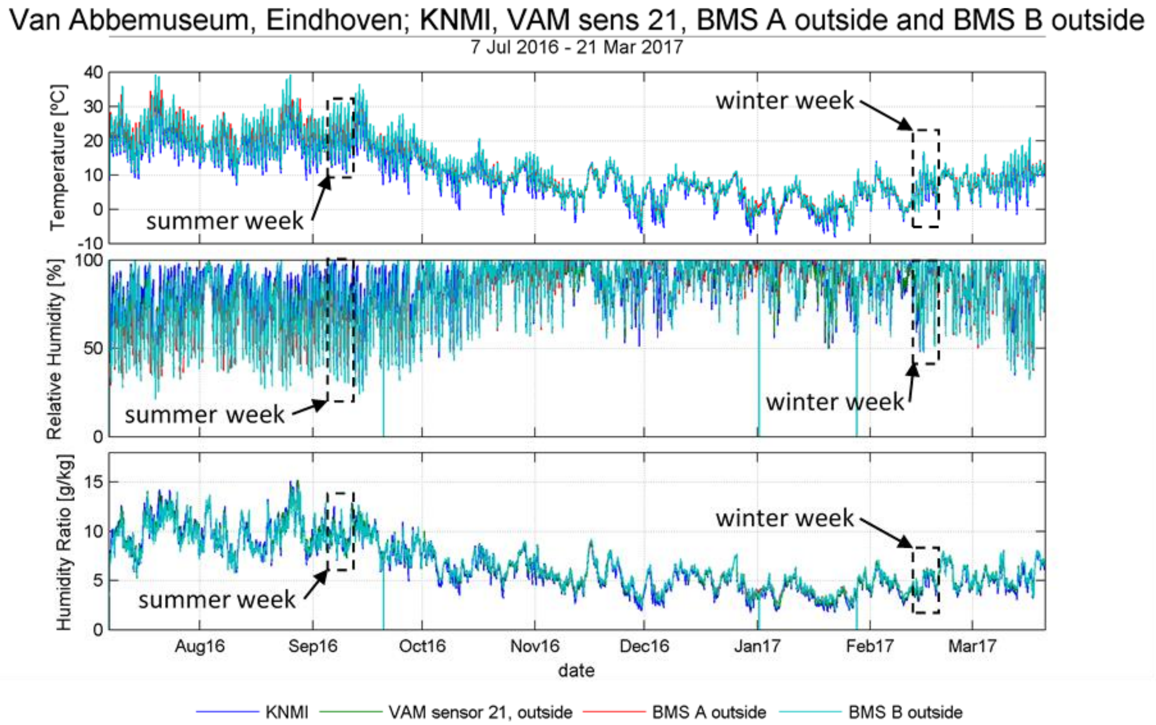


Figure 9.44: Outdoor climate data total measurement period; original KNMI data (KNMI, 2017), data measured by Eltek sensor 21, and two BMS sensors.

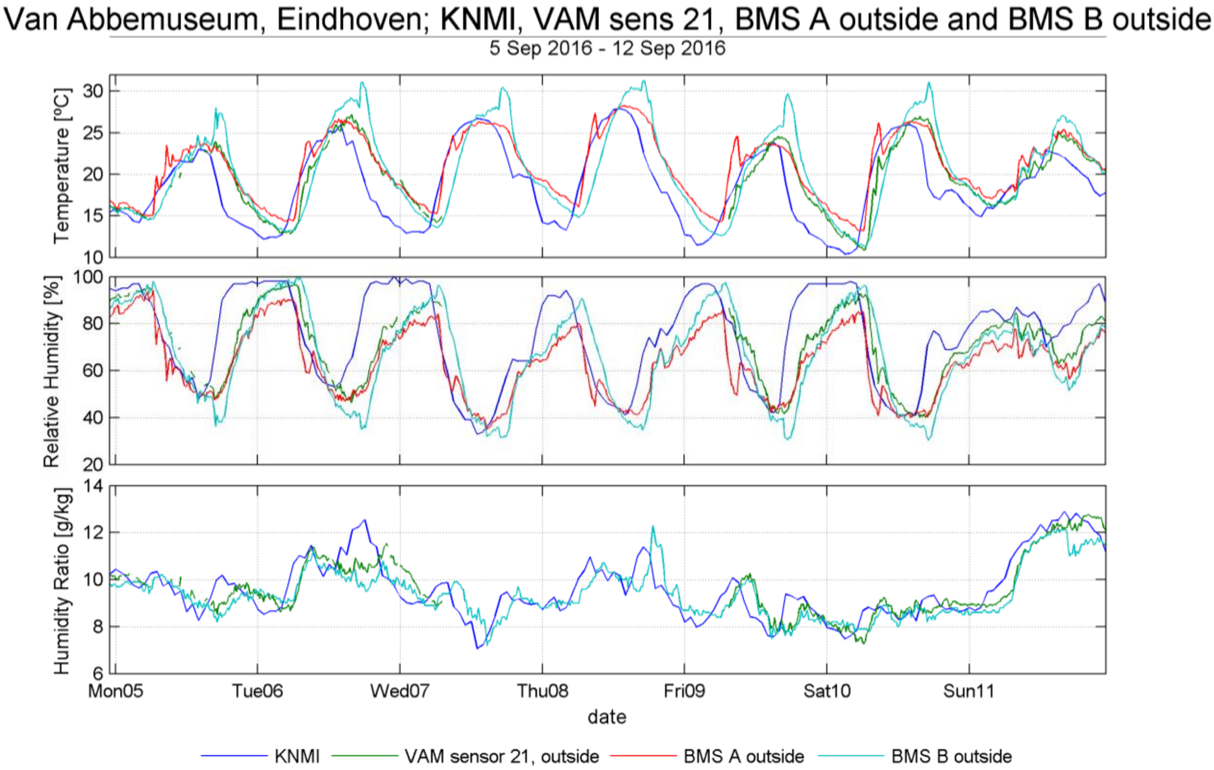


Figure 9.45: Outdoor climate data summer week; original KNMI data (KNMI, 2017), data measured by Eltek sensor 21, and two BMS sensors.

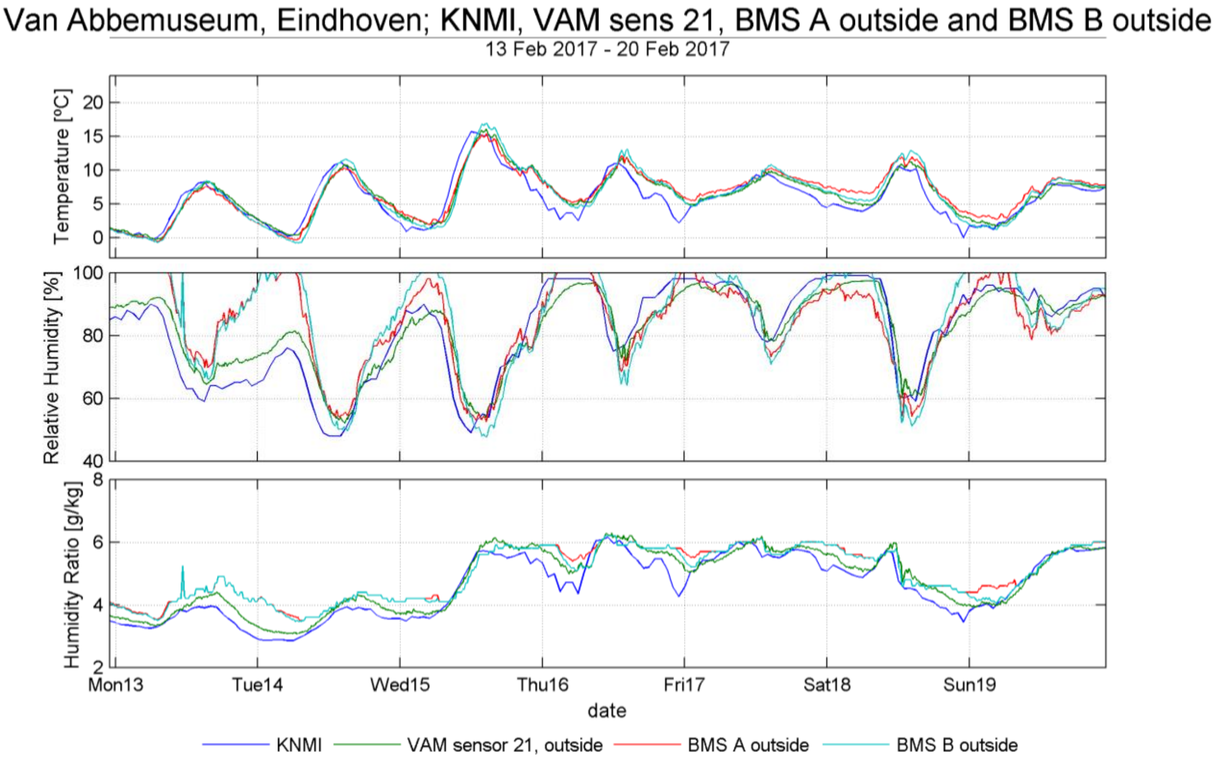


Figure 9.46: Outdoor climate data winter week; original KNMI data (KNMI, 2017), data measured by Eltek sensor 21, and two BMS sensors.

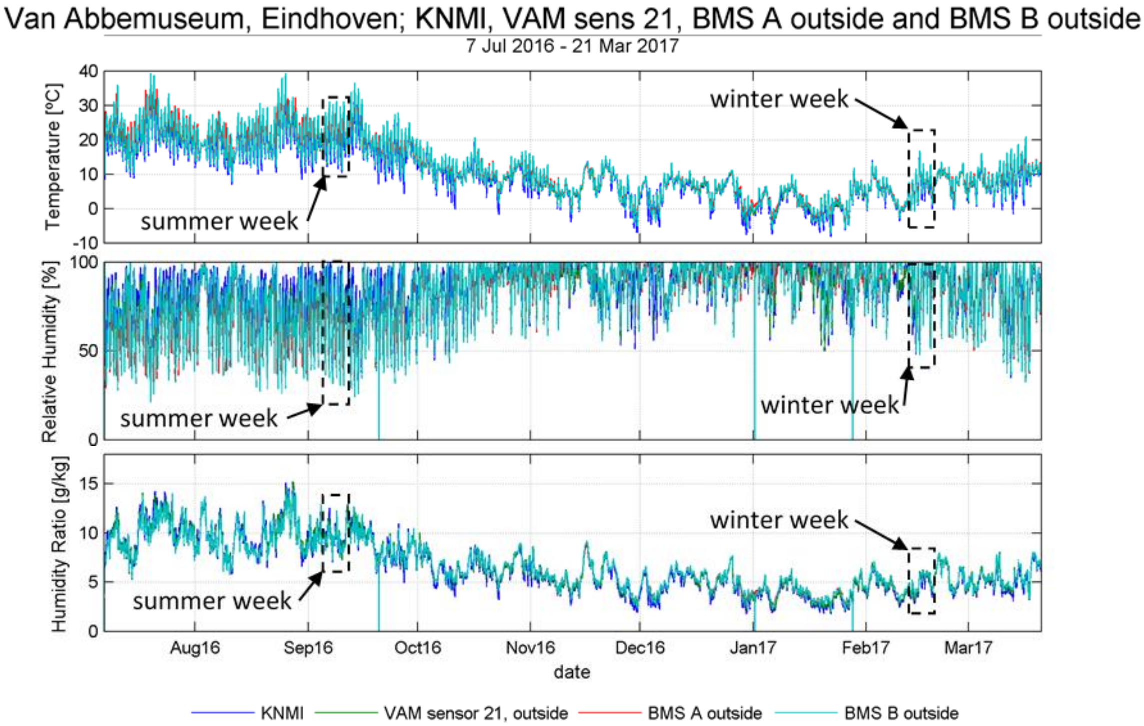


Figure 9.47: Outdoor climate data total measurement period; shifted KNMI data (KNMI, 2017), data measured by Eltek sensor 21, and two BMS sensors.

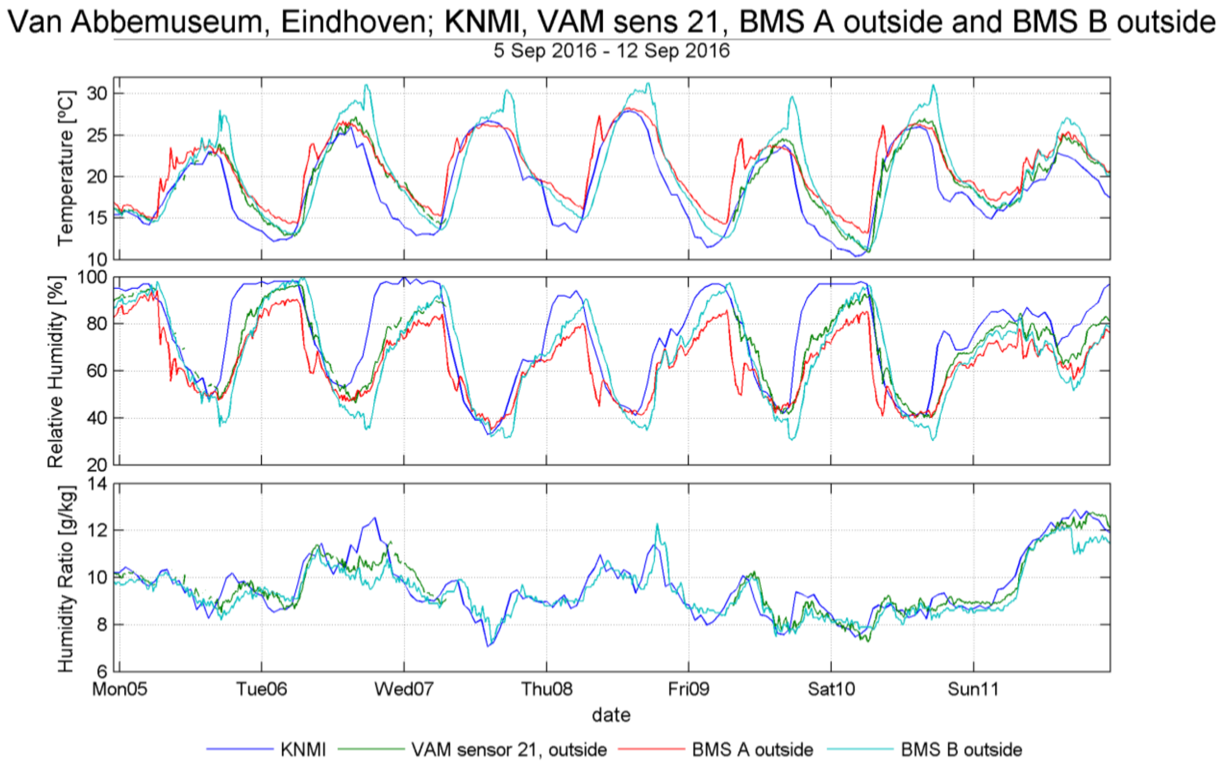


Figure 9.48: Outdoor climate data summer week; shifted KNMI data (KNMI, 2017), data measured by Eltek sensor 21, and two BMS sensors.

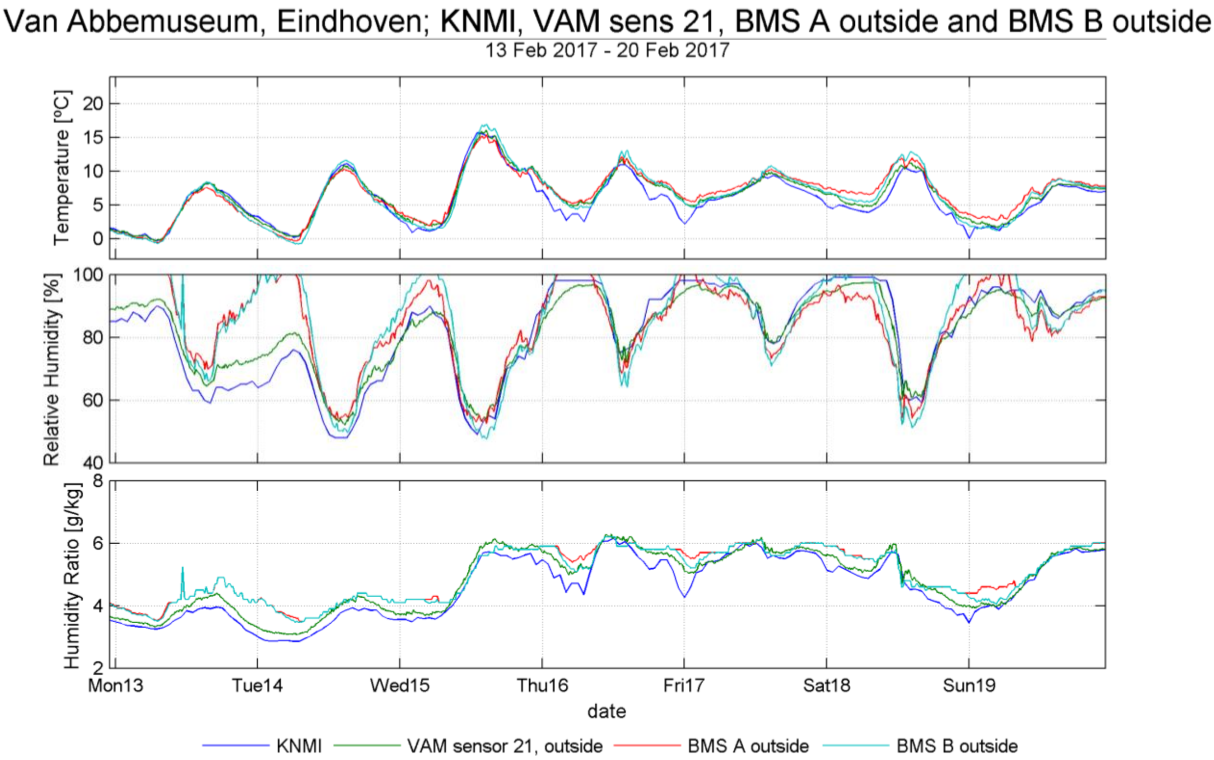


Figure 9.49: Outdoor climate data winter week; shifted KNMI data (KNMI, 2017), data measured by Eltek sensor 21, and two BMS sensors.

Appendix L. Visitors' profile

In order to simulate the impact of visitors on the indoor climate of the VAM in the numerical study, see Paragraph 3.2.1 for more information, the number of visitors as registered at the reception desk has been used. With the number of visitors, the visitors' profiles has been matched to reality as good as possible. The visitors' profile of September 2016 has been used since this is a reference month (no vacation periods or special events). Some large amounts of visitors have been left out of consideration because these visitors have only been in the restaurant or auditorium. Figure 9.50 shows the visitors per day during September 2016, Figure 9.51 shows the visitors per hour per day during September 2016.

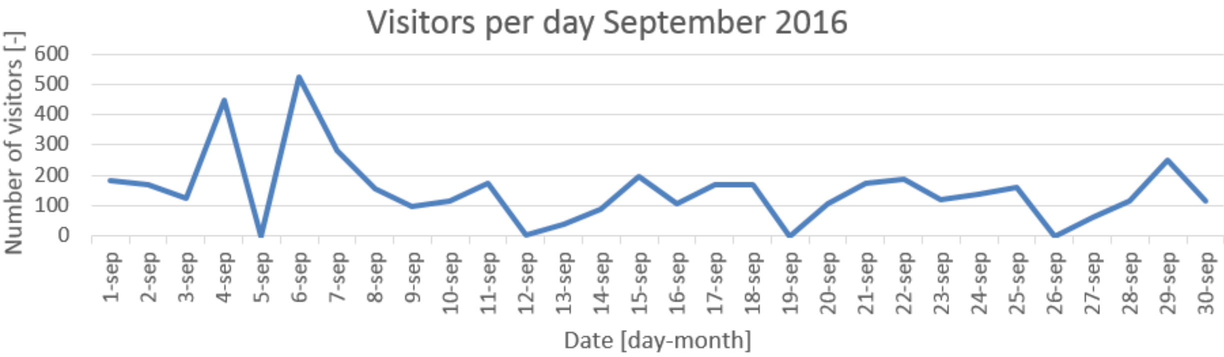


Figure 9.50: Visitors VAM per day during September 2016.

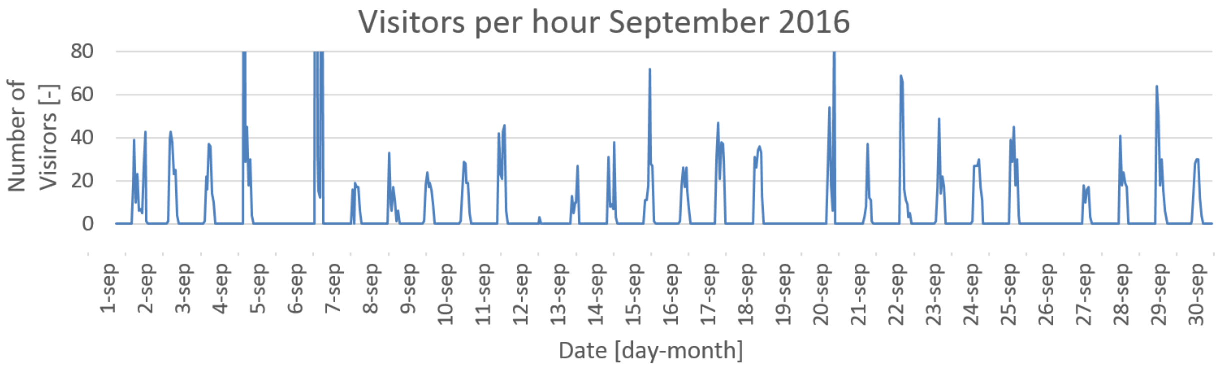


Figure 9.51: Visitors VAM per day per hour during September 2016.

To be able to make a visitors' profile usable for the HAMBase simulation, the amount of visitors per weekday per hour per zone (exhibition room monumental building part A) has been needed. The visitors' profile has been created by taking the average amount of incoming visitors per weekday per hour. An average visit length of three hours is considered. In addition, an assumption is made that ⅓ of the total visitors are present in the monumental building part A, divided over ten exhibition rooms. The number of visitors extracted from the reception desk and the assumptions have led to the visitors' profile as shown in Figure 9.52. The exact numbers of visitors per exhibition room/zone can be found in Appendix M.

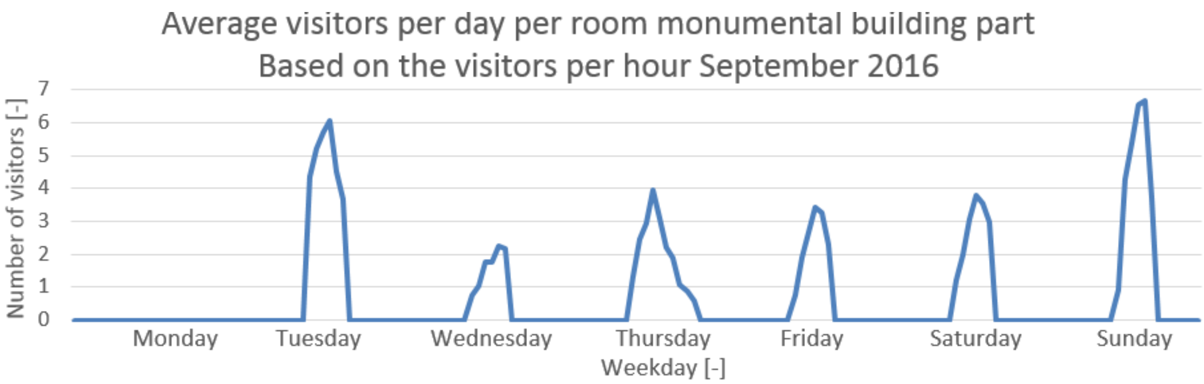


Figure 9.52: Visitors VAM per day per exhibition room in the monumental building part A, based on the visitors as registered at the reception desk during September 2016.

## Appendix M.	HAMBase input reference model

Building

The monumental building part A has been divided in sixteen zones, taking in account the rooms in which are measured with the own T/RH Eltek sensors. The plenums have been considered as separate zones since the plenums have no HVAC installations.

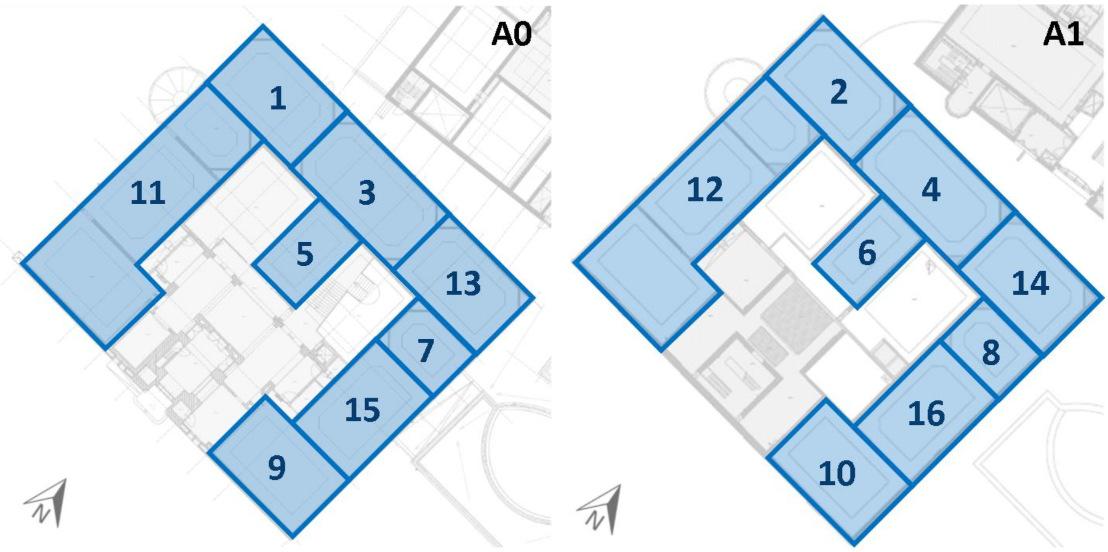


Figure 9.53: Zone numbers HAMBase model, monumental building part A. Floor plan under layers by Cahen (2003).

Table 9.9: Zones and volumes.

zoneNo	vol [m³]	description	Eltek sensor No.
1	444.7	room 4	3
2	230.2	plenum room 4	4
3	562.8	room 5	5
4	291.3	plenum room 5	
5	257.6	room 6	6
6	130.4	plenum room 6	
7	219.5	room 8	19
8	113.6	plenum room 8	

zoneNo	vol [m³]	description	Eltek sensor No.
9	427.0	room 10	1
10	221.1	plenum room 10	2
11	1109.2	room 1/2/3	
12	574.2	plenum room 1/2/3	
13	444.4	room 7	
14	230.0	plenum room 7	
15	436.1	room 9	
16	225.7	plenum room 9	

Table 9.10: Structure materials.

matID	material description
002	moderately ventilated cavity Rcav = 0.17 m²K/W
234	brickwork
341	screed
342	concrete
381	plasterboard

matID	material description
383	glass
452	insulation
501	hardwood
508	multiplex
601	bitumen

Table 9.11: Structure types.

conID	description	Ri	d1 [m]	matID	d2 [m]	matID	d3 [m]	matID	Re	ab [-]	eps [-]
		[m^2K/	d4 [m]	matID	d5 [m]	matID	d6 [m]	matID	[m^2K/		
		W]	d7 [m]	matID					W]		
1	façade South	0.13	0.012	381	0.018	508	0.100	234			
			0.400	002	0.130	234			0.04	0.8	0.9
2	façade W/N/E	0.13	0.012	381	0.018	508	0.100	234			
			0.170	002	0.130	234			0.04	0.8	0.9
3	door	0.13	0.040	501					0.04	0.9	0.9
4	inner wall 1	0.13	0.012	381	0.018	508	0.220	234			
			0.018	508	0.012	381			0.13	0.4	0.9
5	inner wall 2	0.13	0.012	381	0.018	508	0.220	234	0.13	0.4	0.9
6	inner wall 3	0.13	0.220	234					0.13	0.4	0.9
7	inner wall 4	0.13	0.012	381	0.018	508	0.100	234	0.13	0.4	0.9
8	inner wall 5	0.13	0.012	381	0.018	508	0.285	002	0.13	0.4	0.9
			0.220	234							
9	inner wall 6	0.13	0.012	381	0.018	508	0.100	234			
			0.200	002	0.100	234			0.13	0.4	0.9
10	inner wall 7	0.13	0.012	381	0.018	508	0.100	234			
			0.200	002	0.100	234	0.018	508			
			0.012	381					0.13	0.4	0.9
11	inner wall 8	0.13	0.012	381	0.018	508	0.100	234			
			0.200	002	0.100	234	0.080	002			
			0.150	234					0.13	0.4	0.9
12	inner wall 9	0.13	0.100	234	0.200	002	0.100	234			
			0.080	002	0.150	234			0.13	0.4	0.9
13	inner wall 10	0.13	0.012	381	0.018	508	0.214	234	0.13	0.4	0.9
14	inner wall 11	0.13	0.012	381	0.018	508	0.214	234			
			0.018	508	0.012	381			0.13	0.4	0.9
15	inner wall 12	0.13	0.012	381	0.018	508	0.100	234			
			0.300	002	0.018	508	0.120	381	0.13	0.4	0.9
16	old floor	0.13	0.030	341	0.120	342			0.13	0.6	0.9
17	new floor 1 (2003)	0.13	0.180	342					0.13	0.6	0.9
18	new floor 2 (2003)	0.13	0.150	342					0.13	0.6	0.9
19	plenum concrete	0.13	0.150	342					0.13	0.4	0.9
20	plenum glass	0.13	0.020	383					0.13	0.4	0.9
21	old roof	0.1	0.037	501	0.004	601			0.04	0.9	0.9
22	new roof (2003)	0.1	0.100	452	0.004	601			0.04	0.9	0.9
23	façade plenum South	0.13	0.100	234	0.400	002	0.130	234	0.04	0.8	0.9
24	façade plenum W/N/E	0.13	0.100	234	0.170	002	0.130	234	0.04	0.8	0.9
25	plenum wall	0.13	0.220	234					0.13	0.6	0.9

Table 9.12: Glazing types.

glaID	Uglas [W/m^2K]	CFr [-]	ZTA [-]	ZTAw [-]	CFrw [-]	Uglasw [W/m^2K]	description
1	2.5	0.03	0.8	0.8	0.03	2.5	polycarbonate plates
2	3.2	0.03	0.7	0.7	0.03	3.2	double glazing

Table 9.13: Orientations.

orNO	tilt [°]	azimuth [°]	description	orNO	tilt [°]	azimuth [°]	description
1	90	0	south wall	5	22	0	south roof
2	90	90	west wall	6	22	90	west roof
3	90	180	north wall	7	22	180	north roof
4	90	-90	east wall	8	22	-90	east roof

Table 9.14: Exterior walls.

ex No	zone No	surf. [m²]	con ID	or No	brid-ge	description	ex No	zone No	surf. [m²]	con ID	or No	brid-ge	description
1	1	35.2	2	2	0	façade	26	12	105.1	21	6	0	roof
2	1	51.0	2	3	0	façade	27	12	88.3	21	8	0	roof
3	2	25.7	21	6	0	roof	28	12	25.6	21	7	0	roof
4	2	8.6	21	8	0	roof	29	13	53.3	2	3	0	façade
5	2	43.2	21	7	0	roof	30	13	35.2	2	4	0	façade
6	2	25.6	21	5	0	roof	31	14	43.2	21	7	0	roof
7	3	66.7	2	3	0	façade	32	14	25.7	21	8	0	roof
8	4	64.9	21	7	0	roof	33	14	8.6	21	6	0	roof
9	4	64.9	21	5	0	roof	34	14	25.6	21	5	0	roof
10	6	10.1	22	7	0	roof	35	15	52.5	2	4	0	façade
11	6	22.5	22	6	0	roof	36	16	51.1	21	8	0	roof
12	6	10.1	22	5	0	roof	37	16	51.1	21	6	0	roof
13	6	22.5	22	8	0	roof	38	2	17.1	24	2	0	façade plenum
14	7	25.8	2	4	0	façade	39	2	25.9	24	3	0	façade plenum
15	8	25.1	21	8	0	roof	40	4	32.4	24	3	0	façade plenum
16	8	25.1	21	6	0	roof	41	8	12.5	24	4	0	façade plenum
17	9	34.9	2	4	0	façade	42	10	16.9	24	4	0	façade plenum
18	9	51.3	1	1	0	façade	43	10	24.9	23	1	0	façade plenum
19	10	25.7	21	8	0	roof	44	12	24.9	23	1	0	façade plenum
20	10	43.2	21	5	0	roof	45	12	56.6	24	2	0	façade plenum
21	10	25.6	21	7	0	roof	46	14	25.9	24	3	0	façade plenum
22	10	8.6	21	6	0	roof	47	14	17.1	24	4	0	façade plenum
23	11	51.3	1	1	0	façade	48	16	25.5	24	4	0	façade plenum
24	11	116.5	2	2	0	façade	49	1	2.3	3	3	0	door
25	12	43.2	21	5	0	roof							

Table 9.15: Windows in exterior walls.

win No	ex No	surf. [m²]	gla ID	sha No	description	win No	ex No	surf. [m²]	gla ID	sha No	description
1	14	2.1	2	0	zone 7 window	15	19	19.3	1	0	zone 10 plenum
2	24	2.1	2	0	zone 11 window	16	20	33.3	1	0	zone 10 plenum
3	3	19.3	1	0	zone 2 plenum	17	21	21.7	1	0	zone 10 plenum
4	4	7.8	1	0	zone 2 plenum	18	22	7.8	1	0	zone 10 plenum
5	5	33.3	1	0	zone 2 plenum	19	25	33.3	1	0	zone 12 plenum
6	6	21.7	1	0	zone 2 plenum	20	26	83.6	1	0	zone 12 plenum
7	8	51.8	1	0	zone 4 plenum	21	27	72.3	1	0	zone 12 plenum
8	9	51.8	1	0	zone 4 plenum	22	28	21.7	1	0	zone 12 plenum
9	10	6.8	1	0	zone 6 plenum	23	31	33.3	1	0	zone 14 plenum
10	11	17.5	1	0	zone 6 plenum	24	32	19.3	1	0	zone 14 plenum
11	12	6.8	1	0	zone 6 plenum	25	33	7.8	1	0	zone 14 plenum
12	13	17.5	1	0	zone 6 plenum	26	34	21.7	1	0	zone 14 plenum
13	15	20.0	1	0	zone 8 plenum	27	36	40.8	1	0	zone 16 plenum
14	16	20.0	1	0	zone 8 plenum	28	37	40.8	1	0	zone 16 plenum

Table 9.16: Adiabatic external walls.

ia No	zone No	surf. [m²]	con ID	description
1	1	14.5	11	wall
2	3	6.5	12	wall
3	3	12.3	11	wall
4	3	12.3	10	wall
5	3	6.5	9	wall
6	5	41.0	13	wall
7	5	13.2	15	wall
8	5	13.2	10	wall
9	5	41.0	14	wall
10	7	6.5	9	wall
11	7	13.5	10	wall
12	7	6.5	9	wall
13	9	14.5	5	wall
14	9	34.9	8	wall
15	11	34.9	8	wall
16	11	14.5	5	wall
17	11	27.3	9	wall
18	11	25.5	11	wall

ia No	zone No	surf. [m²]	con ID	description
19	11	6.5	12	wall
20	11	13.5	11	wall
21	11	6.5	12	wall
22	13	14.5	10	wall
23	15	35.8	10	wall
24	15	17.1	9	wall
25	1	419.9	16	floor
26	3	531.8	16	floor
27	5	243.4	17	floor
28	7	207.4	16	floor
29	9	419.9	16	floor
30	11	1048.1	16	floor
31	13	47.3	16	floor
32	15	92.8	16	floor
33	13	47.3	18	floor
34	10	18.8	25	plenum wall
35	12	18.8	25	plenum wall

Table 9.17: Internal walls.

in No	zone No1	zone No2	surf. [m²]	con ID	description
1	1	1	9.8	7	wall
2	1	11	27.9	4	wall
3	1	11	7.3	5	wall
4	11	11	9.8	7	wall
5	1	3	7.3	5	wall
6	1	3	21.0	4	wall
7	1	1	9.8	7	wall
8	1	3	7.3	6	wall
9	3	3	9.8	7	wall
10	3	3	9.8	7	wall
11	3	5	26.3	10	wall
12	3	3	9.8	7	wall
13	3	3	9.8	7	wall
14	3	13	7.3	6	wall
15	13	13	9.8	7	wall
16	3	13	21.0	4	wall
17	13	3	7.3	5	wall
18	13	13	9.8	7	wall
19	13	7	7.3	5	wall
20	7	7	9.8	7	wall
21	7	13	27.9	4	wall
22	7	7	9.8	7	wall
23	15	7	7.3	5	wall
24	7	15	27.9	4	wall
25	9	15	34.9	4	wall
26	11	11	34.9	4	wall
27	11	11	27.9	4	wall
28	11	11	9.8	7	wall
29	11	11	7.3	5	wall
30	12	12	18.8	25	wall
31	12	12	18.8	25	wall
32	2	12	18.8	25	wall
33	2	4	18.8	25	wall
34	4	14	18.8	25	wall
35	8	12	18.8	25	wall
36	8	16	18.8	25	wall
37	10	16	18.8	25	wall
38	1	2	46.6	19	plenum concrete
39	1	2	47.9	20	plenum glass
40	3	4	56.6	19	plenum concrete
41	3	4	63.1	20	plenum glass
42	5	6	31.8	19	plenum concrete
43	5	6	23.0	20	plenum glass
44	7	8	29.9	19	plenum concrete
45	7	8	16.8	20	plenum glass
46	9	10	45.9	19	plenum concrete
47	9	10	48.7	20	plenum glass
48	11	12	122.7	19	plenum concrete
49	11	12	113.4	20	plenum glass
50	13	14	46.6	19	plenum concrete
51	13	14	47.9	20	plenum glass
52	15	16	44.9	19	plenum concrete
53	15	16	47.9	20	plenum glass

Building profiles

Building profiles are different for each zone and opening hour, and dependent of the amount of persons per room and the floor surface per zone. The sensible heat of 100 W/person has been based on a standing activity (metabolism of 160 W/m²) and a clo value of 0.6 (long pants and shirt). The moisture production of 110 gr/h (=3.05556E-05 kg/s) per person has been based on walking/standing activities (Wit M. d., 2013). During the night, a lower air change rate has been maintained. The plenums have no HVAC installations.

Table 9.18: Building profiles. See Table 9.19 for the opening hours, Table 9.20 for the ventilations rates, Table 9.21 for the visitor profile, and Table 9.22 for the calculation of the average Q_{int} from the luminaires in the exhibition rooms.

	room zones	plenum zones	
Ers [W/m²]	100000	100000	, no sun blinds
vvmin day* [1/hr]	0.9	0.1	, plenum: no ventilation
vvmin night** [1/hr]	0.49	0.1	
vvmax day* [1/hr]	0.9	0.1	, no free cooling
vvmax night** [1/hr]	0.49	0.1	
Tfc [°C]	100	100	, no free cooling
Tsetmin [°C]	18	-100	, plenum: no heating
Tsetmax [°C]	19	100	, plenum: no cooling
Qint day* [W per person]	100	0	
Qint day* [W/m²floor surface]	3.87	0	
Qint day* [W per plenum zone]	0	2000	
Qint night** [W]	0	1000	
Gint [kg/s per person]	3.05556E-05	0	
Gint [kg/s per plenum zone]	0	8.33333E-06	
RVmin [%]	55	-1	, plenum: no humidification
RVmax [%]	56.5	101	, plenum: no dehumidification

*Day: opening hours, incl. Monday 11:00 till 17:00.

**Night: closing hours, excl. Monday 11:00 till 17:00.

Table 9.19: Opening hours.

day	open	day	open
Monday	-	Friday	11:00 - 17:00
Tuesday	11:00 - 17:00	Saturday	11:00 - 17:00
Wednesday	11:00 - 17:00	Sunday	11:00 - 17:00
Thursday	11:00 - 21:00		

Table 9.20: Ventilation rates exhibition rooms monumental building part.

Rotations per min.	max. *	1500 **	1200 **	750 **
Ventilation total (exhibition rooms+shop) [m³/hr]	18700 *	15856 **	11870 **	9087 **
Ventilation exhibition rooms (93.05%) [m³/hr]	17400 *	14754	11045	8455
Ventilation rate exhibition rooms [1/hr]***	4.46	3.78	2.83	2.17
Fresh air, 18% of ventilation rate exhibition rooms [1/hr]	0.80	0.68	0.51	0.39
Infiltration [1/hr]	0.10	0.10	0.10	0.10
Total ventilation rate exhibition rooms [1/hr]	0.90	0.78	0.61	0.49

* Based on ventilation principle by Nelissen (2000).

** Based on measurements by Strukton Worksphere (2010).

*** Volume of exhibition rooms is 3901.3 m³.

Table 9.21: Visitor profile: visitors per hour, per room. Based on visitors September 2016 (reference month) see Appendix L.

day	time [hh:mm]										
	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00
Monday	0	0	0	0	0	0	0	0	0	0	0
Tuesday	4	5	6	6	5	4	0	0	0	0	0
Wednesday	1	1	2	2	2	2	0	0	0	0	0
Thursday	1	2	3	4	3	2	2	1	1	1	0
Friday	1	2	3	3	3	2	0	0	0	0	0
Saturday	1	2	3	4	4	3	0	0	0	0	0
Sunday	1	4	5	7	7	4	0	0	0	0	0

Table 9.22: Calculation of the average Qint from the luminaires during the day per m² floor surface.

zoneNo	surf. [m²]	lamps	W per lamp [W]	heat efficiency lamps	Qint day per zone* [W/m²floor surface]	Avg. Qint day* [W/m²floor surface]
1	94.6	28	32	0.35	3.31	**3.87**
3	119.7	36			3.37	
5	54.8	28			5.72	
7.0	46.7	20			4.80	
9.0	90.9	28			3.45	
11	236.0	76			3.61	
13.0	94.6	28			3.32	
15.0	92.8	28			3.38	

*Day: opening hours, incl. Monday 11:00 till 17:00.

Heating, cooling and (de)humidification

There is one HVAC system for all the exhibition rooms (and museum shop) in the monumental building part A. The installation capacities for every zone have been determined by dividing the total capacity by the total floor surface, multiplied by the zone floor surface. The plenums have no installations.

Table 9.23: Heating, cooling and (de)humidification.

zoneNo	floor surf. [m²]	heat [W]	cool [W]	hum [kg/s]	deh [kg/s]	description
total	905.5	50300	-58000	0.0042	-0.0065	total capacity AHU (LBK A01)
1	94.6	5256	-6060	0.0004	-0.0007	room 4
2	94.6	0	0	0	-0	plenum room 4
3	119.7	6651	-7669	0.0006	-0.0009	room 5
4	119.7	0	0	0	-0	plenum room 5
5	54.8	3045	-3511	0.0003	-0.0004	room 6
6	91.5	0	0	0	-0	plenum room 6
7	46.7	2594	-2991	0.0002	-0.0003	room 8
8	46.7	0	0	0	-0	plenum room 8
9	90.9	5047	-5820	0.0004	-0.0007	room 10
10	90.9	0	0	0	-0	plenum room 10
11	236.0	13110	-15117	0.0011	-0.0017	room 1/2/3
12	236.0	0	0	0	-0	plenum room 1/2/3
13	94.6	5252	-6056	0.0004	-0.0007	room 7
14	94.6	0	0	0	-0	plenum room 7
15	92.8	5154	-5943	0.0004	-0.0007	room 9
16	92.8	0	0	0	-0	plenum room 9
shop	75.5	4192	-4833	0.0003	-0.0005	museum shop

Table 9.24: Convection factor and heat exchange.

zoneNo	CFh [-]	CFs [-]	Cfi [-]	Etaww [-]	Twws [°C]	Twwc [°C]	description
each zone	1	1	0.5	0	22	40	same for each zone

Appendix N. Calibration HAMBase reference model

The energy use for room 4 of the monumental building part has been estimated using Equation 8. Since the real mass flow is unknown, an assumption has been made based on previous research (Seuren, 2016) and varying until the estimated energy use and the simulated energy use corresponded. However, according to the air inlet ventilation schemes from 2003 (Nelissen), a maximum mass flow of 0.5805 kg/s could be maintained, instead of a mass flow of 0.9 kg/s as used in the estimation. The specific heat of air has been used, which is 1.006 kJ/kgK. The supply T has been extracted from the BMS, it is unknown where exactly the sensor is placed. However, the sensor is presumably placed near the outlet of the AHU since there is only one supply T measured for the whole monumental building part. The indoor air T has been extracted from the measured data of Eltek sensor 3 in room 4.

$$P = \dot{m} * C * (T_{in} - T_{air}) \quad \text{Equation 8}$$

With:

P	=	Heating of cooling energy in kW.
$\dot{m}$	=	Mass flow in kg/s.
C	=	Specific heat in kJ/kgK.
T_{in}	=	Supply temperature in °C.
T_{air}	=	Indoor air temperature in °C.

