Identifying indoor local microclimates for safekeeping of cultural heritage

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Identifying indoor local microclimates for safekeeping of cultural heritage

Karin Kompatscher

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Karin Kompatscher

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Identifying indoor local microclimates for safekeeping of cultural heritage

Karin Kompatscher

November 2021

To Family

"Only those who attempt the absurd can achieve the impossible."

— *Albert Einstein*

Summary

"When we build, let us think that we build forever."
— John Ruskin

Conservation of cultural heritage often poses a complex problem. To avoid risk for biological, chemical and mechanical degradation, a stable indoor climate is required for cultural objects sensitive to temperature and moisture. Depots and archives can provide stable conditions due to lack of external disturbances such as visitors entering. Often, museums are housed in historic buildings where objects are exposed to climate variations caused by either internal or external climate influence. Internal gains such as hygrothermal loads of visitors or thermal loads induced by a heating system causes locally deviating microclimates. External climate in combination with low thermal quality of the building envelope influences the indoor climate conditions. There is a clear conflict between the museum objective of exhibiting objects and the preservation needs to ensure the future of these objects.

Maintaining stringent indoor climate specifications for temperature and relative humidity through air-conditioning results in high energy demand and therefore, high energy costs. Literature focuses mainly on sustainable climate control solutions in relation to lumped parameter evaluation for indoor climate parameters. Martens has shown that even though climate control is present and requirements are set to stringent setpoints, these requirements are not reached when monitoring ambient conditions [1]. Limited studies take the direct object environment into consideration. In order to get a grasp of local indoor microclimate conditions influencing the object environment it is important to not only evaluate the room-average conditions or object degradation principles. It is also necessary to gain more insight into spatial distributions of environmental parameters.

The main aim of this thesis is to investigate that by **operating existing HVAC systems in a more sustainable way - via temperature and humidity requirements to establish an appropriate indoor climate for preventive conservation - local microclimates improve by reducing spatial gradients and consequently benefit object preservation**. In order to structure and focus the research, multiple objectives are formulated:

- To develop an environmental scan to investigate and represent critical areas with deviating indoor climate conditions compared to ambient climate conditions in buildings with climate control systems present. This gains insight in which different

indoor climate and local microclimates (see figure 1.3) are commonly present in different heritage institutions such as museums, archives and libraries in order to better understand how they impact the object environment.

- To gain insight into climate control strategies, air distribution and the presence of (hygroscopic) collection on indoor climate parameter behavior. This to better understand temporal and spatial distributions in buildings with storage functions and therefore, large thermal and hygric buffer present.
- To investigate the influence of less stringent ambient (risk-accepting) climate control requirements on local microclimates.
- To investigate the possibility to (thermally) separate gallery indoor climate conditions and object environment. A distinction was made between exhibition purposes by means of a box-in-box museum display case design and for storage purposes the use of archival boxes.

In order to address the gaps and achieve the objectives, different case studies have been selected. Selection is based on specific site-related factors, building classification, building use, history of the building, availability of environmental data, and relation to the objectives researched in this study. Experimental studies and numerical modeling comprised the applied methodology. The experimental studies have been carried out with on-site measurements. Continuous and periodic measurements are carried out to monitor environmental conditions. Combined temperature and relative humidity sensors for indoor and outdoor longitudinal and spatial monitoring and infrared thermography for instantaneous data collection is used. The data from the measurements is used to analyze present environmental conditions and to validate the numerical models.

Chapter 2 describes the development of an indoor climate monitoring scan. The climate scan provides a quick assessment to locate critical areas based on both spatial and temporal information. These critical areas are of interest to gain insight in the building on several levels (e.g. building component, building system and object risk management/acceptance).

The second objective is researched in chapters 3 and 4, elaborating on the impact of hygroscopic collection present in library and storage rooms. The building use is different compared to museum buildings. Hygroscopic collection that is present in bulk has impact on the hygrothermal conditions near the collection and ensures equilibrium in changing conditions by adsorption and desorption processes.
Chapter 3 provides an in-depth review of a library case studies where local indoor microclimates have been identified and the impact of intermittent and dynamic setpoint control on energy consumption and object risks has been tested and modeled. Intermittent conditioning strategies and dynamic setpoint control are promising energy saving strategies that consider thermal comfort and collection preservation. Intermittent and dynamic conditioning in libraries and archives show the potential for possible energy savings with need of simple adjustments in mechanical control and minimal impact on environmental conditions when controlled precisely. This type of climate control shows significant fluctuations in poorly insulated archive buildings. The setpoints that need to be reached when the air handling unit is in operational state might determine its difficulty reaching it

(Chapter 3).

Chapter 4 elaborates on air distribution being one of the main factors (i.e. building systems) in reducing or increasing spatial gradients. In open exhibition spaces the air can be mixed due to limited obstacles. Buildings used for storage, libraries or archives, pursue a high material occupancy ratio. Archival racks filled with collection are considered bluff bodies resulting in turbulent behavior of supplied air. Insufficient mixing causes unwanted hygrothermal conditions. In combination with a poorly insulated external wall, the object environment experiences fluctuations and the collection is exposed to increased degradation risks.

Chapter 5 describes a detailed study of a novel museum display case design. In this chapter temperature is actively controlled in a box-in-box museum display case to ensure an appropriate object preservation climate for sensible objects. Separating indoor climate from the object environment creates opportunities for climate control strategies to focus on what matters. If collection is not present in a certain area, focus should be on, for instance, thermal comfort in determining the setpoint strategy. This results in less stringent indoor climate requirements and therefore less energy demand.

The presented approaches and resulting knowledge gathered in this thesis are valuable to continue research in the fields of energy conserving indoor climate strategies and preventive conservation of susceptible objects. Using climate control based on accepting descriptive requirements over stringent normative requirements will not increase spatial and temporal gradients for temperature and relative humidity. In other words, the hypothesis can be answered with yes, with the proviso that adopting a more risk-accepting approach in terms of climate control (i.e. dynamic control or intermittent conditioning) will not automatically result in the *ideal* indoor climate for conservation or storage purposes. This does however, show a preference for doing less: i.e. as little as possible heating in winter (resulting in little humidification) and as little as possible cooling in summer (resulting in little dehumidification). This would reduce thermally driven air flows resulting in deviations. Important is to adopt passive measures such as archival boxes in storage facilities, the use of museum display cases for exhibition purposes, installment of solar blinds to avoid direct solar gains, and improving building envelope thermal quality as a more invasive measure.