The estimated energy use according to Equation 8 has been compared to the simulated energy use of zone 1 (for heating and cooling) as extracted from the reference simulation model. Figure 9.54 to Figure 9.56 show the results.

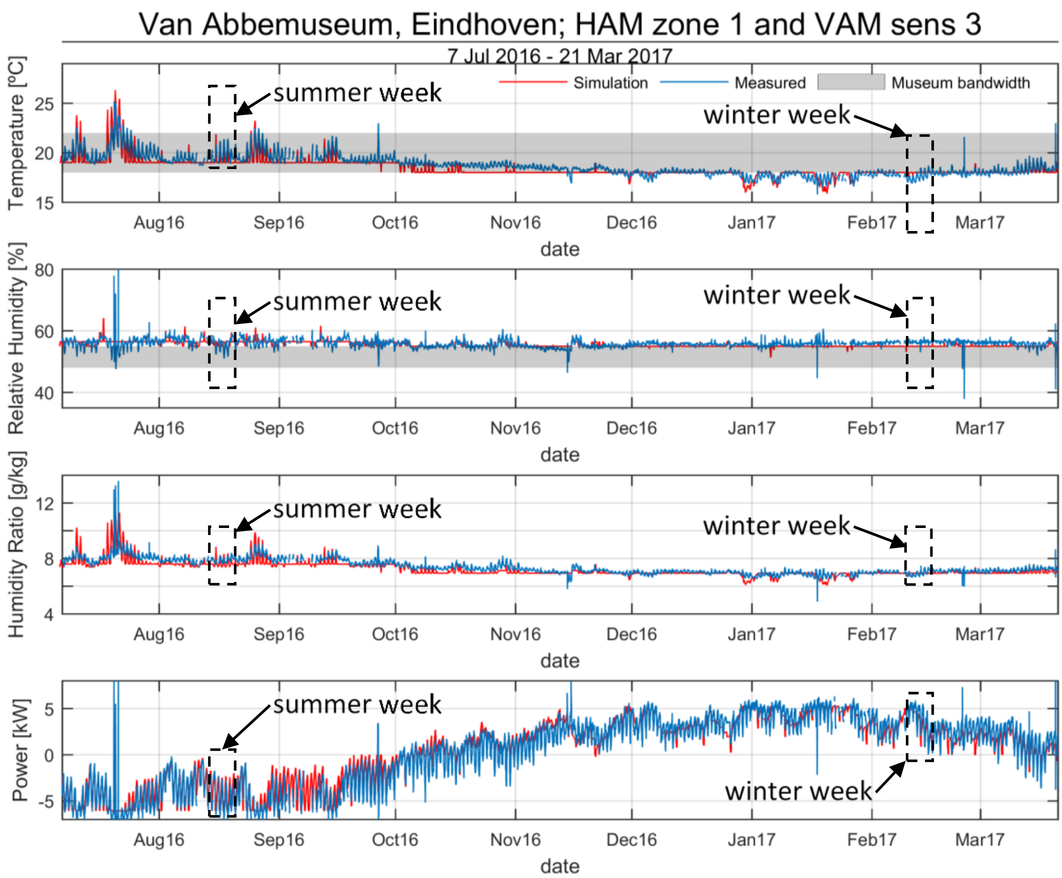


Figure 9.54: Measured and simulated T, RH, humidity ratio, and energy for the measurement position Eltek sensor 3 and HAMBase zone 1, total measurement period (July 7th 2016 till March 21st 2017).

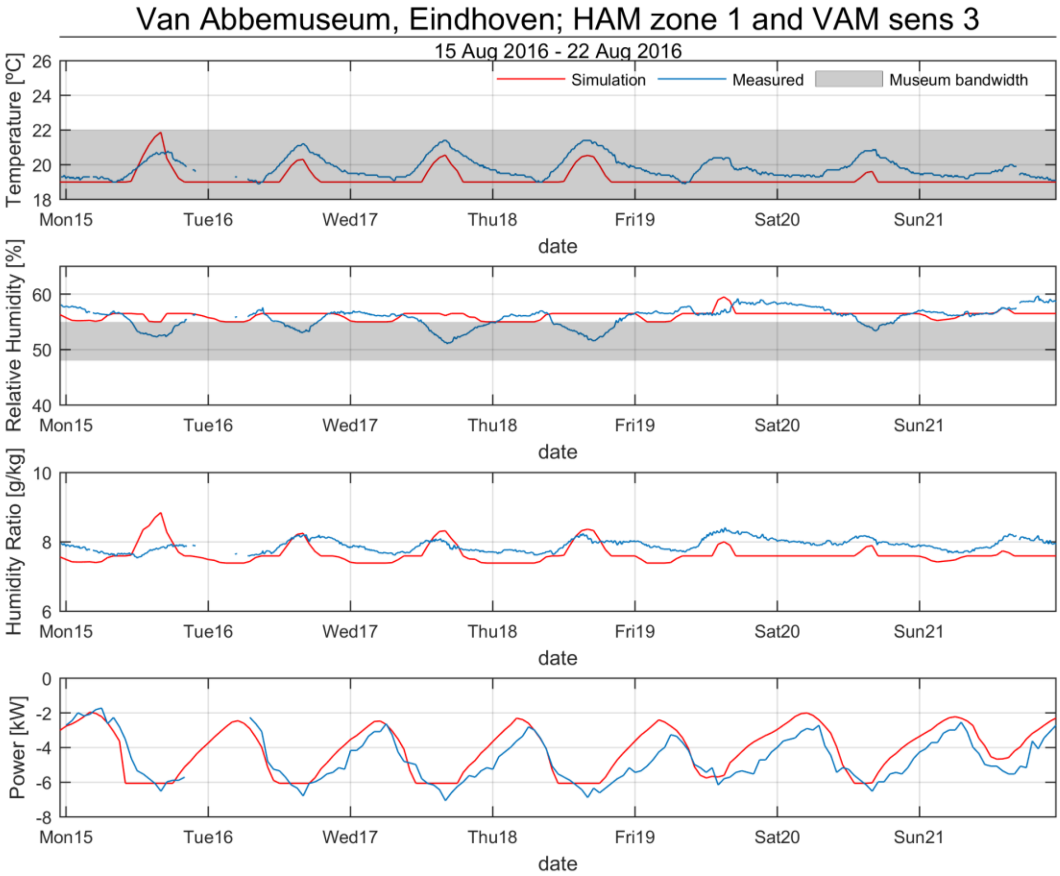


Figure 9.55: Measured and simulated T, RH, humidity ratio, and energy use for the measurement position Eltek sensor 3 and HAMBase zone 1, summer week (August 15th 2016 till August 22nd 2016).

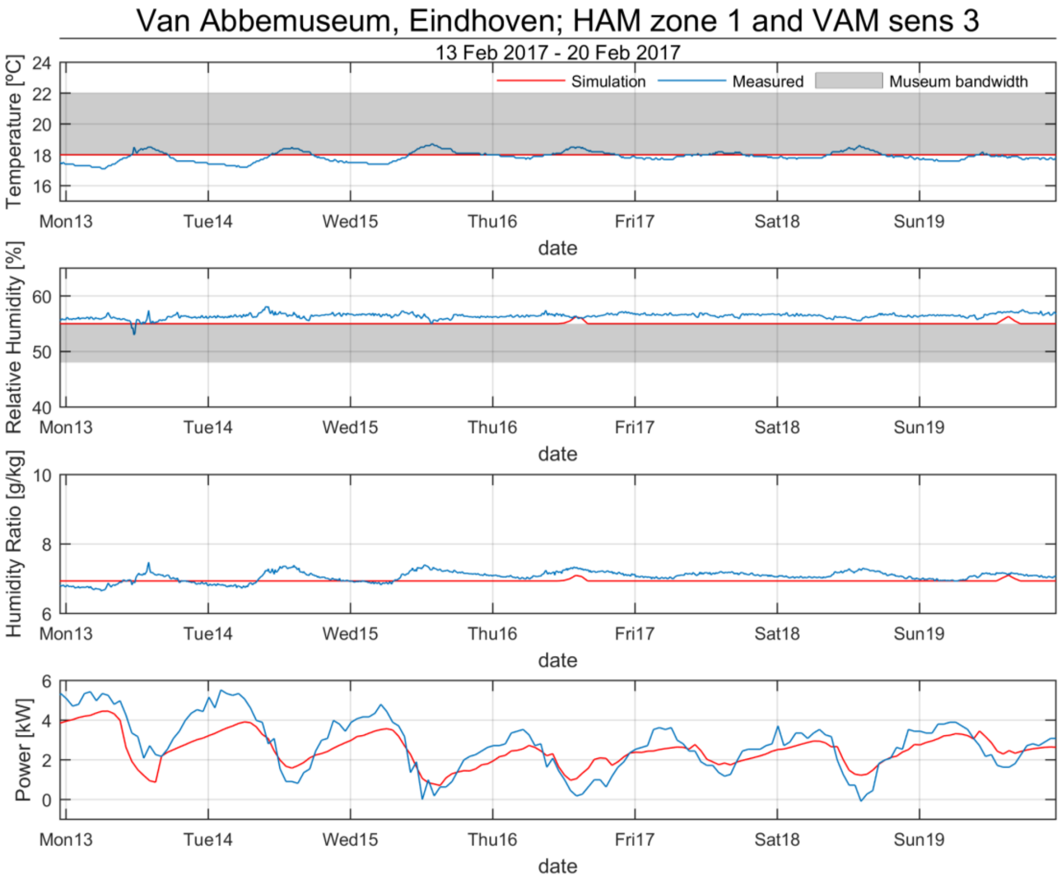


Figure 9.56: Measured and simulated T, RH, humidity ratio, and energy use for the measurement position Eltek sensor 3 and HAMBase zone 1, winter week (February 13th 2017 till February 20th 2017).

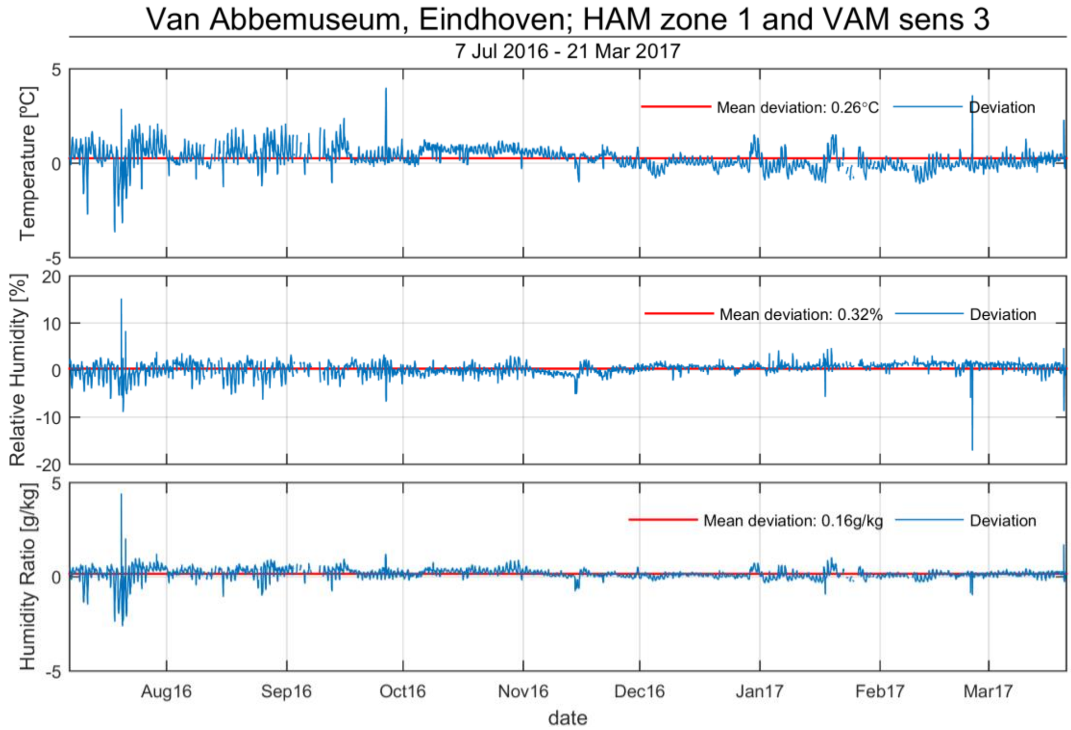


Figure 9.57: (Mean) deviation of the measured and simulated T, RH, humidity ratio for the measurement position Eltek sensor 3 and HAMBase zone 1, total measurement period (July 7th 2016 till March 21st 2017).

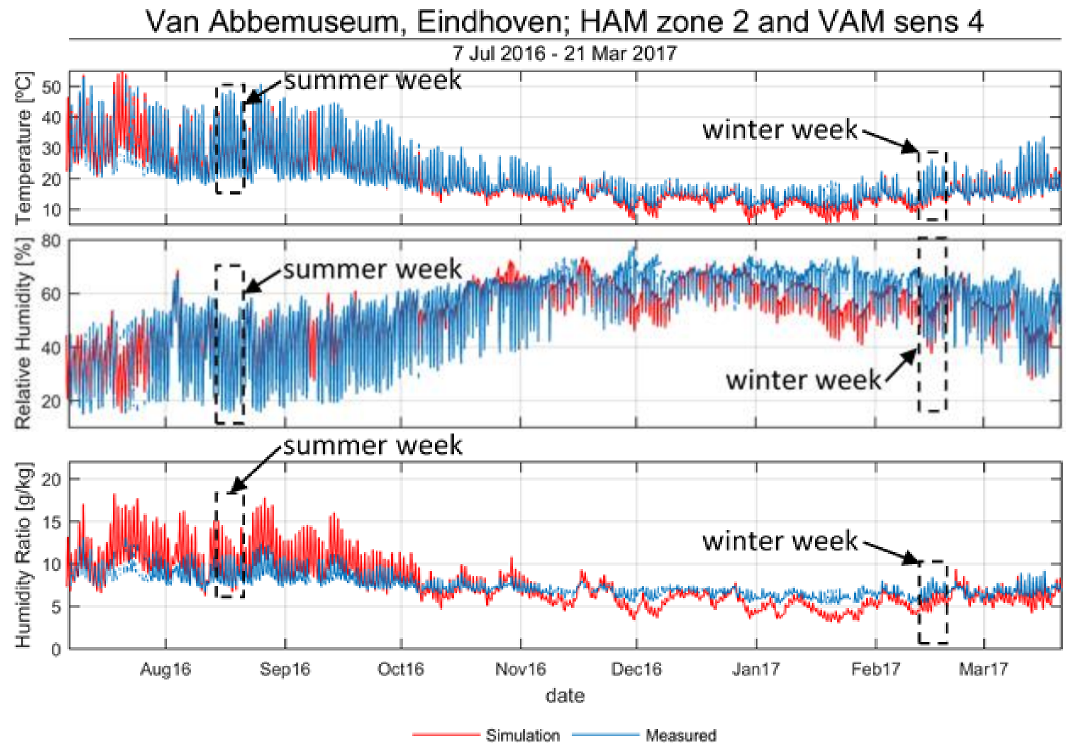


Figure 9.58: Measured and simulated T, RH, and humidity ratio for the measurement position Eltek sensor 4 and HAMBase zone 2, total simulation period (July 7th 2016 till March 21st 2017).

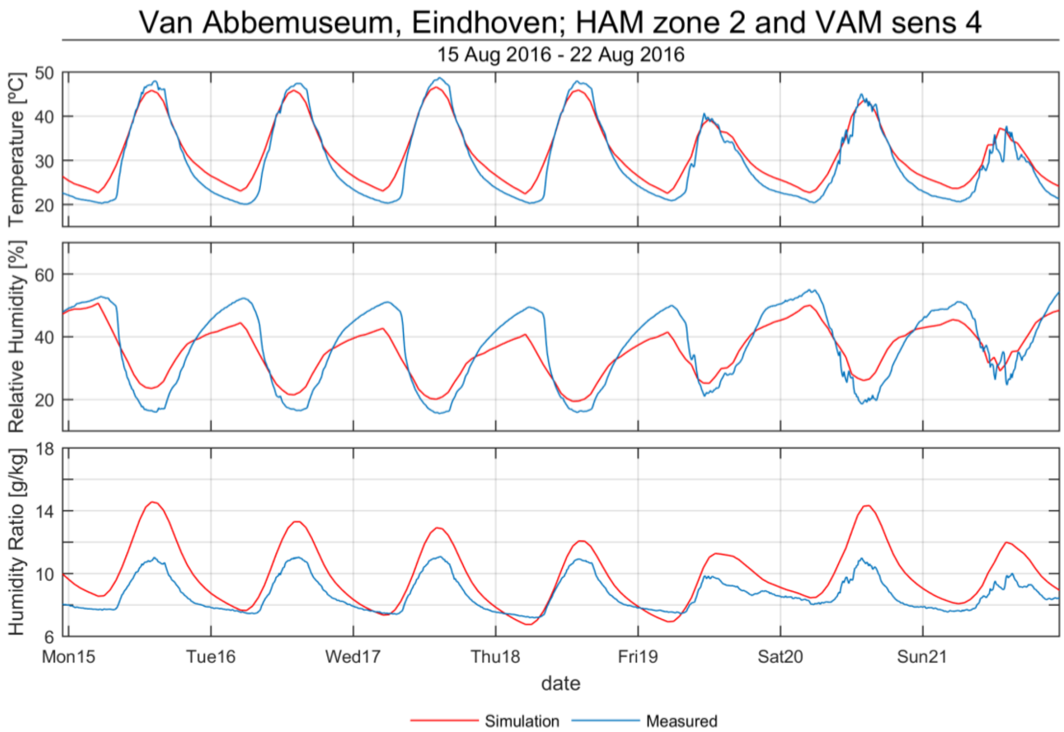


Figure 9.59: Measured and simulated T, RH, and humidity ratio for the measurement position Eltek sensor 4 and HAMBase zone 2, summer week (August 15th 2016 till August 22nd 2016).

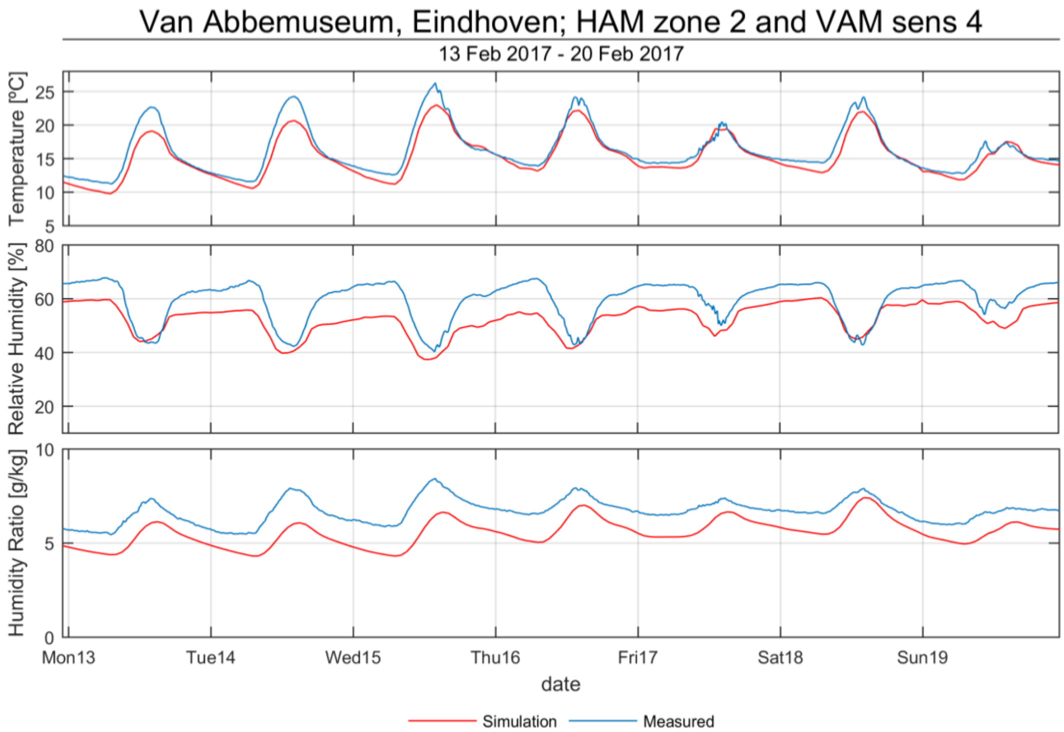


Figure 9.60: Measured and simulated T, RH, and humidity ratio for the measurement position Eltek sensor 4 and HAMBase zone 2, winter week (February 13th 2017 till February 20th 2017).

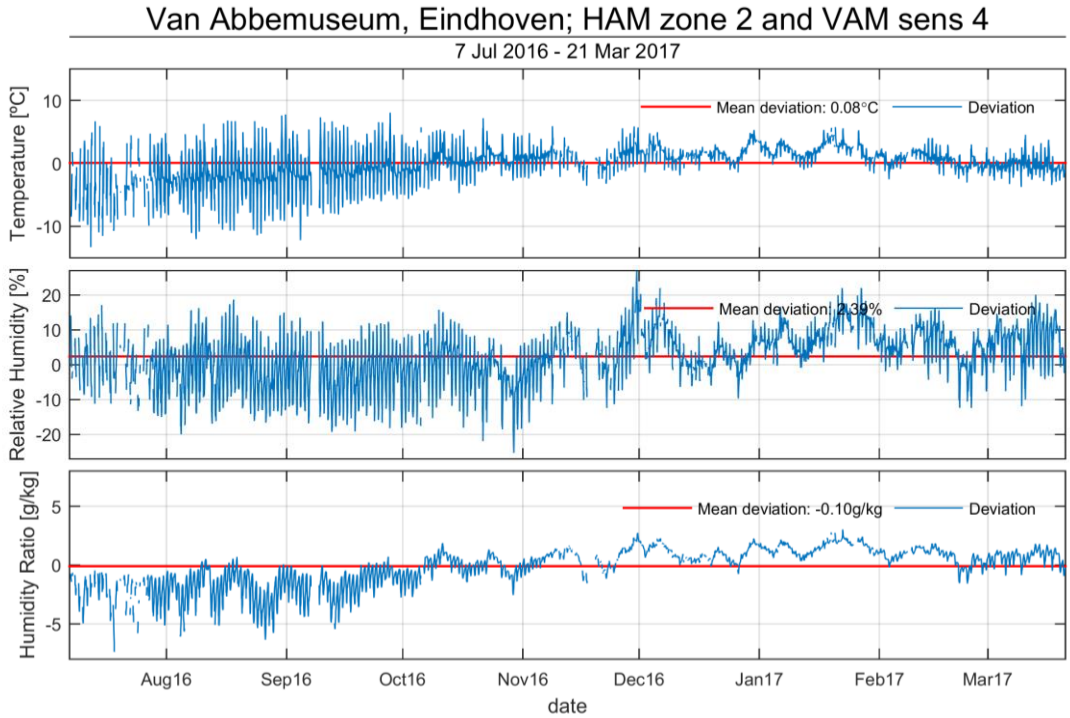


Figure 9.61: (Mean) deviation of the measured and simulated T, RH, humidity ratio for the measurement position Eltek sensor 4 and HAMBase zone 2, total measurement period (July 7th 2016 till March 21st 2017).

Table 9.25: Summary of the compared results of the data measured by the Eltek sensor 3 and reference simulation zone 1 (July 7th 2016 till March 21st 2017). The current indoor climate conditions are described by T_{avg} and RH_{avg}, and by the CEC assessed according to the museum requirements (T_i=18-22°C and RH_i=48-55%, max. Δ/h=0.5 and max. Δ/d=2.0). The risks to objects have been assessed according to the general and specific climate risk assessment. The letter in the general climate risk assessment indicates the best ASHRAE class which is met 100% of time, the letter between the brackets is the class which is met 98% or 99% of time. The specific climate risk assessment represent the average results for the four object types. Thermal comfort is expressed in the percentage of discomfort hours during opening hours, based on the ATG for museums.

Sensor No. / Zone No.	Averages		CEC [%]										
	Tavg [°C]	RHavg [%]	OK	too hot	too humid	too humid/ cold	too cold	too dry	too dry/hot	ΔT/h	ΔT/d	ΔRH/h	ΔRH/d
3 A0, room 4	18.7	55.9	18	1	56	24	1	0	0	1	10	28	62
Zone 1	18.4	55.6	1	0	91	6	1	0	0	1	7	5	5

Sensor No. / Zone No.	Risks to objects					Discom-fort [%h]
	General	Specific				
		Mould	LM	Base layer	Pict. Layer	
3 A0, room 4	B (AA)		**0.992**			98.5
Zone 1	C (AA)		**1.028**			98.2

Appendix O. Results instantaneous measurements temperature and relative humidity

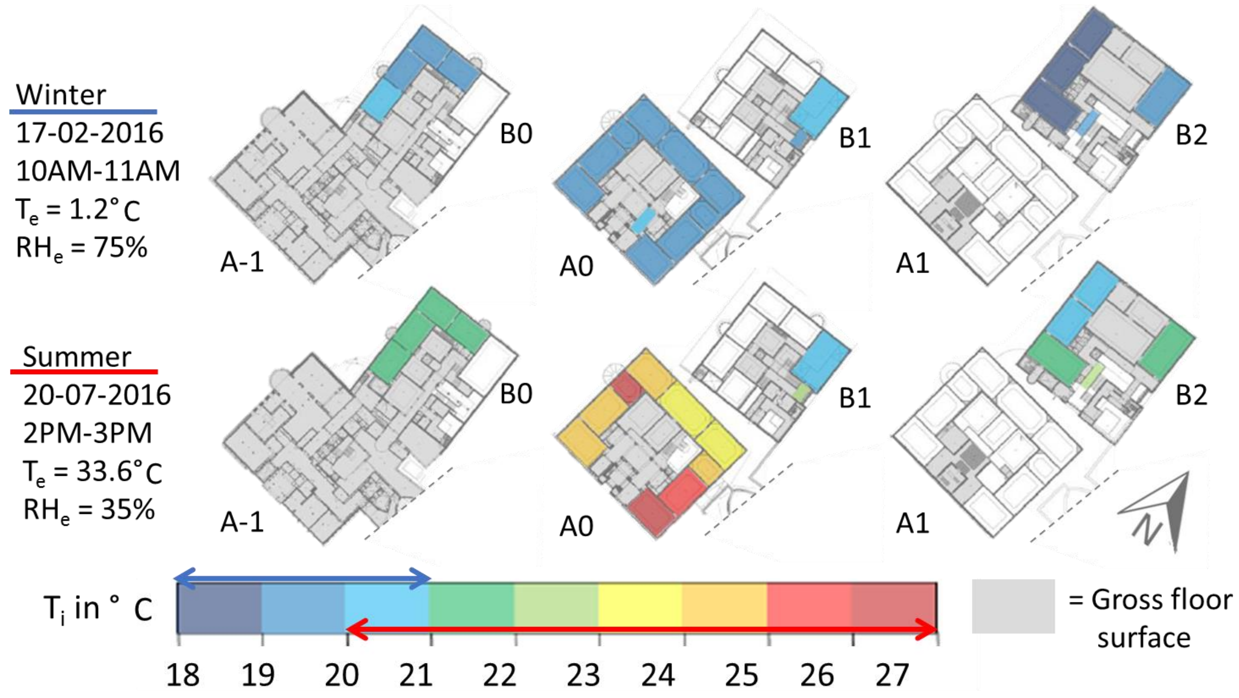


Figure 9.62: T_i spread in museum during instantaneous measurements, floor plan under layer by Cahen (2003).

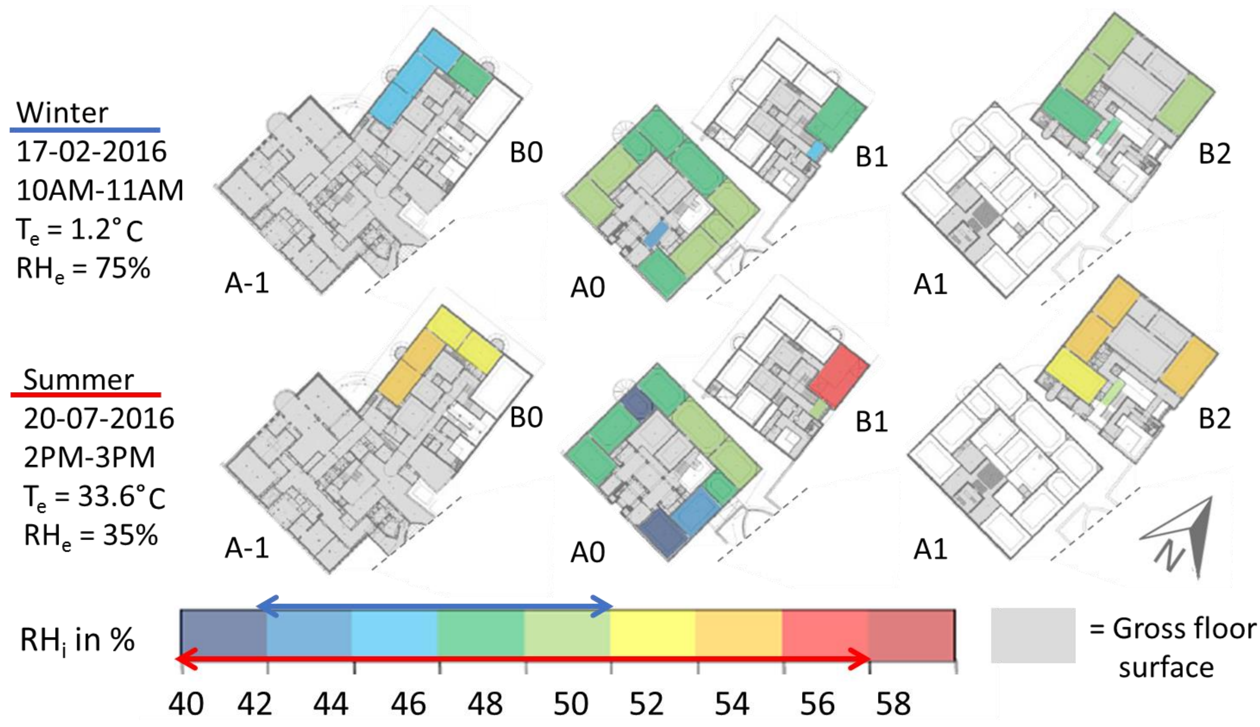


Figure 9.63: RH_i spread in museum during instantaneous measurements, floor plan under layer by Cahen (2003).

Appendix P. Validation BMS results with results Eltek sensors

As explained in Paragraph 3.1.2, 8.5 months of data measured by the BMS have been compared and validated with the 8.5 months of data measured by the Eltek sensors (T and RH) during the experimental study of this research. The comparison and validation is based on the measured T and RH data, and the climate risk assessment analysis method as described in Paragraph 3.3.1. When the data measured by the BMS is validated, one year of this data can be analyzed as well. One full year of data is of importance to be able to draw a complete conclusion of the current indoor climate (Ankersmit, 2010), and to get the 100% reliable results out of the general and specific climate risk assessment methods instead of estimations (Martens, 2012).

Table 9.26 shows an overview of the measured T and RH data by several Eltek sensors and BMS sensors. In this table, similar measurement positions of both sensor types are compared, based on their location in the museum, see Appendix H for the exact locations. As can been seen in Table 9.26, most of the data measured by the BMS sensors and the Eltek sensors match. Even though the results are not exactly the same, the accuracy of all the sensors should be taken in mind. See Table 9.7 and Table 9.8 in Appendix H for the sensor specifications. In addition, the BMS sensors and the Eltek sensors are not placed at the exact same locations, sometimes they are placed at the other side at the room, and at a different height. While the BMS sensors are placed at eye height, most Eltek sensors are placed high in the room (for esthetic reasons).

Table 9.26: Overview of T and RH for the measurement positions of the Eltek and the BMS sensors (July 7th 2016 till March 21st 2017).

Sensor T/RH		Temperature [°C]						Relative humidity [%]					
		mean	drop	rise	min	max	range	mean	drop	rise	min	max	range
5	A0, room 5	19.2	0.3	0.1	18.0	22.9	4.9	54.8	3.0	4.3	44.2	62.6	18.4
6	A0, room 6	20.8	0.4	0.6	19.4	24.2	4.8	50.3	1.8	2.7	43.1	56.6	13.5
BMS	A0, room 5 / 6	21.9	1.1	1.9	19.6	27.3	7.7	48.8	1.0	0.9	44.1	55.1	11.0
19	Ao, room 8	20.4	1.7	3.0	16.6	27.6	11.0	49.5	4.0	2.0	40.3	57.3	17.0
1	A0, room 10	19.7	1.3	1.7	16.4	24.7	8.3	54.1	1.7	1.5	45.4	59.1	13.7
BMS	A0, room 9 / 10	20.5	0.5	0.8	18.1	23.8	5.7	50.3	1.2	1.8	46.2	54.2	8.0
17	B-1, tower bottom	20.0	0.6	0.6	18.0	21.2	3.2	52.2	0.8	1.5	46.4	56.3	9.9
BMS	B-1, sens 6	21.0	0.5	0.6	18.9	22.6	3.7	51.4	0.8	1.0	47.7	53.9	6.2
7A	B0	20.0	0.7	0.7	17.0	21.7	4.7	51.9	0.8	1.2	36.7	54.8	18.1
20	B0	20.3	0.6	2.0	16.6	23.3	6.7	49.7	1.9	0.7	34.8	54.0	19.2
BMS	B0, sens 5	22.1	0.6	0.6	18.7	24.0	5.3	50.3	0.8	1.3	34.9	53.4	18.5
9	B2	20.6	0.3	0.5	18.5	21.6	3.1	50.2	0.9	2.2	43.2	54.0	10.8
11	B2	18.5	0.5	1.4	14.6	20.6	6.0	54.1	0.3	0.4	47.5	56.3	8.8
BMS	B2, sens 1	20.3	0.6	0.7	17.6	21.4	3.8	54.0	0.4	0.6	50.0	56.7	6.7
9	B2	20.6	0.3	0.5	18.5	21.6	3.1	50.2	0.9	2.2	43.2	54.0	10.8
13	B2	19.8	0.6	0.8	16.4	21.9	5.5	53.5	0.4	0.8	48.7	58.3	9.6
BMS	B2, sens 2	20.9	0.3	0.3	17.3	21.8	4.5	51.8	1.2	1.8	48.0	56.9	8.9

Figure 9.64 - Figure 9.69 show the measured T and RH data of similar measurement positions in more detail. The results are discussed per figure below. See Appendix H for the exact locations of the sensors.

Figure 9.64 shows the data measured by BMS sensor placed in the monumental building part between room 5 and 6 and the data measured by Eltek sensors 5 (room 5) and 6 (room 6). Higher T and lower RH are measured by the BMS sensor, during the summer period the difference between the Eltek and BMS sensors is bigger than during the autumn and winter period. Nevertheless, the impact of the outdoor climate on the indoor climate is equal for all the locations.

Figure 9.65 shows the data measured by BMS sensor placed in the monumental building part between room 9 and 10 and the data measured by Eltek sensors 19 (room 8) and 1 (room 10). During the summer period, the T and RH measured by the BMS sensor, is similar to the data measured by Eltek sensor 1. During the autumn and winter period, little higher T and little lower RH are measured by the BMS sensor. Also, the BMS sensor shows more day/night fluctuations during the autumn and winter than the Eltek sensors.

Figure 9.66 shows the data measured by BMS sensor 6 placed in the basement of the modern building part and the data measured by Eltek sensor 17. During the whole measurement period, the T and RH show similar results, although the T is little higher and the RH is little lower at the Eltek sensor.

Figure 9.67 shows the data measured by BMS sensor 5 placed in the modern building part on the 1st floor and the data measured by Eltek sensors 7A and 20. These sensors are located near works of art consisting luminaires, see also the tubular fluorescent and halogen lamps in Figure 2.3. The luminaires are turned on during the opening hours of the museum, so not on Mondays. The luminaires emit much heat, approximately 650W at the tubular fluorescent lamps and 1250W for the halogen lamps, resulting in extreme daily fluctuations of T and RH. Although the constantly higher T and lower RH measured by the BMS sensor compared to the data measured by Eltek sensor 7A, the results are very similar. BMS sensor 5 is placed at eye height right under Eltek sensor 7A, which is placed under the ceiling. The data measured by Eltek sensor 20, more closely located near the tubular fluorescent lamps, shows extremer daily fluctuations. The seasonal fluctuations are similar for all the locations.

Figure 9.68 shows the data measured by BMS sensor 1 placed in the modern building part on the 2nd floor and the data measured by Eltek sensors 9 and 11. Although there is are lot of data loss for the Eltek sensors 9 and 11, the available data still gives a good impression of the current indoor climate. All measurement locations show little daily fluctuations. The T measured by the BMS sensor is similar to the T measured by Eltek sensor 9, and the RH measured by the BMS sensor is similar to the RH measured by Eltek sensor 11. All locations show the seasonal fluctuations of T.

Figure 9.69 shows the data measured by BMS sensor 2 placed in the modern building part on the 2nd floor and the data measured by Eltek sensors 9 and 13. Although there is are lot of data loss for the Eltek sensor 9, the available data still gives a good impression of the current indoor climate. The T and RH measured by the BMS sensor are very similar to the data measured by Eltek sensor 9. The data measured by Eltek sensor 13 is shows a little lower T and little higher RH than the data measured at the other locations. The increased daily fluctuations from September 2016 to February 2017 measured by Eltek sensor 13, and to a smaller extent measured by BMS sensor 2, are a result of the work of art consisting an extreme amount of incandescent lamps, see Figure 2.3 for an impression. All locations show the same seasonal fluctuations of T and RH.

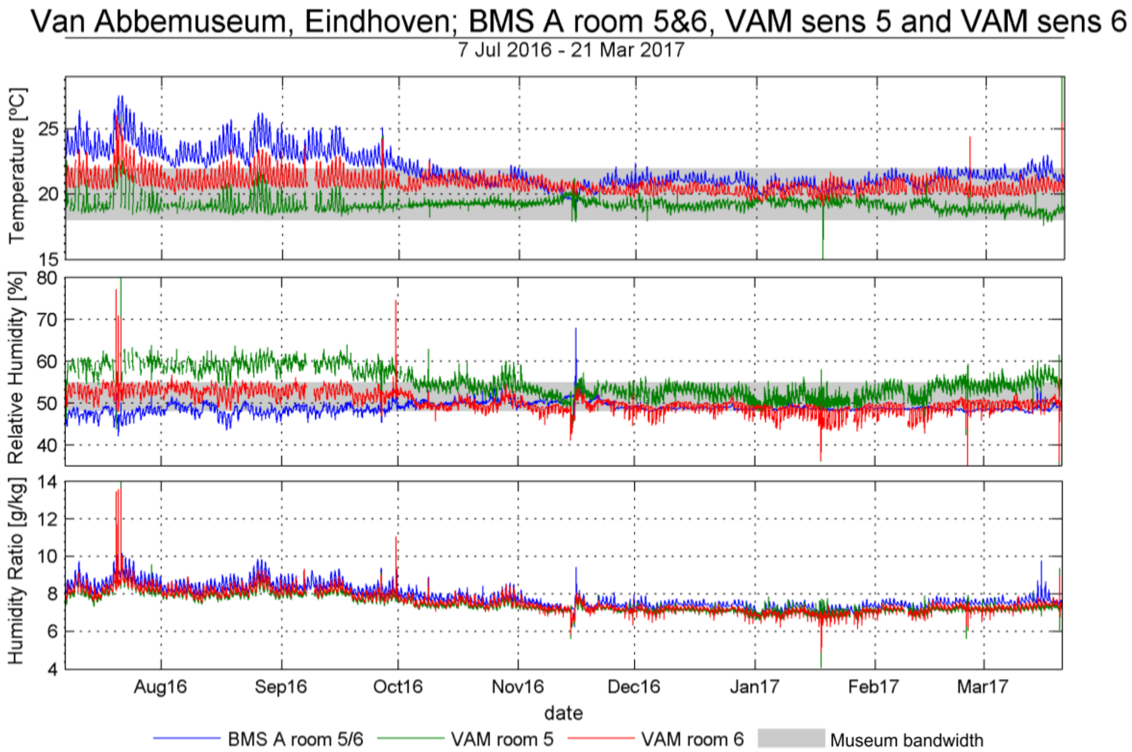


Figure 9.64: Measured T, RH, and humidity ratio for the measurement positions BMS sensor room 5/6 (building part A) and the Eltek sensors 5 and 6 (July 7th 2016 till March 21st 2017).

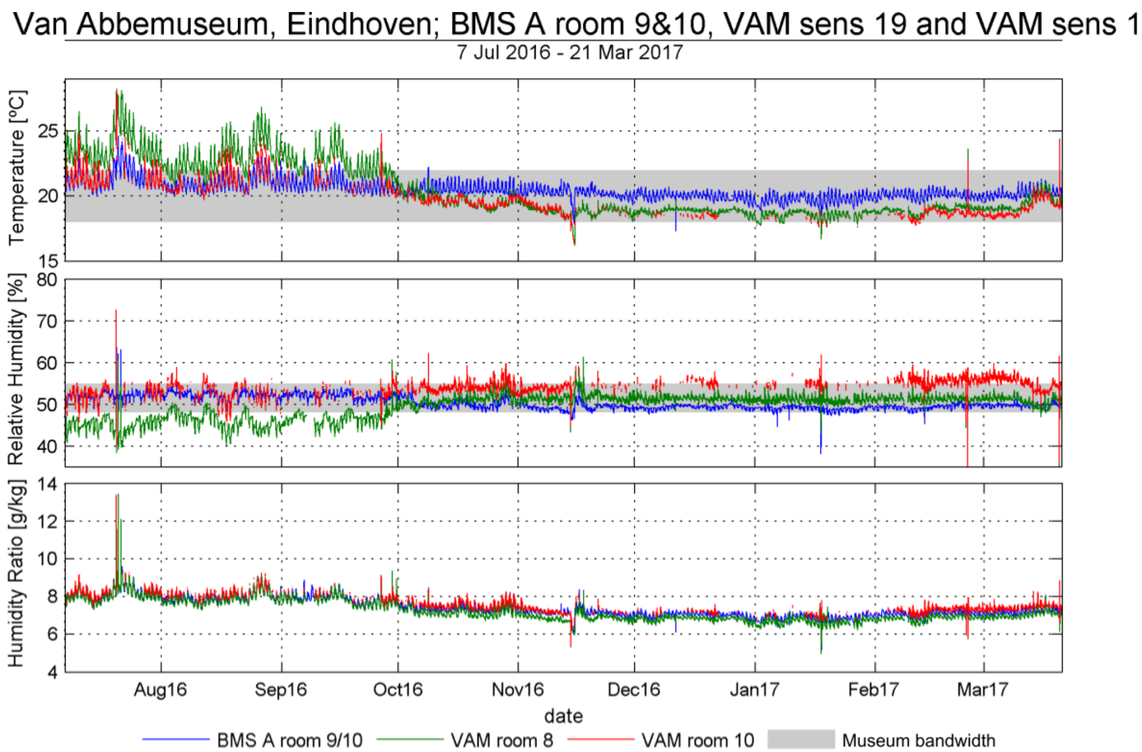


Figure 9.65: Measured T, RH, and humidity ratio for the measurement positions BMS sensor room 9/10 (building part A) and the Eltek sensors 19 and 1 (July 7th 2016 till March 21st 2017).