Nomenclature

Acronyms

AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CDF	Cumulative Distribution Function
CFD	Computational Fluid Dynamics
CV RMSE	Coefficient of Variation Root Mean Square Error
FAC	Fraction of Data
FB	Fractional Bias
FEM	Finite Element Method
HR	Humidity Ratio
HVAC	Heating, Ventilation and Airconditioning
ICMS	Indoor Climate Monitoring Scan
ICOM	International Council of Museums
IIC	International Institute for Conservation of Historic and Artistic Works
IRT	Infrared Thermography
LIC	Local Indoor Climate
LM	Lifetime Multiplier
LoC	Level of Control
MBE	Mean Bias Error
PDE	Partial Differential Equation
QoE	Quality of Envelope
RH	Relative Humidity

RMSE	Root Mean Square Error	

Greek Symbols

δ_a	Vapor permeability of stagnant air	$kg/(m \cdot s \cdot Pa)$
λ	Thermal conductivity	$W/(m \cdot K)$
μ	Diffusion resistance factor	$(-)$
ϕ	Relative humidity	$(-)$
ψ	Fraction	$(-)$
ρ	Density	kg/m^3
θ	Temperature	K
ξ	Moisture capacity	kg/m^3

Roman Symbols

c_p	Specific heat capacity	$J/(kg \cdot K)$
T	Temperature	K
w	Moisture content	kg/m^3

Subscripts

a	Air
e	Exterior
i	Interior
p	Paper
s	Surface
sat	Saturated
x	Environmental

Contents

1 | General introduction

> *"Great things are done by a series of small things brought together."*
> *— Vincent van Gogh*

This first chapter motivates the conducted research by giving background information on the topic of museum, archive and library indoor environments. Museums, archives, libraries and storage rooms house a major part of movable cultural heritage (e.g. paintings, historical and archaeological objects). Preservation of artworks and artefacts is largely influenced by the indoor environment. Inappropriate indoor temperature and relative humidity are two factors that increase the risk of object degradation. Section 1.1 provides a background on developments of museum and storage buildings and indoor climate conditioning throughout history. Section 1.2 presents the challenges that are faced in this field in modern society and section 1.3 the research objectives. The methodology is described in section 1.4 in broad lines. The last section, section 1.5, provides the outline of this thesis.

1.1 Background

Conservation of cultural heritage often poses a complex problem. Cultural institutions, e.g. museums, libraries, archives and storage depots have the objective to manage their collection by the (i) use, (ii) preservation and (iii) development of their collection for people now and in the future. The publication *Risk management for collections* provides an overview of risks causing all kinds of value loss [2]. These agents of deterioration are: physical forces, water, fire, thieves and vandals, pests and plants, radiation, contaminants and dissociation. The last two, and the ones that are investigated more in-depth in this thesis, are incorrect indoor temperature and incorrect indoor relative humidity. Cultural objects, sensitive to temperature and moisture that need to be preserved for future generations, require indoor climate conditions to minimize the risk of biological, chemical and mechanical degradation. Storage and archives can provide such stable conditions due to the lack of disturbances such as people entering. Museums, either housed in historic buildings or purpose-built buildings, have trouble maintaining extremely stable climate parameters. Objects are therefore often exposed to climate variations caused by either internal or external climate influence. Internal gains such as (day)light, solar gains, hygrothermal loads of visitors or thermal loads induced by a heating system cause locally deviating microclimates. The external climate in combination with low thermal quality of the building envelope influences the indoor climate conditions. There is a conflict between the museum objective of exhibiting objects and the preservation needs to ensure the future of these objects. Figure 1.1 shows an overview of the historic development of the museum objective, conservation objective, and building physics and systems development to achieve these objectives.

1.1.1 Historical museum buildings

Over the years, multiple individuals, institutions and associations provided literature on why to pursue an ideal indoor climate for museums, libraries and archives [3, 4, 5, 6, 7]. To understand the current positions of researchers, conservators and curators, it is important to know the history of object conservation and indoor climate control. The first section of figure 1.1 starts with the early museums (e.g. Louvre (1793), Teyler Museum (1778), Ashmolean (1683)). It is from all ages to collect and exhibit objects of great value. The indoor climates of museums and houses exhibiting these items were generally not favorable for object conservation. In the mid to late 19th century most large European museums, such as the Rijksmuseum (The Netherlands), British Museum (England), Staatsmuseum (Germany), Nationalmuseum (Sweden), were concerned about low temperatures and draught during the winter periods and warm galleries in the summer. To overcome low temperatures in winter time, hot air heating systems were developed to increase internal temperature in some museums. However, a new risk was created: fluctuating relative humidity due to temperature control. Panel paintings exhibited in the National Gallery (London) started to crack and deform. In 1874 already, Yale University installed a steam heating system to reduce the deterioration of panel paintings [8]. With this control of the indoor climate, the field of object conservation became interested in the effect of temperature and relative humidity on the degradation of cultural heritage and to what extent these parameters need to be adjusted in control systems.

The 19th century marks the introduction of several climate control innovators (e.g. central heating, piped coal gas, and air tightness of the building envelope). The last decades of the 19th century improved ventilation to remove toxic levels of soot resulted from the previous developments [9]. Thermal comfort of staff and visitors was not considered primarily the driving factor for temperature control during winter. Temperature levels were generally controlled between 13-15°C to ensure enough buoyancy to drive the ventilation system [9]. Relative air humidity levels could reach high levels in summer while in winter, the levels dropped down significantly. In the first decade of the 20th century electricity made its appearance in the form of replacing pollutant gas burners with electrical illumination [9]. Outdoor air quality (due to coal burning) lacked significantly and water spray systems were introduced to clean the outdoor air from pollutants. This humidifying system became attractive to increase relative humidity indoors. 1908 marked the year that the Boston Museum of Fine Arts installed a humidification and ventilation system where relative humidity levels were reported to be kept within the first specifications for museum mentioned: 55-60% [9, 10]. In order to be able to reach these setpoints, building systems were added (in the case of the Boston Museum of Fine Arts resulting in an installment of central humidification and air washing). These setpoints were linked to avoid risk to paintings and disregarded temperature throughout the year.

Pre World War II

In 1934, a conference was held organized by the Office International des Musées in Madrid. The contributions and proceedings of this conference are important to gain insight in

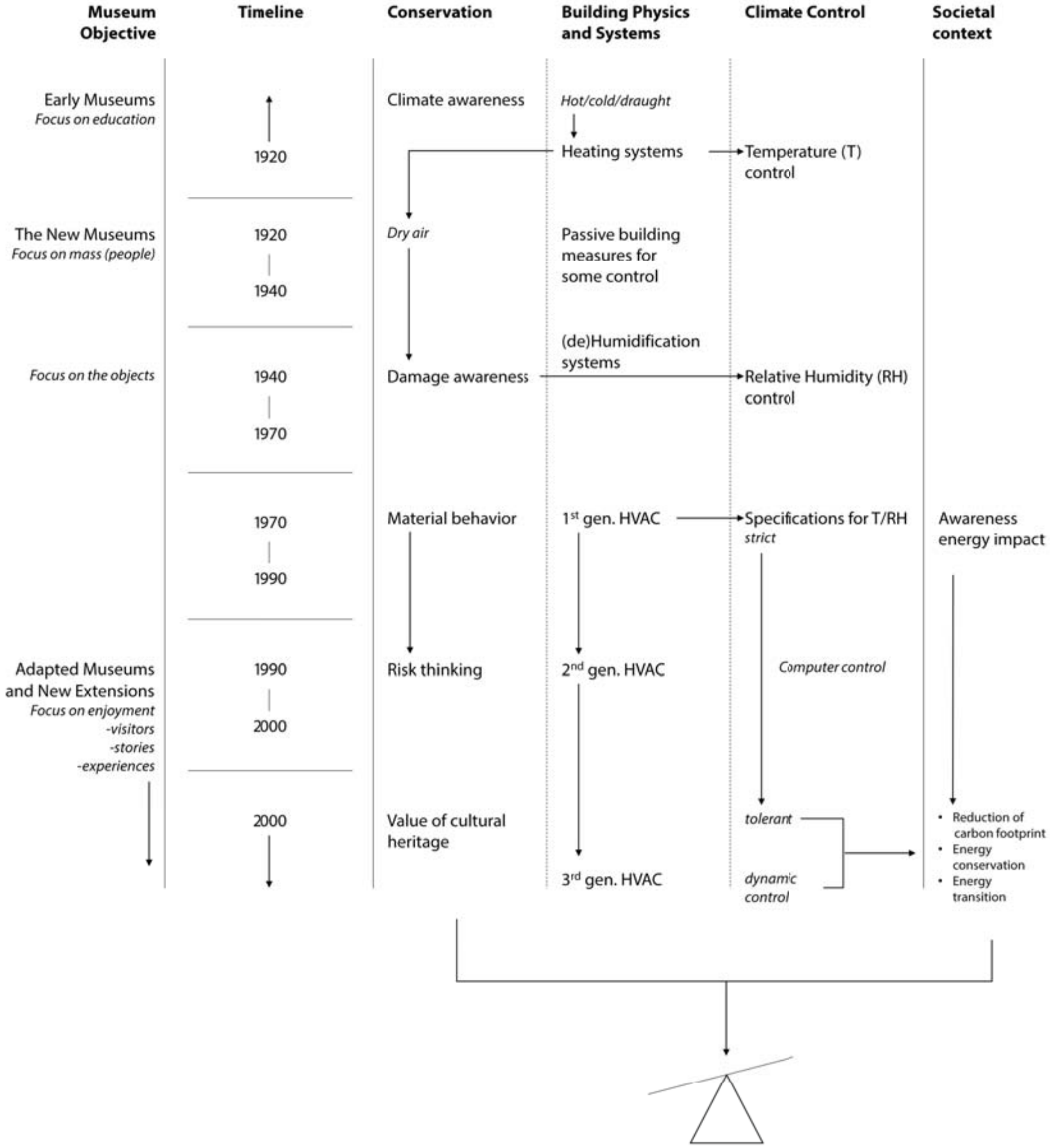


Figure 1.1: *Development of the museum environment.*

the first steps between conservation science and technological innovation in the museum environment with the notion of damage awareness to objects. A contribution of MacIntyre described the urgency for suitable collection needs if climate systems were installed in a museum [11]. The bundled proceedings provide a large piece of information on climate control and its role in the museum environment during these years and descriptions of deterioration processes of specific cultural objects under certain environmental conditions. However, no clear statements were made considering collection specifications in relation to the technological innovation of climate systems [12].

During World War II, the collection from several British museums were preventively stored in quarries. The climate in the Manod quarry, where the collection of the National Gallery was housed, resulted in maintaining a constant 58% RH and 63°F (17°C). While being stored under these conditions, the technician responsible for repairs of the paintings experienced a reduction in restoration work on the collection. As soon as the collection was returned to the uncontrolled National Gallery, the restoration work on the paintings resumed due to reoccurring deterioration [9]. Rawlins of the British Museum mentioned in his paper a first strict limit of 60°F (16°C) and 60% relative humidity ("*which incidentally, is easy to remember*"). Rawlins' observations could be expressed as a safe range by including a lower limit to avoid too large fluctuations. Rawlins however, kept using the strict numbers for T and RH as setpoint throughout the entire year [13]. In the United States, multiple museums and archives were equipped with air conditioning. Kooistra mentioned the ability of climate systems to condition the air to a 55% relative humidity in summer, and 35-45% during the other seasons [14]. This statement of Kooistra was written as an HVAC system engineer and not as a materials scientist, noting that this might not be a suitable climate for particular materials. A shift in British and U.S. standards was noted and attributed to the difference in their outdoor climate. However, lower humidities showed better permanence according to research done by the US National Bureau of Standards. Research focus shifted towards moisture response behavior of wooden panels and other hygroscopic materials. This shift in focus was negated by reports of the stable indoor climate in the quarries during WWII and its effect on the paintings when they returned to the fluctuating museum environment. The development of air conditioning systems led to the possibility to reproduce this stable climate registered in the quarries during WWII quarries in the museum environment. Purpose-built museums were equipped with passive measures, e.g. avoiding direct sunlight, to control the indoor climate. While these measures were already used in pre-WWII purpose-built museums as described in [15], the post-WWII museums used these passive measures to equal the indoor climate of the quarries to minimize damage to sensitive objects.

1.1.2 Modern museum buildings

Post World War II

After WWI the museum objective shifted from presenting objects as educational pieces towards providing exhibitions the mass could enjoy. During the 1930s the objective shifted from exhibiting objects to the mass towards the preservation of objects on display. Warping of panels in the National Gallery of London as a result of dry winters resulted in the notion that long-term relative humidity fluctuations could be harmful. Relative humidity control seemed inevitable for museums to maintain suitable preservation conditions. Collection needs were considered a valuable criterion. Human comfort levels, which resulted in the use of radiators during the 20th century, were considered appropriate for temperature control. Collection needs were based on a relative humidity of 55-60% as experienced in the Manod quarries. During the 1950s, Plenderleith published a textbook which, besides repeating the story of the Manod quarry, also mentions a lower and upper limit for relative humidity. With a lower and upper limit for relative humidity of 50% and 65% respectively, "all organic materials" should still be safe within this range [16]. The generalization of the indoor climate specifications used for panel paintings during wartime to all organic materials seems rash. In the same publication Plenderleith discusses the degradation process of parchment being exposed to reduced relative humidity levels of 40% and lower, causing irreversible loss of moisture and large stresses in the material. A European standard was set when the International Council of Museums (ICOM) dedicated an issue of Museum to the ideal climatic conditions [17]. The previous post-WWII publications where re-used and set in contrast to the pre-WWII papers (e.g. [10]).

In the United States, a slightly lower relative humidity specification was suggested to overcome the difference in external climate between Europe and Northern America. Buck suggested a range between 45 and 65%. Research was performed on a variety of hygroscopic materials, describing the damage caused by exceedance of tolerance bands [18]. The humidity range was later adjusted by Macleod to 35-55% [19]. Short-term fluctuations were not specified in both these specifications. Lafontaine filled this gap by establishing daily fluctuations for temperature (±1.5°C) and relative humidity (±2%). The relative humidity would later be adjusted to a range of ±3% since the original strict humidity levels could not be maintained in certain seasons and Canadian regions [20].