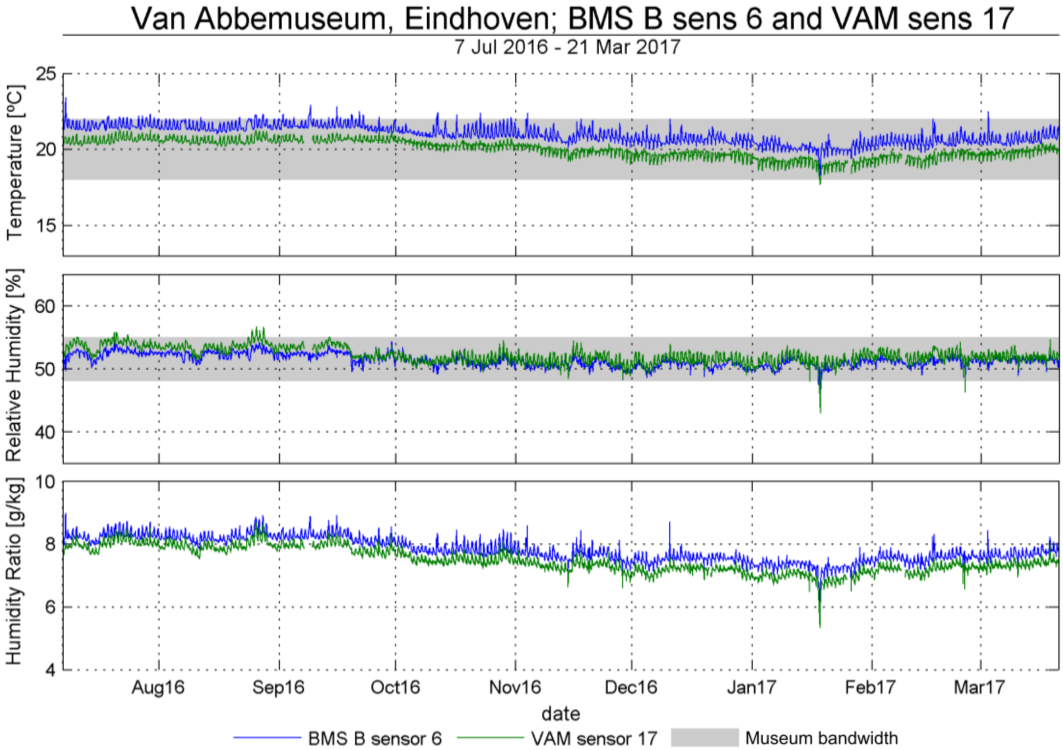


Figure 9.66: Measured T, RH, and humidity ratio for the measurement positions BMS sensor 6 (building part B-1) and the Eltek sensor 17 (July 7th 2016 till March 21st 2017).

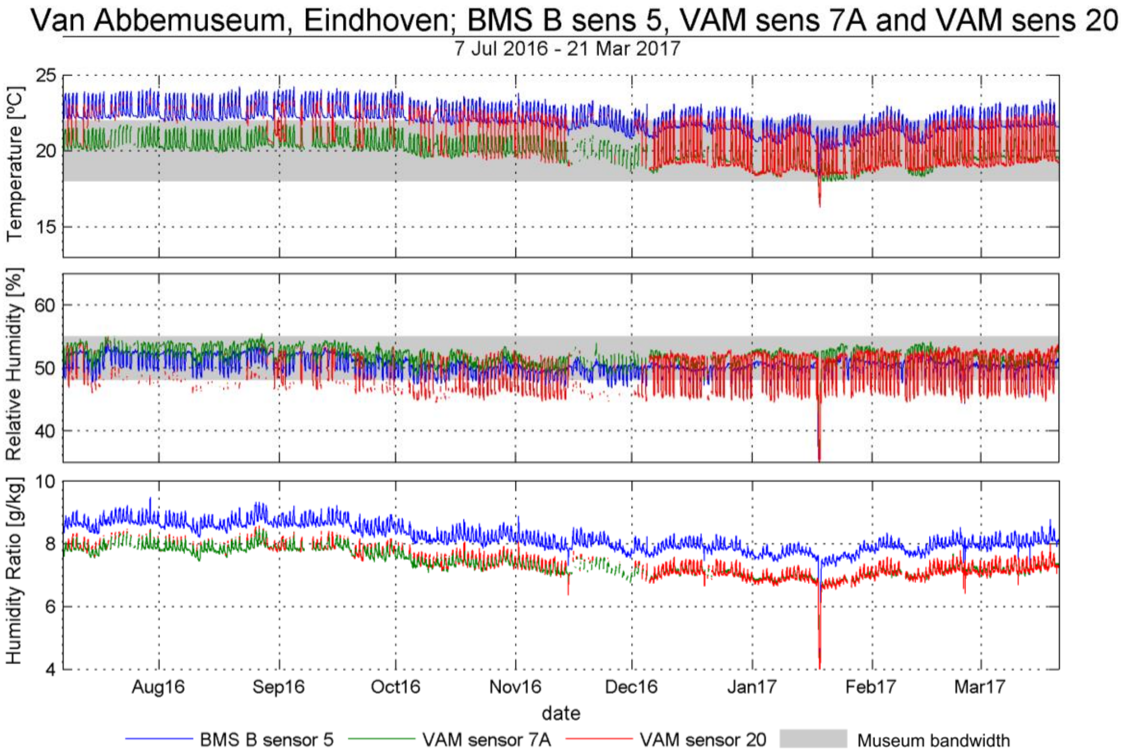


Figure 9.67: Measured T, RH, and humidity ratio for the measurement positions BMS sensor 5 (building part B0) and the Eltek sensors 7A and 20 (July 7th 2016 till March 21st 2017).

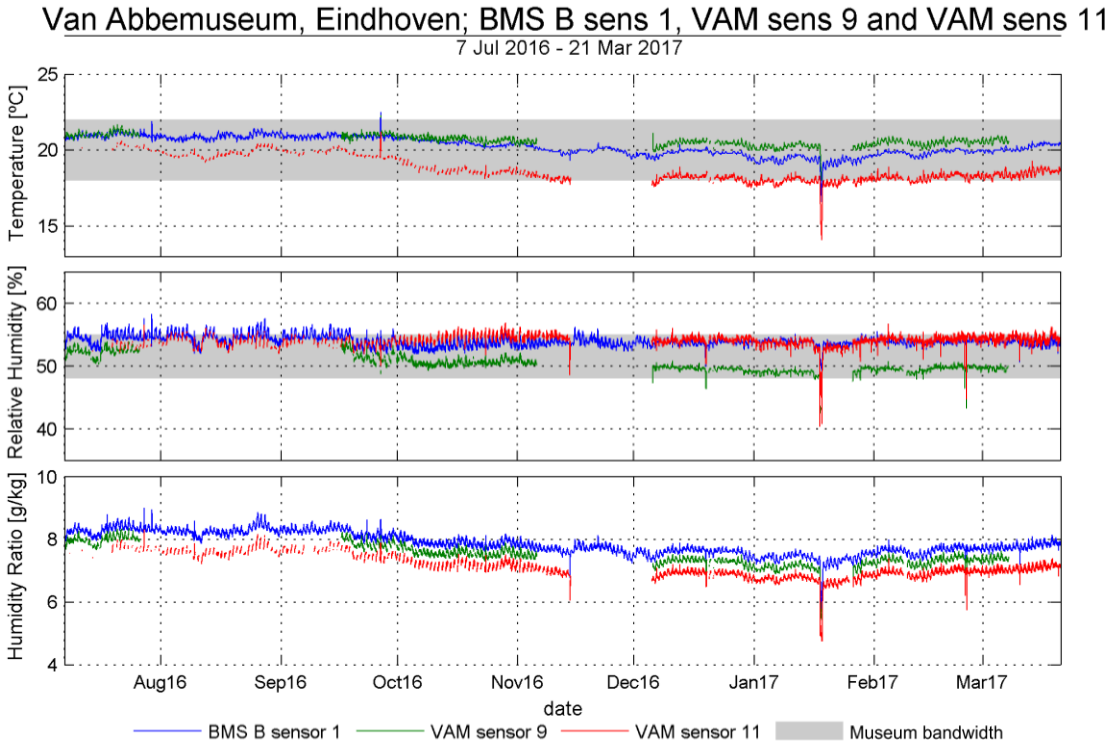


Figure 9.68: Measured T, RH, and humidity ratio for the measurement positions BMS sensor 1 (building part B2) and the Eltek sensors 9 and 11 (July 7th 2016 till March 21st 2017).

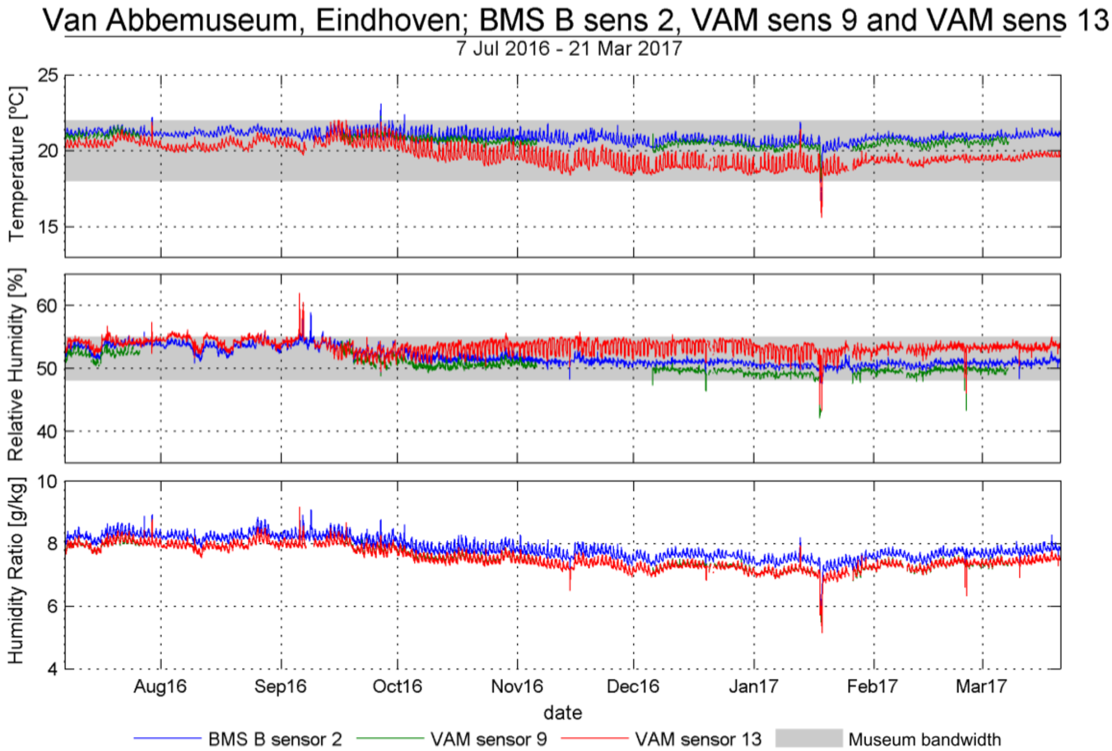


Figure 9.69: Measured T, RH, and humidity ratio for the measurement positions BMS sensor 2 (building part B2) and the Eltek sensors 9 and 13 (July 7th 2016 till March 21st 2017).

Table 9.27 shows the percentage of time the measured data meets the museum requirements, see Table 2.1. In the table below, similar measurement positions of the Eltek and BMS sensors are compared, based on their location in the museum, see Appendix H for the exact locations. As can been seen in Table 9.27, most results of the BMS and corresponding Eltek sensors match. However, some difference are present, which are discussed below.

The BMS sensor placed in the monumental building part between room 9 and 10 meets the museum requirements better than Eltek sensors 19 (room 8) and 1 (room 10). As can be seen in Figure 9.65, Eltek sensor 19 shows a too high T and too low RH during the summer to fit in the museum bandwidth. Eltek sensor 1 shows a too high RH during the winter period.

The data measured by BMS sensor 5 placed in the modern building part on the 1st floor does not fit, to a larger extent than Eltek sensors 7A and 20, in the museum bandwidth. Especially during the summer period, the T is constantly above 22°C.

Table 9.27: Overview CEC results using the museum requirements for the measurement positions of the Eltek and the BMS sensors (July 7th 2016 till March 21st 2017).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	ΔT/h	ΔT/d	ΔRH/h	ΔRH/d
5 A0, room 5	60	0	0	39	0	0	0	0	0	1	11	69	98
6 A0, room 6	84	5	0	0	0	0	0	11	0	1	12	25	85
BMS A0, room 5 / 6	63	20	0	0	0	0	0	1	16	1	13	8	37
19 Ao, room 8	69	0	0	0	0	1	0	4	25	3	23	40	78
1 A0, room 10	63	5	0	30	1	1	0	0	1	2	15	53	68
BMS A0, room 9 / 10	95	4	0	0	0	0	0	2	0	1	8	14	40
17 B-1, tower bottom	99	0	0	1	0	0	0	0	0	1	0	9	36
BMS B-1, sens 6	98	1	0	0	0	0	0	0	0	0	1	4	10
7A B0	100	0	0	0	0	0	0	0	0	2	1	14	75
20 B0	62	3	0	0	0	0	0	18	17	12	70	21	75
BMS B0, sens 5	46	49	0	0	0	0	0	1	4	4	1	13	84
9 B2	99	0	0	0	0	0	0	1	0	0	0	5	11
11 B2	77	0	0	8	0	15	0	0	0	0	1	31	25
BMS B2, sens 1	92	0	0	8	0	0	0	0	0	0	0	22	31
9 B2	99	0	0	0	0	0	0	1	0	0	0	5	11
13 B2	97	0	0	3	0	0	0	0	0	2	1	15	54
BMS B2, sens 2	99	0	0	1	0	0	0	0	0	0	1	8	13

Table 9.28 shows the result overview of the general climate risk assessment, as explained in Paragraph 3.3.1. Please note that the results are an estimation, since at least one full year of data is necessary to get the 100% reliable results out of the general climate risk assessment method (Martens, 2012). Appendix A shows the conditions of the ASHRAE classes. In the table below, the results of similar measurement positions of the Eltek and BMS sensors are compared, based on their location in the museum, see Appendix H for the exact locations. As can been seen in Table 9.28, most results of the BMS and corresponding Eltek sensors match. However, some difference are present. The results of BMS sensor 1 placed in the modern building part on the 2nd floor fits for 100% in ASHRAE class AA, while the corresponding Eltek sensors 9 and 11 fit for 100% in ASHRAE classes A and B. This can be explained by the fact that the Eltek sensors measured extremer deviating T and RH during the fire alarms on January 17th 2017 and February 24th 2017. As a result of the fire alarms, malfunctioning of the AHUs occurred, see also Appendix J. Despite the fact that the data measured at Eltek sensors 9 and 11 did not met ASHRAE class AA for 100% of the time, they did met the ASHRAE class for 99,8% of the time, which is similar.

Table 9.28: Overview general climate risk assessment results for the measurement positions of the Eltek and the BMS sensors (July 7th 2016 till March 21st 2017).

Sensor T/RH		ASHRAE climate classes					
		AA	As	A	B	C	D
5	A0, room 5	85.6	99.0	99.3	100	100	100
6	A0, room 6	97.5	99.2	99.4	100	100	100
BMS	A0, room 5 / 6	98.0	98.1	98.2	100	100	100
19	Ao, room 8	91.0	95.9	96.2	100	100	100
1	A0, room 10	96.8	97.5	97.8	100	100	100
BMS	A0, room 9 / 10	99.7	99.7	99.7	100	100	100
17	B-1, tower bottom	100	100	100	100	100	100
BMS	B-1, sens 6	100	100	100	100	100	100
7A	B0	99.9	99.9	99.9	99.9	100	100
20	B0	90.2	89.8	90.5	99.8	100	100
BMS	B0, sens 5	99.9	99.9	99.9	99.9	100	100
9	B2	99.8	99.8	100	100	100	100
11	B2	99.8	99.8	99.8	100	100	100
BMS	B2, sens 1	100	100	100	100	100	100
9	B2	99.8	99.8	100	100	100	100
13	B2	99.9	99.9	99.9	100	100	100
BMS	B2, sens 2	99.9	99.9	99.9	100	100	100

Table 9.29 shows the result overview of the specific climate risk assessment, as explained in Paragraph 3.3.1. Please note that the results are an estimation, since at least one full year of data is necessary to get the 100% reliable results out of the specific climate risk assessment method (Martens, 2012). In the table below, the results of similar measurement positions of the Eltek and BMS sensors are compared, based on their location in the museum, see Appendix H for the exact locations. As can been seen in Table 9.29, most results of the BMS and corresponding Eltek sensors match. All measurement locations show that the risks of mould growth (Mould), and possible damage of the base material (Base) and pictorial layer (Pict) are on the safe side. However, the Lifetime Multiplier (LM) is almost always <1 for all object types. This means that the objects have an increased risk regarding chemical degradation. Risks are caused by T_{avg} and RH_{avg} higher than the conditions of 20°C and 50%. In most cases, the LM value of the data measured by the BMS sensors is little lower than the LM value of the data measured by the corresponding Eltek sensors.

Table 9.29: Overview specific climate risk assessment results for the measurement positions of the Eltek and the BMS sensors (July 7th 2016 till March 21st 2017).

Sensor T/RH	Paper		Panel painting				Furniture			Wooden sculpture		
	Mould	LM	Mould	LM	Base	Pict	Mould	LM	Base	Mould	LM	Base
5 A0, room 5		0.985		0.954				0.949			0.955	
6 A0, room 6		0.885		0.915				0.912			0.916	
BMS A0, room 5 / 6		0.785		0.855				0.856			0.855	
19 Ao, room 8		0.945		0.974				0.980			0.974	
1 A0, room 10		0.931		0.926				0.929			0.927	
BMS A0, room 9 / 10		0.924		0.945				0.942			0.945	
17 B-1, tower bottom		0.940		0.942				0.940			0.942	
BMS B-1, sens 6		0.840		0.977				0.976			0.877	
7A B0		0.955		0.955				0.953			0.956	
20 B0		0.890		0.925				0.925			0.928	
BMS B0, sens 5		0.740		0.808				0.806			0.809	
9 B2		0.896		0.923				0.920			0.923	
11 B2		1.070		1.020				1.020			1.020	
BMS B2, sens 1		0.870		0.881				0.880			0.881	
9 B2		0.896		0.923				0.920			0.923	
13 B2		0.945		0.937				0.936			0.938	
BMS B2, sens 2		0.837		0.871				0.868			0.871	

From the results comparisons and validations of the data measured by the BMS and Eltek sensors as described in this Appendix, can be concluded that the BMS data is representative for the real indoor climate. Therefore, one year from March 21st 2016 of the data measured by the BMS has been further used for the results analysis in Paragraph 4.1.

# Appendix Q.	Results graphs

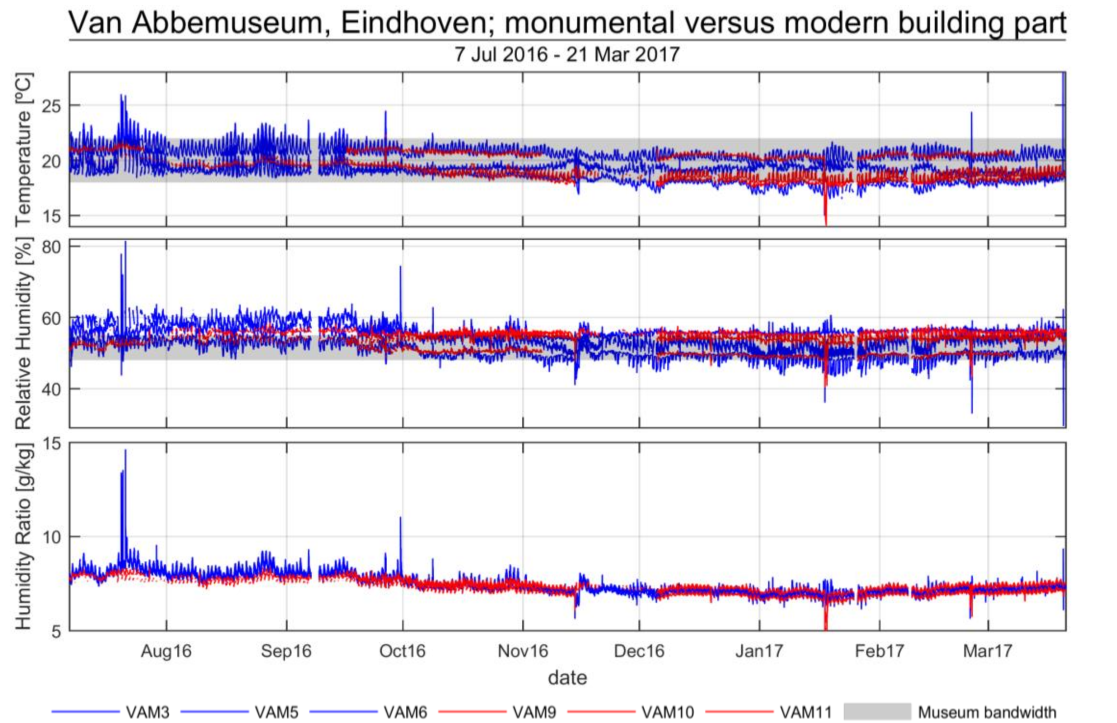


Figure 9.70: Measured T and RH for the measurement positions Eltek sensors 3, 5, and 6 (monumental building part room 4, 5, and 6) and Eltek sensors 9, 10, and 11 (modern building part rooms at B2) during the total measurement period (July 7th 2016 till March 21st 2017).

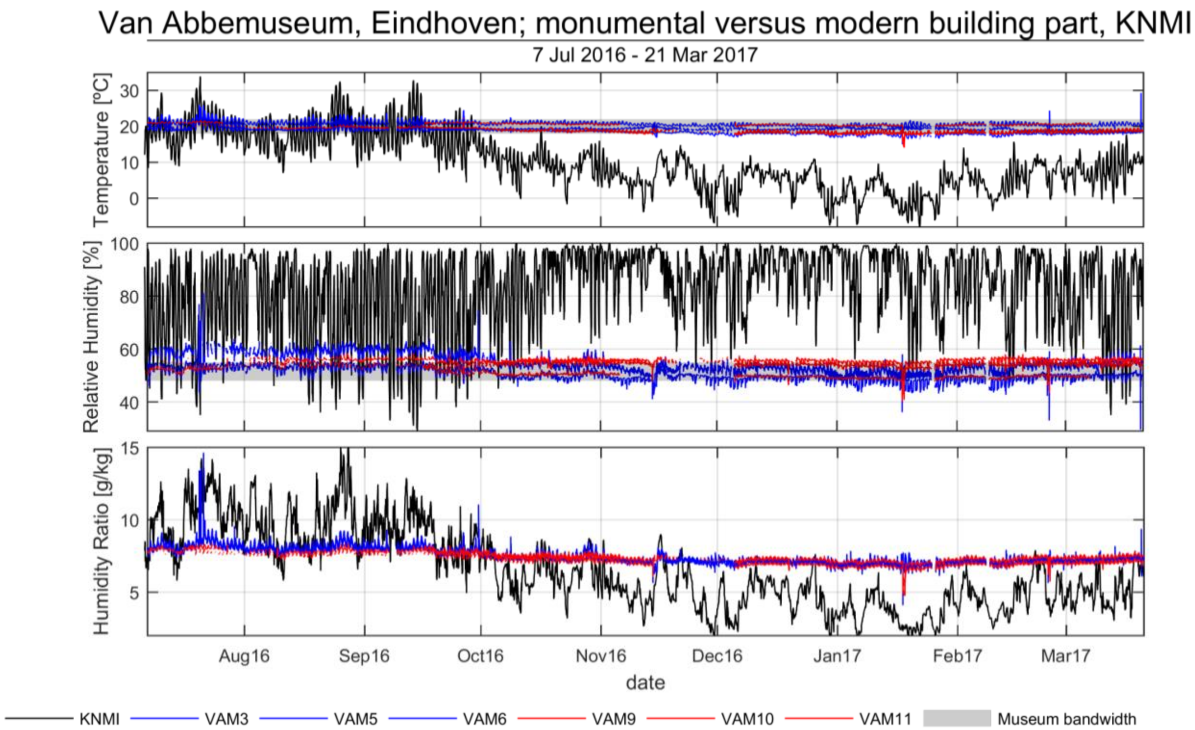


Figure 9.71: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 3, 5, and 6 (monumental building part room 4, 5, and 6) and Eltek sensors 9, 10, and 11 (modern building part rooms at B2) during the total measurement period (July 7th 2016 till March 21st 2017).

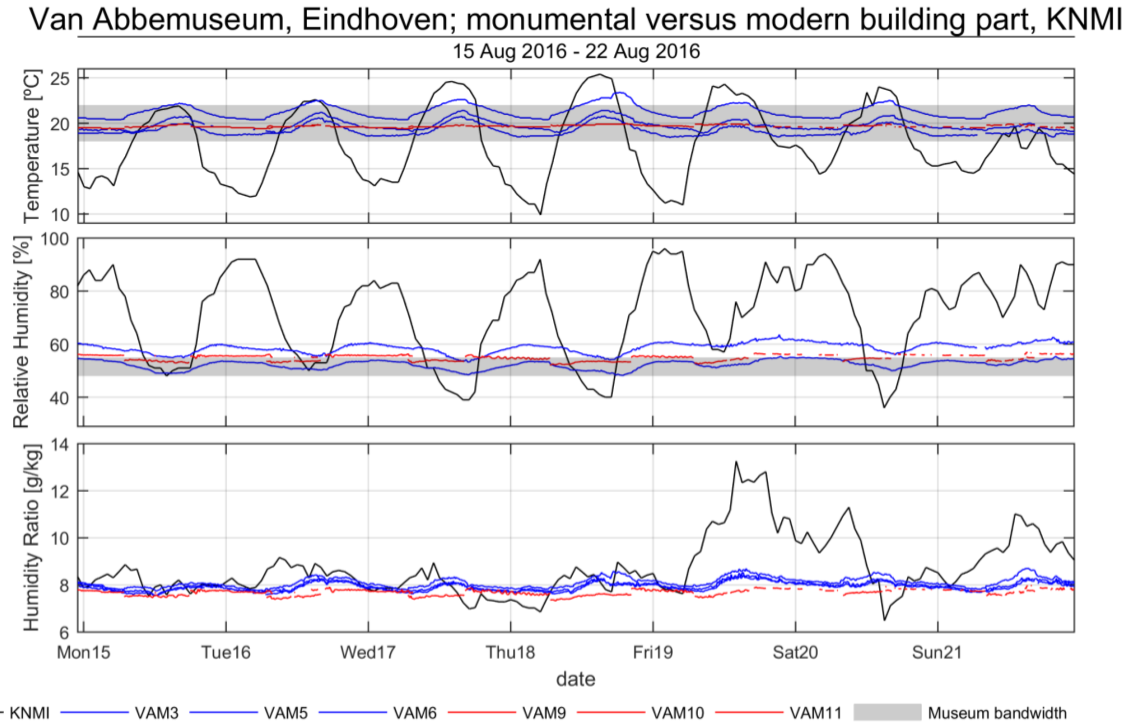


Figure 9.72: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 3, 5, and 6 (monumental building part room 4, 5, and 6) and Eltek sensors 9, 10, and 11 (modern building part rooms at B2) during a typical summer week (August 15th 2016 till August 22nd 2016).

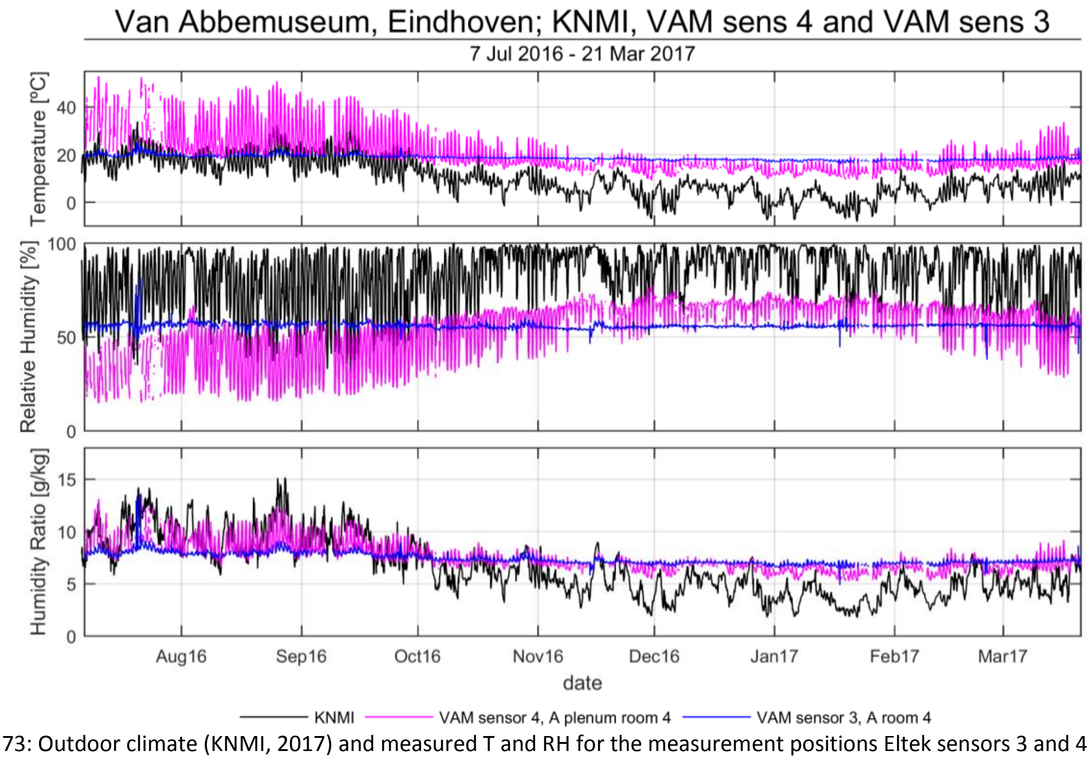


Figure 9.73: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 3 and 4 (monumental building part room 4 and plenum room 4) during the total measurement period (July 7th 2016 till March 21st 2017).

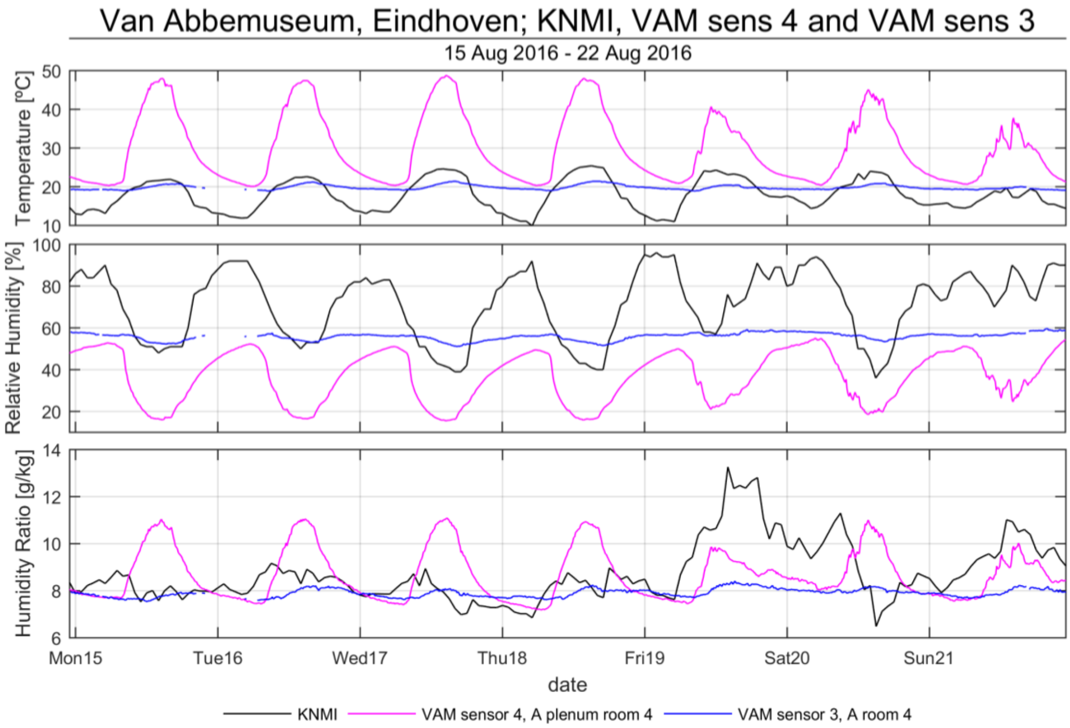


Figure 9.74: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 3 and 4 (monumental building part room 4 and plenum room 4) during a typical summer week (August 15th 2016 till August 22nd 2016).

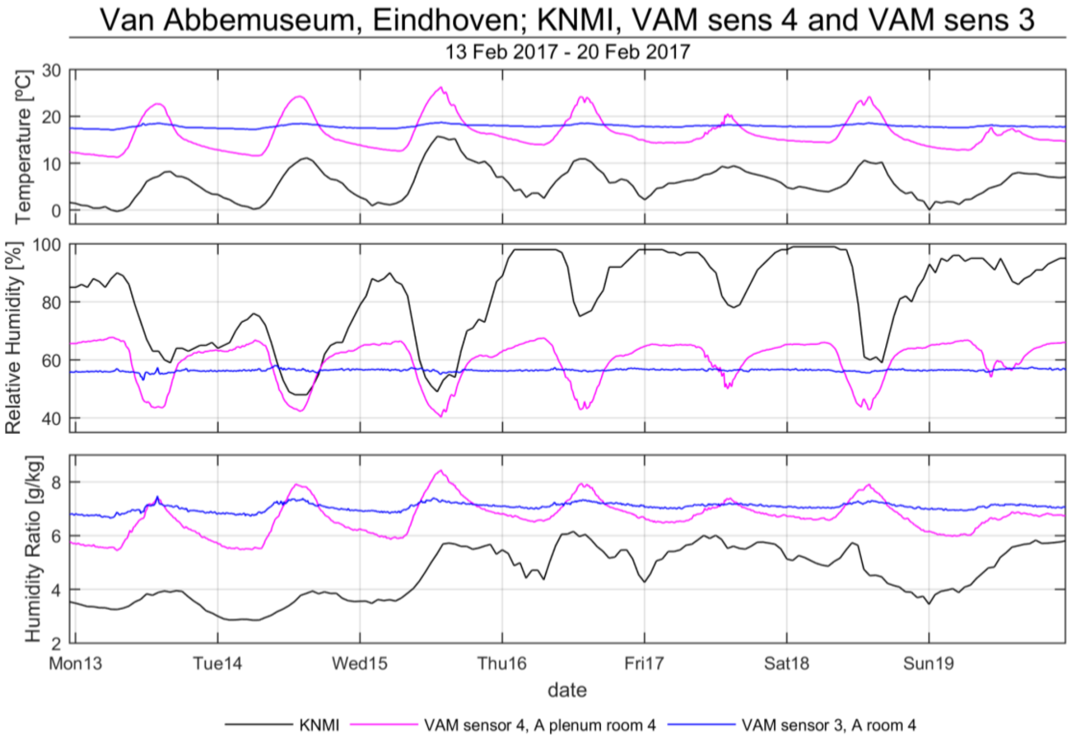


Figure 9.75: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 3 and 4 (monumental building part room 4 and plenum room 4) during a typical winter week (February 13th 2017 till February 20th 2017).

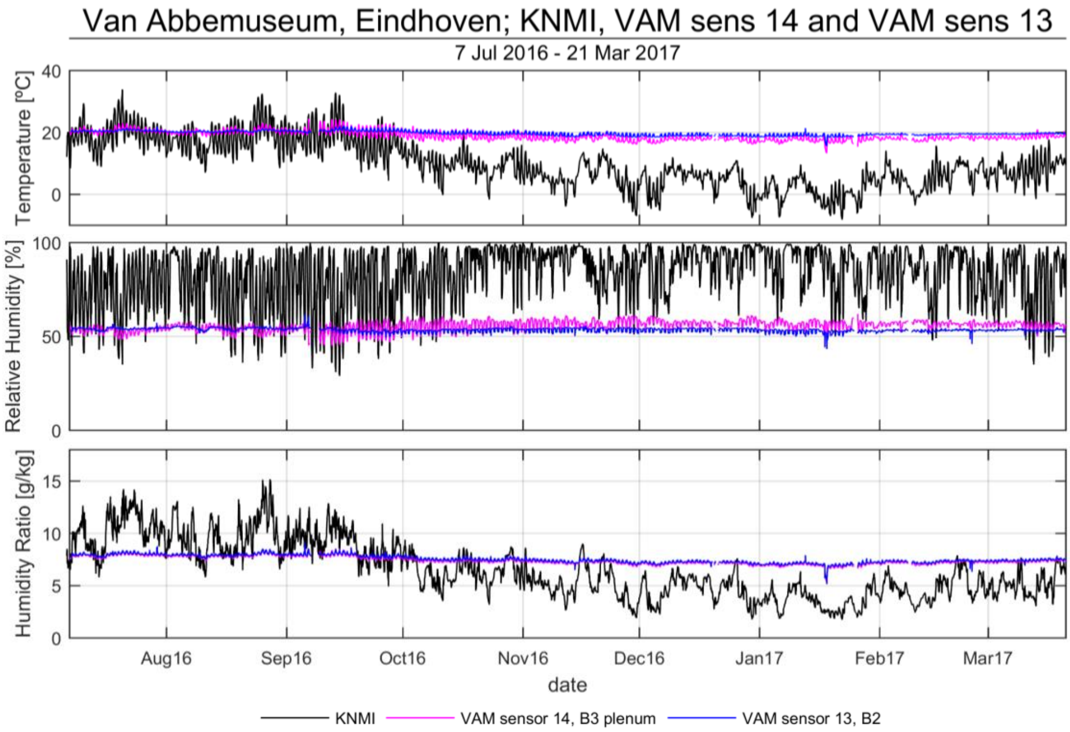


Figure 9.76: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 13 and 14 (modern building part room at B2 and corresponding plenum) during the total measurement period (July 7th 2016 till March 21st 2017).

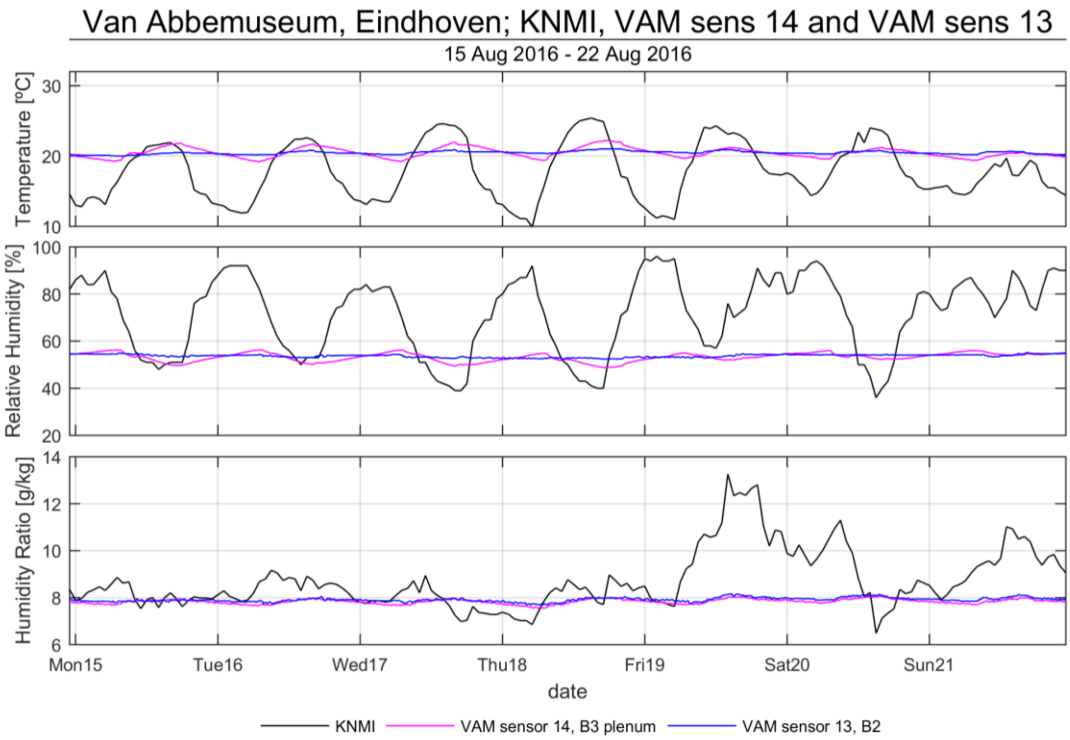


Figure 9.77: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 13 and 14 (modern building part room at B2 and corresponding plenum) during a typical summer week (August 15th 2016 till August 22nd 2016).

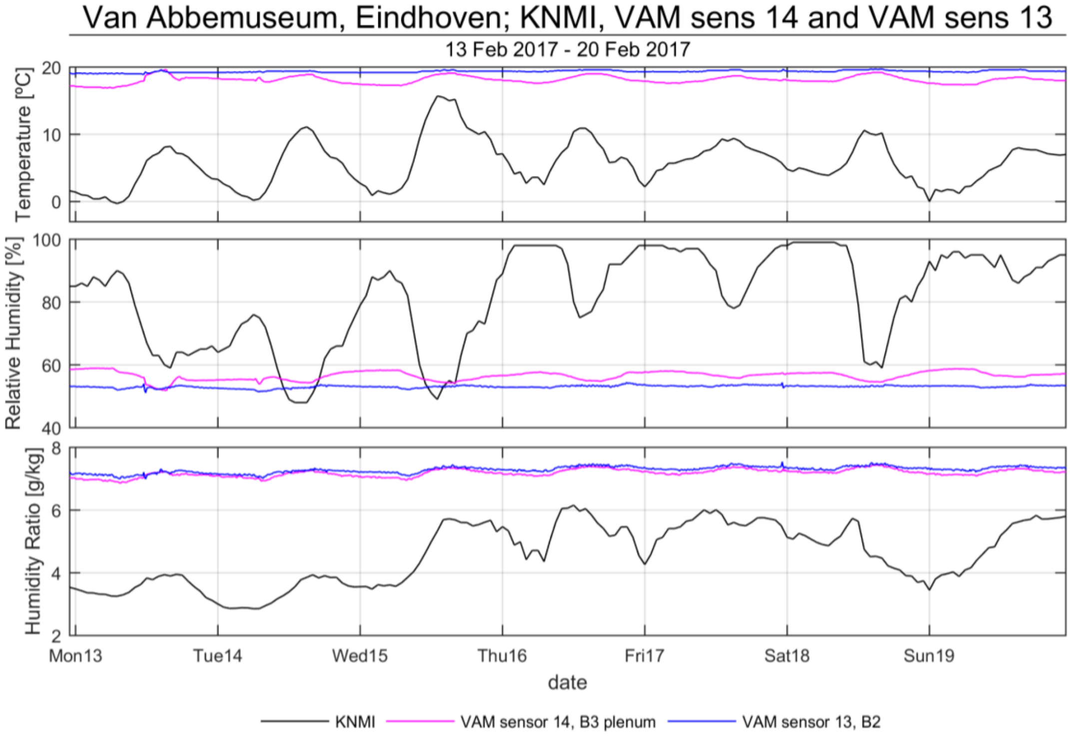


Figure 9.78: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 13 and 14 (modern building part room at B2 and corresponding plenum) during a typical winter week (February 13th 2017 till February 20th 2017).