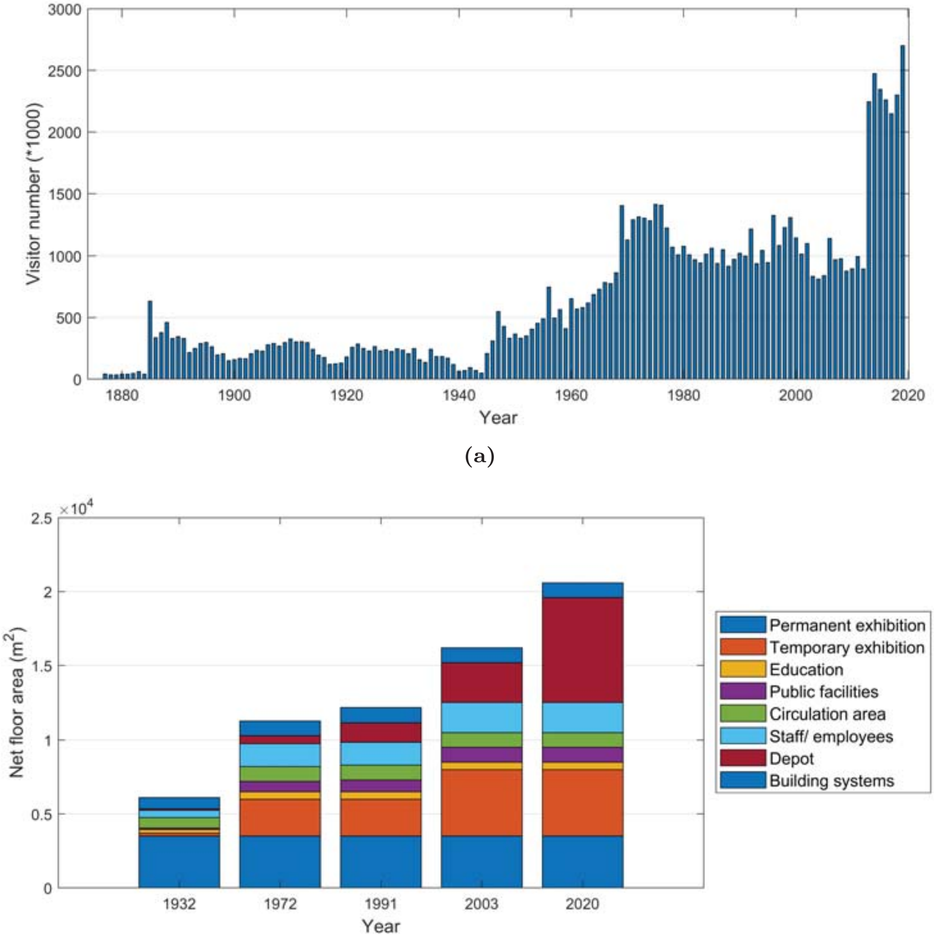
In 1978, and later updated in 1986, Thomson collected and described the many aspects of the museum environment. In the first edition, Thomson states that the choice for relative humidity should not be too far from 50% or 55% with a fluctuation of ±4-5%, which is based on the general recommendations for certain object materials. If risk for condensation is present the relative humidity should be lowered to 45-50%. The publication further discusses what little knowledge is present in terms of change in museum materials and what causes this change, compared to the extensive framework of preventive conservation that is already in place. Thomson mentions the fact that fluctuation specifications are mainly based on what equipment is able to maintain than the impact of fluctuations on museum objects. In the second edition of his book he introduced two classes. The first class recommended setpoints of 50% or 55% for relative humidity with a fluctuation of ±5%, other ranges were also possible for mixed collection as long as it would stay in the safe range of 45–65% according to Thomson. This first class could be used by the major museums (e.g. national museums). The second class recommended a range of 40-70% for relative humidity and a supporting role for temperature to stabilize the relative humidity. This class was aimed at historic buildings where the building envelope was of significant influence to the indoor climate conditions [21, 22]. Somewhere along the line, readers focused on a few numbers and 50±5% became established as the relative humidity setpoint ideal for object conservation.

1.1.3 Adapted museums and new extensions

The museum objective shifted in the past from the focus on education (1880-1920) to exhibition of all objects (1920-1990) to the focus on enjoyment (>1990). Museum collections had active expansion of their collection and required increasing storage space. Temporary exhibitions grew in size and frequency to offer visitors a new experience when they returned to the museum. International oriented blockbuster exhibitions (i.e. an exhibition focused on enjoyment that is highly popular and financially successful) increased the visitor rate resulted in high internal gains regarding heat and moisture (see figure 1.2a and 1.2b). With a limited budget, the same objective as national museums were to be reached by smaller museums and strict loan requirements due to international exposure needed to be met in terms of indoor climate. Figure 1.2b shows the increase in the past decades of temporary exhibition in the Boijmans van Beuningen Museum in the Netherlands. Another aspect shown in this figure is the increase in depot area. Not all objects are shown in the permanent exhibition and require safe storage. Research into the topic of safe storage - and storage of object in bulk - increased during the past decade and has a relation to research based on archive and library preventive conservation [23, 24, 25, 26, 27, 28].

Brown and Rose's extensive review in 1996 showed that the specifications became more stringent due to the improvement of mechanical systems [9]. This trend of strict climate specifications continued until the last decade of the 20th century. Around the same time, Michalski and Mecklenburg presented a shift in preventive conservation by suggesting a broader range of climate specifications. Michalski and others were even able to present this way of risk thinking to the engineers in the important handbook for engineers: ASHRAE HVAC Applications, with a chapter for museums, libraries and archives [30, 7, 4]. The publication clearly presented the relation between building physics - climate class and risks. Currently considered a guideline for many institutions, the publication provides several classes based on possible risk for certain objects types. Class AA is considered the most strict class. Within this class a seasonal adjustment is allowed only for temperature. Class AA does not pose a mechanical risk for most objects. Class D is considered least strict and only provides a setpoint for relative humidity to prevent mold growth. This class is considered to have an increased risk to most objects [7]. With these publications the sector was aware that climate control was able to differentiate from risk averse to risk aware to even risk accepting. The shift to adopt more risk aware and even risk accepting climate control has not been initiated.

After many years of very strict standards such as British Standard 5454:2000, the British Standard PAS 198 provides a framework for risk-based decision making which will result in suitable climate specifications instead of a recommended fit-for-all. It went from prescriptive requirements to descriptive ways to set-up the climate specifications. This standard also addresses the high amount of energy consumption caused by strict climate specifications and provides information on possible degradation risks that the updated British Standard PD 5454:2012 uses to determine new, more tolerant environmental specifications [31, 32, 33]. Another shift was made when the historic climate of objects was used to determine suitable climate specifications in the European Standard 15757 [34]. This standard is based on the assumption that not all objects are located in favorable climates but show no continuing degradation. Available data on relative humidity - preferably over the period of a year - is used to determine short-term fluctuations. If these data show short-term fluctuations larger than 10% relative humidity the values outside the 7th and 93rd percentile will be excluded and a new target range is formed. This new target range for relative humidity climate control excludes thereby 14% of the "most dangerous fluctuations" according to the standard. In other words, the considered most dangerous fluctuations should not occur



(a)

(b)

Figure 1.2: *Visitor numbers of the Rijksmuseum, Amsterdam from 1875 to 2019 (a) and division of space based on museum use of Boijmans van Beuningen, Rotterdam (b) [29].*

with the new relative humidity setpoint range which is stricter. However, a drawback of this method is repeating this exclusion of the 7th and 93rd percentile resulting in an ever narrower bandwidth with each iteration [34]. This narrow bandwidth will then result in high energy demand.