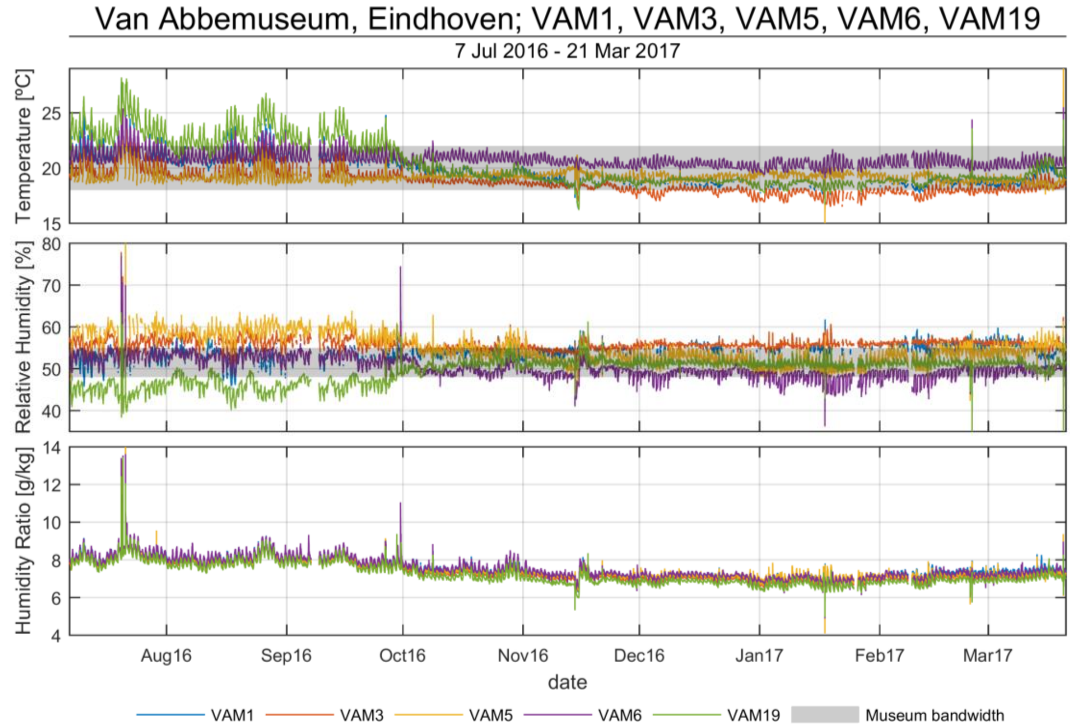


Figure 9.79: Measured T and RH for the measurement positions Eltek sensors 1, 3, 5, 6, and 19 (monumental building part room 10, 4, 5, 6, and 8) during the total measurement period (July 7th 2016 till March 21st 2017).

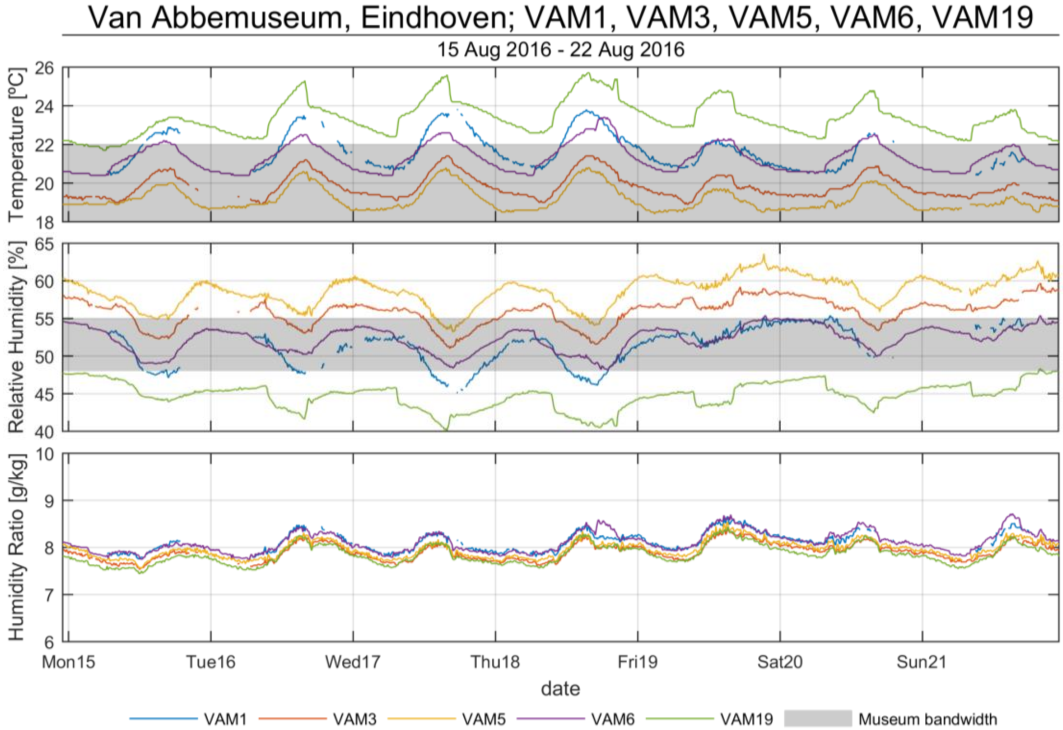


Figure 9.80: Measured T and RH for the measurement positions Eltek sensors 1, 3, 5, 6, and 19 (monumental building part room 10, 4, 5, 6, and 8) during a typical summer week (August 15th 2016 till August 22nd 2016).

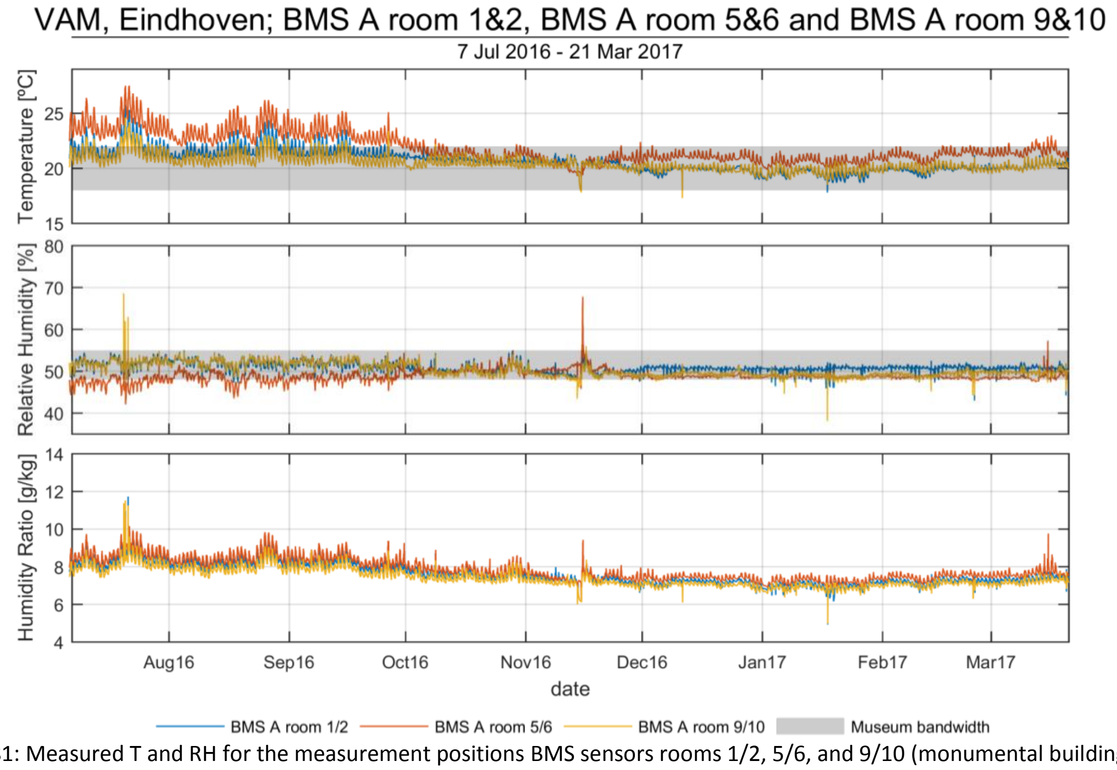


Figure 9.81: Measured T and RH for the measurement positions BMS sensors rooms 1/2, 5/6, and 9/10 (monumental building part) during the total measurement period (July 7th 2016 till March 21st 2017).

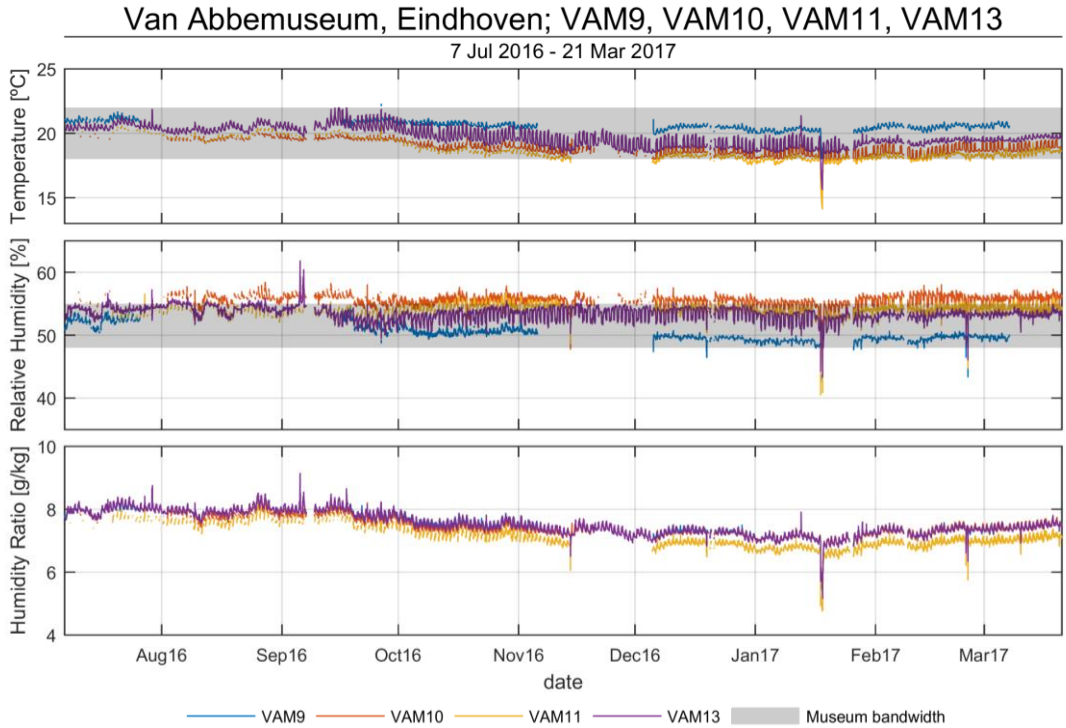


Figure 9.82: Measured T and RH for the measurement positions Eltek sensors 9, 10, 11, and 13 (modern building part rooms at B2) during the total measurement period (July 7th 2016 till March 21st 2017).

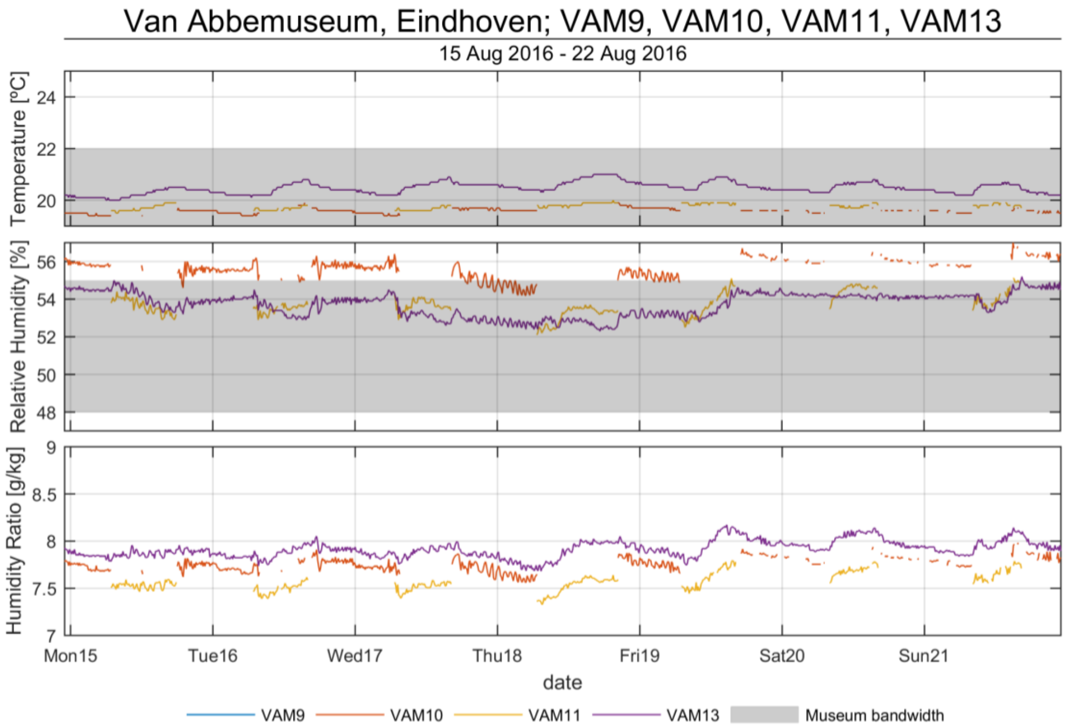


Figure 9.83: Measured T and RH for the measurement positions Eltek sensors 9, 10, 11, and 13 (modern building part rooms at B2) during a typical summer week (August 15th 2016 till August 22nd 2016).

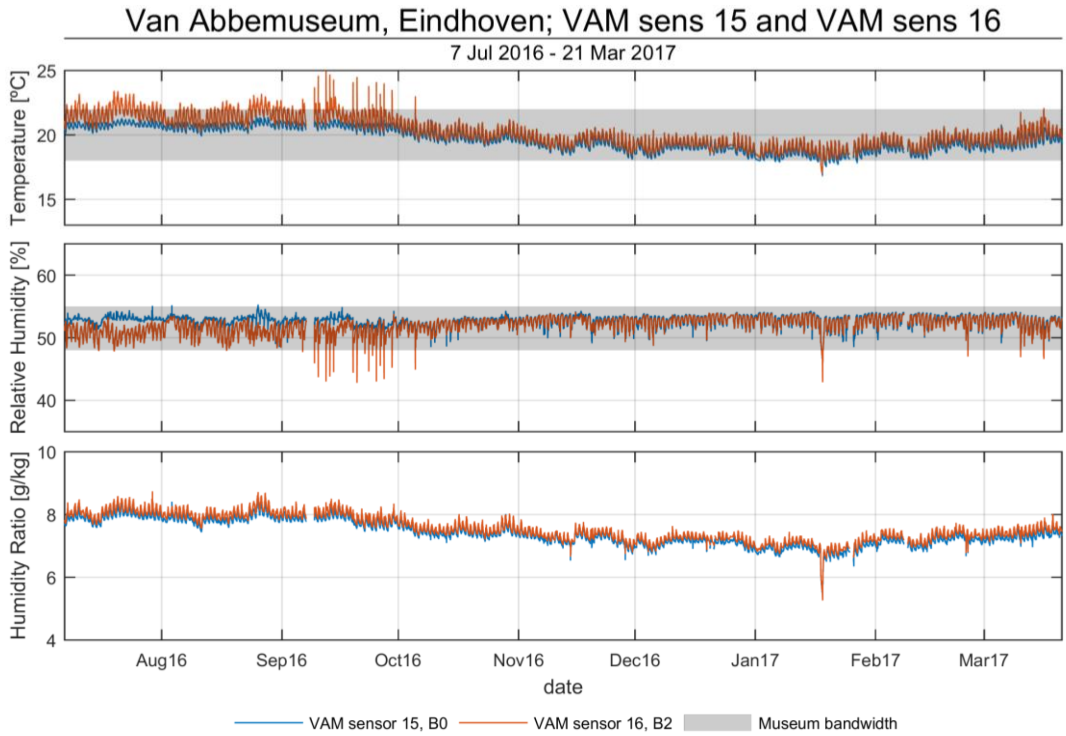


Figure 9.84: Measured T and RH for the measurement positions Eltek sensors 15 and 16 (corridor at the bottom and at the top in the modern building part) during the total measurement period (July 7th 2016 till March 21st 2017).

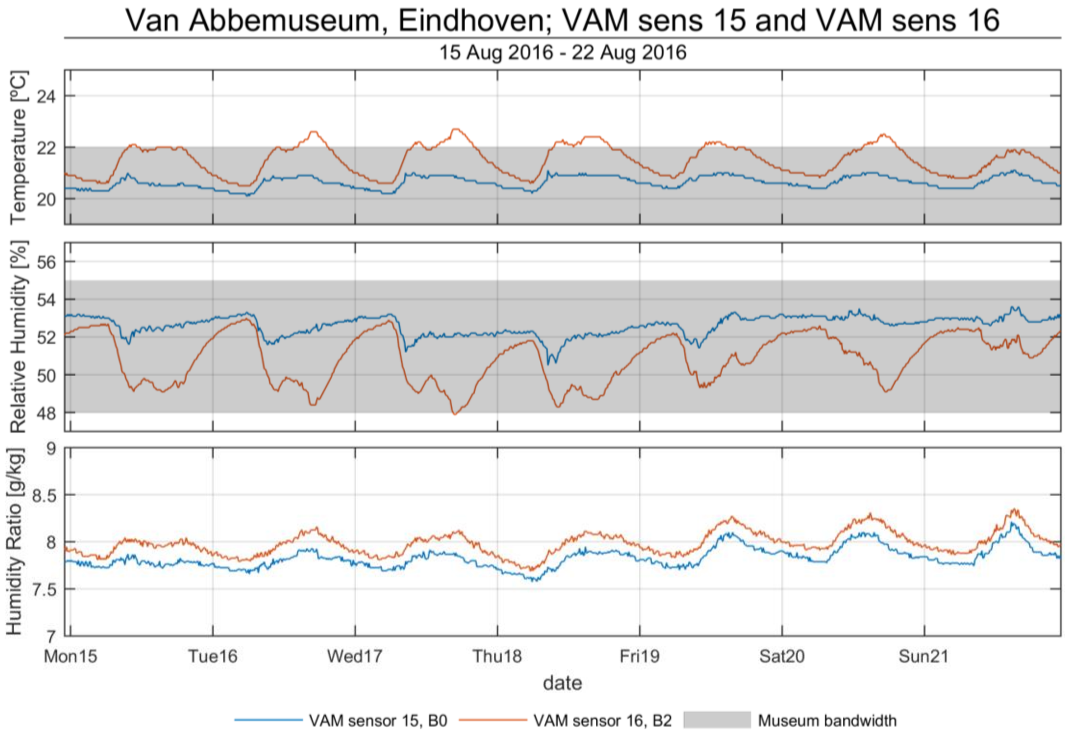


Figure 9.85: Measured T and RH for the measurement positions Eltek sensors 15 and 16 (corridor at the bottom and at the top in the modern building part) during a typical summer week (August 15th 2016 till August 22nd 2016).

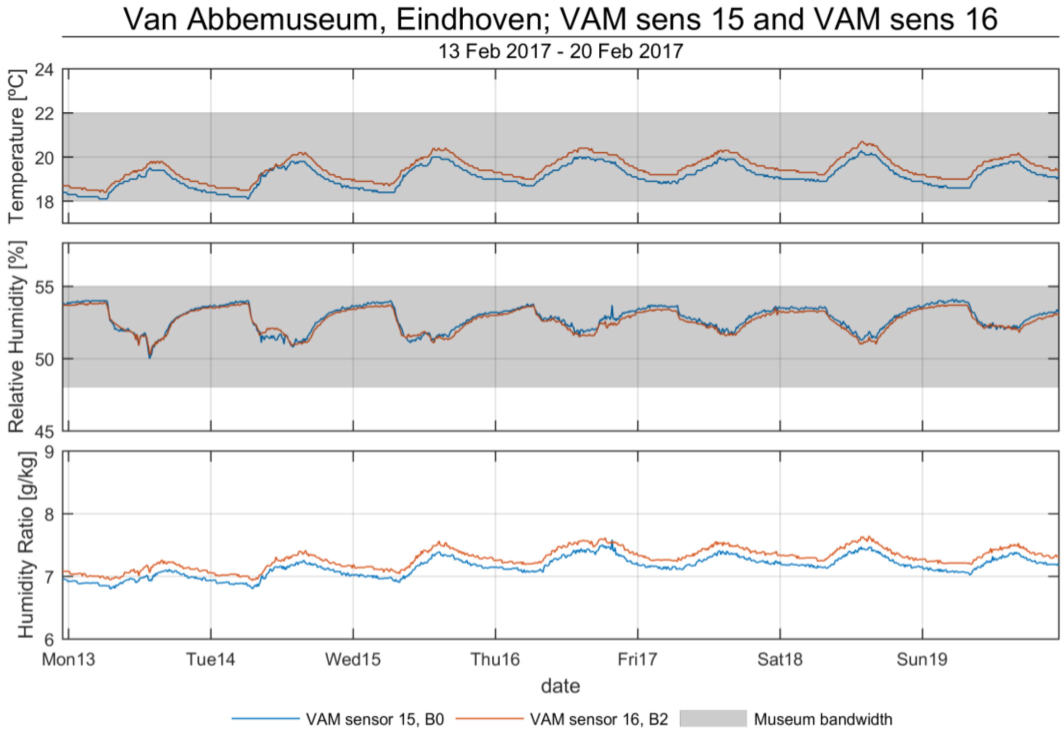


Figure 9.86: Measured T and RH for the measurement positions Eltek sensors 15 and 16 (corridor at the bottom and at the top in the modern building part) during a typical winter week (February 13th 2017 till February 20th 2017).

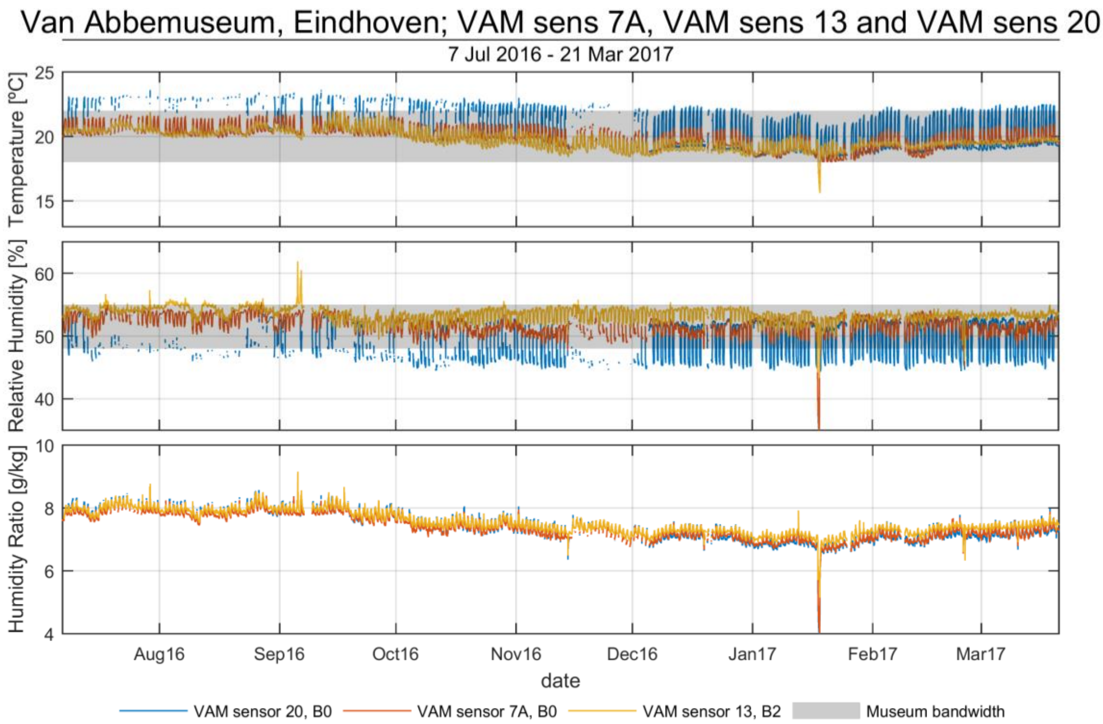


Figure 9.87: Measured T and RH for the measurement positions Eltek sensors 7A and 20 (modern building part room at B0) and Eltek sensor 13 (modern building part room at B2) during the total measurement period (July 7th 2016 till March 21st 2017).

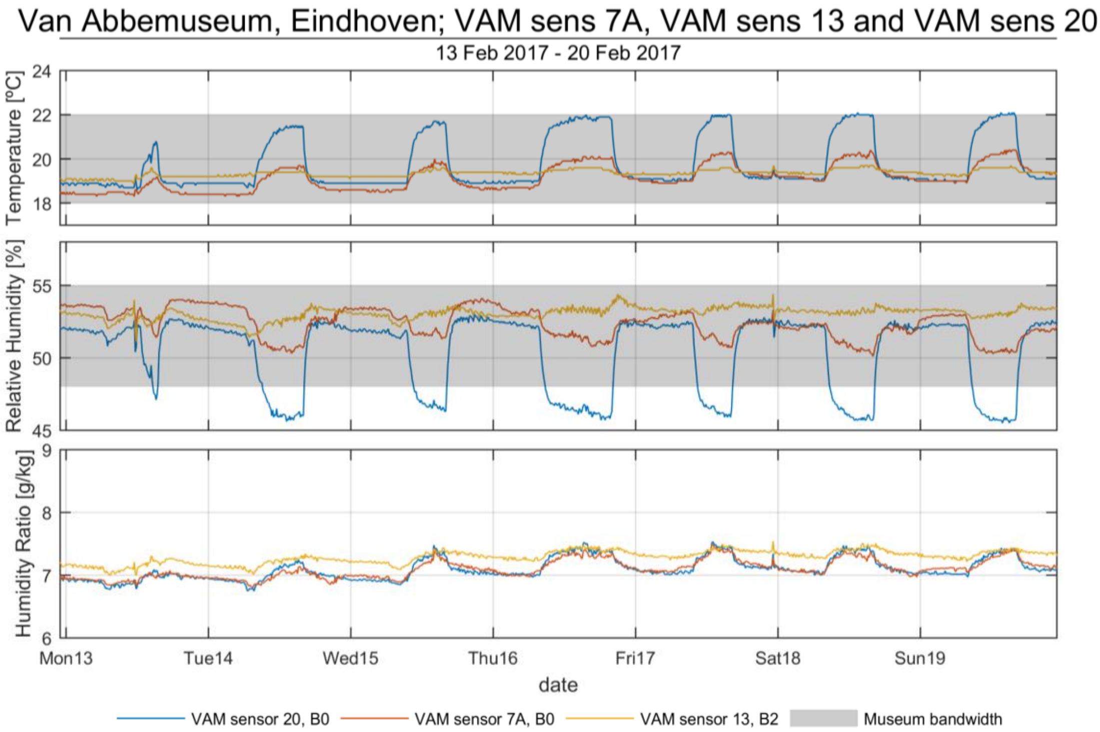


Figure 9.88: Measured T and RH for the measurement positions Eltek sensors 7A and 20 (modern building part rooms at B0) and Eltek sensor 13 (modern building part room at B2) during a typical winter week (February 13th 2017 till February 20th 2017).

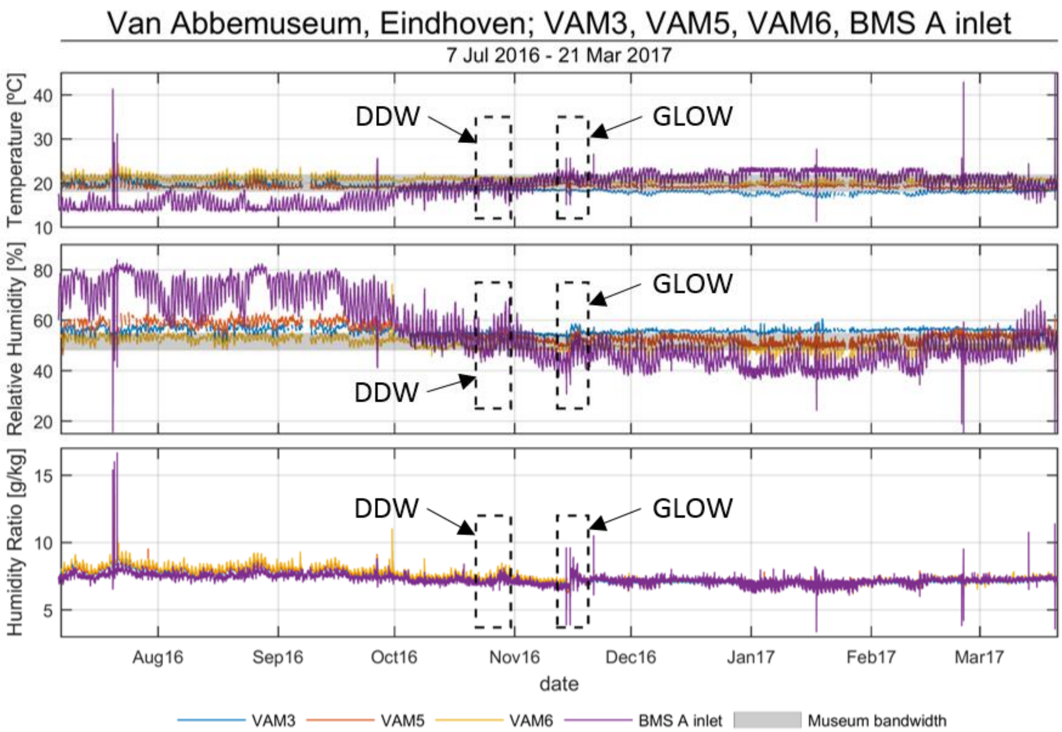


Figure 9.89: Measured T and RH for the measurement positions Eltek sensors 3, 5, and 6 (monumental building part room 4, 5, and 6) and BMS sensor inlet (monumental building part) during the total measurement period (July 7th 2016 till March 21st 2017).

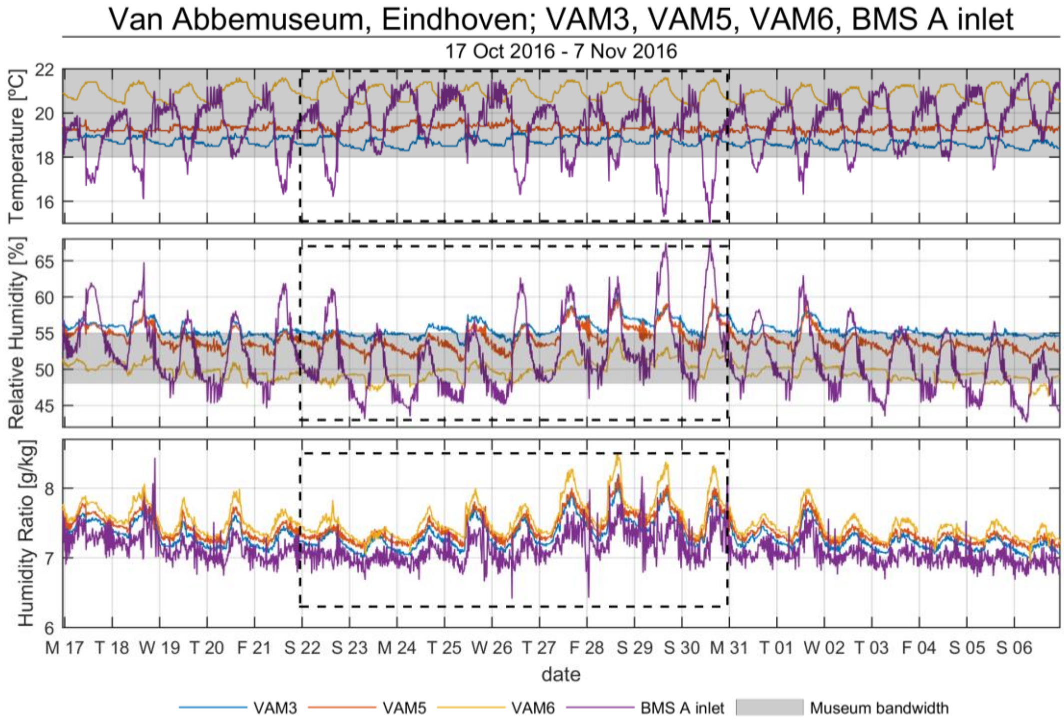


Figure 9.90: Measured T and RH for the measurement positions Eltek sensors 3, 5, and 6 (monumental building part room 4, 5, and 6) and BMS sensor inlet (monumental building part) during the period around Dutch Design Week (October 17th 2016 till November 7th 2016). The dashed boxes represent the period of DDW.

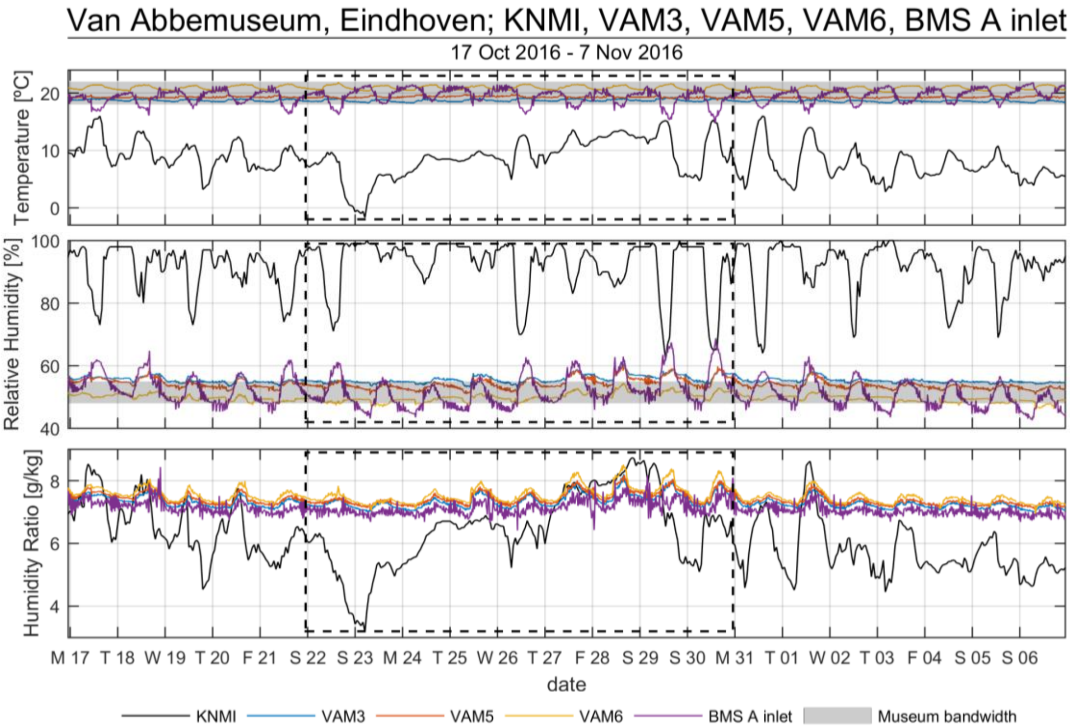


Figure 9.91: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 3, 5, and 6 (monumental building part room 4, 5, and 6) and BMS sensor inlet (monumental building part) during the period around Dutch Design Week (October 17th 2016 till November 7th 2016). The dashed boxes represent the period of DDW.

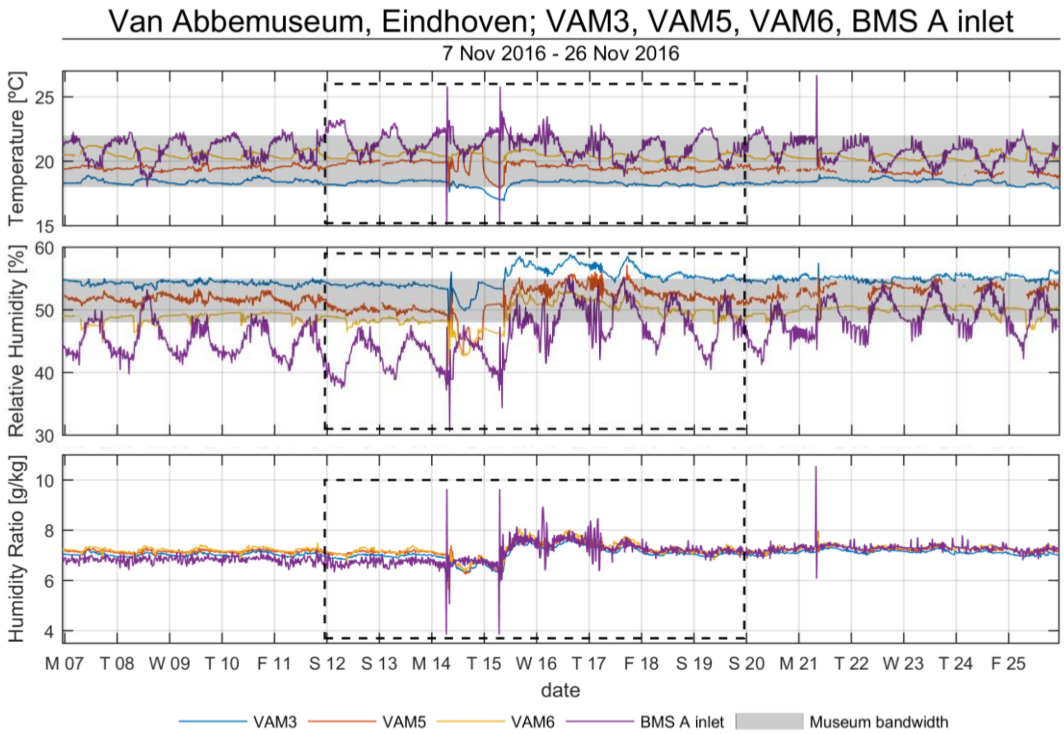


Figure 9.92: Measured T and RH for the measurement positions Eltek sensors 3, 5, and 6 (monumental building part room 4, 5, and 6) and BMS sensor inlet (monumental building part) during the period around GLOW (November 7th 2016 till November 26th 2016). The dashed boxes represent the period of GLOW.

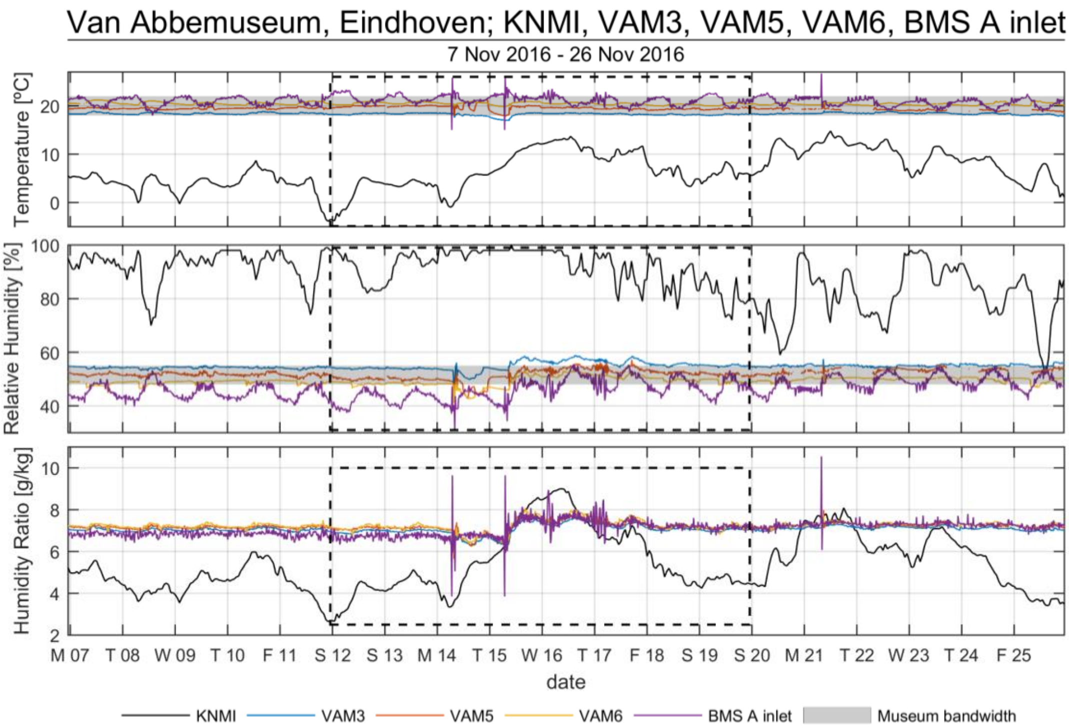


Figure 9.93: Outdoor climate (KNMI, 2017) and measured T and RH for the measurement positions Eltek sensors 3, 5, and 6 (monumental building part room 4, 5, and 6) and BMS sensor inlet (monumental building part) during the period around GLOW (November 7th 2016 till November 26th 2016). The dashed boxes represent the period of GLOW.

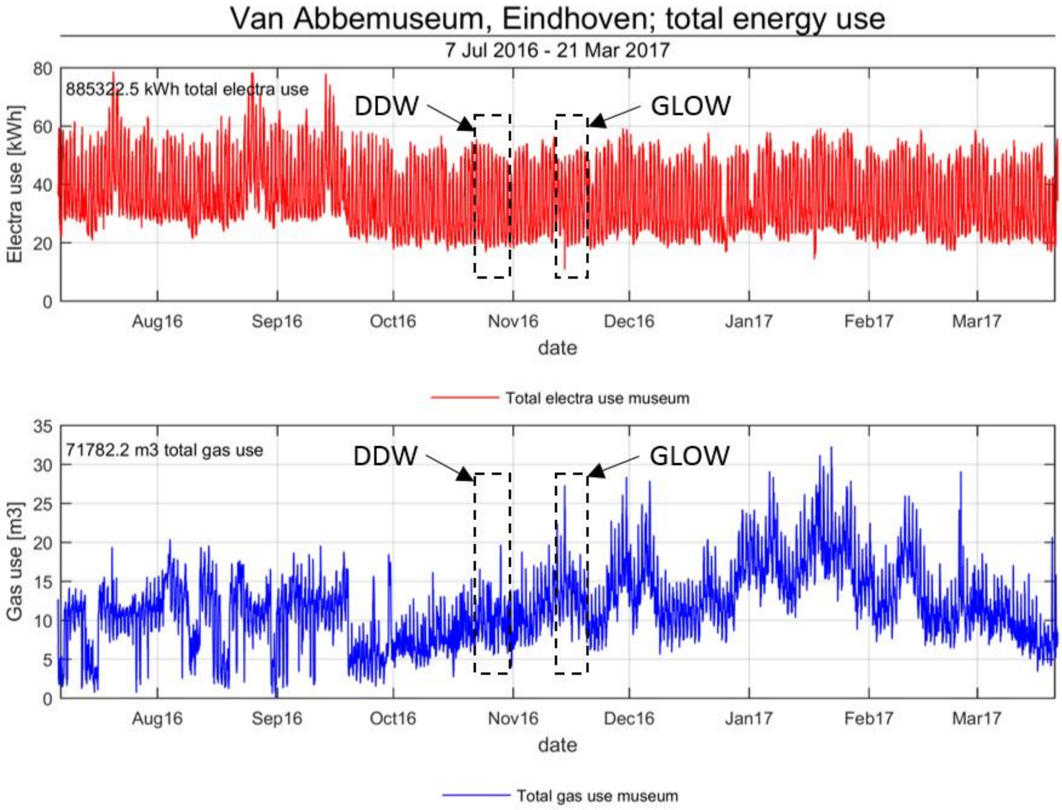


Figure 9.94: Total real energy use of the Van Abbemuseum during the total measurement period (July 7th 2016 till March 21st 2017), including the energy use for all the building parts, use, HVAC systems, etc.