In 2014 a discussions in two international conservation councils, ICOM-CC and IIC, resulted in accepted specifications of 40-60% relative humidity and 15-25°C [35]. These specifications were guidelines established by different initiatives and resulted in multiple short-term fluctuation limits. While the Bizot Interim Guidelines for Hygroscopic Materials (mainly referring to collection mobility) state fluctuations of no more than ±10% per 24 hours are allowed, the AICCM guidelines are restricted to ±5% per 24 hours. No elaboration on these short-term fluctuations have been mentioned. The conservation councils stated that these specifications should be used for (international) loan collections. Michalski stresses that the uncertainty and difficulty of risk assessment models do not lie in the direction of material science but in estimation of the loss of value when objects are affected [4]. Therefore, Ankersmit & Stappers [36] include the valuation of heritage assets explicitly to manage indoor climate risks and focus in this latest edition on the decision making process compared to the 2009 publication of Ankersmit [37].

The many views, interests and opinions result in different interpretation and therefore limited full potential use of guidelines and standards in practice. A deep understanding of preventive conservation is needed in order to make an optimal decision so that the measures taken in terms of indoor climate control, fit the organization, the budget, the collection and its building use.

1.2 Problem statement

The previous section showed the development of climate and damage awareness resulting in understanding the effect of incorrect indoor temperature and indoor relative humidity conditions on degradation principles of objects and development of guidelines and standards. Preventive conservation evolved with guidelines and standards (as mentioned in section 1.1.3) for indoor climate conditions resulting in increased mechanical climate control presence in (historic) museum buildings.

1.2.1 Building environment

Guidelines and standards have evolved from strict to less stringent indoor climate specifications, a shift is noted from normative guidelines (zero risk tolerance) to descriptive guidelines (risk acceptance) with room for decision making. It still requires a paradigm shift in terms of acceptance in the museum environment. The shifting objective of museums towards enjoyment in the past decades, provides an impulse in visitor rates and therefore profit. Buildings undergo refurbishment to make them future-proof. Without in-house knowledge, clear guidelines and standards are needed that have room to make appropriate decisions for preventive conservation by museum organizations, this could result in implementing different requirements for different organizations. The interest of visitors in large blockbuster exhibitions creates an increase in short-term fluctuations of indoor temperature and indoor relative humidity. Short-term fluctuations are in most guidelines and standards not well described/explained and leave room for interpretation compared to (seasonal) long-term fluctuations. This creates uncertainties and strengthens the notion for strict environmental specifications throughout the year to maintain a sense of control by museum organizations even though dynamic use of the exhibition spaces is beneficial for temporal exhibitions.

In the last decade the balance between heritage value and decision making strategies for indoor environment specifications became important [38, 36]. An increased background knowledge on different topics is needed by decision makers in order to correctly implement this strategy. The ideal environment was replaced by the appropriate environment when focus on sustainability increased [39, 40]. This was underlined by the research of Martens that showed that with the implementation of strict requirements, the majority of investigated museums did not reach those indoor climate requirements [1]. Research led to insights on dynamic control strategies and intermittent conditioning strategies to reduce the energy demand needed while maintaining an appropriate preservation environment [41, 42]. Besides active control solutions (e.g. HVAC), passive control (e.g. thermal mass) was also looked into. Focus tended to be on relative humidity control and shifted to temperature control, mainly in storage buildings to reduce moisture transport. Over the past decade research into passive conditioning of purpose-built buildings housing museums [43, 44, 45], storage facilities [46, 47, 48] and on smaller scale in museum display cases [49, 50] was performed. From these studies it can be concluded that passive climate control is promising in storage spaces with sufficient air-tightness and can even lead to low-energy or off-grid buildings [51, 46, 52]. It is important to add mechanical aids to reduce moisture accumulation and avoid internal pollutants by recirculating the air through a filter [53]. Museum exhibition rooms tend to have more difficulty when it comes to passive climate control. Larger air exchanges are needed due to visitors acting as fluctuating heat and moisture source. Museum display cases provide a product solution to create an object environment optimized to the artifacts on display. Fast and large fluctuations in T and RH are muted and delayed by the display case due to it's buffer between the indoor climate and object environment. In order to regulate T and RH as stable parameters, thermal capacity and absorbent media (i.a. silica gel or phase change materials) were studied [50, 49, 54]. While display cases and their contents seemed to stabilize the object environment, some drawbacks were noted as well. Internal pollution through volatile organic compounds (VOCs) generated by the objects on display can cause fogging or risk to the objects [55, 53]. Adsorbent media is able to reduce pollutant levels, however, certain media act as emission source [56].

1.2.2 Local indoor climate

To accommodate the need for a controlled ambient indoor climate to reach an appropriate preservation climate in museum environments, historical buildings were adapted to house HVAC systems. Implementing climate systems, installing ducts and providing air inlets generally have a large impact on the (historic) building. Condensation occurred due to humidified air condensing on cold surfaces and wooden ornaments and building components suffered from rot. This resulted, in combination with an increased visitor rate, into irreversible damage to the building structures [43, 57]. When it comes to historic buildings it is often a challenge to increase thermal resistance of the building envelope when the building is part of the heritage collection. The historic building fabric has an influence on the indoor climate in terms of thermal losses, thermal bridges and air leakages [58]. The influence of the envelope would result in local microclimates near the building structure. Figure 1.3 shows the definition of different environments that can be found in a (museum) building. Besides the building envelope, internal heat and moisture sources such as visitors, light systems and climate control systems may cause local deviations from the prevailing indoor climate that can influence object preservation.

In general, case studies in the field of preventive conservation tend to monitor mainly temporal room-averaged indoor climate conditions and often exclude more in-depth research on spatial local microclimate monitoring or near-object environment monitoring. Hence, evaluation of an appropriate indoor climate for safekeeping is often based on lumped parameter evaluation with the assumption that a homogeneous indoor climate is present

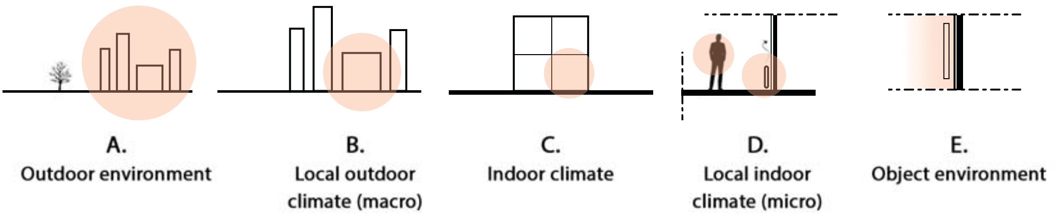


Figure 1.3: *Overview of different definitions of environment for this thesis.*

[1]. The necessity of indoor climate evaluation based on the amount of time the conditions fit within certain guidelines and standards can be questioned, however, very much used in research and in practice. In the past two decades many research has been done on environmental parameters in historic buildings of which the building use differed from religious ([59, 60, 61, 62, 63, 64, 65]), residential ([66, 67]), museum ([68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79]), archive ([51, 44, 46]), and library ([23, 24, 25, 80]). The majority of this literature used the room-average conditions of the case-study to classify the indoor climate (by an already existing or newly developed index) and therefore list it as either appropriate or inappropriate for preventive conservation of heritage objects. It provides insight in ambient conditions, however, it is dependent on the location of the sensor logging climate data, resulting in a representation of only room-averaged (ambient environment) conditions or very specific local microclimate conditions considered to be present in the entire area. Fluctuations that might have major influence on the objects deterioration principles are often not considered. Results from these evaluations might not reflect possible risks related to objects. Camuffo described in earlier research a method to measure this microclimate and visualize it by microclimate mapping [81, 82, 83]. The method uses a measurement grid on which quick response measurement equipment is moved over a certain period of time for different seasons. Contour lines are then plotted to visualize the measurement data. In these studies Camuffo et al. showed the influence of building envelope, visitors and solar gains on the indoor microclimate behavior in both temporal and spatial distribution. All buildings were in use as church, chapel or hall with limited to no influence of ventilation systems. This visualizing method has been mainly used in Italian literature [84, 85]. It is visually easy to determine local occurring deviating climates, however, the measurement setup needed to be able to make these plots is extensive and not every heritage institution has the means to spend on such an elaborate measurement.

The use of ambient environment data compared to spatial climate distribution has been discussed in [58, 86, 87]. Martens expresses concern in using risk assessment methods for evaluating object risk while data collected may not be representative for the objects location [1]. Schito et al. provide the Spatial Homogeneity Index (SHI) that evaluated the amount of time the indoor climate is within allowed spatial variations in a defined volume [86]. Though established guidelines like ASHRAE mention these allowed spatial variations [7], studies using these guidelines as evaluative method often consider only temporary short-term and long-term fluctuations [42]. Camuffo et al. developed a way to provide more insight in spatial distributions by plotting the isotherms of measured data in a floorplan calling it micromapping [88]. During this study Camuffo et al. showed the impact of mechanical aids to control the indoor climate parameters. Homogeneities occured and did not remain stationary but where locally influenced by the climate systems being switched on or off, affecting paintings in the vicinity. In order to get a grasp of local microclimate conditions it is important to not only evaluate the ambient environment or object degradation principles. It is also necessary to gain more insight into spatial distributions of environmental parameters. Deviating climate occur on different scales and are influenced by the building and the building use. Linking of different microclimate causes could benefit preventive conservation by mapping out critical areas for heritage objects both temporal and spatial. Absolute humidity might be uniform throughout an area, differences in indoor temperature result in differences in indoor relative humidity which impacts susceptible objects.

1.2.3 Current research topics

Another aspect that cannot be ignored in the 21^{st} century is the reduction of our carbon footprint by reducing energy demand and the use of fossil fuels. Governmental goals of carbon footprint reduction and budget cuts force museums to explore new possibilities of energy reduction and cost reduction. The first decades of the 21^{st} century marked increased awareness of topics such as the impact of climate change on cultural heritage. HVAC systems contribute approximately 50% to the energy consumption of a building [89]. Cultural institutions placed this into the societal context of environmental awareness for future generations. This environmental awareness resulted in the need to reduce the carbon footprint of buildings and move towards energy transition.

Extensive research in the field of museum refurbishments in historic buildings to reduce energy demand has been performed [90, 91, 92, 93]. Studies show a wide range of energy conservation methods. Loan objects often dictate the use of more stringent indoor climate specifications than can be reached in most historic buildings due to a low envelope quality [1]. Deep renovation of the building seems often the best solution to reduce energy and comply with collection needs, but comes with high costs. Focus on passive control resulted in studies on increasing thermal quality of the building envelope, buffering capacity and building performance in general [94, 44, 52]. The shift from housing permanent museum collection towards more temporal exhibitions and large blockbuster exhibitions demands more dynamic climate control in order to adjust the indoor climate to an increase in visitor rate without increasing possible risks to objects. Dynamic climate control was researched by measures on improved air-conditioning [44, 95], and optimizing HVAC control to reduce energy demand [96, 94, 42]. Dynamic climate control uses predictive control and the full bandwidth of allowed fluctuations that is described in the guidelines and standards [42]. The research into dynamic control is mostly assessed by room-averaged conditions and indices though without extensive renovation a significant reduction in energy demand could be realized. Understanding whether this type of assessment of ambient environment is suitable or deviates from near object conditions is necessary. This understanding would result in more certainty in terms of possible increased/decreased object risk. The complexity of this research field is still present today. It requires a vast amount of knowledge to reach a balance between collection needs, human needs, and buildings needs.

Concluding from the previous sections, the following research gaps have been identified and need to be addressed:

- A gap has been noted that shows limited studies of indoor climate control strategies and their impact on the near-object environment. Particularly with respect to climate control and *local* indoor microclimate conditions in various buildings with a conservation purpose (e.g. museums, archives and libraries).
- Knowledge of cause and effect of local indoor microclimate conditions to understand the impact of (in)correct T and RH near an object. For this, localization, monitoring and prevention of local indoor microclimates needs to be established.
- Currently, the majority of research in the preventive conservation field is conducted by solely monitoring or modeling temporal indoor climate conditions of (only) the ambient environment. Bridging the gap on spatial impact of indoor climate and *local* indoor climate conditions on the object environment is relevant.

1.3 Research objectives

In order to achieve the most stable indoor climate conditions, climate control strategies for temperature and relative humidity requirements are stringent. This is based on the option to choose the most stringent requirements to realize an ideal indoor climate in heritage conservation, after all: *"if close control (+2%RH) provided no benefit for the objects than wider control (±5%RH), then at least it did no harm"* [9]. The consequences of such decisions in terms of sustainable use of climate control is often not considered. Maintaining stringent indoor climate specifications for temperature and relative humidity through air-conditioning results in high energy demand and therefore high energy costs.

Research thus far focuses mainly on sustainable climate control solutions in relation to lumped parameter (e.g. room-average) evaluation for indoor climate parameters and show that indoor climate requirements are frequently not met. However, no increased risk for object preservation based on this lumped parameter approach is noted, resulting in the notion that less stringent conditions could be applied and energy consumption could be reduced significantly [1, 97]. In order to account for the influence of less stringent temperature and humidity requirements in preservation environments, research by a distributed parameter approach (temporal and spatial distribution of indoor climate conditions) to assess homogeneous indoor climate conditions is beneficial. Limited studies take the (direct) near-object environment into consideration which could result in local indoor microclimate conditions inappropriate for object preservation. **This study hypothesizes that operating existing HVAC systems in a more sustainable way - via temperature and humidity requirements to establish an appropriate indoor climate for preventive conservation - improves local microclimates by reducing spatial gradients and consequently benefits object preservation**. In order to structure and focus the research, multiple research objectives are formulated:

- To develop an environmental scan to investigate and represent critical areas with deviating indoor climate conditions compared to ambient climate conditions in buildings with climate control systems present. This gains insight in which different indoor climate and local microclimates (see figure 1.3) are commonly present in different heritage institutions such as museums, archives and libraries in order to better understand how they impact the object environment.

- To gain insight into climate control strategies, air distribution and the presence of (hygroscopic) collection on indoor climate parameter behavior. This to better understand temporal and spatial distributions in buildings with storage functions and therefore, large thermal and hygric buffer present.
- To investigate the influence of less stringent ambient (risk-accepting) climate control requirements on local microclimates.
- To investigate the possibility to (thermally) separate gallery indoor climate conditions and object environment. A distinction was made between exhibition purposes by means of a box-in-box museum display case design and for storage purposes the use of archival boxes.