Appendix R. Detailed climate evaluation chart results, overview per season

Table 9.30: Overview CEC results using the museum requirements for the measurement positions of the BMS sensors, spring period (March 21st 2016 till June 21st 2016).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	ΔT/h	ΔT/d	ΔRH/h	ΔRH/d
A0, room 1 / 2	77	20	0	0	0	0	0	0	2	2	24	19	60
A0, room 5 / 6	26	38	0	0	0	0	0	1	36	2	32	15	51
A0, room 9 / 10	89	9	0	0	0	0	0	1	1	2	26	18	57
B outlet tower	56	1	0	0	0	0	0	28	15	0	1	10	79
B-1, sens 6	98	2	0	0	0	0	0	0	0	1	2	7	25
B0, sens 5	50	40	0	0	0	0	0	0	9	5	2	12	73
B1, sens 3	0	91	0	0	0	0	0	0	9	0	0	15	27
B1, sens 4	74	1	0	0	0	0	0	25	1	0	0	9	31
B2, sens 1	91	1	0	7	0	0	0	0	0	0	1	34	29
B2, sens 2	98	2	0	0	0	0	0	0	0	0	3	28	26

Table 9.31: Overview CEC results using the museum requirements for the measurement positions of the Eltek sensors, summer period (July 7th 2016 till September 21st 2016).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	ΔT/h	ΔT/d	ΔRH/h	ΔRH/d
3 A0, room 4	12	3	0	84	0	0	0	0	0	1	28	31	93
5 A0, room 5	1	0	0	98	0	0	0	0	0	2	25	49	98
6 A0, room 6	83	16	0	1	0	0	0	0	0	2	34	26	96
19 Ao, room 8	10	1	0	0	0	0	0	8	81	8	64	18	93
1 A0, room 10	71	18	0	8	0	0	0	0	3	5	41	45	82
17 B-1, tower bottom	97	0	0	3	0	0	0	0	0	0	0	2	9
7A B0	100	0	0	0	0	0	0	0	0	1	0	12	74
20 B0	48	22	0	0	0	0	0	0	30	7	46	12	50
8 B0, Picasso	99	0	0	1	0	0	0	0	0	0	0	7	12
15 B0, stairs bottom	100	0	0	0	0	0	0	0	0	1	0	6	27
16 B2, stairs top	79	21	0	0	0	0	0	0	0	1	16	15	89
9 B2	100	0	0	0	0	0	0	0	0	0	0	7	14
10 B2	9	0	0	91	0	0	0	0	0	0	0	12	13
11 B2	92	0	0	8	0	0	0	0	0	0	0	6	12
13 B2	91	0	0	9	0	0	0	0	0	0	0	9	24
18 B3, tower top	100	0	0	0	0	0	0	0	0	1	0	12	68

Table 9.32: Overview CEC results using the museum requirements for the measurement positions of the BMS sensors, summer period (June 21st 2016 till September 21st 2016).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	ΔT/h	ΔT/d	ΔRH/h	ΔRH/d
A0, room 1 / 2	72	28	0	0	0	0	0	0	0	1	23	19	89
A0, room 5 / 6	0	53	0	0	0	0	0	0	47	1	41	14	74
A0, room 9 / 10	89	11	0	0	0	0	0	0	0	1	22	20	76
B outlet tower	24	7	0	0	0	0	0	19	50	0	8	9	74
B-1, sens 6	94	6	0	0	0	0	0	0	0	0	3	4	10
B0, sens 5	8	92	0	0	0	0	0	0	0	7	1	13	90
B1, sens 3	0	100	0	0	0	0	0	0	0	0	0	11	32
B1, sens 4	96	1	0	0	0	0	0	2	0	1	0	12	52
B2, sens 1	74	0	0	26	0	0	0	0	0	0	0	19	44
B2, sens 2	98	0	0	2	0	0	0	0	0	0	0	8	19

Table 9.33: Overview CEC results using the museum requirements for the measurement positions of the Eltek sensors, autumn period (September 21st 2016 till December 21st 2016).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	$\Delta T_{/h}$	$\Delta T_{/d}$	$\Delta RH_{/h}$	$\Delta RH_{/d}$
3 A0, room 4	34	0	0	53	12	1	0	0	0	0	1	29	50
5 A0, room 5	77	0	0	22	0	0	0	1	0	2	3	68	97
6 A0, room 6	92	0	0	0	0	0	0	7	0	1	1	24	70
19 Ao, room 8	90	0	0	1	0	1	0	4	4	1	7	43	73
1 A0, room 10	81	0	0	17	1	1	0	0	0	1	3	50	61
17 B-1, tower bottom	100	0	0	0	0	0	0	0	0	1	0	11	50
7A B0	100	0	0	0	0	0	0	0	0	1	0	13	67
20 B0	44	0	0	0	0	0	0	18	38	13	69	22	80
8 B0, Picasso	99	0	0	0	0	0	0	1	0	1	0	10	23
15 B0, stairs bottom	100	0	0	0	0	0	0	0	0	1	0	14	57
16 B2, stairs top	100	0	0	0	0	0	0	0	0	1	8	10	55
9 B2	100	0	0	0	0	0	0	0	0	0	0	9	16
10 B2	24	0	0	76	0	0	0	0	0	0	0	53	32
11 B2	78	0	0	16	0	5	0	0	0	0	0	45	29
13 B2	100	0	0	0	0	0	0	0	0	3	0	21	89
18 B3, tower top	66	0	0	0	0	0	0	34	0	1	0	62	85

Table 9.34: Overview CEC results using the museum requirements for the measurement positions of the BMS sensors, autumn period (September 21st 2016 till December 21st 2016).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	$\Delta T_{/h}$	$\Delta T_{/d}$	$\Delta RH_{/h}$	$\Delta RH_{/d}$
A0, room 1 / 2	99	0	0	0	0	0	0	1	0	1	3	16	46
A0, room 5 / 6	87	10	0	0	0	0	0	0	2	1	2	9	33
A0, room 9 / 10	98	0	0	0	0	0	0	2	0	1	4	15	31
B outlet tower	93	0	0	0	0	0	0	6	1	0	0	7	39
B-1, sens 6	99	1	0	0	0	0	0	0	0	0	0	6	16
B0, sens 5	52	41	0	0	0	0	0	0	7	4	1	12	78
B1, sens 3	0	74	0	0	0	0	0	0	26	0	0	17	40
B1, sens 4	99	0	0	0	0	0	0	1	0	1	1	8	14
B2, sens 1	98	0	0	1	0	0	0	0	0	0	0	31	37
B2, sens 2	100	0	0	0	0	0	0	0	0	0	1	13	12

Table 9.35: Overview CEC results using the museum requirements for the measurement positions of the Eltek sensors, winter period (December 21st 2016 till March 21st 2017).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	$\Delta T_{/h}$	$\Delta T_{/d}$	$\Delta RH_{/h}$	$\Delta RH_{/d}$
3 A0, room 4	5	0	0	35	58	2	0	0	0	0	3	25	48
5 A0, room 5	86	0	0	13	0	0	0	0	0	1	6	85	99
6 A0, room 6	77	0	0	0	0	0	0	23	0	1	3	26	91
19 Ao, room 8	98	0	0	0	0	2	0	0	0	1	3	54	71
1 A0, room 10	35	0	0	62	2	1	0	0	0	1	3	63	64
17 B-1, tower bottom	100	0	0	0	0	0	0	0	0	2	0	12	45
7A B0	99	0	0	0	0	0	1	0	0	2	2	17	84
20 B0	72	0	0	0	0	0	1	22	6	13	90	24	92
8 B0, Picasso	91	0	0	0	0	0	0	9	0	1	0	10	22
15 B0, stairs bottom	97	0	0	0	0	3	0	0	0	1	1	15	79
16 B2, stairs top	99	0	0	0	0	0	0	0	0	1	4	11	63
9 B2	99	0	0	0	0	0	0	1	0	0	1	2	5
10 B2	27	0	0	70	1	2	0	0	0	2	2	26	74
11 B2	73	0	0	3	0	23	0	0	0	0	2	31	32
13 B2	99	0	0	0	0	1	0	0	0	2	3	13	45
18 B3, tower top	38	0	0	0	0	0	0	61	0	1	2	43	82

Table 9.36: Overview CEC results using the museum requirements for the measurement positions of the BMS sensors, winter period (December 21st 2016 till March 21st 2017).

Sensor T/RH	Distribution of T and RH [%]									Percentage out of limits [%]			
	OK	too hot	too humid + too hot	too humid	too humid + too cold	too cold	too dry + too cold	too dry	too dry + too hot	$\Delta T_{/h}$	$\Delta T_{/d}$	$\Delta RH_{/h}$	$\Delta RH_{/d}$
A0, room 1 / 2	99	0	0	0	0	0	0	1	0	0	0	17	43
A0, room 5 / 6	94	2	0	0	0	0	0	3	1	0	0	2	9
A0, room 9 / 10	97	0	0	0	0	0	0	3	0	0	0	11	17
B outlet tower	96	0	0	0	0	3	0	1	0	1	3	12	72
B-1, sens 6	100	0	0	0	0	0	0	0	0	1	2	4	9
B0, sens 5	78	17	0	0	0	0	0	2	3	3	2	14	85
B1, sens 3	0	40	0	0	0	0	0	0	59	0	0	11	24
B1, sens 4	99	0	0	0	0	0	0	1	0	0	0	7	13
B2, sens 1	99	0	0	0	0	0	0	0	0	0	1	16	15
B2, sens 2	99	0	0	0	0	0	0	0	0	0	2	3	7

Appendix S. Results climate evaluation chart

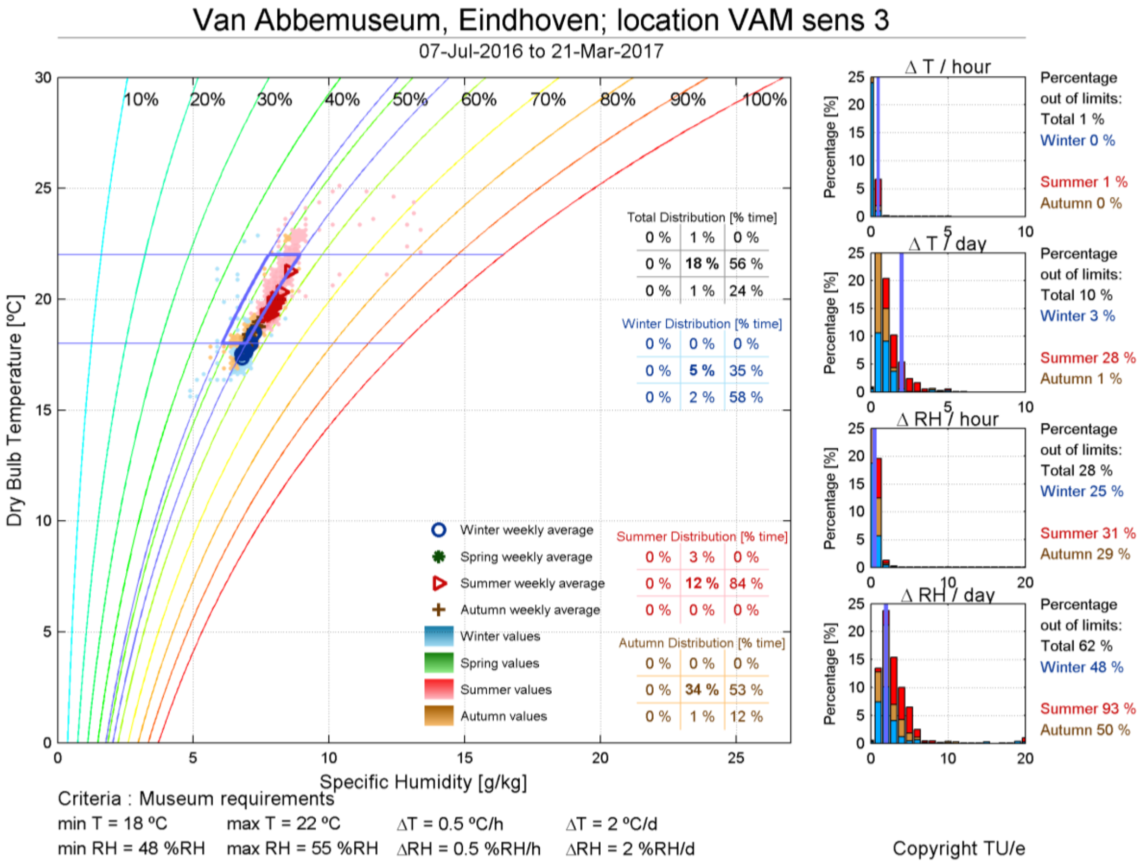


Figure 9.95: CEC result of Eltek sensor 3 (room 4 monumental building part), criteria of museum requirements.

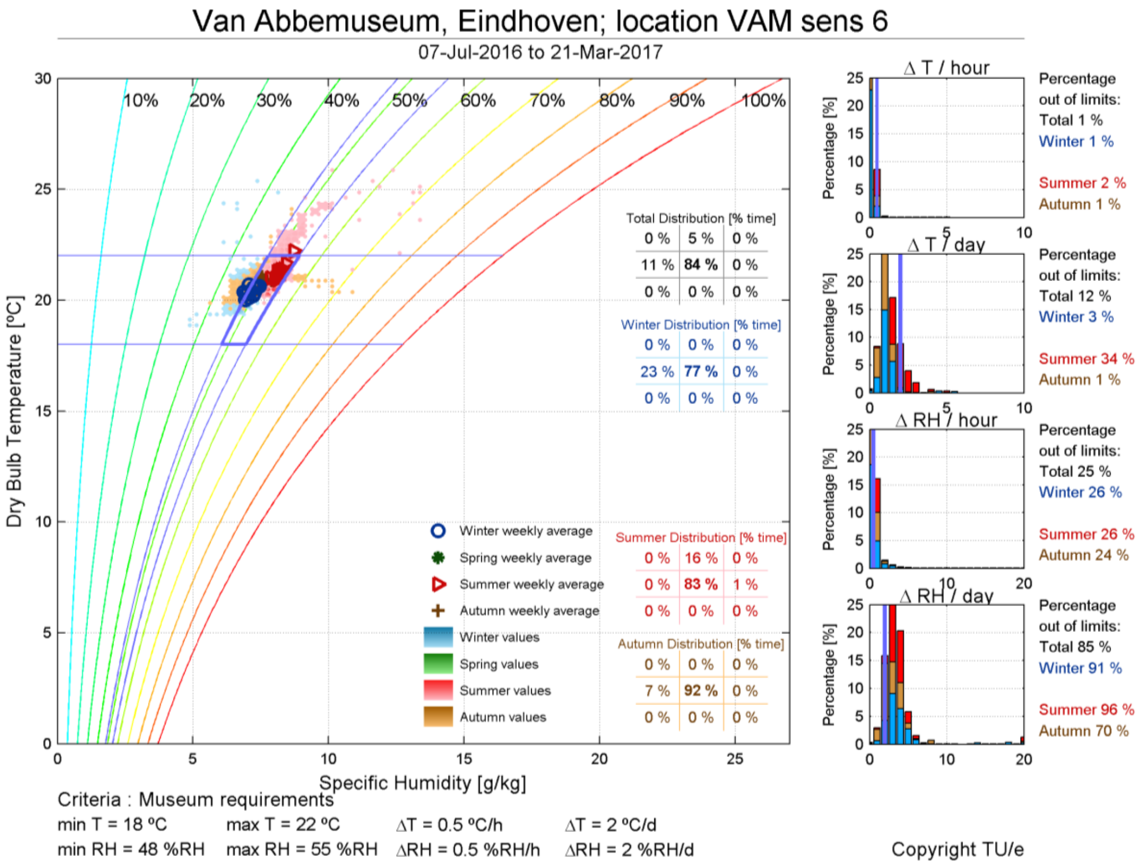


Figure 9.96: CEC result of Eltek sensor 6 (room 6 monumental building part), criteria of museum requirements.

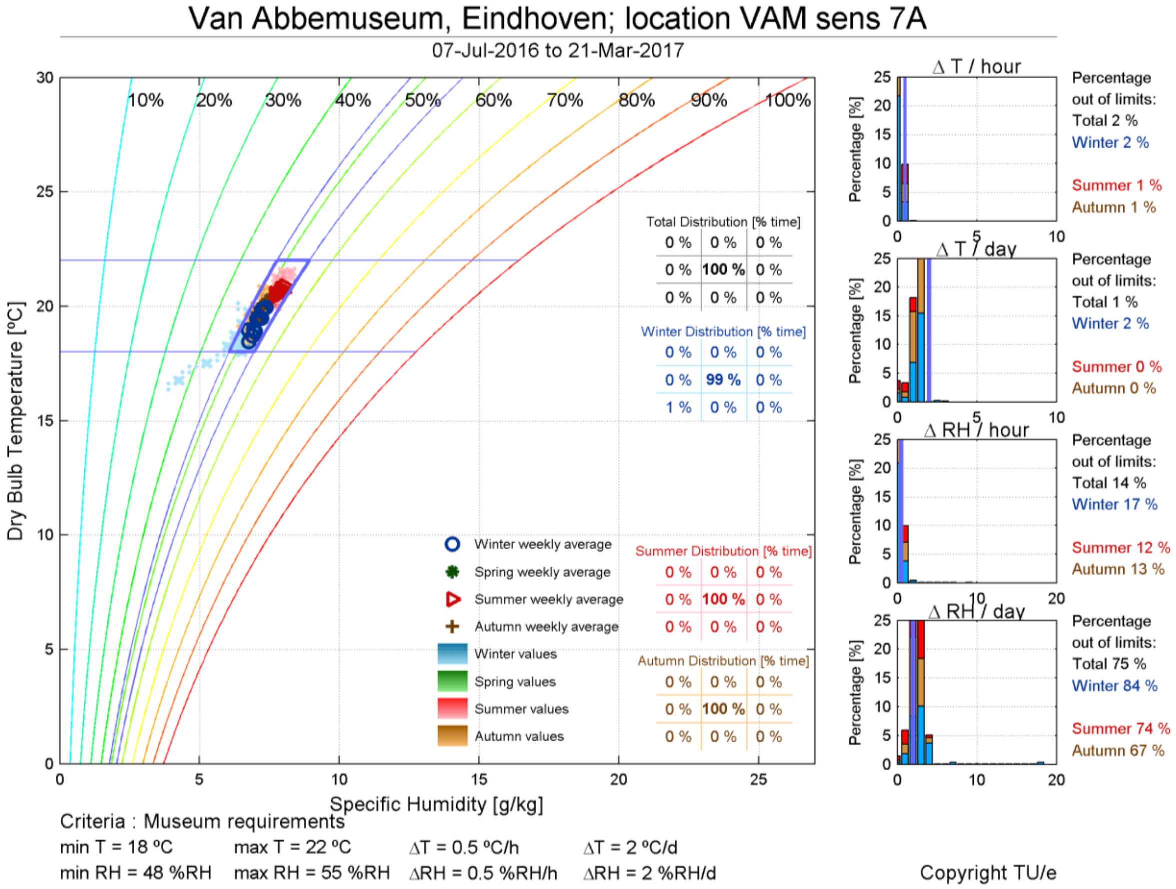


Figure 9.97: CEC result of Eltek sensor 7A (1st floor modern building part), criteria of museum requirements.

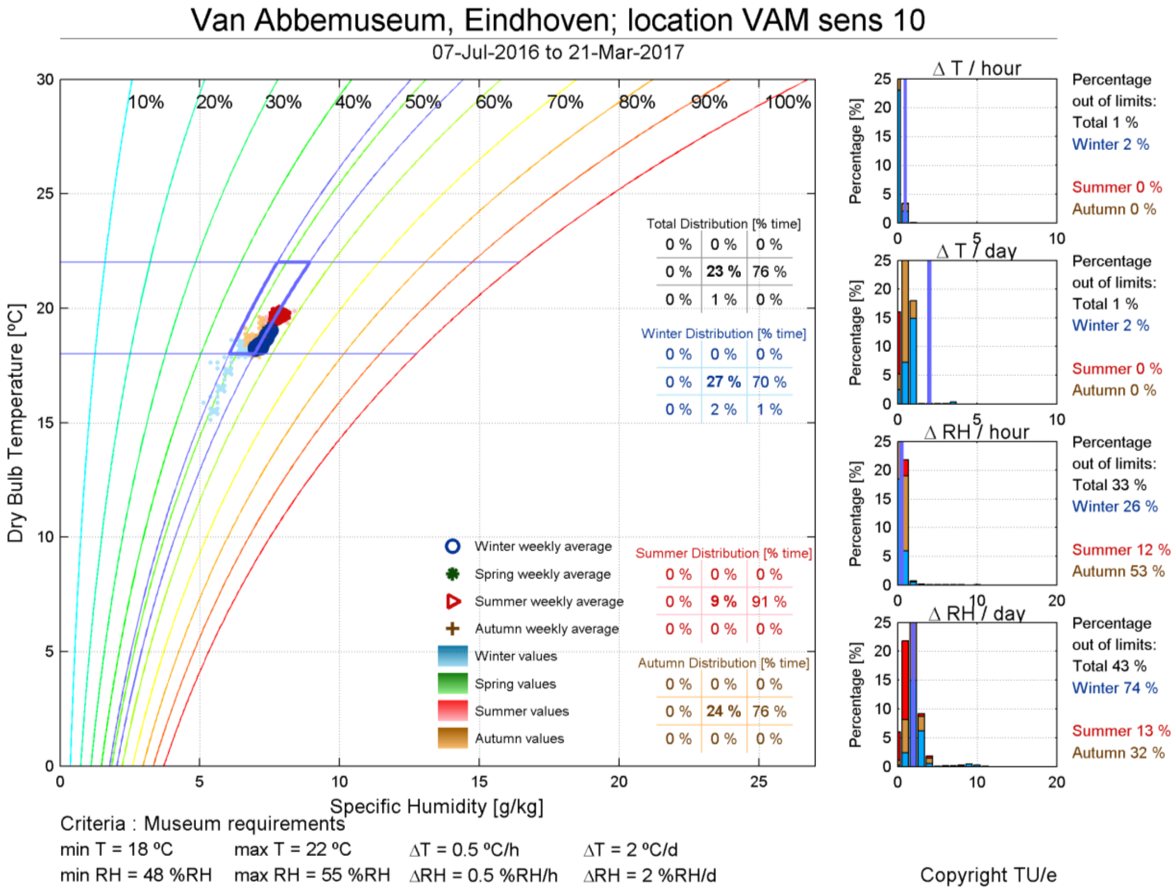


Figure 9.98: CEC result of Eltek sensor 10 (2nd floor modern building part), criteria of museum requirements.

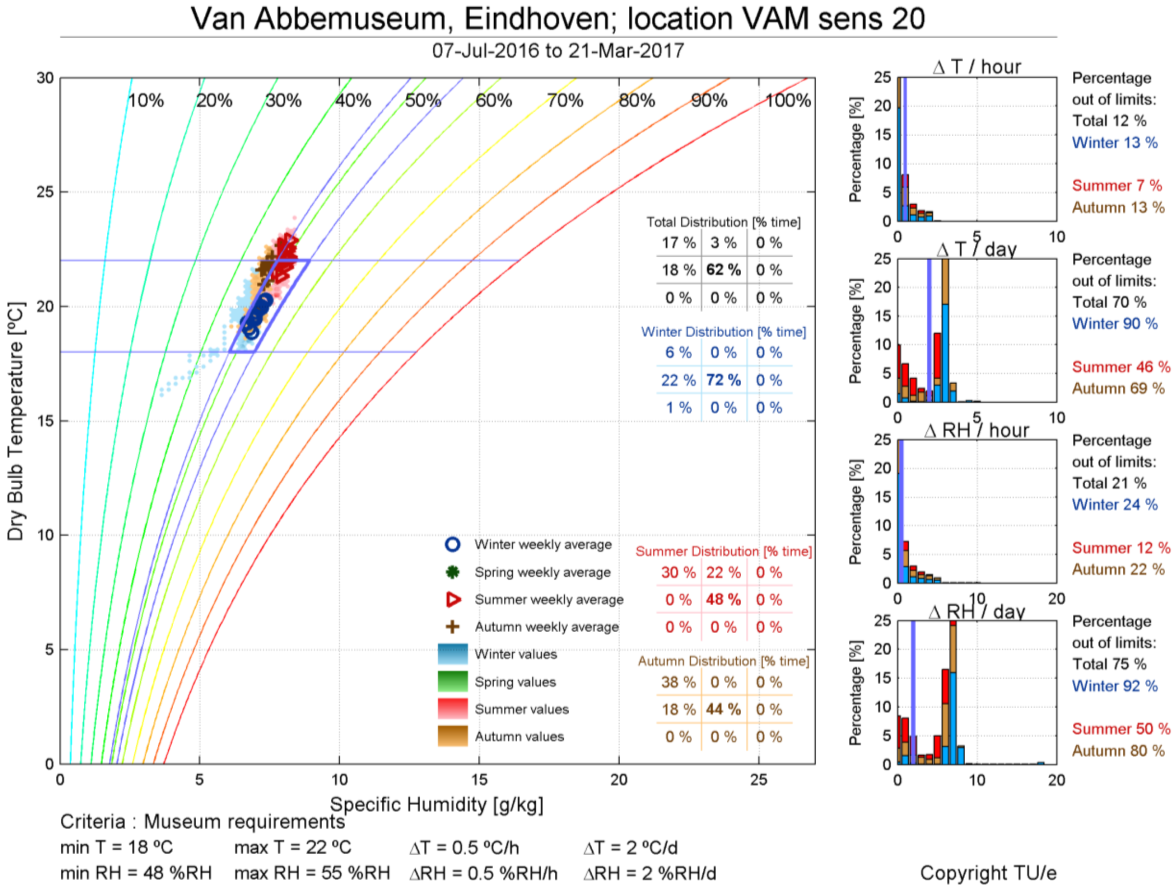


Figure 9.99: CEC result of Eltek sensor 20 (1st floor modern building part), criteria of museum requirements.

Appendix T. Results general climate risk assessment

Figure 9.100: Best ASHRAE classes met 100% of the time, based on general climate risk assessment, during the total measurement period, floor plan under layer by Cahen (2003).

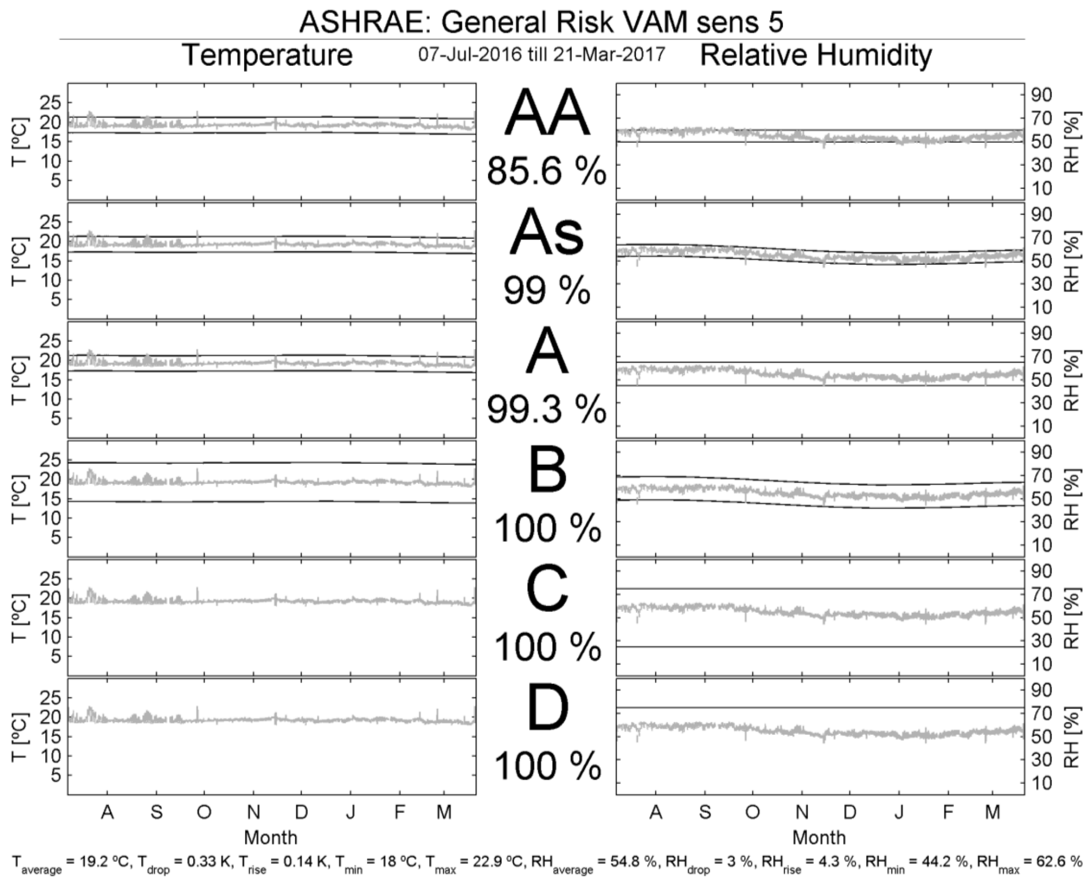


Figure 9.101: General climate risk assessment result of Eltek sensor 5 (room 5 monumental building part).

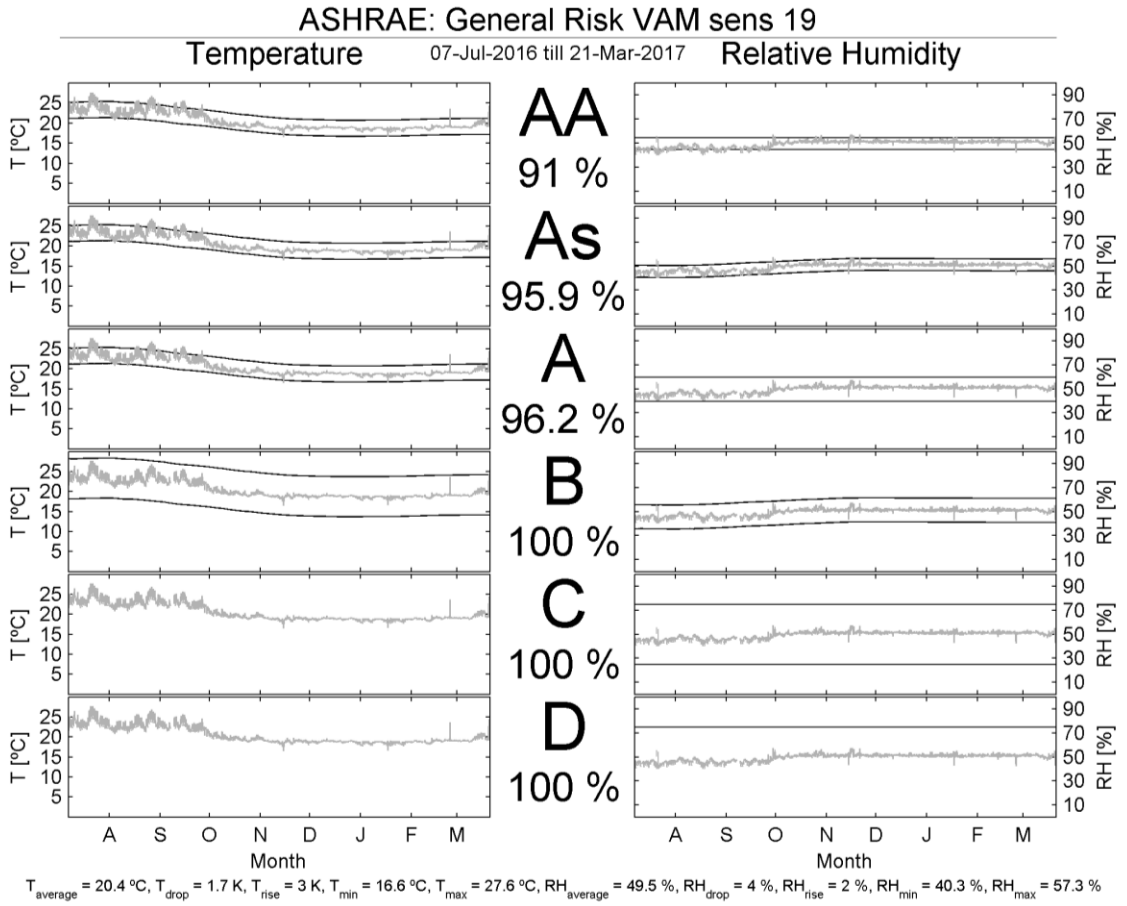


Figure 9.102: General climate risk assessment result of Eltek sensor 19 (room 8 monumental building part).

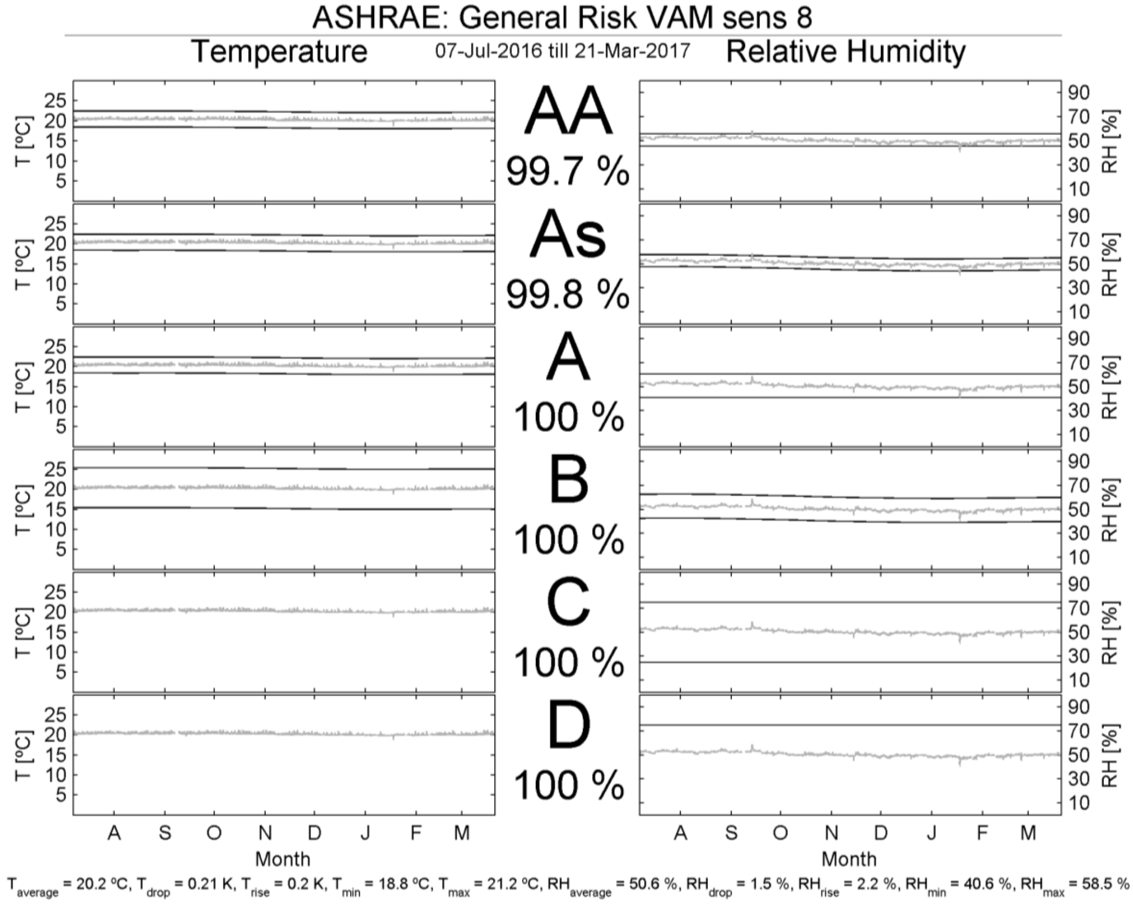
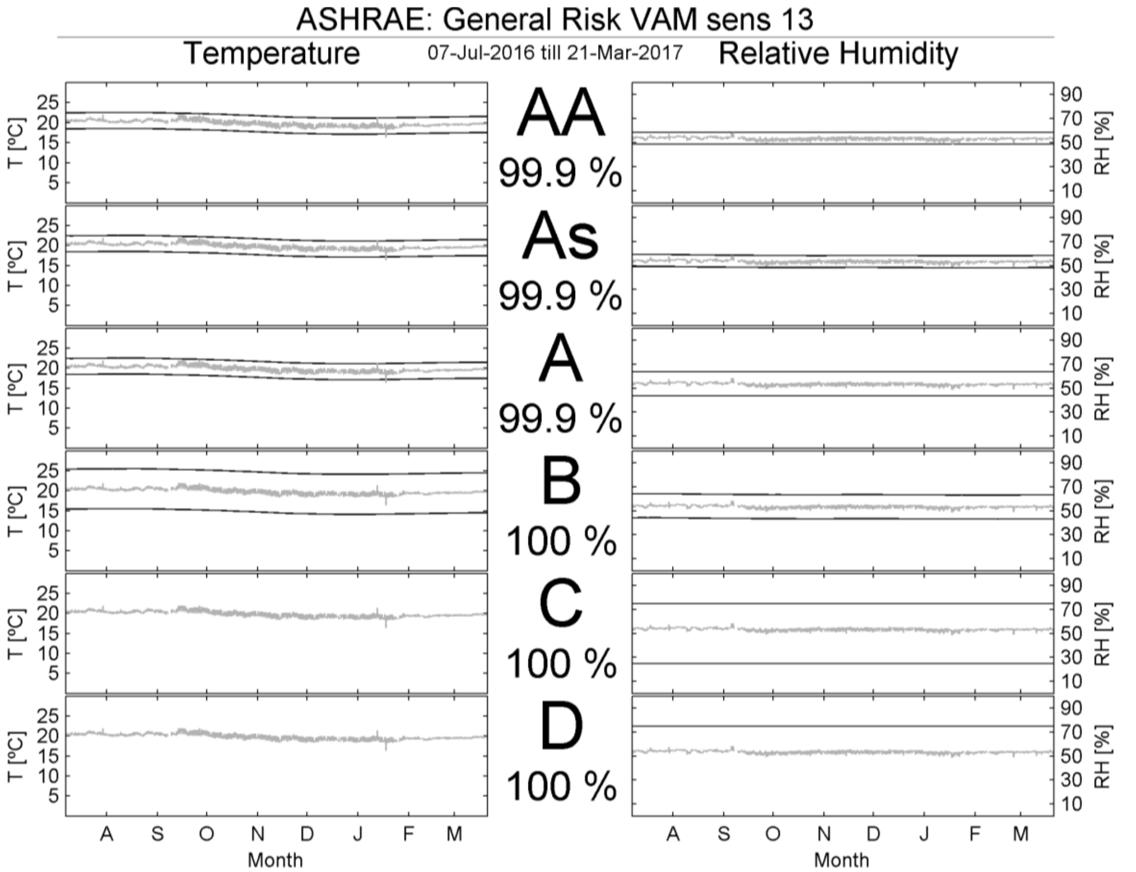
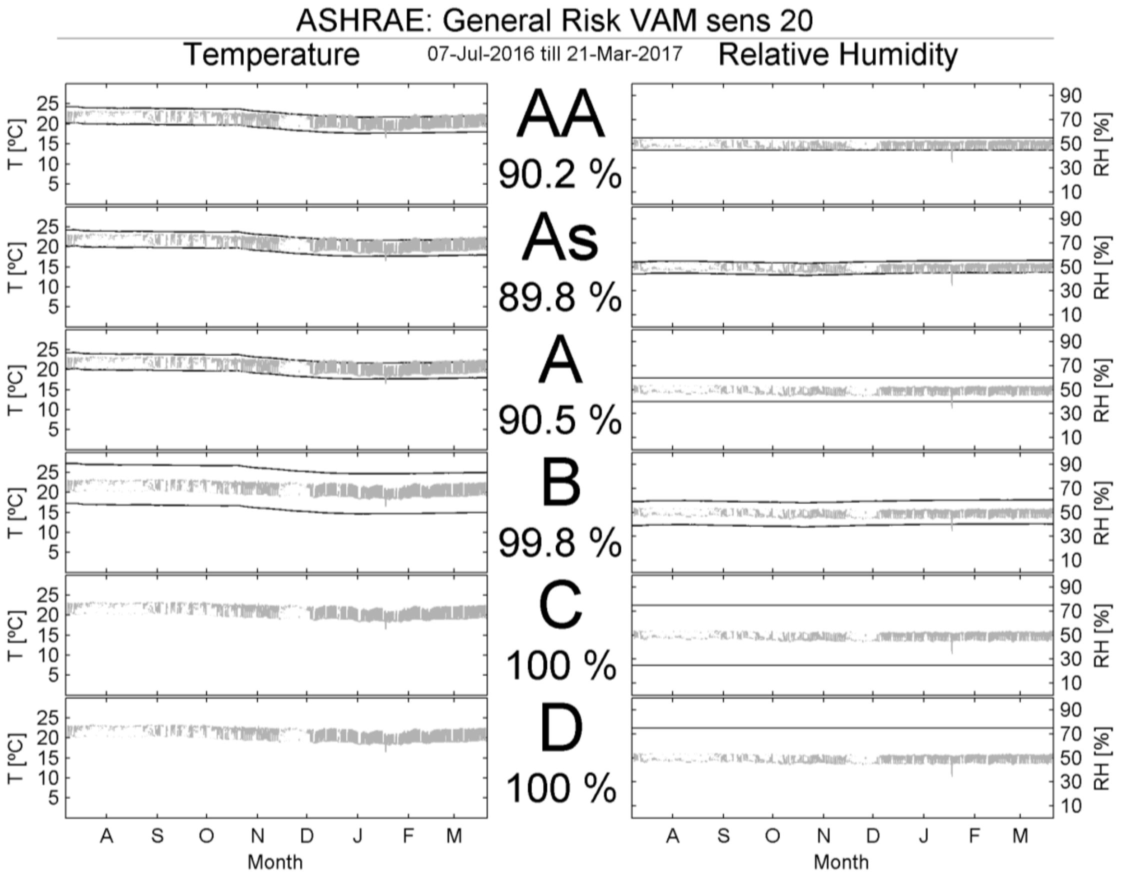


Figure 9.103: General climate risk assessment result of Eltek sensor 8 (1st floor modern building part).



$T_{average}$ = 19.8 ºC, T_{drop} = 0.64 K, T_{rise} = 0.77 K, T_{min} = 16.4 ºC, T_{max} = 21.9 ºC, $RH_{average}$ = 53.5 %, RH_{drop} = 0.38 %, RH_{rise} = 0.77 %, RH_{min} = 48.7 %, RH_{max} = 58.3 %

Figure 9.104: General climate risk assessment result of Eltek sensor 13 (2nd floor modern building part).



$T_{average}$ = 20.3 ºC, T_{drop} = 0.64 K, T_{rise} = 2 K, T_{min} = 16.5 ºC, T_{max} = 23.3 ºC, $RH_{average}$ = 49.7 %, RH_{drop} = 1.9 %, RH_{rise} = 0.7 %, RH_{min} = 34.8 %, RH_{max} = 54 %

Figure 9.105: General climate risk assessment result of Eltek sensor 20 (1st floor modern building part).

Appendix U. Results specific climate risk assessment

Van Abbemuseum, Eindhoven; location VAM sens 3

	Mould	LM	Base material	Pictorial layer
PAPER	safe	1.03	-	-
PANEL PAINTING	safe	0.979	safe	safe
FURNITURE	safe	0.979	safe	-
SCULPTURE	safe	0.98	safe	-

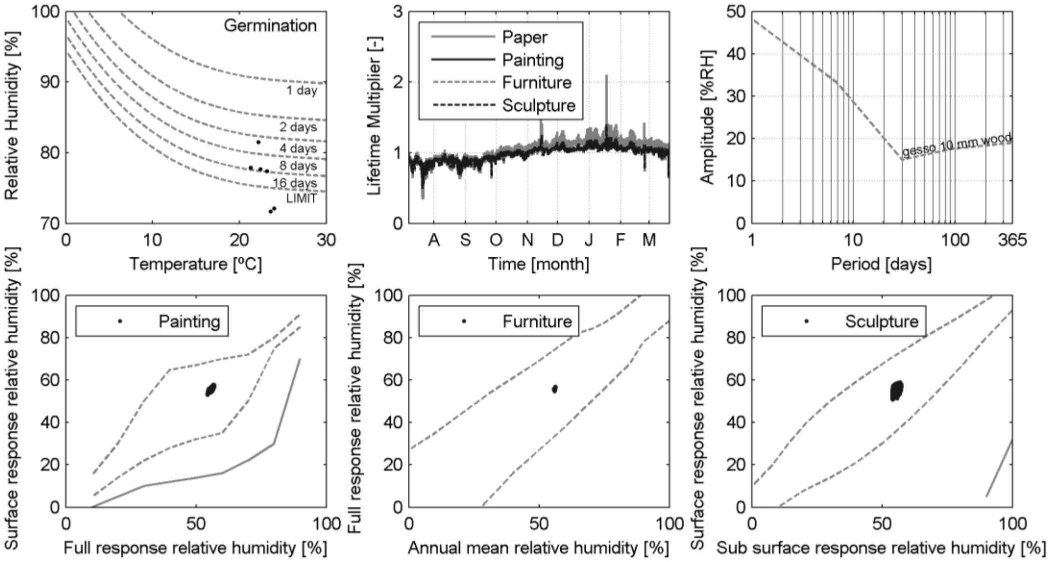


Figure 9.106: Specific climate risk assessment result of Eltek sensor 3 (room 4 monumental building part), data derived from July 7th 2016 till March 21st 2017.