1.4 Approach

In order to address the gaps and achieve the objectives, different case studies have been selected. Selection was done based on specific site-related factors, building classification, building use, history of the building, availability of environmental data, and relation to the objectives researched in this study.

The applied methodology consists of experimental studies and numerical modeling. The experimental studies have been carried out with on-site measurements. Continuous and periodic measurements were carried out to monitor environmental conditions of the different case studies. Combined temperature and relative humidity sensors for indoor and outdoor longitudinal monitoring and infrared thermography for instantaneous data collection were used. The data from the measurements were used to analyze present environmental conditions and to validate the numerical models.

Insight in the impact of climate control strategies on local climate conditions and object environment can be gained through coupled heat, air and moisture numerical modeling. The numerical modeling was performed with the multi-zone hygrothermal building simulation tool HAMBase ([98]) and finite element method COMSOL Multiphysics ([99]). The COMSOL models were set-up with the heat transfer module coupled with the computational fluid dynamics module to study (forced) air flow distribution as was recommended by Huijbregts [100]. Per chapter the considered decisions for the used methodology will be explained in more detail.

1.5 Thesis outline

This dissertation is composed of a general introduction, four chapters (chapter 2-5) and the general conclusions. Chapter 2 elaborates on the impact of climate control on the indoor environment in buildings housing heritage collection. Chapter 2 shows differences between temporal and spatial distribution of local indoor climate data taken in the museum environment and how this relates to the object environment. Chapter 3 provides results on temporal and spatial distribution in an archive environment and how the presence of hygrothermal collection influences the local climate conditions. The next chapter zooms in on the different local microclimates and object environment in a repository (chapter 4).

The fifth chapter provides results of a practical application of a state-of-the-art museum display case in which object environment and indoor environment are actively separated and the gallery indoor climate conditions are less dependent on object preservation. The objectives are covered within the four chapters (see table 1.1). This thesis is wrapped up in the last chapter by expressing the discussion and limitations that occurred during this research, stating the conclusions drawn from this thesis, and recommendations for further research.

Table 1.1: Objectives related to the chapters in this thesis.

Objective	**Chapter 2**	**Chapter 3**	**Chapter 4**	**Chapter 5**
Development of environmental scan	○			
Gain insight into temporal and spatial distributions		○	○	
Investigate influence of climate control on microclimates		○	○	○
Investigate separation of gallery and object environment				○

2 Development of an indoor climate monitoring scan

Abstract

This chapter aims to describe the development of an indoor climate monitoring scan. The climate scan can make a quick assessment to investigate if possible spatial and temporal deviations are present in buildings housing cultural heritage. These critical areas are of interest to gain insight in the building on several levels (e.g. building component, building system and object risk management). Temporal room-averaged measurements are currently used to evaluate appropriate indoor climate for preservation conditions, however, spatial distributions of environmental parameters need to be considered in this assessment as well. The climate scan maps out already present information sources. The climate scan begins with general insight of the building and its use by means of an inventory and visit through the building guided by experts (e.g. the facility manager or conservator). This information is narrowed down to more detailed quick scan spatial measurements by means of infrared imaging and short-term hygrothermal measurements to locate deviating local indoor climates. These critical areas can then be used to perform long-term measurements to research the temporal influences such as (in)appropriate fluctuations.

Combining temporal and spatial information on the indoor climate occurring in a museum, archive or library provides valuable information on critical areas and how they impact the object environment. Impact on the object environment can occur through the building envelope (e.g. thermal bridging), building system (e.g. malfunction or dynamic control) or building use (e.g. exhibition or storage).

2.1 Introduction

According to UNESCO, cultural heritage can be defined as “the legacy of physical artifacts and intangible attributes of a group or society that are inherited from past generations, maintained in the present and bestowed for the benefit of future generations”. As a society, there is a need for preservation in the present to strive for the best quality of cultural heritage for the future [101]. Oxford Dictionary describes preservation as the action to maintain something in its original or existing state. Preventive conservation are the actions one takes to limit damage by changing the surroundings of the objects. Knowledge is needed to gain insight in the causes for object degradation and preventive conservation, over the past decades, a plethora of research has been performed on multiple topics revolving around preventive conservation.

2.1.1 Importance of indoor climate in preventive conservation

Conservation requirements

Specific risks are caused by (originally) nine agents of deterioration as described in [102]. These agents - physical forces, fire, water, criminals, pests, contaminants, light and UV radiation, incorrect indoor temperature (T), incorrect indoor relative humidity (RH), and (the tenth agent) dissociation - can be categorized in three risk types: rare and catastrophic; sporadic and severe; continual and mild/gradual [103]. Three degradation principles with impact on buildings and objects related to the indoor climate can be differentiated. Biological, chemical and mechanical degradation can be initiated or accelerated by an unfavorable climate [21].

Indoor climate definitions

Environmental parameters that are considered of importance for preventive conservation are temperature, humidity, illumination, noise and vibration, and atmospheric pollution. For buildings housing heritage objects this was underlined by the publication of Pavlogeorgatos [104]. The indoor climate parameters are determined firstly by the outdoor climate in which a building is located. A regional outdoor climate can be distinguished based by the Köppen climate classification system [105], a local (outdoor) climate refers to a specific geographic area (e.g. rural, urban) and microclimate refers to a specific part of this area (e.g. street). Definitions of indoor (micro)climate depend on the field of research they are used in [58]. Camuffo describes the microclimate as “the whole ambience which is necessary to study in order to know the factors which have a direct influence on the physical state of the monument and the interactions with the air and surrounding objects”. Camuffo proposes to use regional climate for the main characteristics of the location of a specific monument and microclimate for a small location [58]. To make sure that the terminology and definitions in this research are clear for the reader, a nuance in the term microclimate is necessary (see also figure 1.3):

- Indoor climate refers to the indoor climate of a zone. A zone is seperated in terms of climate from different zones in a building. An example is the difference in indoor climate between an entrance hall with frequently opened doors and a closed gallery where sensitive objects are exhibited. More fluctuations in terms of T and RH caused by influence from the external climate can be expected in the first.

- Local indoor micro-climate (LIC) indicates the indoor climate surrounding an area of interest (e.g. wall surface, radiator, part of building component). The dimensions influenced by the LIC is several m^2s.

- The object environment surrounds, as the term suggest, the heritage object (e.g. microclimate frame, museum display case or archival box). A local indoor climate can influence the object environment.

Now that the terminology is defined, we return to the risks involved in conservation. A suitable conservation environment is one of the goals for cultural institutions to strive for [36].

In order to reach this conservation environment, control of the indoor climate parameters is needed.

Systems requirements

To accommodate the need for a controlled indoor climate and to focus on collection comfort requirements and thermal comfort requirements, historical buildings with conservation purposes were adapted to house heating, ventilation and air conditioning (HVAC) systems. Implementing climate systems, installing ducts and providing air inlets generally has a large impact on the (historic) building [106]. Therefore, decisions made for indoor climate control are important. In the past century, climate control made a big development in terms of presence in the building. With the technical development the indoor climate could be controlled more accurately and institutions implemented the climate systems [9].