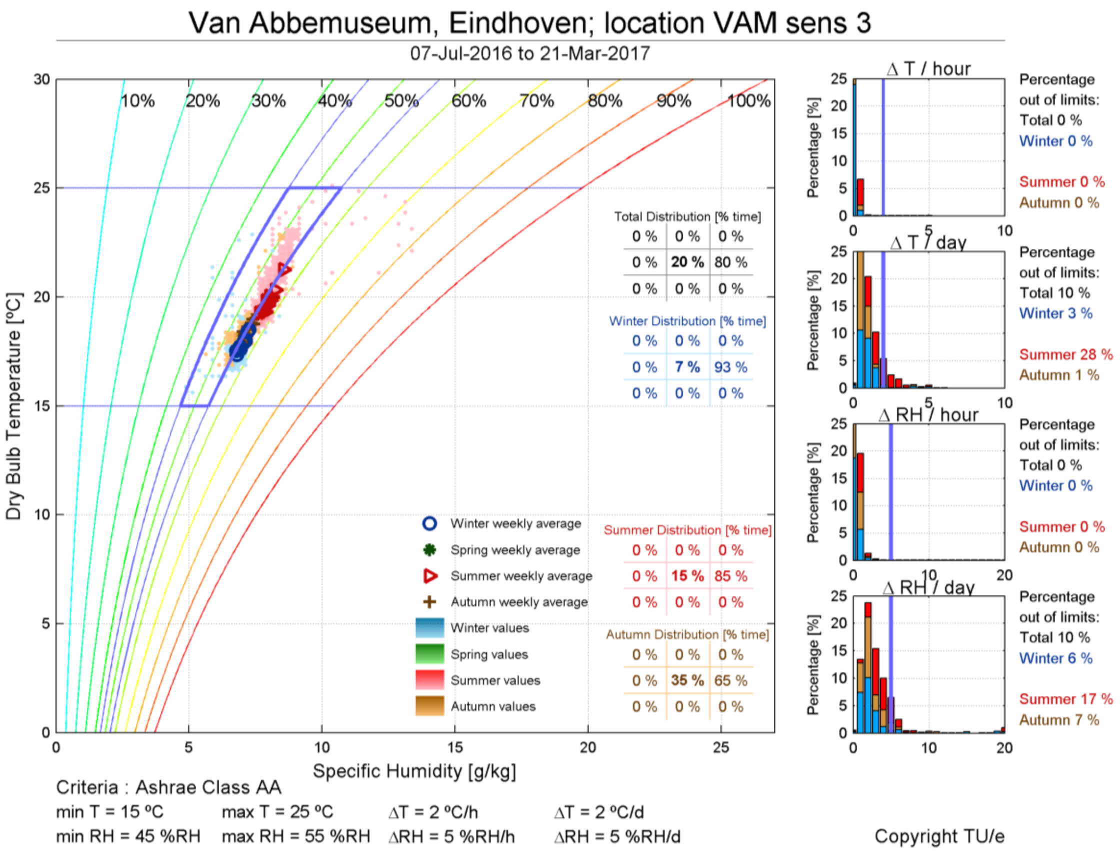


Figure 9.107: CEC result of Eltek sensor 3 (room 4 monumental building part), criteria of ASHRAE class AA.

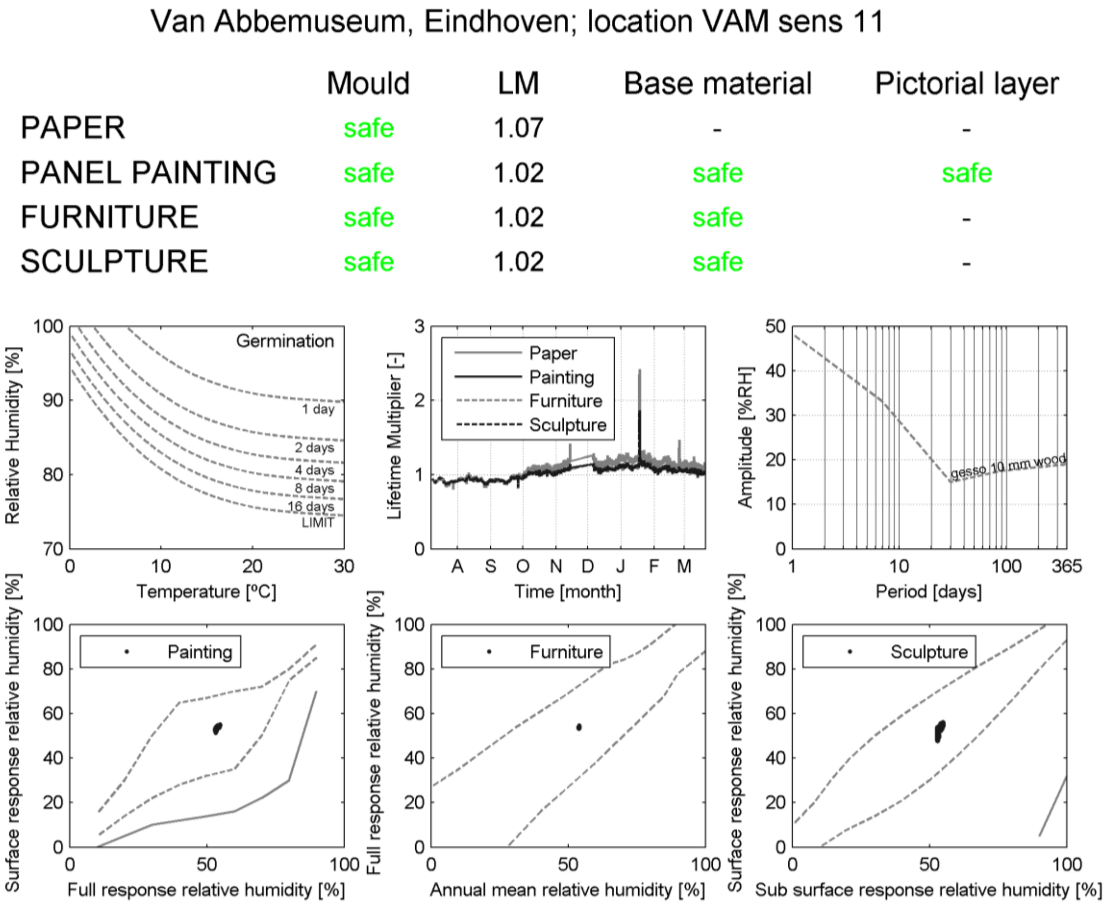


Figure 9.108: Specific climate risk assessment result of Eltek sensor 11 (2nd floor modern building part), data derived from July 7th 2016 till March 21st 2017.

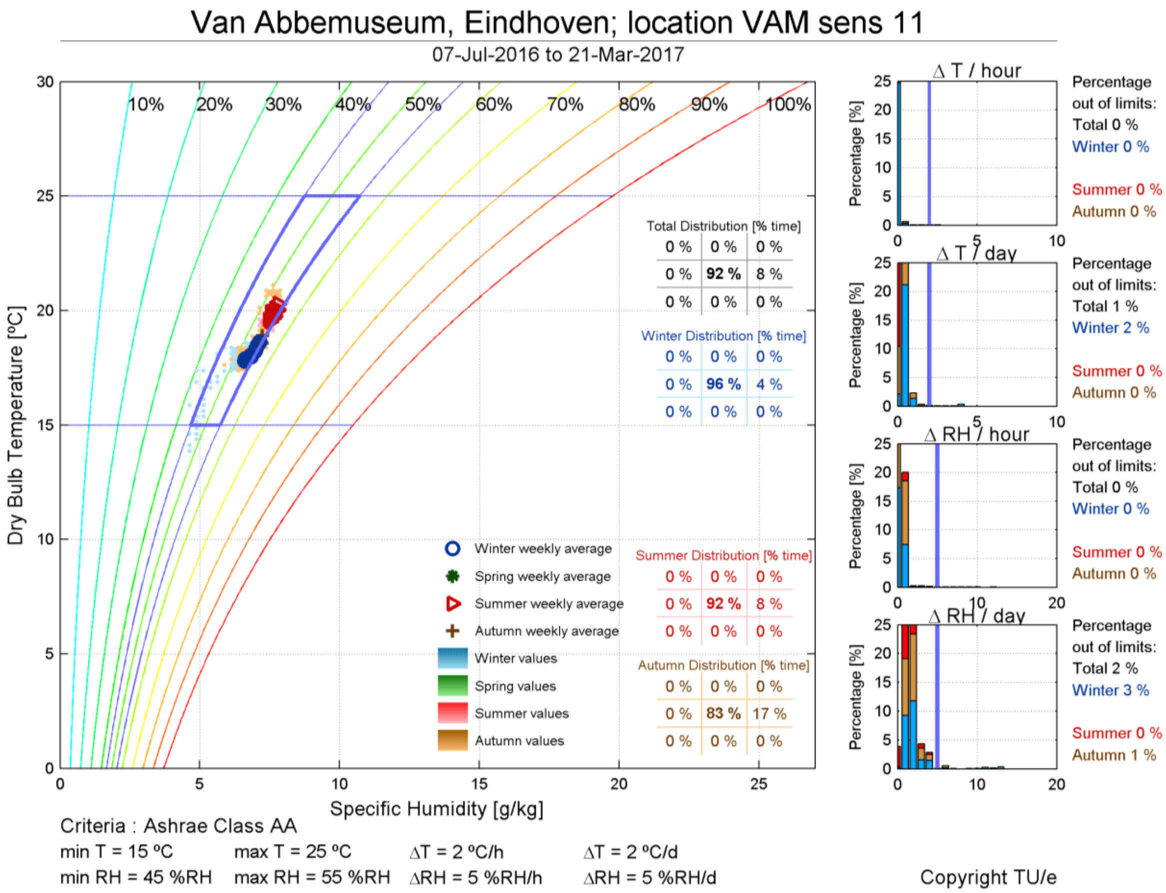


Figure 9.109: CEC result of Eltek sensor 11 (2nd floor modern building part), criteria of ASHRAE class AA.

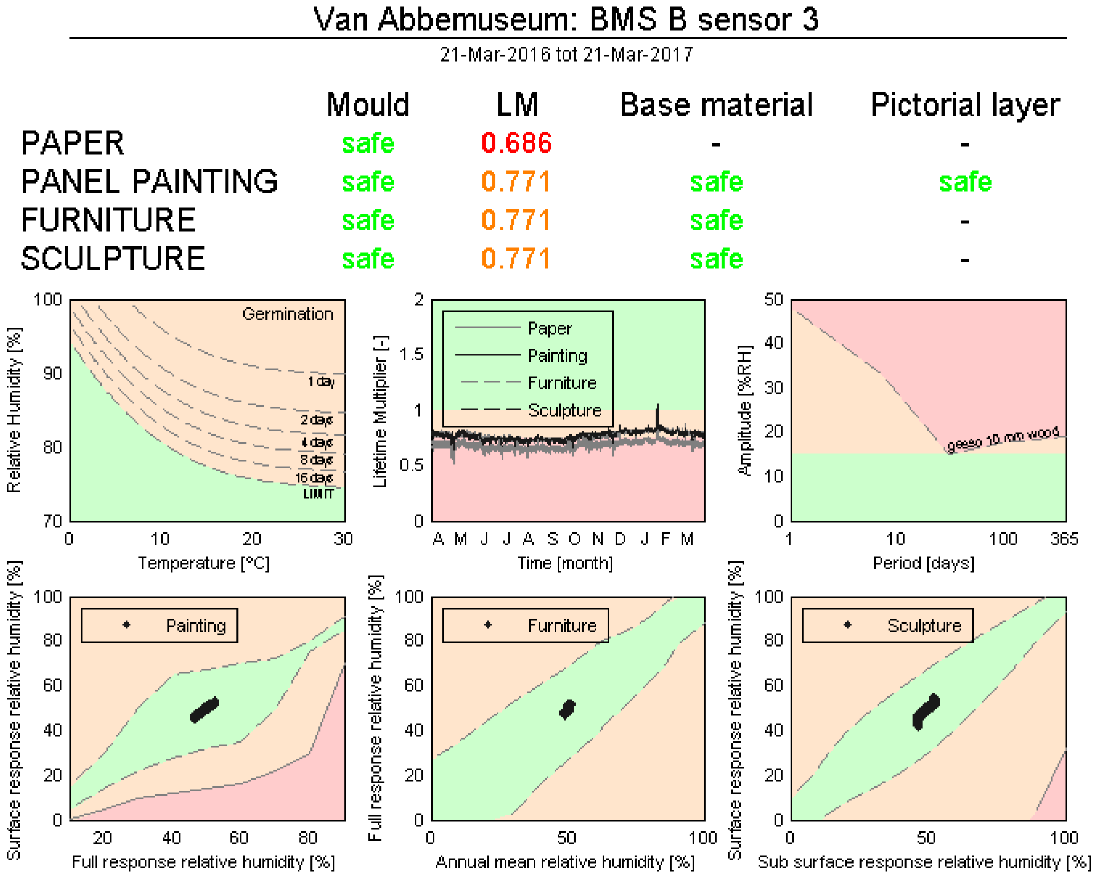


Figure 9.110: Specific climate risk assessment result of BMS sensor 3 (between 1st and 2nd floor modern building part).

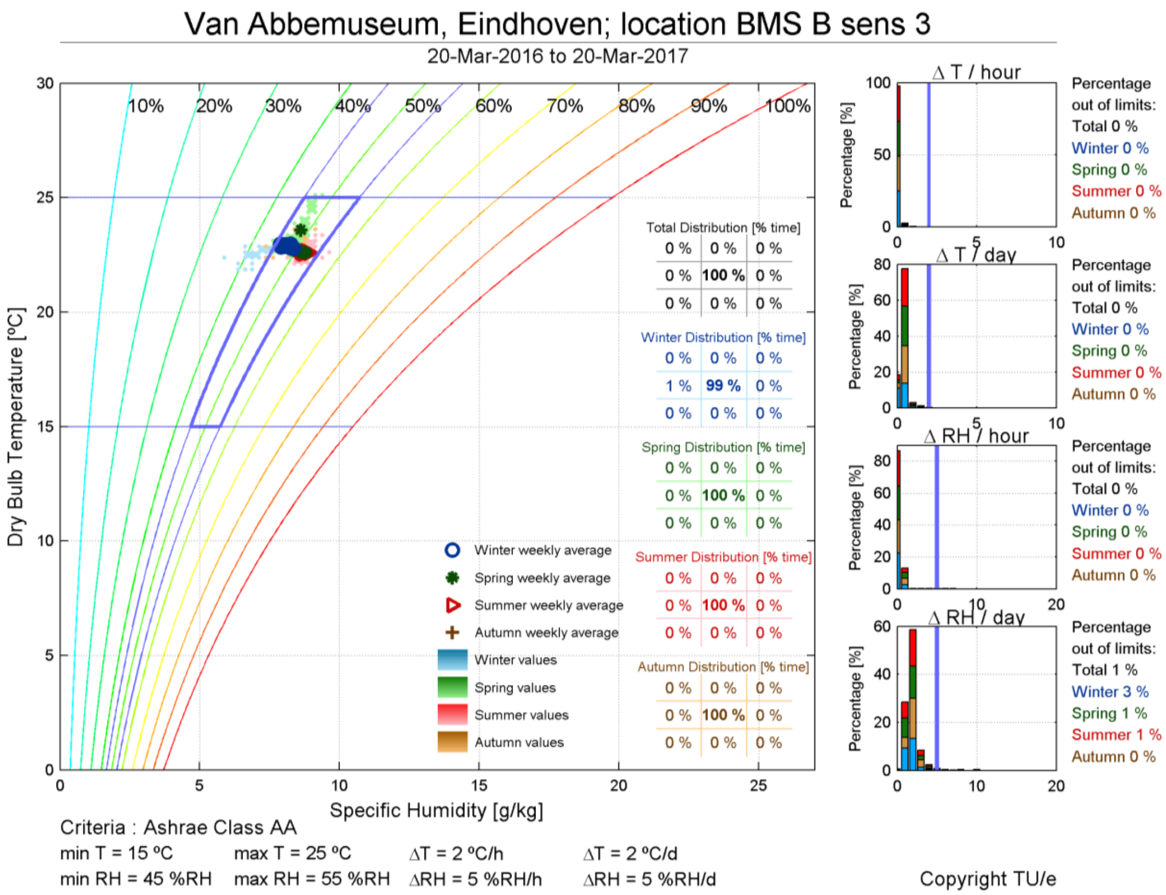


Figure 9.111: CEC result of BMS sensor 3 (between 1st and 2nd floor modern building part), criteria of ASHRAE class AA.

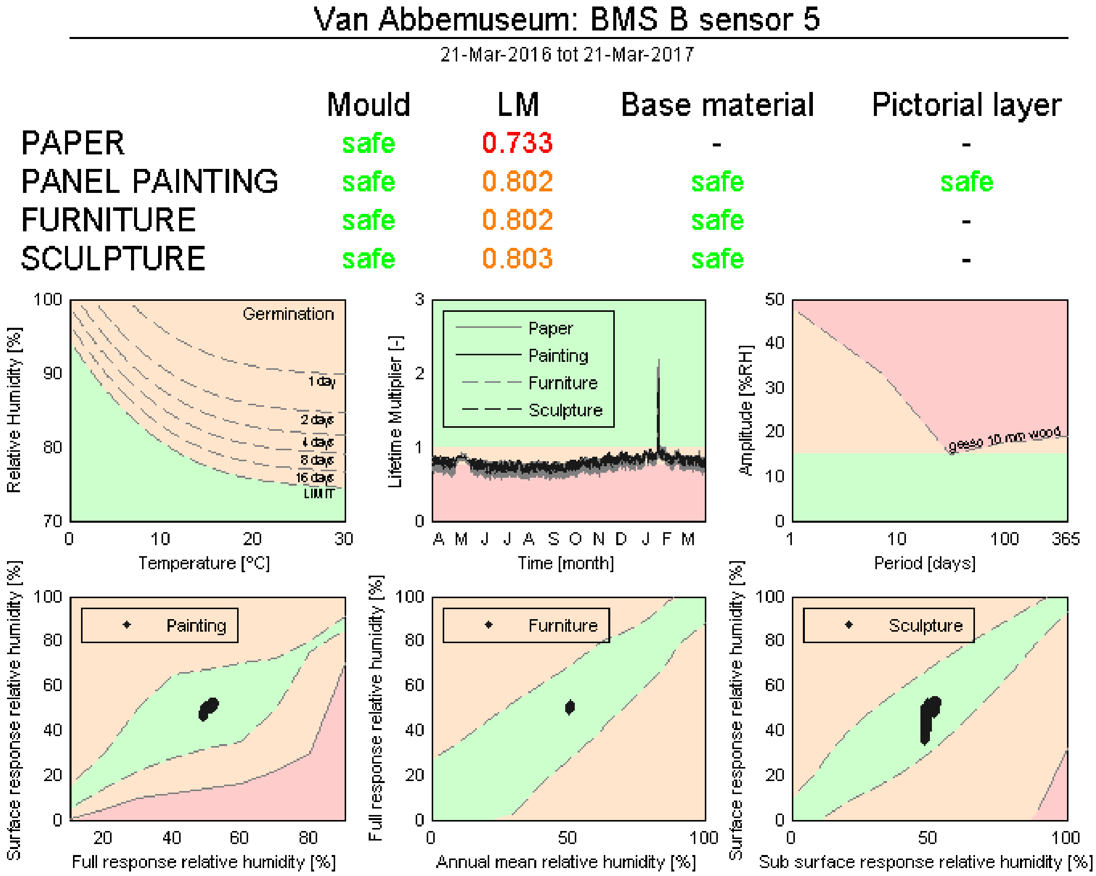


Figure 9.112: Specific climate risk assessment result of BMS sensor 5 (1st floor modern building part).

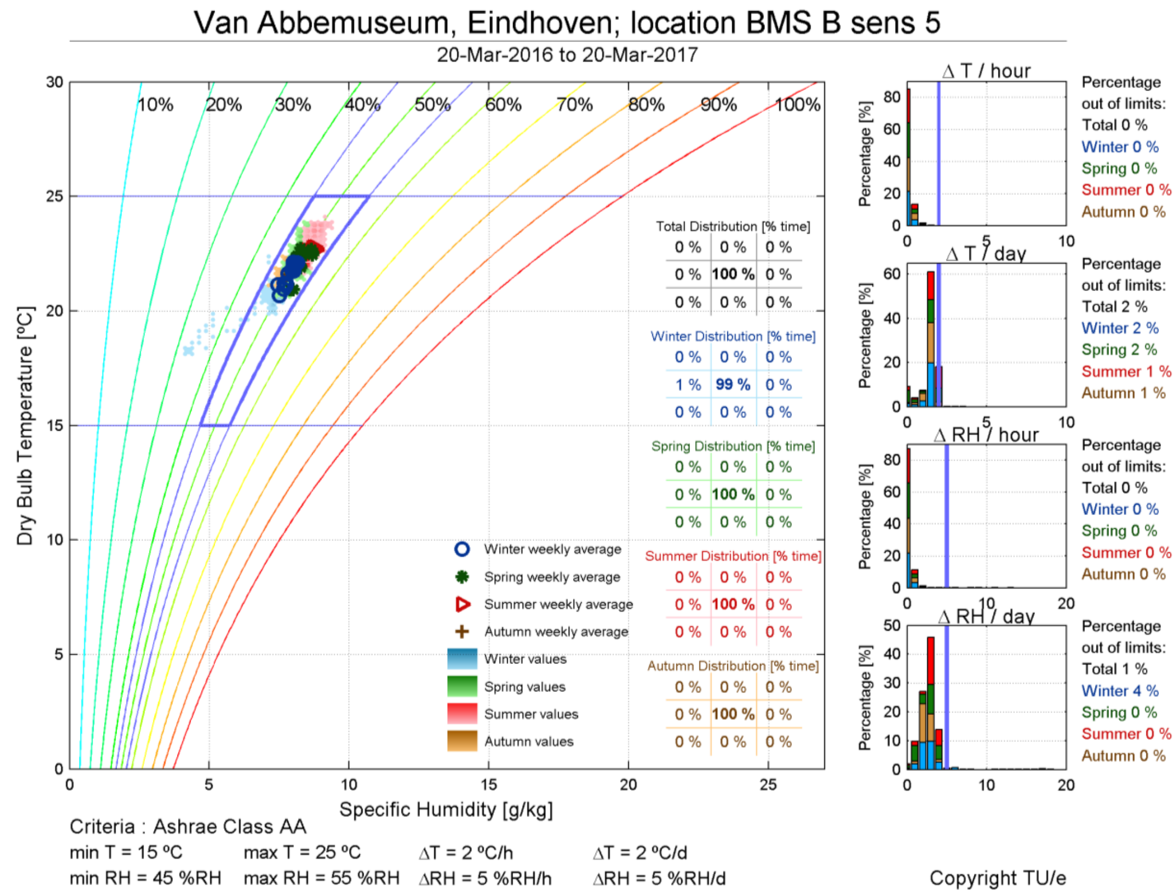


Figure 9.113: CEC result of BMS sensor 5 (1st floor modern building part), criteria of ASHRAE class AA.

Appendix V. Results adaptive temperature guideline for museums

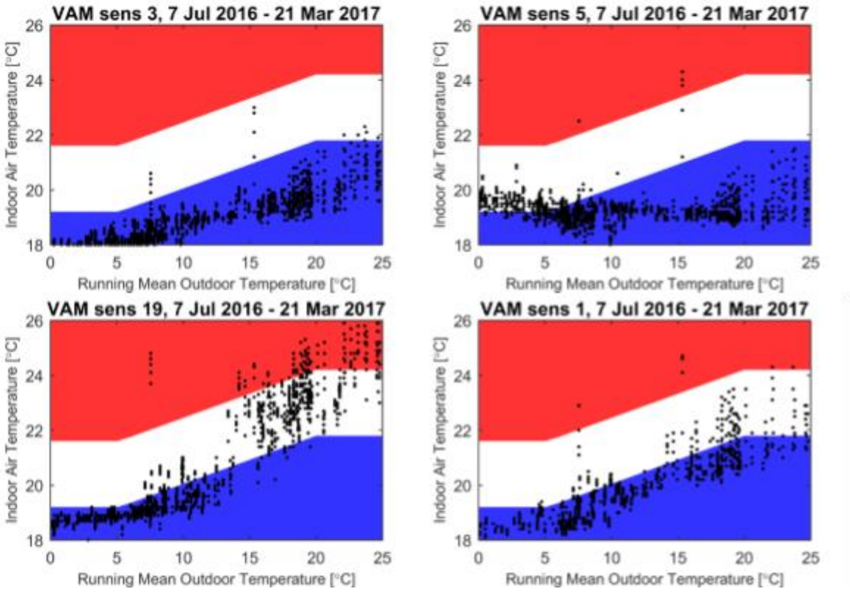


Figure 9.114: ATG for museums results Eltek sensors in the monumental building part.

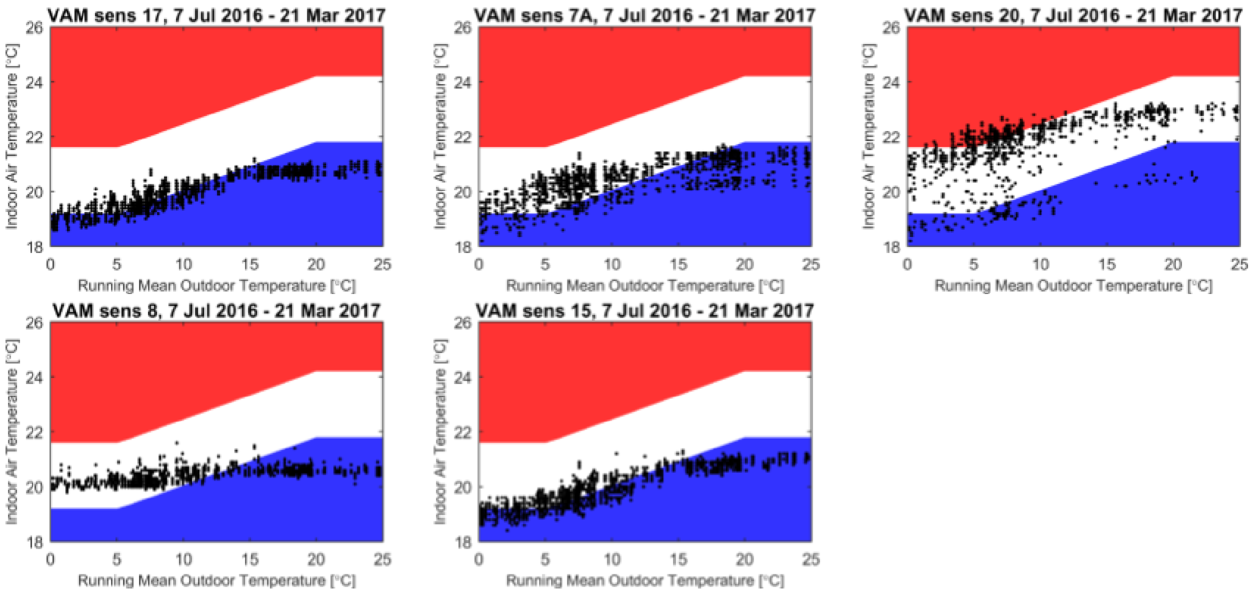


Figure 9.115: ATG for museums results Eltek sensors on the 1st floor of the modern building part.

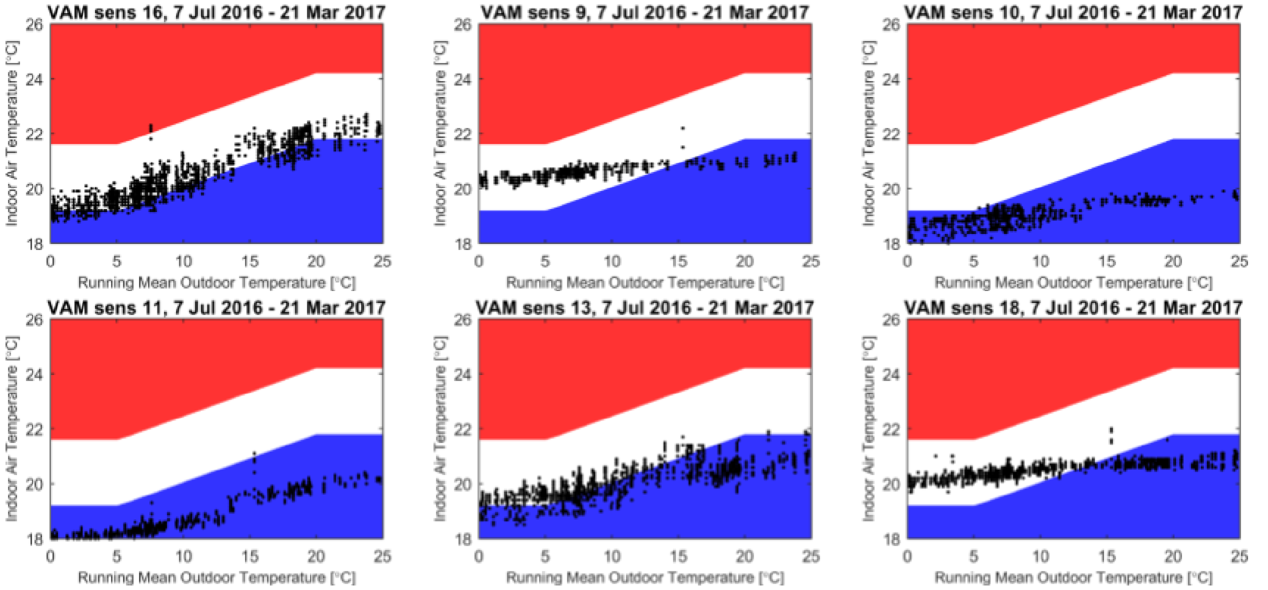


Figure 9.116: ATG for museums results Eltek sensors on the 2nd floor of the modern building part.

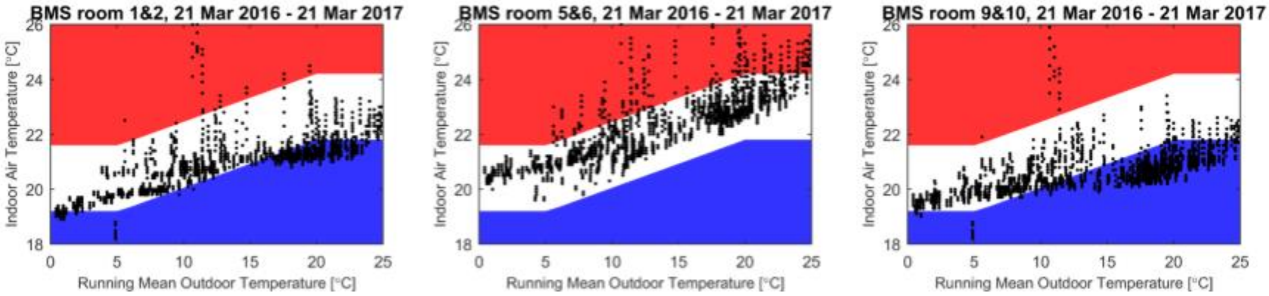


Figure 9.117: ATG for museums results BMS sensors in the monumental building part.

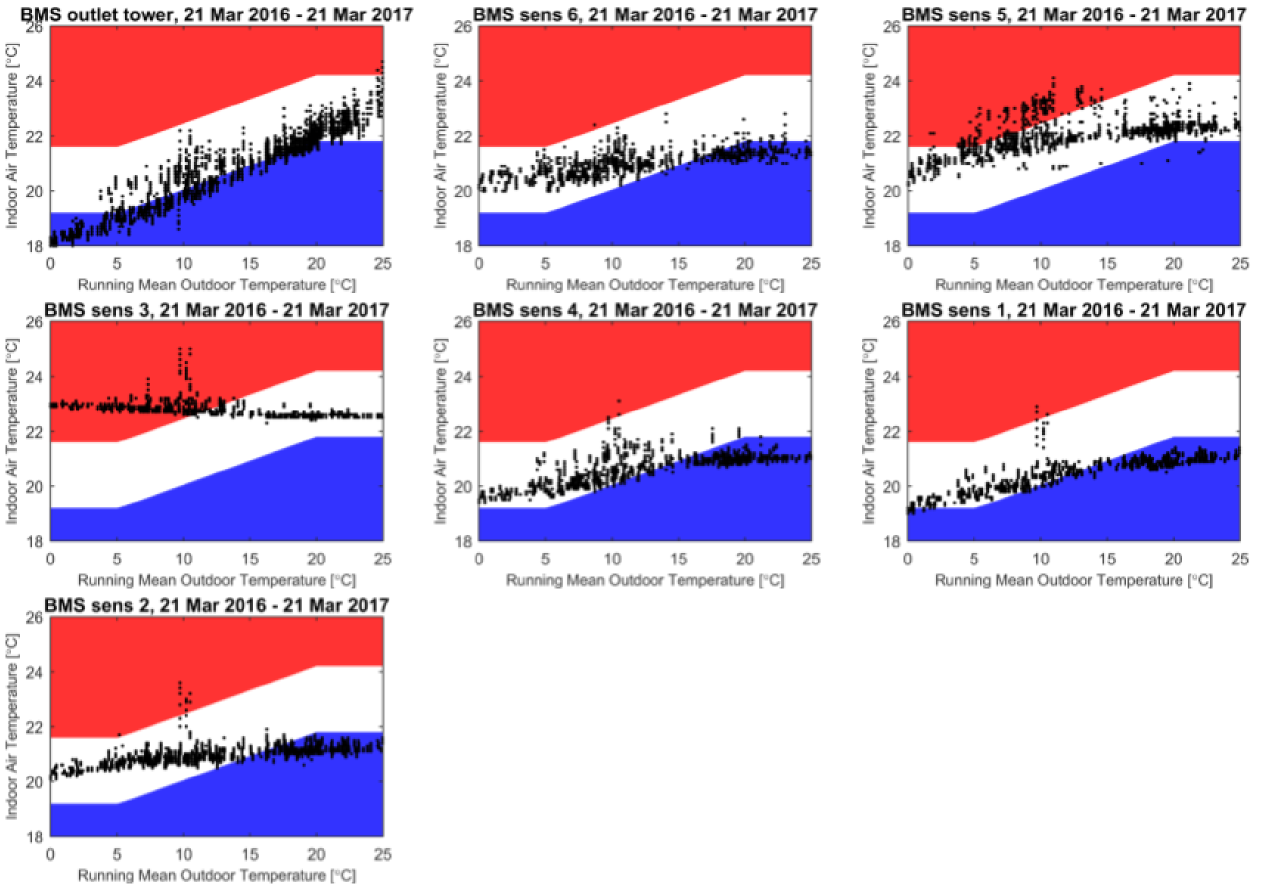


Figure 9.118: ATG for museums results BMS sensors in the modern building part.

Appendix W. Results microclimate measurements

The measurement locations of the IR thermograms are shown in Appendix G.

Former door surface, monumental building part

T_s sensors 5 and 6 are placed in room 5 of the monumental building part. T_s sensor 5 is placed on a bricked former door surface, and T_s sensor 6 is placed on a part of the wall which has always been bricked. During the winter, the former door surface shows a lower T_s at the inside of the façade than the rest of the wall, see Figure 9.119. From the outside, this part of the façade has a higher T_s, see Figure 9.120. During the summer period no clear T_s difference is shown, see Figure 9.121 and Figure 9.122. The T graphs of these locations are shown in Figure 9.123, and show that during the summer the T_s at the former door is slightly colder during the night. During the day, the T_s of both locations are equal. The T_s of both locations have increased T compared to the room T_i. During the winter, the T_s is always colder and shows extremer fluctuations than the room T_i. In addition, the T_s at the former door surface is always slightly colder than at the rest of the surface.

IR location 7, February 17th 2016 10:10, T_i = 19.5°C and RH_i = 46.1%

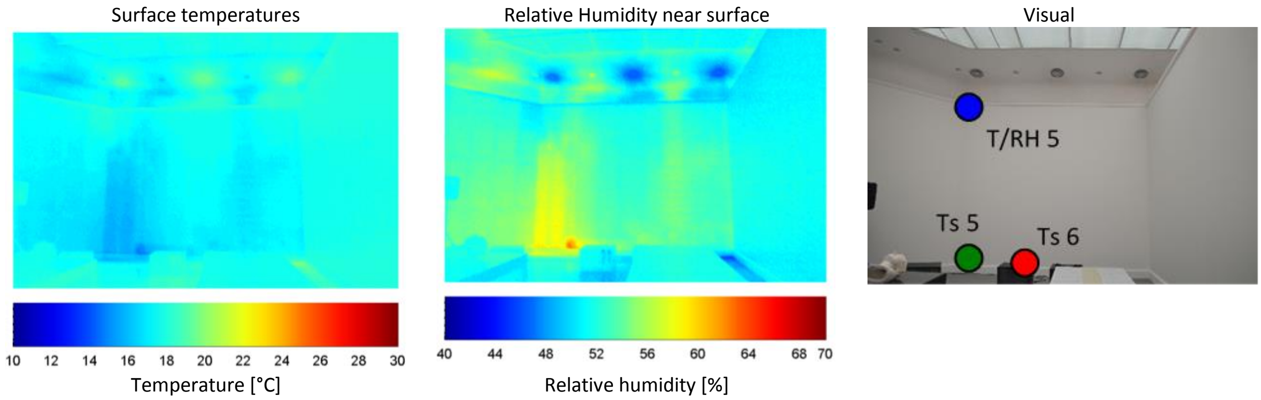


Figure 9.119: IR thermogram and hygrogram of IRT measurement location 7, conducted on February 17th 2016.

IR location 36, February 17th 2016 11:16, T_e = 5.0°C and RH_e = 46.8%

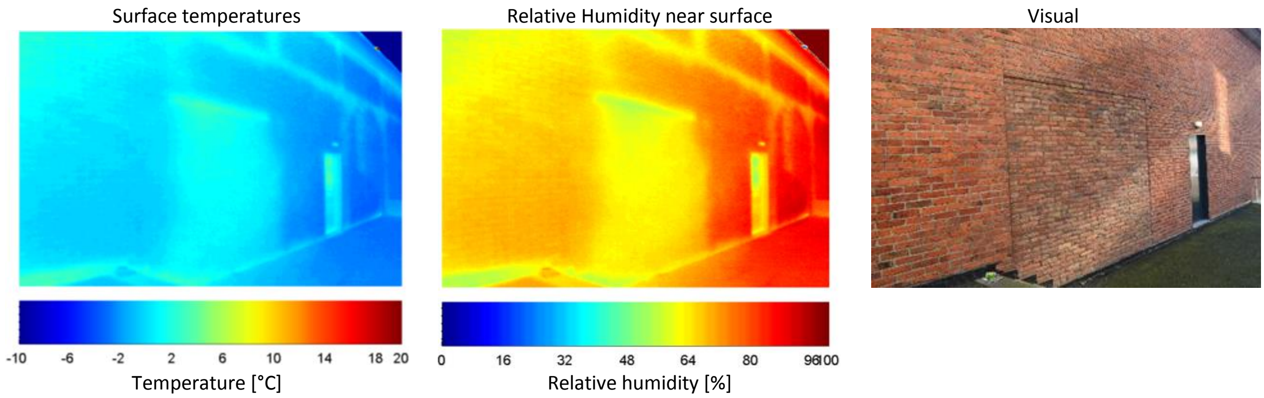


Figure 9.120: IR thermogram and hygrogram of IRT measurement location 36, conducted on February 17th 2016.

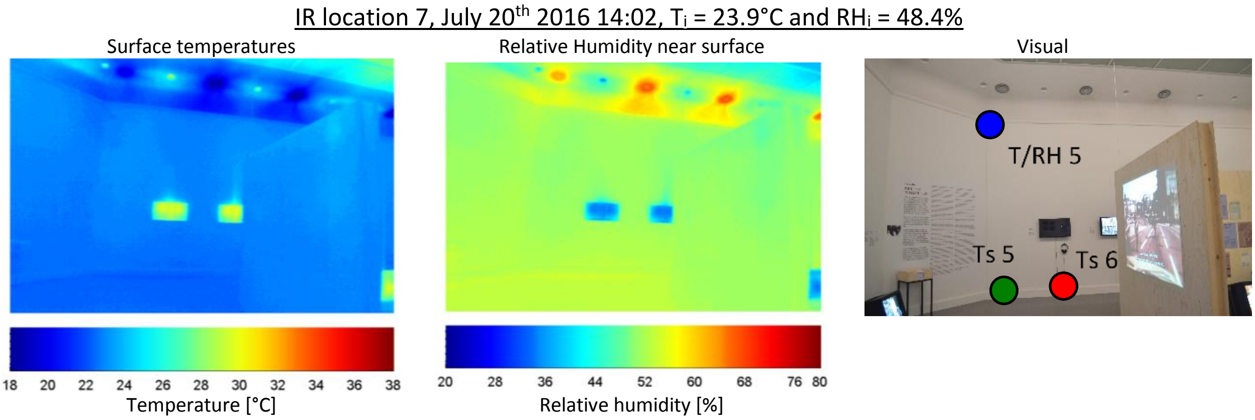


Figure 9.121: IR thermogram and hygrogram of IRT measurement location 7, conducted on July 20th 2016.

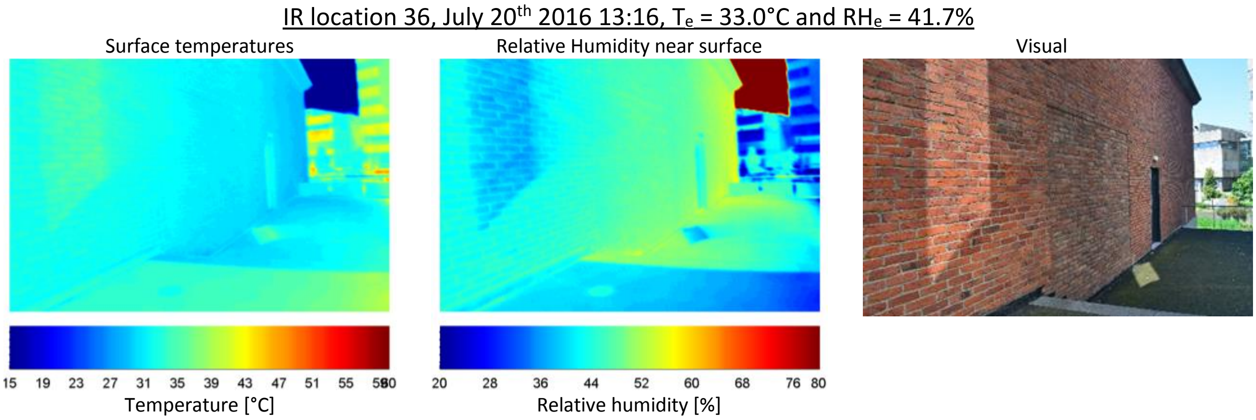


Figure 9.122: IR thermogram and hygrogram of IRT measurement location 36, conducted on July 20th 2016.

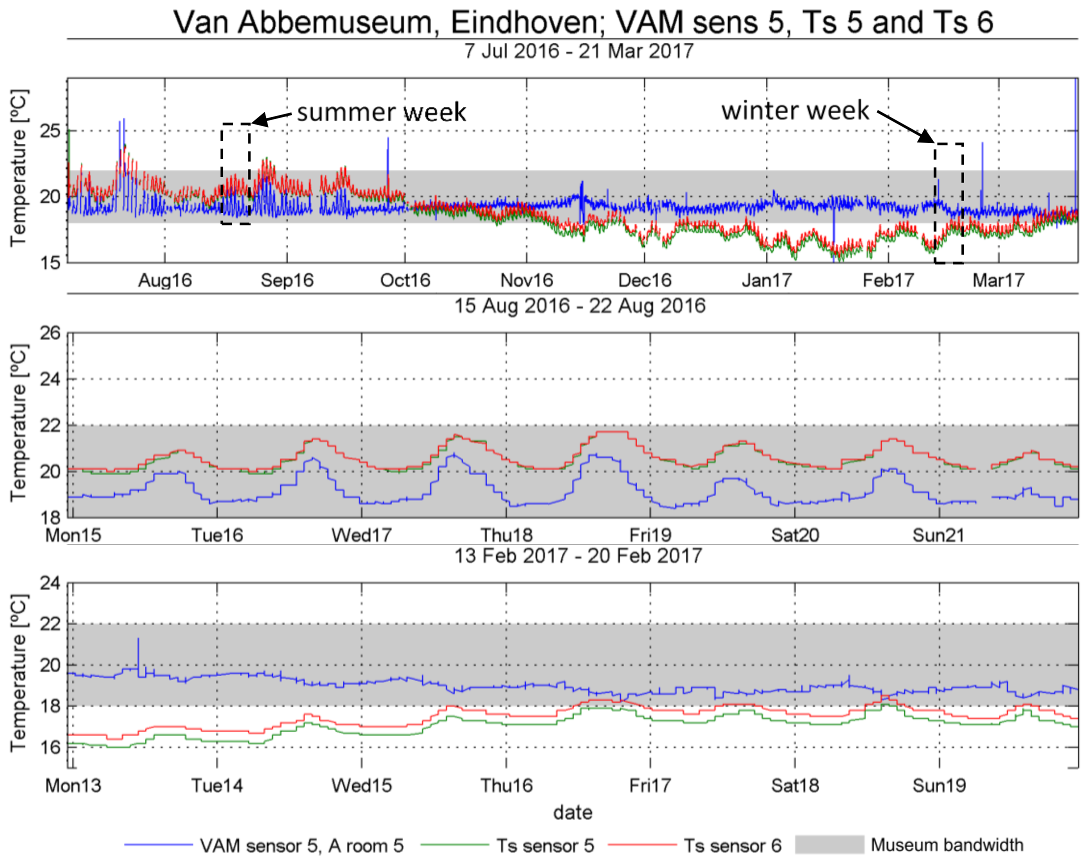


Figure 9.123: T_i and RH_i measured by Eltek sensor 5, and the T_s measured by T_s sensors 5 and 6.

Columns, monumental building part

T_s sensors 7 and 8 are placed in room 10 of the monumental building part. T_s sensor 7 is placed on the wall, T_s sensor 8 was intended to be placed on column in the façade. The location of the column was estimated by using the IR thermogram conducted on February 17th 2016, see Figure 9.124. However, the IR thermograms and T_s measurements, see Figure 9.124 to Figure 9.128, show that the T_s sensor 8 was not placed on a column, since the results are not equal. During the winter IR measurements, the columns show a lower T_s at the inside of the façade than the rest of the wall, see Figure 9.124. During the summer IR measurements, the columns show a higher T_s, see Figure 9.126. This could be correct if the columns have a lower thermal resistance than the rest of the wall and the T_e is lower than the T_i in the winter and the T_e is higher than the T_i in the summer. However, the graphs in Figure 9.128 show that at T_s sensor 8 a lower T_s is measured than at T_s sensor 7 during the summer, and a higher T_s is measured in the winter. This is in contrast with the IR results. Over the year, the surface temperatures at T_s sensor 7 and 8 are lower than the T_i and RH_i measured by Eltek sensor 1.

IR location 15, February 17th 2016 10:25, T_i = 19.8°C and RH_i = 47.3%

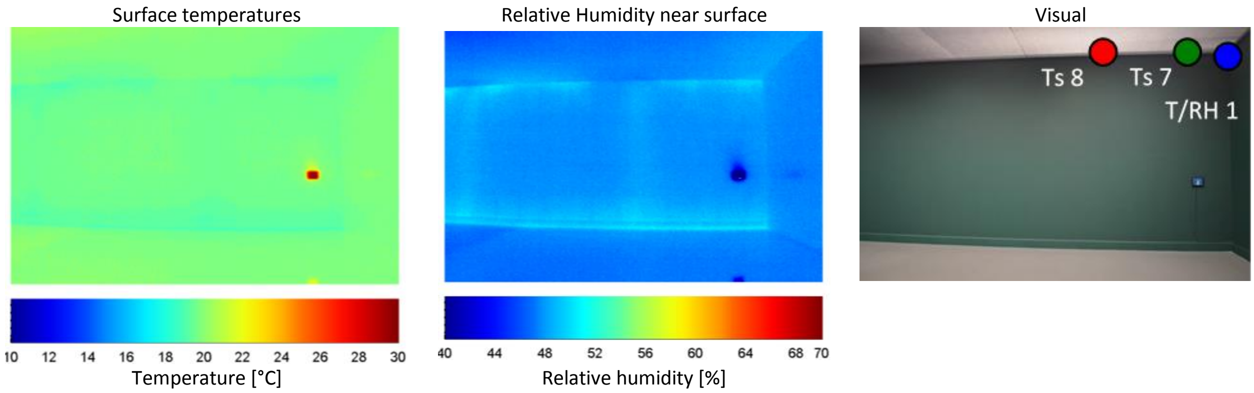


Figure 9.124: IR thermogram and hygrogram of IRT measurement location 15, conducted on February 17th 2016.

IR location 34, February 17th 2016 11:14, T_e = 5.0°C and RH_e = 46.8%

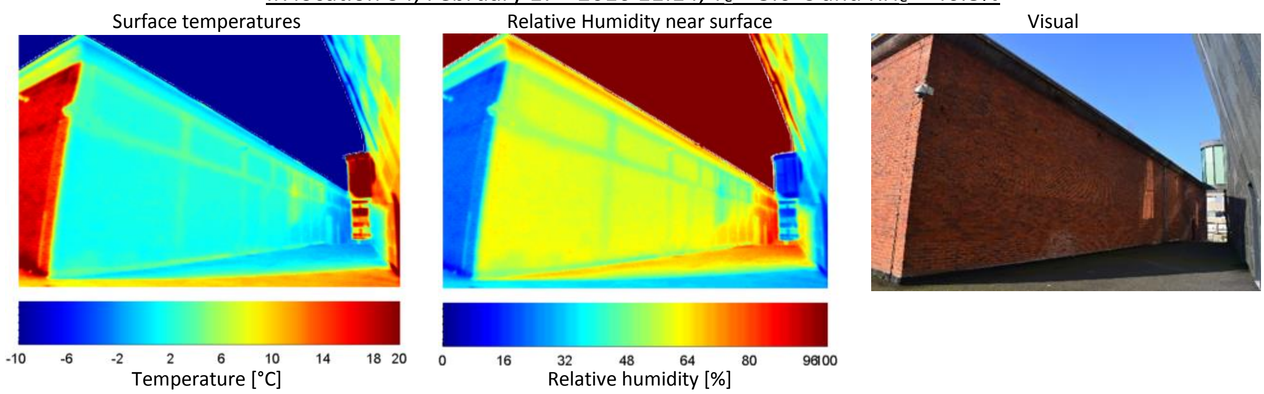


Figure 9.125: IR thermogram and hygrogram of IRT measurement location 34, conducted on February 17th 2016.

IR location 15, July 20th 2016 14:12, T_i = 26.3°C and RH_i = 41.6%

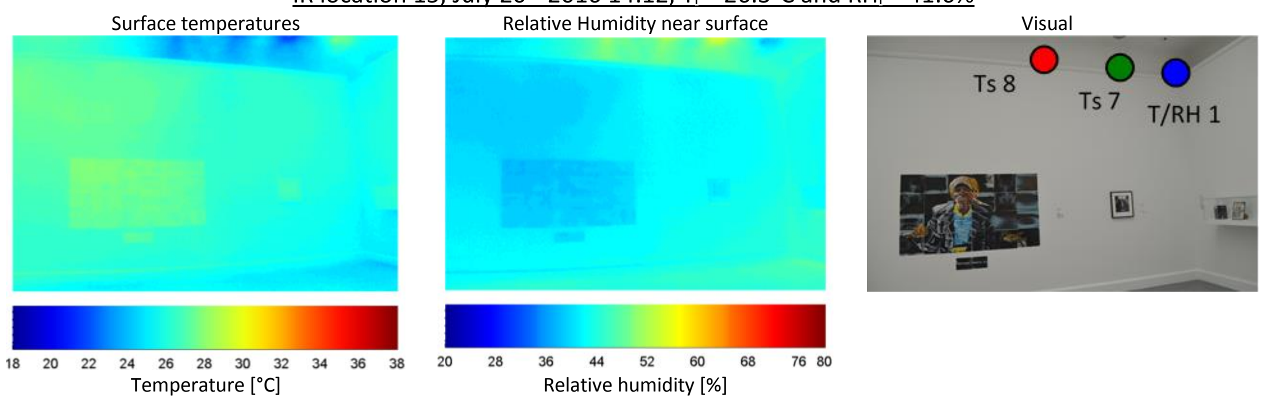


Figure 9.126: IR thermogram and hygrogram of IRT measurement location 15, conducted on July 20th 2016.

IR location 34, July 20th 2016 13:11, T_e = 33.0°C and RH_e = 41.7%

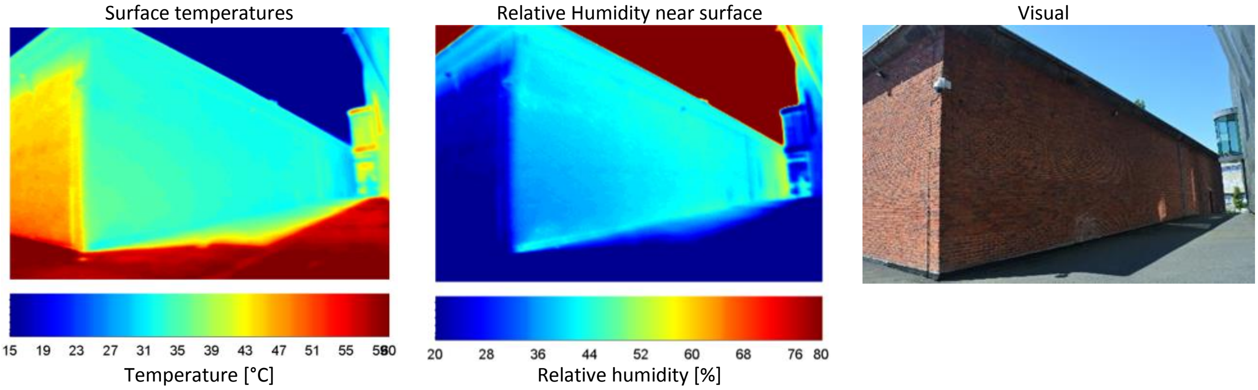


Figure 9.127: IR thermogram and hygrogram of IRT measurement location 34, conducted on July 20th 2016.

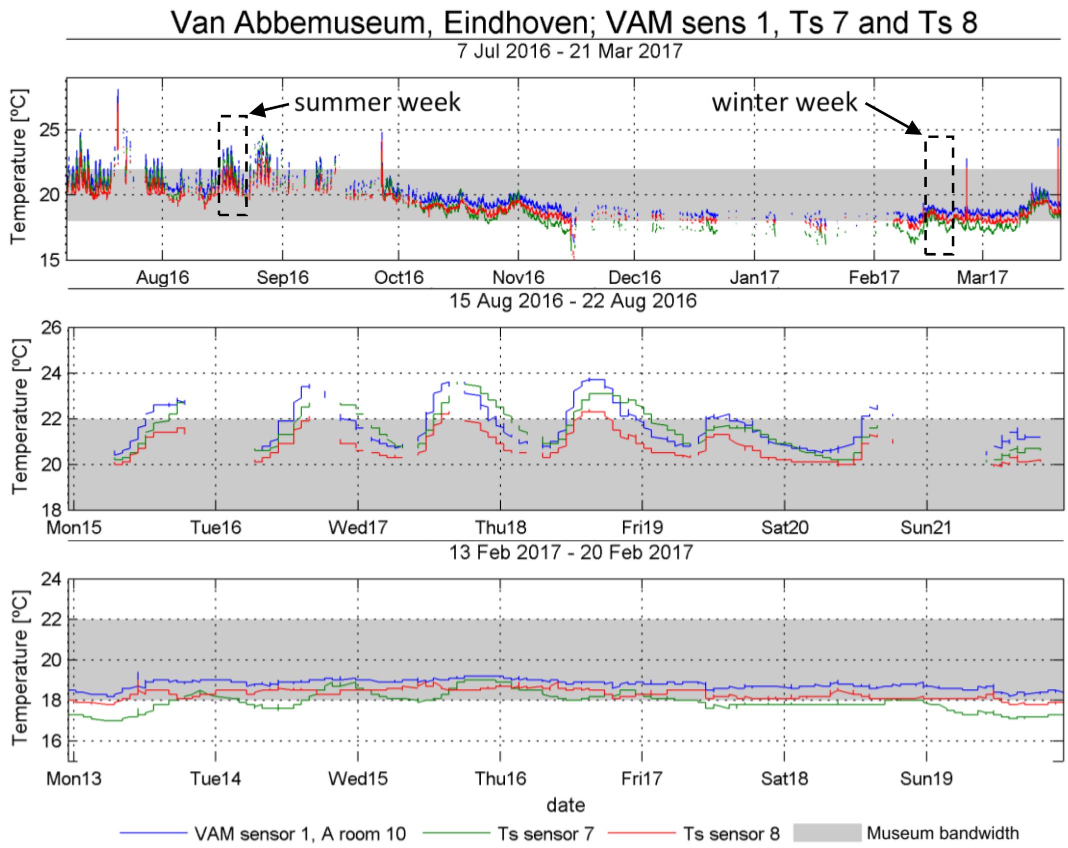


Figure 9.128: T_i and RH_i measured by Eltek sensor 1, and the T_s measured by T_s sensors 7 and 8.

Façade adjacent to veranda, modern building part

T_s sensors 1, 2, 3 and 4 are placed in sequence from bottom to top on a Façade adjacent to a veranda at the 1st floor of the modern building part. Unfortunately, T_s sensor 2 did not measure the T_s during the measurement period and could not be changed after noticing due to the difficult placement (wires behind double wall). During the winter, the IR thermogram of this locations clearly shows deviations in T_s, see Figure 9.129. The T_s is colder at the bottom than at the top. During the summer, the T_s measured over the façade adjacent to the veranda are very similar to each other, see Figure 9.130. Figure 9.131 shows the T graphs of these locations. The graphs show that during the summer, the T_s over the height of the façade and the room T_i are very similar. During the winter, The T_s often colder and shows extremer fluctuations than the room T_i.

IR location 22, February 17th 2016 10:44, T_i = 19.6°C and RH_i = 46.5%

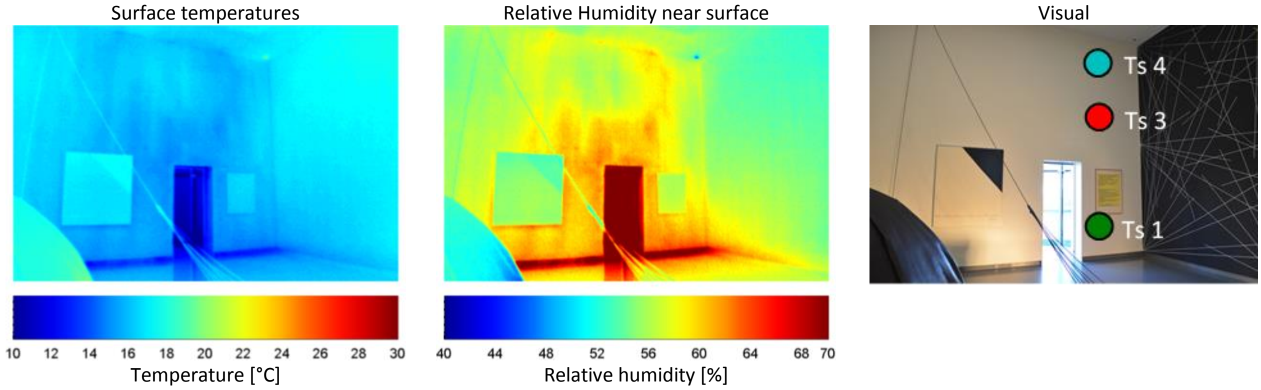


Figure 9.129: IR thermogram and hygrogram of IRT measurement location 22, conducted on February 17th 2016.

IR location 22, July 20th 2016 14:24, T_i = 21.9°C and RH_i = 50.5%

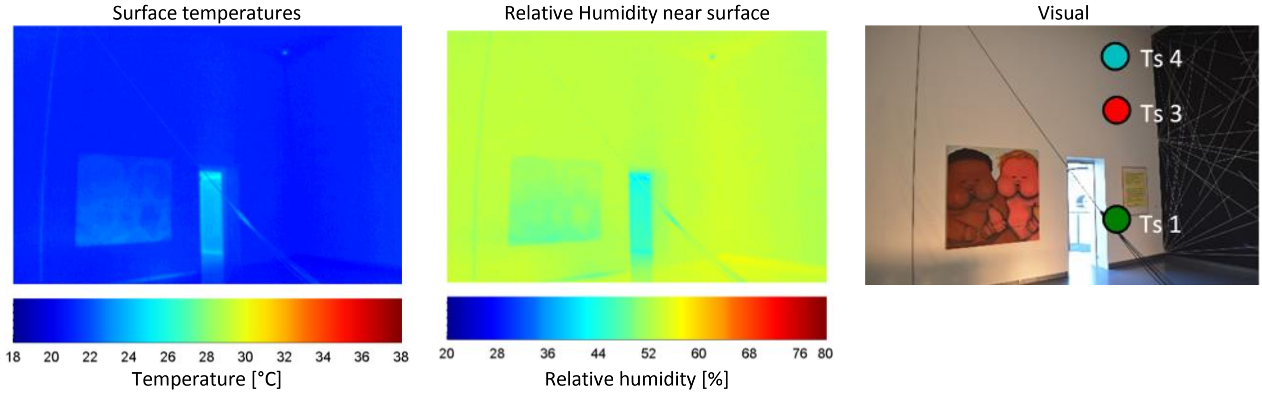


Figure 9.130: IR thermogram and hygrogram of IRT measurement location 22, conducted on July 20th 2016.

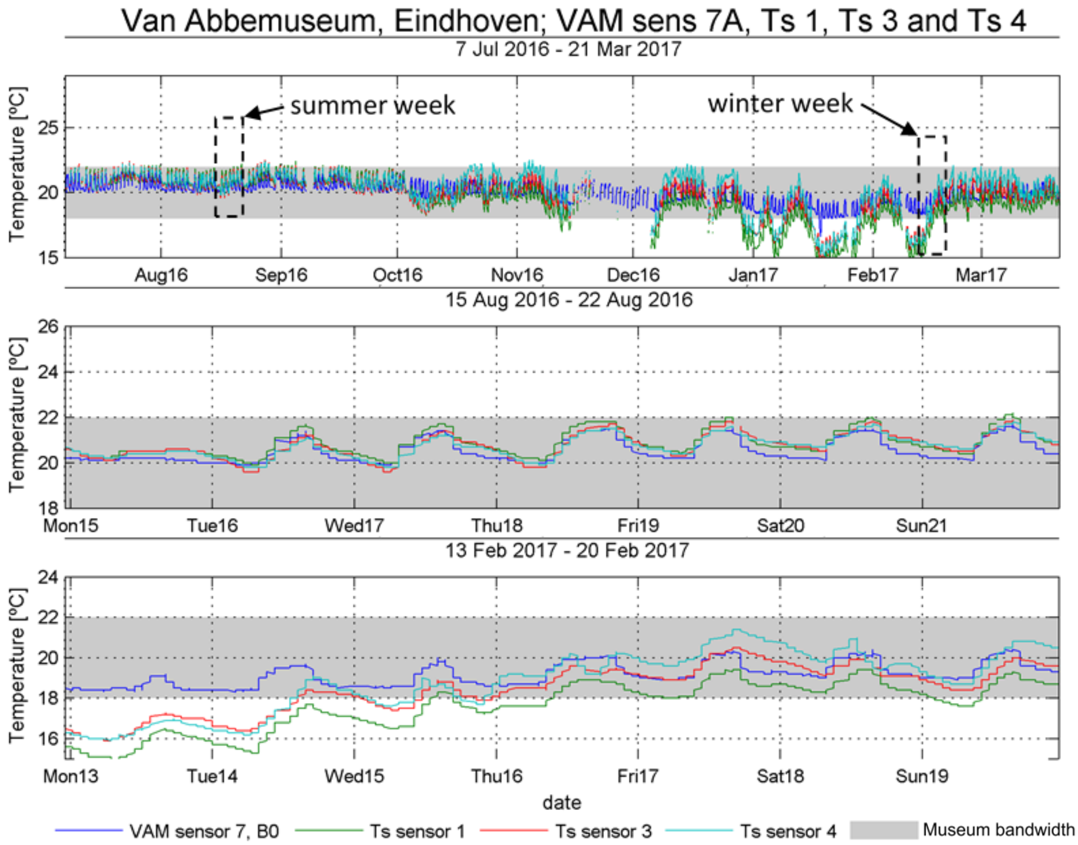


Figure 9.131: T_i and RH_i measured by Eltek sensor 7A, and the T_s measured by T_s sensors 1, 3 and 4.

Wall without and with solar radiation, monumental building part

T_s sensor 6 is placed in room 5 of the monumental building part at the bottom of a façade (double wall) without solar radiation on the façade (facing north), T/RH sensor 5 is placed in the same room. T_s sensor 7 is placed in room 10 of the monumental building part at the top of a façade (bricked wall) with solar radiation on the façade (facing south), T/RH sensor 1 is placed in the same room. Figure 9.119, Figure 9.121, Figure 9.124, and Figure 9.126 show the IR thermograms made in the winter and summer. In both periods, the IR thermograms show that the façade of room 10 has higher T_s, of approximately 2°C to 3°C. On both measurement moments, the sun shone on the outer façade facing south. The T graphs of these locations are shown in Figure 9.132. The graphs of room 5 show that during the summer the T_s is warmer than the T_i. The graphs of room 10 show that during the summer the T_s is lower than the T_i during the day and higher than the T_i during the night. For both locations applies that during the winter the T_s is lower than the T_i. In addition, the measurement results show that during the summer the fluctuations of T_i and T_s are similar, but during the winter the T_s fluctuates much more than the T_i. The difference between the T_i and T_s is larger in room 5 than room 10.

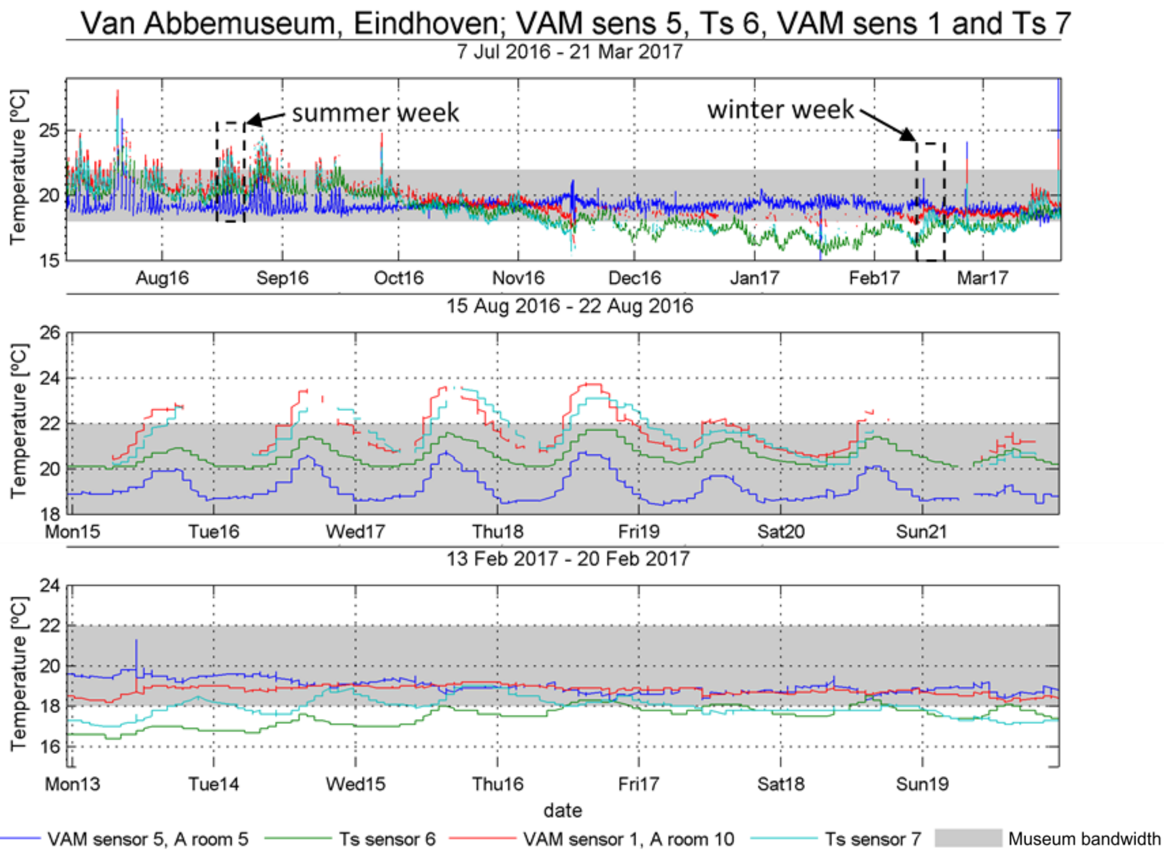


Figure 9.132: T_i and RH_i measured by Eltek sensors 5 and 1, and the T_s measured by T_s sensors 6 and 7.

Wall without and with solar radiation, modern building part

T_s sensor 9 is placed at the 2nd floor of the modern building part underneath the ceiling at the façade (double wall) without solar radiation on the façade (facing north), T/RH sensor 11 is placed in the same room. T_s sensor 11 is located under the same conditions as T_s sensor 9, the only difference is that this sensor is placed at a wall with solar radiation on the façade (facing west). T/RH sensor 13 is placed in the same room as T_s sensor 11. Figure 9.133 and Figure 9.134 show the IR thermograms made in the winter and summer of the location of T_s sensor 9. Unfortunately there is only an IR thermogram made of the location of T_s sensor 11 during the summer, see Figure 9.135. The IR thermograms made in the summer of both locations do not show much differences, both do not clearly show microclimates (color differences). The IR thermogram of the location of T_s sensor 9 conducted during the winter shows more deviations. Figure 9.136 shows the T graphs of these locations. The graphs show that the T_s measured on the wall without solar radiation on the façade (T_s sensor 9) is always lower than the T_s measured on the wall with solar radiation on the façade (T_s sensor 11). The T_i measured near T_s sensor 9 is also always lower than the T_i measured near T_s sensor 11.

IR location 30, February 17th 2016 11:03, T_i = 18.7°C and RH_i = 49.6%

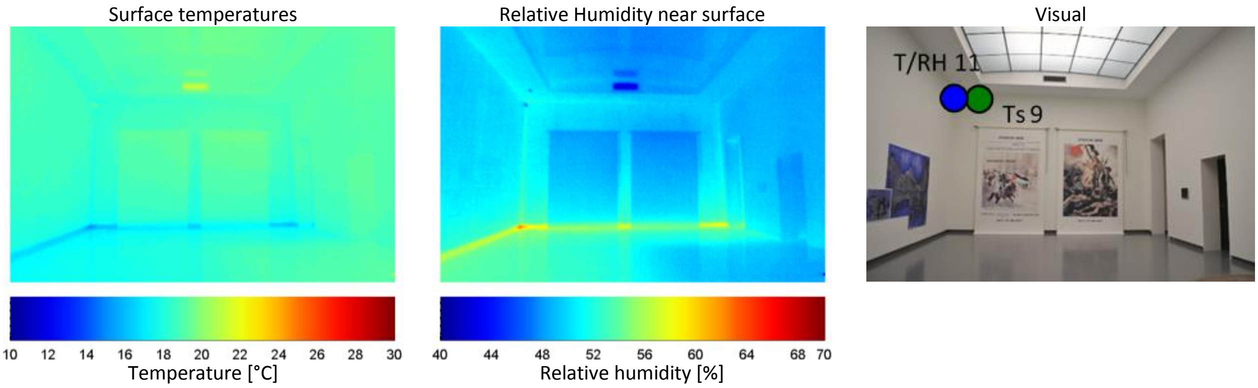


Figure 9.133: IR thermogram and hygrogram of IRT measurement location 30, conducted on February 17th 2016.

IR location 30, July 20th 2016 14:34, T_i = 20.8°C and RH_i = 53.6%

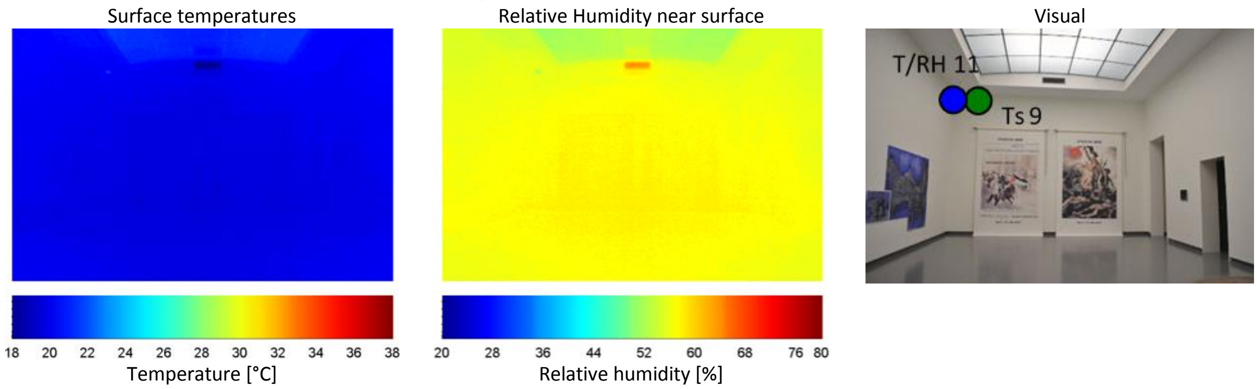


Figure 9.134: IR thermogram and hygrogram of IRT measurement location 30, conducted on July 20th 2016.

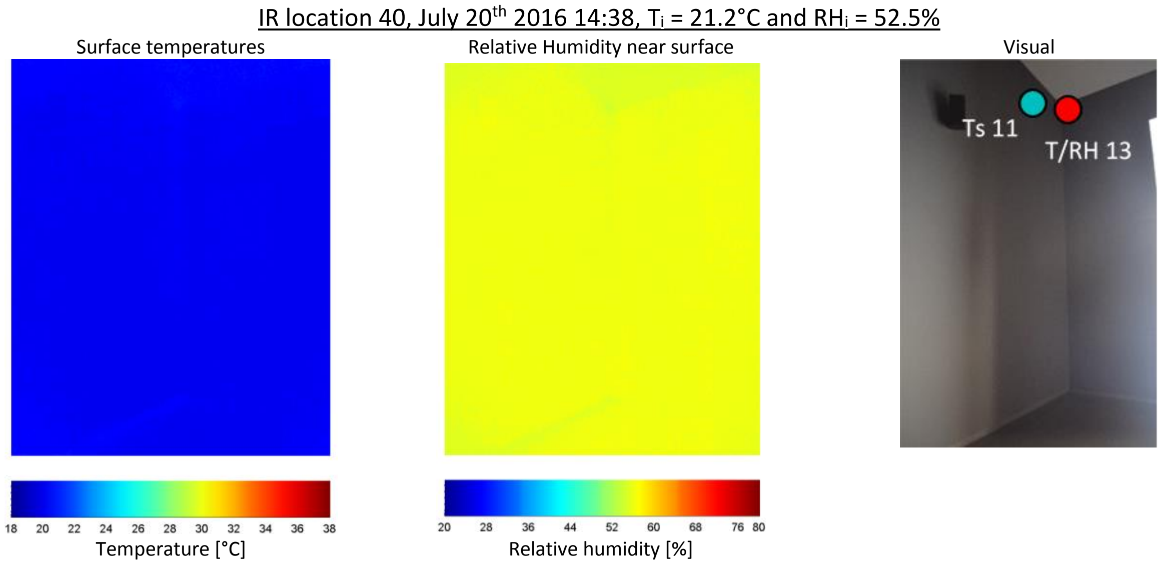


Figure 9.135: IR thermogram and hygrogram of IRT measurement location 40, conducted on July 20th 2016.

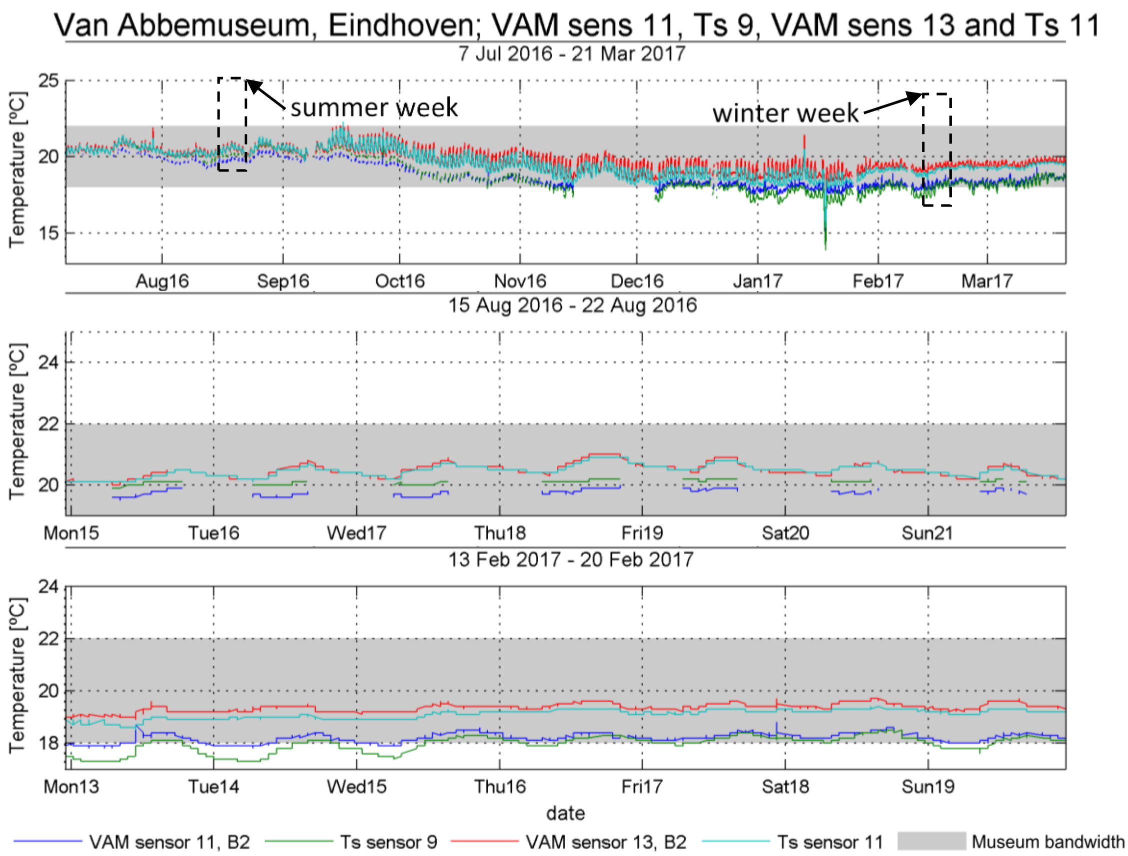


Figure 9.136: T_i and RH_i measured by Eltek sensors 11 and 13, and the T_s measured by T_s sensors 9 and 11.

Plenums, monumental building part

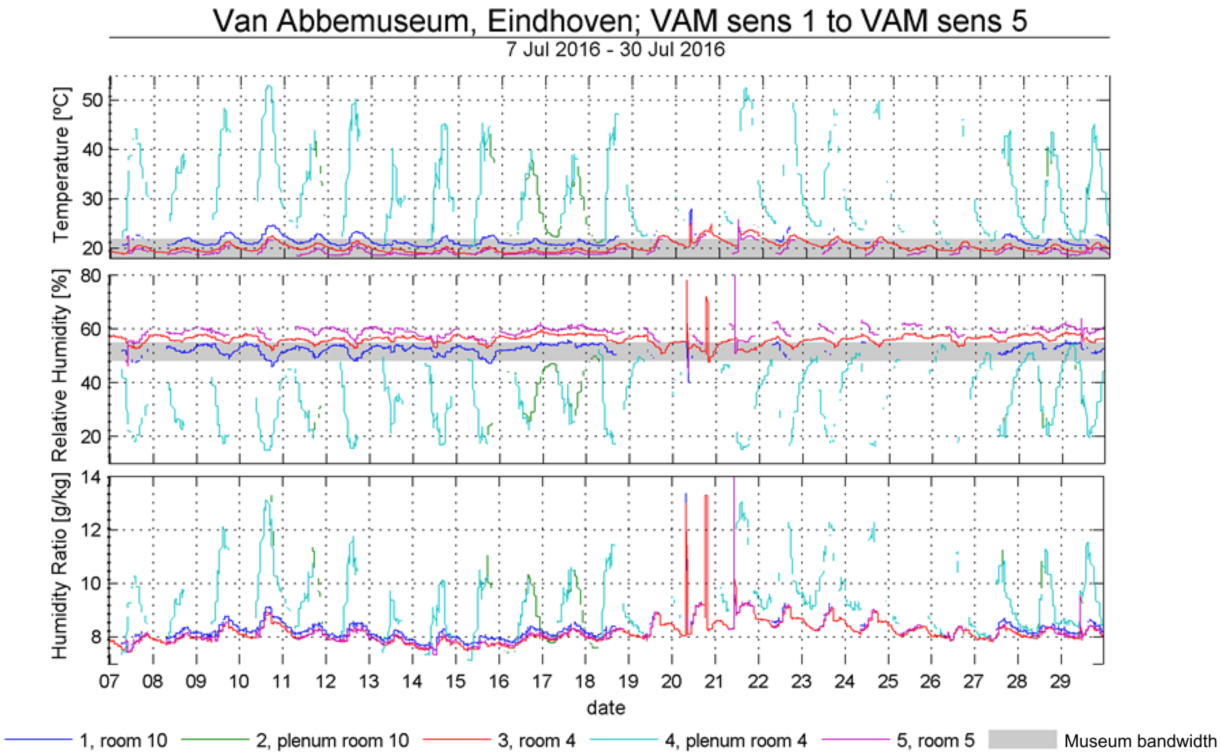


Figure 9.137: T_i and RH_i measured by Eltek sensors 1 to 5 in rooms 4, 5 and 10 of the monumental building part.

Appendix X. Results setpoint strategies

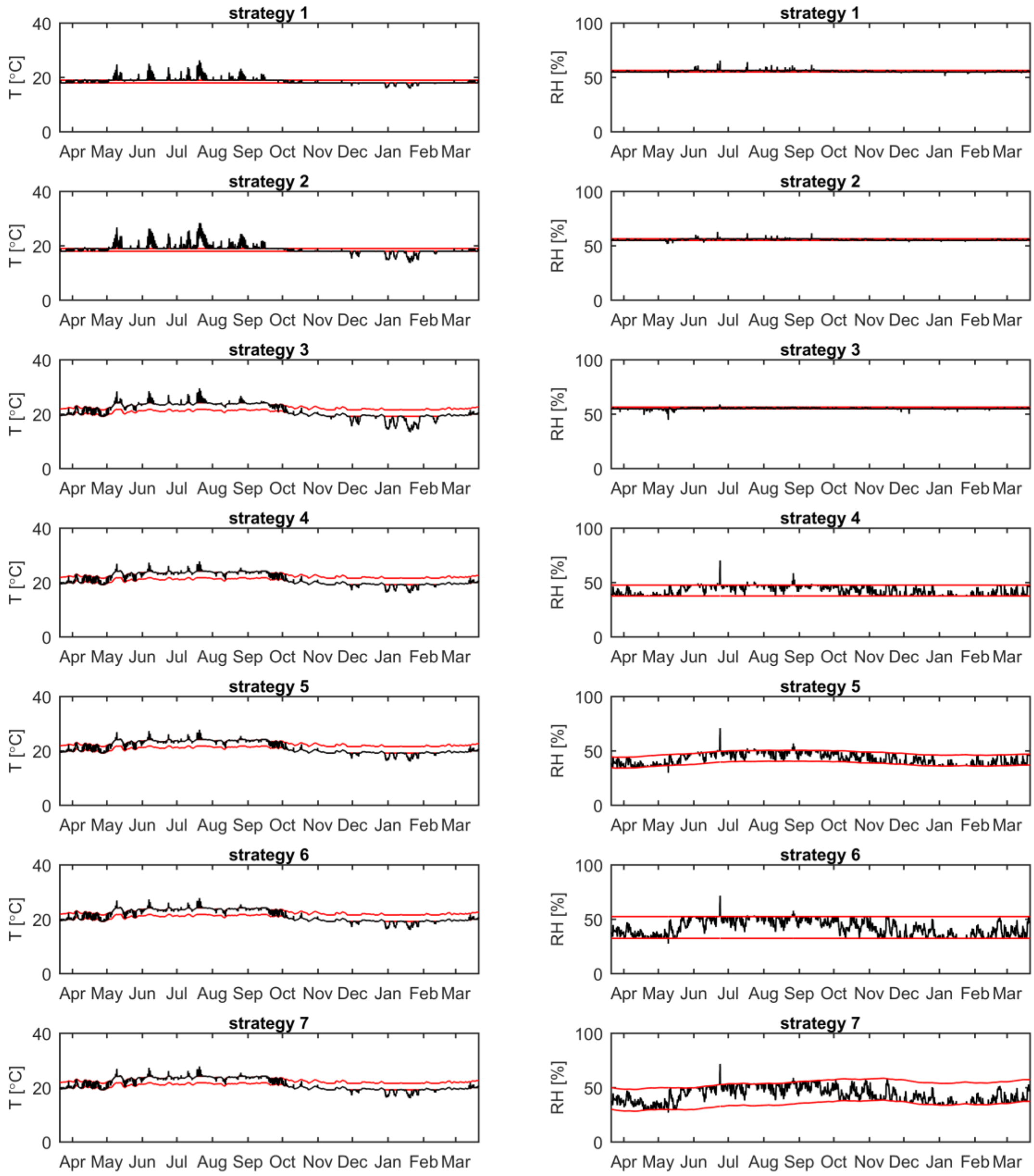


Figure 9.138: Overview of simulated setpoint strategies 1-7. The setpoints per strategy can be found in Table 4.11.

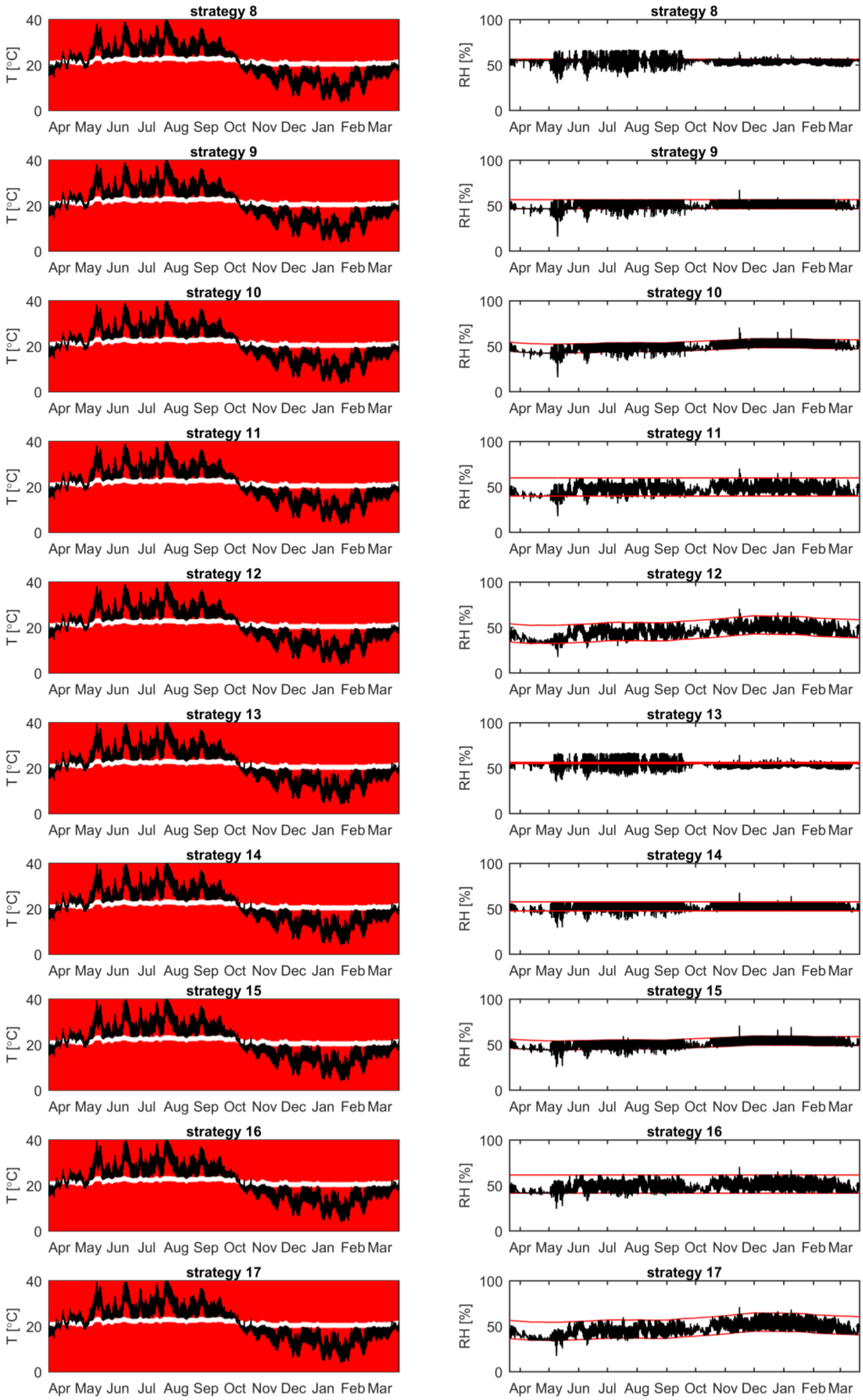


Figure 9.139: Overview of simulated setpoint strategies 8-17. The setpoints per strategy can be found in Table 4.11.

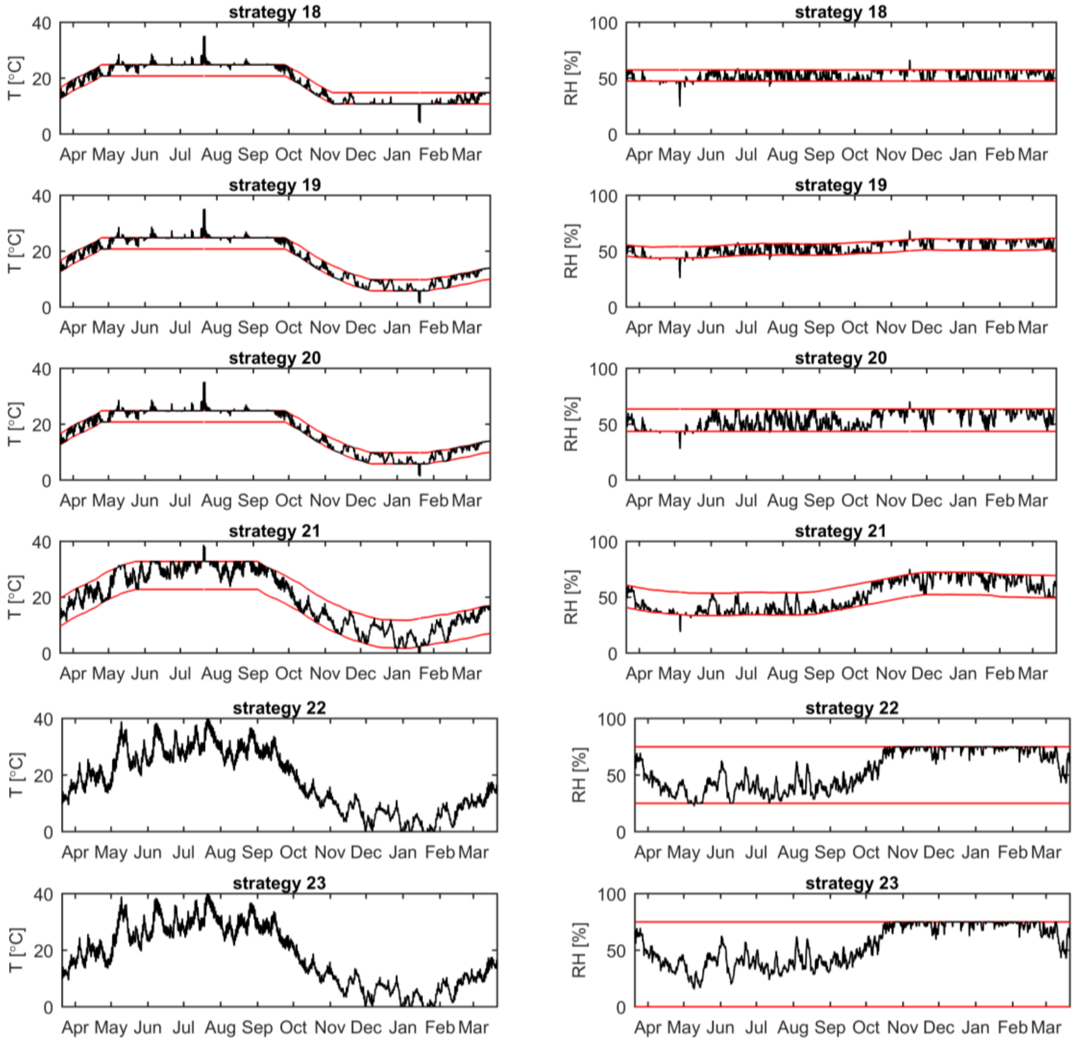


Figure 9.140: Overview of simulated setpoint strategies 18-23. The setpoints per strategy can be found in Table 4.11.

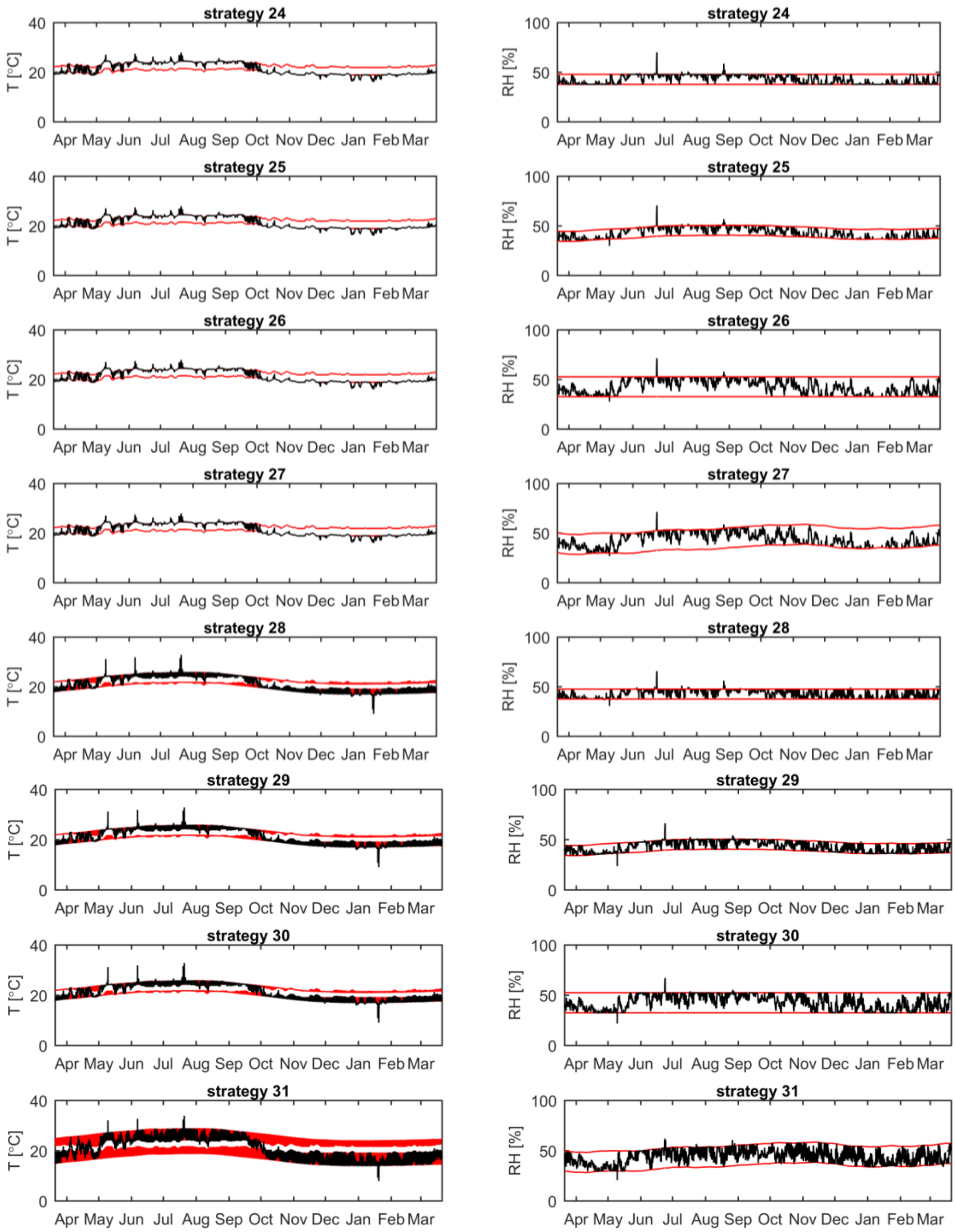


Figure 9.141: Overview of simulated setpoint strategies 24-31. The setpoints per strategy can be found in Table 4.11.

Appendix Y. Potential effect of (structural) measures on temperature and relative humidity

Method

Within the research of this thesis, the effect on the indoor climate (temperature (T) and relative humidity (RH)) and the energy use of different setpoint strategies of the Heating, Ventilation, and Air Conditioning (HVAC) system have been discussed. In order to get a first perception of the potential effect of possible (structural) measures on the indoor climate (T and RH) of the exhibition rooms and the plenums of the monumental building part, some extra simulations have been made using the calibrated numerical model of the current situation (reference model). The HAMBase input of the reference model can be found in Appendix M. The simulated measures are schematically shown in Figure 9.142. This additional study focusses on the potential effect on the indoor climate (T and RH), however, other aspects should be considered as well in future research in order to let the Van Abbemuseum (VAM) make a well-considered decision before implementing any measure. Other aspects that should be considered are for example the monumental value, investment costs, and quality of (day)light.

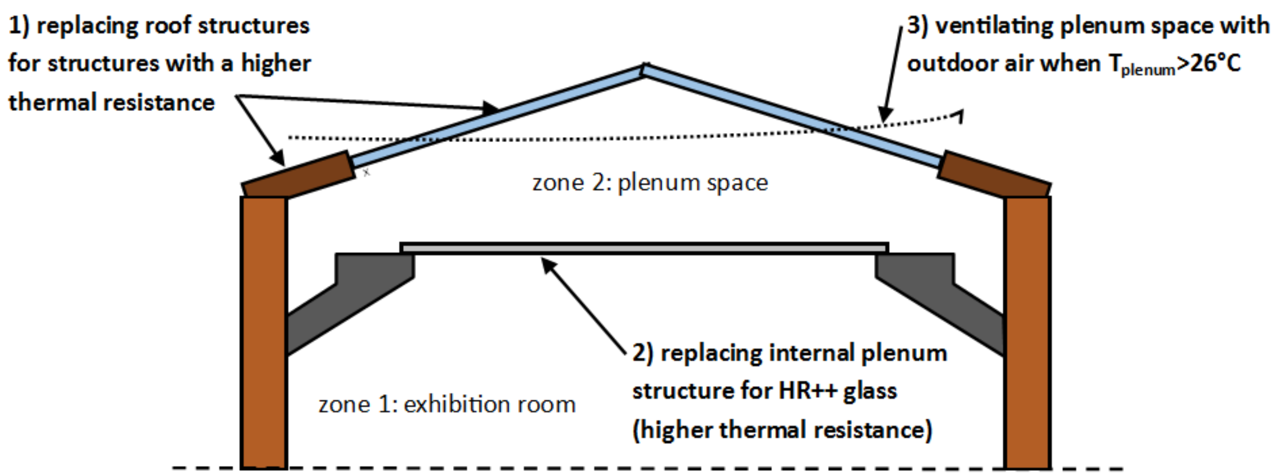


Figure 9.142: Schematic section view of an exhibition room and a plenum of the monumental building part, showing three possible measures to improve the indoor climate (T and RH) of the exhibition room and the plenum.

The first simulated measure has been modeled by changing the current roof structures for modern roof structures with a higher thermal resistance (including insulation). The material structures of the current roof structures, see conID 21 and 22 in Table 9.37 have been replaced for conID 26. The corresponding matIDs can be found in Table 9.10 in Appendix M. The polycarbonate channel plates (glaID 1 in Table 9.38) have been replaced for HR++ glass (glaID 3). The current roof is placed on a steel construction. In order to carry the weight of the new roof structures, the steel construction should be replaced as well.

Table 9.37: Additional structure types in HAMBase.

conID	description	Ri [m²K/W]	d1 [m]	matID	d2 [m]	matID	d3 [m]	matID	Re [m²K/W]	ab [-]	eps [-]
			d4 [m]	matID	d5 [m]	matID	d6 [m]	matID			
			d7 [m]	matID							
21	old roof	0.1	0.037	501	0.004	601			0.04	0.9	0.9
22	new roof (2003)	0.1	0.100	452	0.004	601			0.04	0.9	0.9
26	modern roof	0.1	0.012	501	0.228	452	0.018	501			
			0.004	601					0.04	0.9	0.9
20	plenum glass	0.13	0.020	383					0.13	0.4	0.9
27	HR++ glass	0.13	0.024	388					0.13	0.4	0.9

Table 9.38: Additional glazing types in HAMBase.

glaID	Uglas [W/m²K]	CFr [-]	ZTA [-]	ZTAw [-]	CFrw [-]	Uglasw [W/m²K]	description
1	2.5	0.03	0.8	0.8	0.03	2.5	polycarbonate plates
3	1.2	0.03	0.65	0.65	0.03	1.2	HR++ glass

The second simulated measure has been modeled by replacing the translucent internal plenum structure (conID 20 in Table 9.37) for HR++ glass (conID 27), i.e. increasing the thermal resistance. Since HR++ glass is not a standard construction material in HAMBase, the properties of HR++ glass have been manually added in the material list. Table 9.39 shows the material properties of the reference internal plenum structure (383: glass (standard)) and the added material properties of HR++ glass (388: HR++ glass). The thermal conductivity has been lowered (λ = 0.029 W/mK), in order to simulate a higher thermal resistance (Rc = 0.83 m^2K/W) and lower thermal transmittance (U = 1.2 W/m^2K).

Table 9.39: Material properties, 388(HR++ glass) is manually added to the material list in HAMBase based on the material properties of 383(glass (standard)).

material	λ [W/mK]	ρ [kg/m3]	C [J/kgK]	ε [-]	μ [-]	ξ [kg/m3]	bv.10^7
383: glass (standard)	0.8	2500	840	0.9	900000	0	0
388: HR++ glass	0.029	2500	840	0.9	900000	0	0

Within the third simulated measure, the building structures have been kept the same as in the reference model, see Appendix M. However, the building profiles of the plenum zones have been changed: the plenum will be naturally ventilated with outdoor air when the T in the plenum is above 26°C (Engelen, 2006). To implement this measure, some parts of the roof structures should be able to be opened. Within the building profile of the plenum zones, the following input from Table 9.18 (Appendix M) have been changed:
$vv_{max} = 0.1hr^{-1} \rightarrow vv_{max} = 10hr^{-1}$, and $T_{fc} = 100°C \rightarrow T_{fc} = 26°C$.

Despite simulating the three measures using the current setpoint strategy (reference), the optimum setpoint strategies as described in Paragraph 4.3.6 (strategies 5 and 29) have been simulated as well in combination with the three measures. The results for zone 1 (exhibition room 4) have been compared regarding energy use, risks to objects and thermal comfort during opening hours. The risks to objects have been analyzed with the climate risk assessment method of Martens (2012), and the Adaptive Thermal Guideline (ATG) for museums of Kramer et al. (2016) has been used to analyze the thermal comfort.

Results

The results of the possible measures are discussed in this paragraph. Table 9.40 and Figure 9.143-Figure 9.150 show the T and RH results of the calibrated reference model and the three measures added in the reference model. Table 9.41 shows the results of the three measures combined with the optimum setpoint strategies (5 and 29).

Table 9.40, Figure 9.144 and Figure 9.146 show that the first measure, changing the current roof structures for structures with a higher thermal resistance, increases the T and decreases the RH in the plenum throughout the year. As a result, the T increases in the exhibition rooms (and therefor the RH decreases), see Figure 9.143 and Figure 9.145. Table 9.41 shows that the first measure (1b. Roof) comes with a higher energy use, lower ASHRAE class met 100% of the time, and a lower LM value compared to the results of the reference model (1a. Ref). The thermal comfort of the exhibition room is slightly better within the indoor climate of the first measure. The results regarding energy savings, risks to objects and thermal comfort of the optimum setpoint strategies added to the first measure (5b. and 29b.) are similar compared to the optimum setpoint strategies added to the reference model (5a. and 29a.).

Table 9.40: Overview of simulated T and RH for zone 1 (exhibition room 4) and 2 (plenum room 4) for the reference model and the three measures (March 21st 2016 till March 21st 2017).

Zone No.	Temperature [°C]						Relative humidity [%]					
	mean	drop	rise	min	max	range	mean	drop	rise	min	max	range
Zone 1: reference model	18.6	0.8	0.8	16.1	25.1	9.0	55.6	0.6	0.8	53.0	62.1	9.1
Zone 2: reference model	22.3	9.6	9.3	5.7	53.8	48.1	47.5	12.0	14.0	12.9	72.6	59.7
Zone 1: roof structure	18.8	0.8	1.1	18.0	27.0	9.0	55.6	0.6	0.8	51.7	61.2	9.5
Zone 2: roof structure	25.9	9.6	9.5	11.5	57.7	46.2	38.3	11.0	11.0	9.8	63.0	53.2
Zone 1: internal plenum structure	18.5	0.5	0.6	17.2	21.2	4.0	55.6	0.6	0.9	52.8	66.1	13.3
Zone 2: internal plenum structure	23.4	12.0	11.0	3.9	59.9	56.0	45.8	15.0	18.0	9.7	74.7	65.0
Zone 1: ventilating plenum T>26°C	18.5	0.6	0.6	16.1	22.6	6.5	55.6	0.6	0.9	53.6	64.8	11.2
Zone 2: ventilating plenum T>26°C	20.0	7.3	6.1	5.7	38.8	33.1	48.4	16.0	13.0	13.3	73.5	60.2

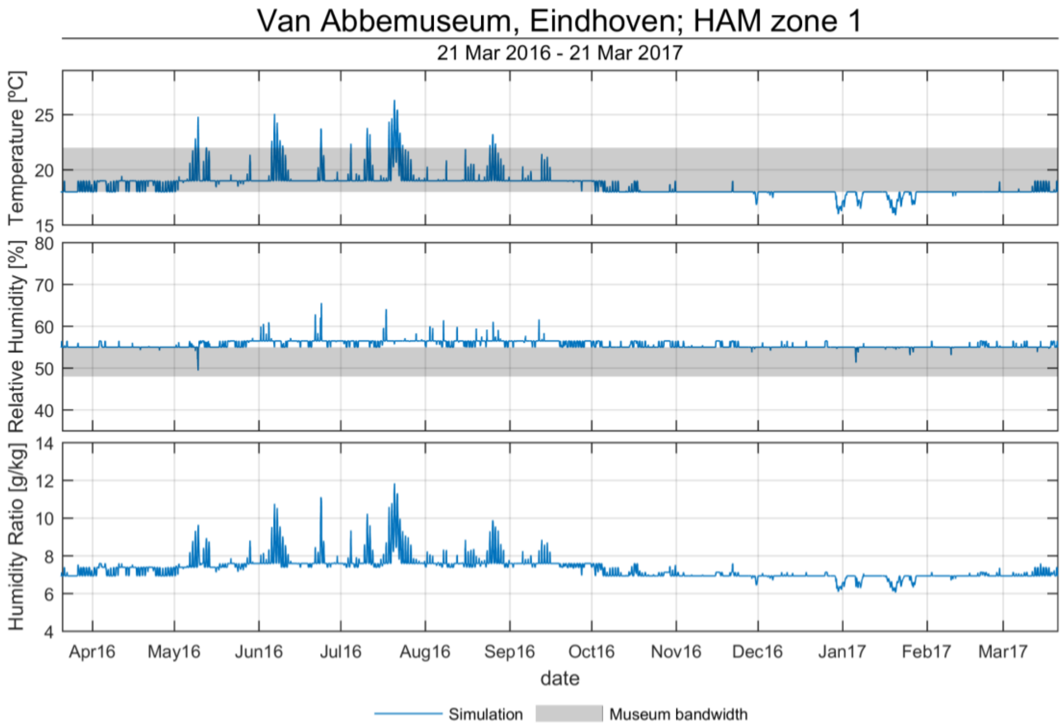


Figure 9.143: Simulated T, RH, and humidity ratio for HAMBase zone 1 (room) of the calibrated reference model.

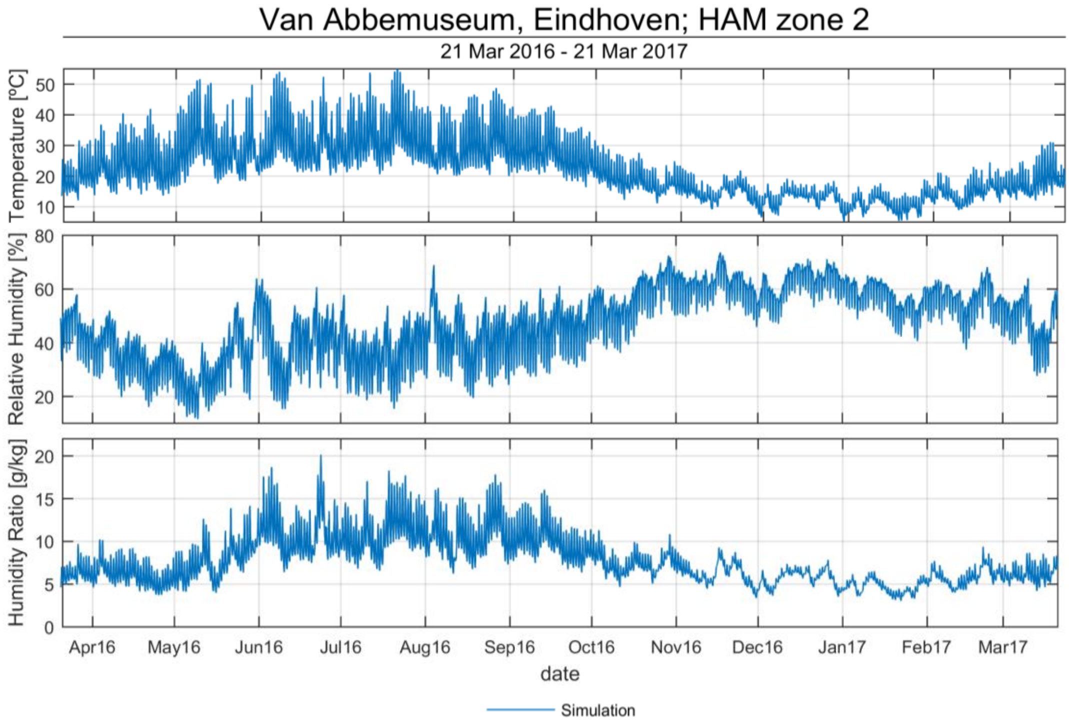


Figure 9.144: Simulated T, RH, and humidity ratio for HAMBase zone 2 (plenum) of the calibrated reference model.

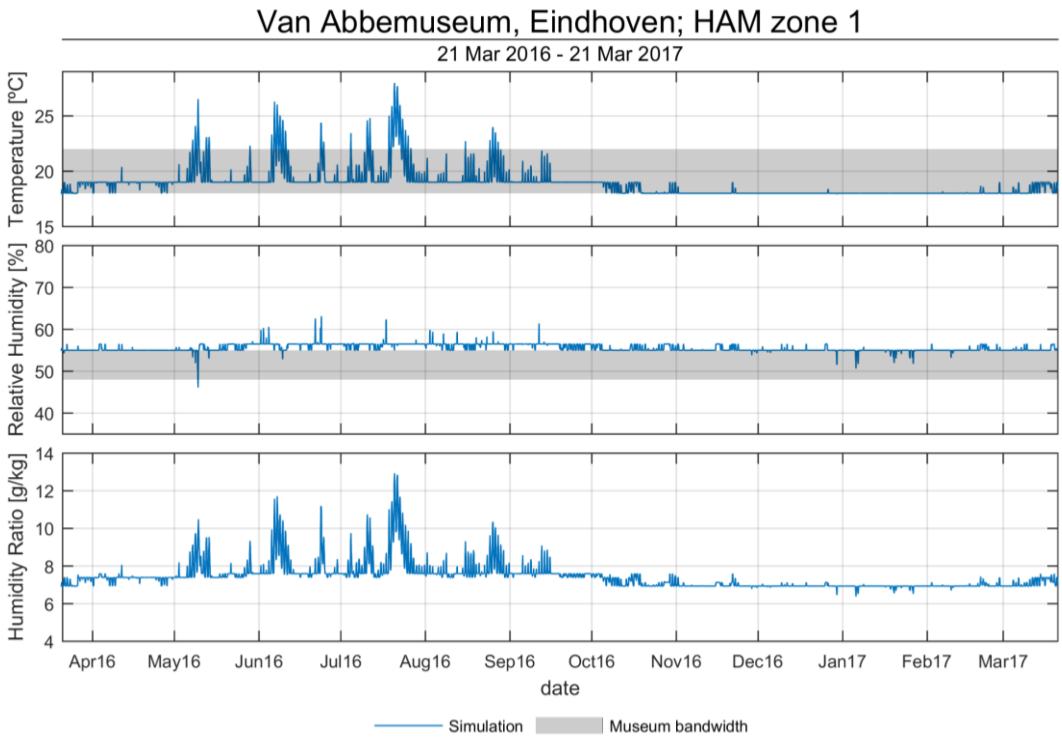


Figure 9.145: Simulated T, RH, and humidity ratio for HAMBase zone 1 (room) of the first possible measure: changing the roof structures for structures with a higher thermal resistance.

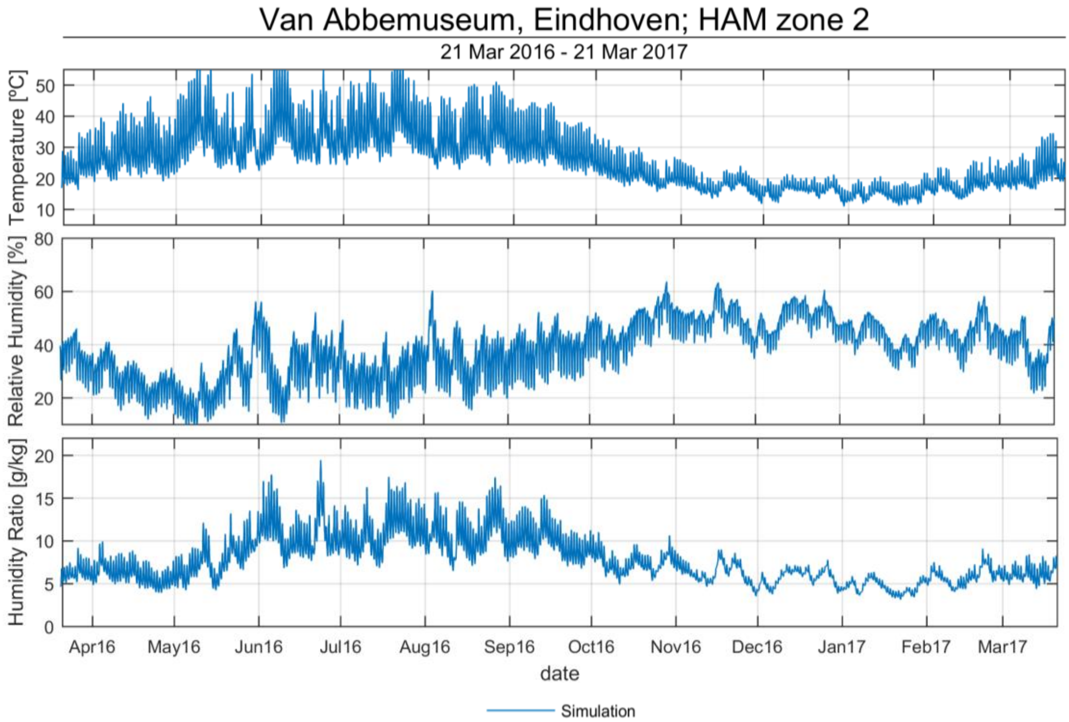


Figure 9.146: Simulated T, RH, and humidity ratio for HAMBase zone 2 (plenum) of the first possible future measure: changing the roof structures for structures with a higher thermal resistance.

Table 9.41: Simulation results for zone 1 (March 21st 2016 to March 21st 2017) of different possible measures and setpoint strategies. The energy use includes the energy required for heating, cooling, and (de)humidification. The risks to objects have been assessed according to the general and specific climate risk assessment. The specific climate risk assessment represents the average results for the four object types. Thermal comfort is expressed in the percentage of discomfort hours in the exhibition room during opening hours, based on the ATG for museums.

Stra-tegy	Setpoint T [°C]	Setpoint RH [%]	Energy Total [kWh/ m2/year]	Energy Vs. ref [%]	General AA	General As	General A	General B	General C	General D	Specific Mould	Specific LM	Specific Base layer	Specific Pict. Layer	Discom-fort [%h]
1a. Ref	18-19	55-56.5	352.2	0	92.4	92.4	92.4	99.2	100	100		**0.995**			95.1
5a.	RMOT	As	236.2	-33	45.5	87.6	96.0	100	100	100		**1.012**			10.0
29a.	RMOT/As	As	201.6	-43	51.0	82.4	93.6	100	100	100		**1.009**			15.1
1b. Roof	18-19	55-56.5	366.3	4	84.1	84.1	84.1	97.0	100	100		**0.901**			92.0
5b.	RMOT	As	233.7	-34	45.8	88.7	97.7	99.9	100	100		**1.019**			7.4
29b.	RMOT/As	As	200.0	-43	52.7	83.9	95.7	100	100	100		**0.994**			13.4
1c. Ple	18-19	55-56.5	316.4	-10	98.3	98.3	98.4	100	100	100		**1.025**			99.5
5c.	RMOT	As	202.3	-43	39.7	88.6	96.4	100	100	100		**1.002**			5.2
29c.	RMOT/As	As	171.9	-51	49.7	85.2	95.6	100	100	100		**1.001**			9.2
1d. VV	18-19	55-56.5	316.9	-10	99.0	99.1	99.4	100	100	100		**1.025**			99.2
5d.	RMOT	As	205.9	-42	40.5	87.6	95.3	100	100	100		**1.004**			7.6
29d.	RMOT/As	As	174.1	-51	48.1	84.3	94.2	100	100	100		**1.013**			11.9

The results of the second measure, increasing the thermal resistance of the internal plenum structure, show that the T in plenum increases in the summer and decreases in the winter, see Table 9.40, Figure 9.144 and Figure 9.148. Within this measure, the indoor climate (T and RH) of the exhibition room and the plenum have less impact on each other due to the higher thermal resistance of the separation structure between each other. Table 9.40, Figure 9.143 and Figure 9.147 show that the T in the exhibition room decreases in the summer and increases in the winter within the second measure compared to the results of the reference model. In addition, the RH in the exhibition room increases in the summer and decreases in the winter. Table 9.41 shows that the second measure (1c. Ple) comes with a lower energy use, higher percentages of time ASHRAE classes AA to B are met, and a higher LM value compared to the results of the reference model (1a. Ref). However, the thermal comfort is poorer than in the reference model. The results of the optimum setpoint strategies added to the second measure (5c. and 29c.) compared to the optimum setpoint strategies added to the reference model (5a. and 29a.), are higher regarding energy savings and thermal comfort, and similar regarding the risks to objects.

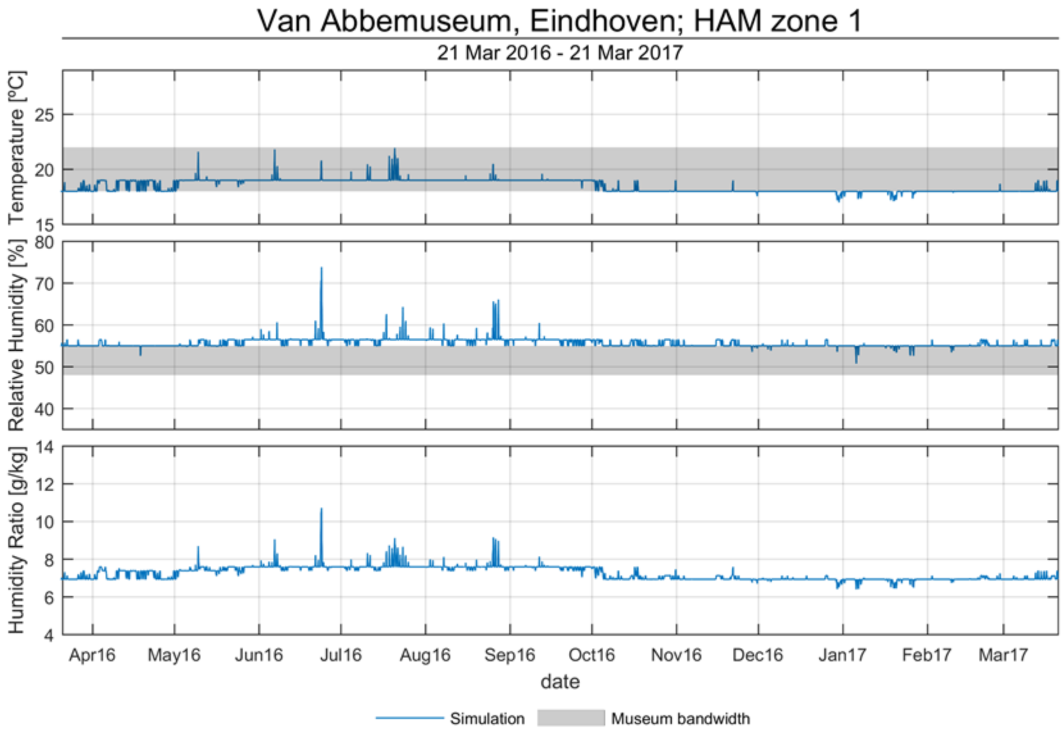


Figure 9.147: Simulated T, RH, and humidity ratio for HAMBase zone 1 (room) of the second possible future measure: changing the internal plenum structure for a structure with a higher thermal resistance.

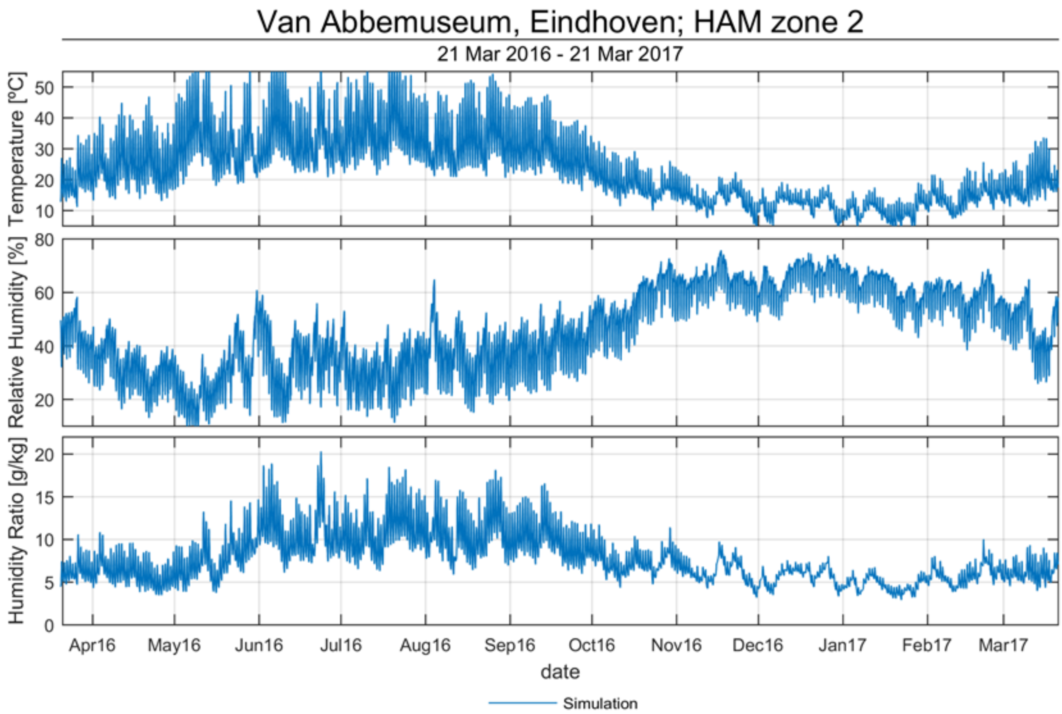


Figure 9.148: Simulated T, RH, and humidity ratio for HAMBase zone 2 (plenum) of the second possible future measure: changing the internal plenum structure for a structure with a higher thermal resistance.

The results of the third measure, natural ventilation of the plenum with outdoor air when the T in the plenum is above 26°C, show that the T in the plenum decreases and the RH fluctuates extremer in the summer, see Table 9.40, Figure 9.144 and Figure 9.150. As a result, the T decreases in the exhibition rooms as well in the summer, see Figure 9.143 and Figure 9.149. Table 9.41 shows that the results for the indoor climate (T and RH) of the exhibition rooms of the third measure (1d. VV, 5d. and 29d.) are similar to the results of the second measure (1c. Ple, 5c. and 29c.). However, the third measure is the only simulated measure in which the indoor climate (T) of the plenum improves regarding the thermal comfort of the museum staff during the summer.

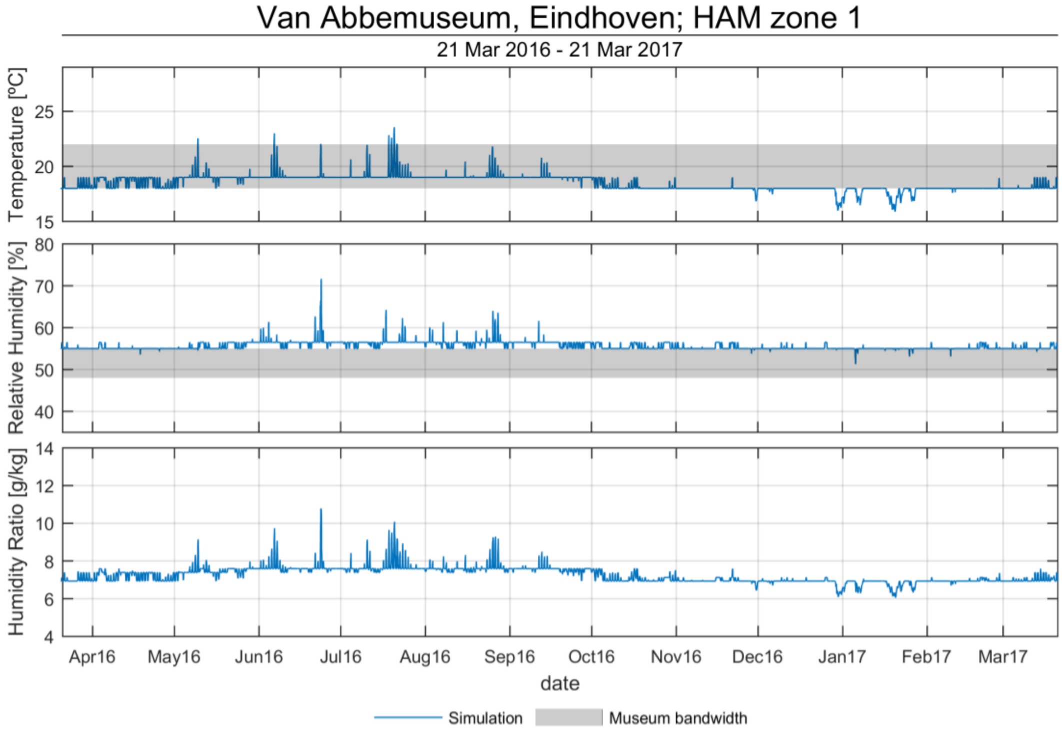


Figure 9.149: Simulated T, RH, and humidity ratio for HAMBase zone 1 (room) of the third possible future measure: ventilating the plenum with outdoor air when T_{plenum}>26°C.

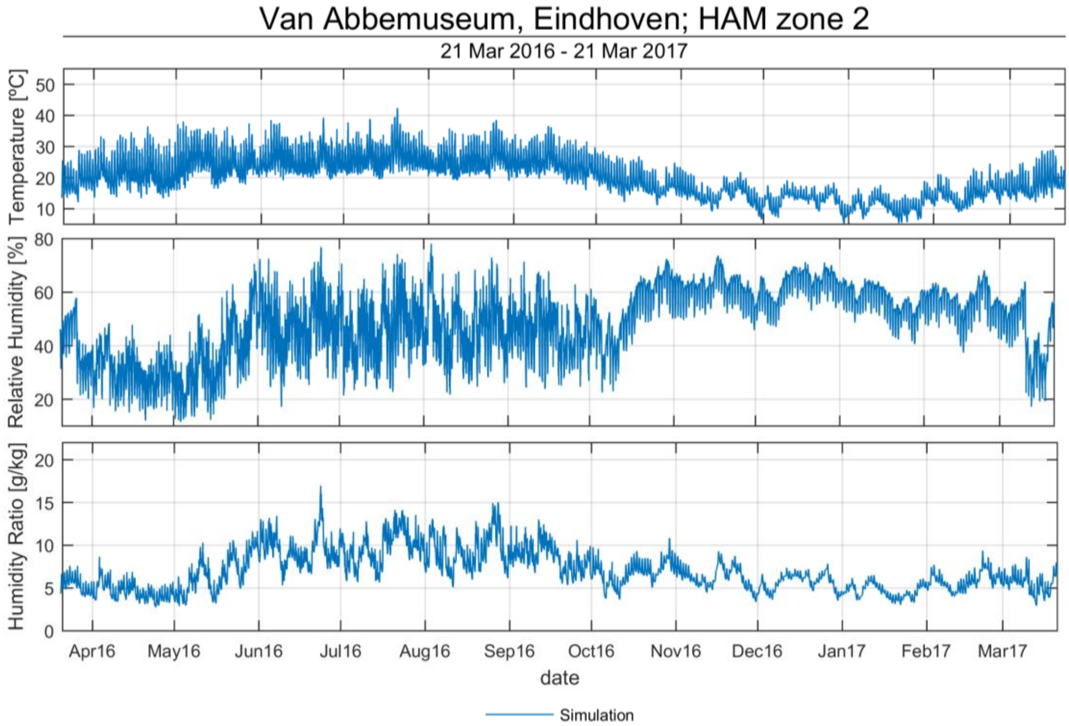


Figure 9.150: Simulated T, RH, and humidity ratio for HAMBase zone 2 (plenum) of the third possible future measure: ventilating the plenum with outdoor air when T_{plenum}>26°C.

Discussion and conclusion

The first measure, changing the current roof structures for structures with a higher thermal resistance, is not an interesting measure considering to improve the indoor climate (T and RH) of the exhibition rooms and the plenums. The indoor climate of the exhibition rooms declines regarding energy savings and risks to objects. The T in the plenums increases throughout the year due to the higher thermal resistance of the roof structure, causing a poorer thermal comfort for the museum staff than in the current situation.

The second measure, increasing the thermal resistance of the internal plenum structure, is an interesting option considering to improve the indoor climate (T and RH) of the exhibition rooms. The risks to objects decrease because lower T reached during the summer and a more stable indoor climate is maintained during the year. However, the thermal comfort in the plenums for the museum staff gets poorer, since the T increases in the summer and decreases in the winter. Due to the higher thermal resistance of the internal plenum structure, the indoor climate of both spaces have less impact on each other.

From the three simulated measures, the third measure, natural ventilation of the plenum with outdoor air when the T in the plenum is above 26°C, is the most interesting option considering to improve the indoor climate (T and RH) of both the exhibition rooms and the plenums. Compared to the current (reference) situation, this measure comes with energy savings and lower risks to objects in the exhibition rooms. Combining the measure with the optimum setpoint strategies, the thermal comfort will increase as well. Due to the lower T reached in the plenum during the summer, the plenum will be more comfortable to work in for the museum staff.

This additional study has focused on the potential effect of a few measures on the indoor climate (T and RH) of the monumental building part of the VAM. The measures have been implemented in a calibrated numerical model. To get more accurate predictions, validation of the reference simulation model would be needed. Besides the potential effects on the indoor climate (T and RH), other aspects should be considered as well in future research in order to let the VAM make a well-considered decision before implementing any measure. Other aspects that should be considered are for example the monumental value, the constructional implementation, investment costs, and quality of (day)light.

The results of the simulated measures have shown that plenum related measures have a significant impact on the indoor climate (T and RH) of the exhibition rooms, due to the thermal radiation effects of the internal plenum structures. To study the exact thermal radiation effects of the internal plenum structures for different possible measures, the plenums and exhibition rooms should modeled in COMSOL, since it is impossible to extract the radiation temperature of a single surface from HAMBase.