2.1.2 Current trends in indoor climate specifications and requirements

The need for climate control and resulting renovations to add HVAC systems resulted in a need for specifications for temperature and relative humidity which where chronicled in the work of Thomson [21] and later updated with an appendix summarizing the necessary climate specifications for T and RH [22]. The appendix made it possible to get the information needed on climate control without the underlying knowledge, becoming fit-for-all specifications. In the 1990s, risk assessment and risk management were further developed and resulted in more case-specific requirements [107, 108]. The combination of strict control of indoor environmental conditions for collection and building safeguarding by climate systems resulted in excessive energy consumption [109, 110, 111].

Energy conservation

Recent awareness of topics such as the impact of climate change resulted in the need to reduce the carbon footprint of buildings. This development resulted in extensive research in the field of energy efficiency in museum buildings [91, 92, 112, 42]. An important result was the notion that with a reduced level of control, the energy consumption drops exponentially [113]. However, the effect this has on spatial indoor climate parameters and resulting in possible critical areas surrounding objects was not investigated as of yet.

Risk management

The discussion on suitable indoor climate for preservation objectives resulted in several international standards and guidelines [7, 114, 33]. Michalski [115] provides an extensive overview of the current available climate guidelines. More recent guidelines and standards provide tools suitable for decision making [33, 36]. This has an advantage that museum management and decision makers are not required to have an extensive background knowledge on every aspect of preventive conservation. The science-practice gap between knowledge present and knowledge needed for museum management is noted. In-house knowledge is needed to implement guidelines and standards to their full potential and to be able to assess risks and other effects induced by possible measures.

However, decision makers often grasp back to static indoor climate setpoints with low tolerance for (proofed) fluctuations [4]. This links to the practical knowledge gap on the present indoor environment and evaluation of implemented guidelines. It is often not possible to set up a measurement campaign in compliance to proposed measurement guidelines such as [116]. Room averages or bulk environments are measured in locations where visitors are not able to influence the measurements. The equipment is often placed where it is not obstructing the view of visitors while enjoying the objects on display. Measurement equipment is often placed in close vicinity of a wall and at a distance from the collection. The collected measurement data represent a local indoor microclimate and often has a large impact on the decision making for further indoor climate control decisions. It is therefore important to have appropriate background knowledge on monitoring, collecting, and evaluating building, indoor or local microclimate data.

Figure 2.1 summarizes the previous paragraphs in a schematic overview showing how hygrothermal parameters are affected by the building envelope, impact of thermal and moisture sinks/sources, and museum use (e.g. museum display cases or microclimate frames). The blue, orange and purple hatched areas indicate possible indoor, local and microclimates respectively. The different colored arrows show different heat (red) and vapor (blue/ green) flows influenced by variables such as the building envelope, building systems and building use. The figure shows that though every building housing heritage objects have a similar objective, due to differences in one of these variables the local indoor microclimates might vary and critical areas may occur. The building envelope serves as a buffer for heat and vapor flows. Solar gains (orange) enter the building envelope and influences the indoor climate. Building systems related both local (radiator, local (de-)humidifier) and central (HVAC) systems influence local climates. A radiator locally radiates heat which creates a critical area if a susceptible object is placed near it. An HVAC system supplies conditioned air which is distributed and mixed in the gallery. A visitor entering the gallery serves as a local heat or vapor source, in large quantities this could influence the local climates.

2.1.3 Spatial and temporal information through existing (climate) scans

In order to achieve the objective of this study, important existing (climate) scans including spatial distribution will be described in this section. The use of room averaged measurements compared to spatial indoor climate distribution has been lightly discussed in [58, 1, 117]. Though design guidelines like ASHRAE mention these allowed spatial variations [7], studies using these guidelines as evaluative method often consider only temporal short-term and long-term fluctuations [42]. The application of ASHRAEs climate classes as optimal indoor climate specifications needs to be re-evaluated according to [118]. Picking out a climate class seems easy, however, the consequences of this choice are not described in the guideline and are hard to understand.

Micromapping for spatial distribution

Camuffo uses the term *micromapping* to visually present a microclimate [58]. For instance, figure 2.2 shows the temperature isolines from the Correr Museum on a specific date and time. Micromapping was based on a number of observations taken at different predetermined gridpoints. The observations were taken with the same measurement instrument to avoid

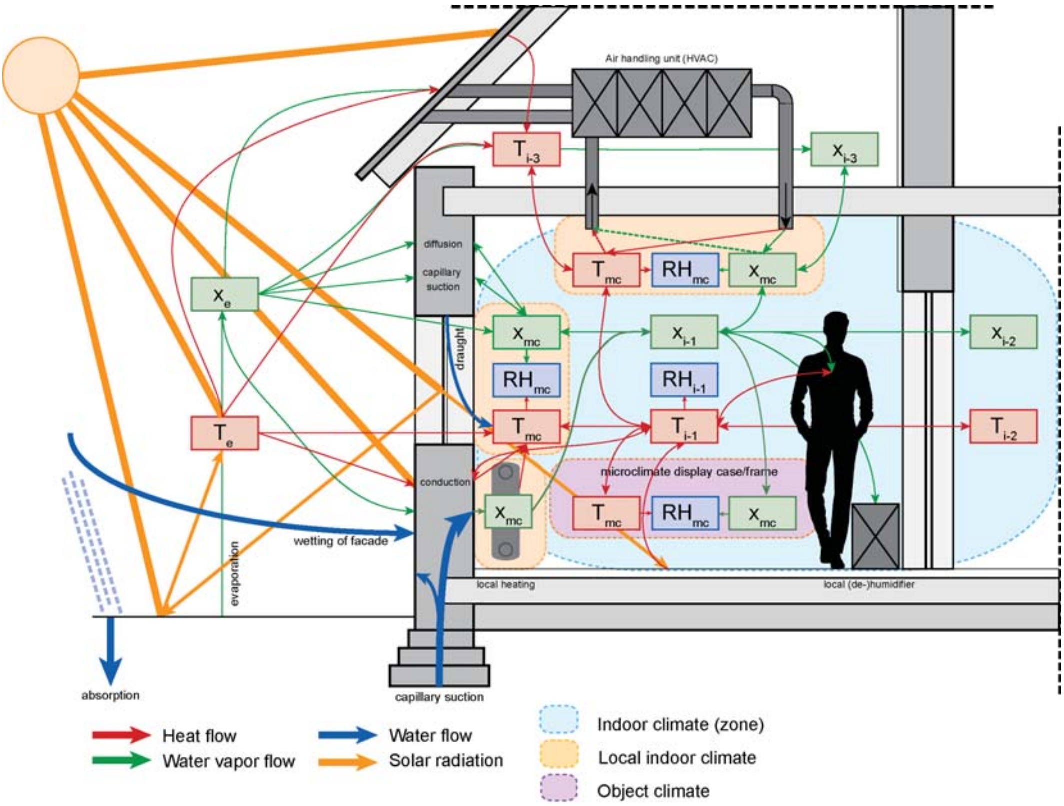


Figure 2.1: *Schematic overview of different influencing (boundary) conditions on the indoor climate, the local indoor climate, and the object environment (adapted from [36]). Temperature (T), relative humidity (RH), and absolute humidity (x) are shown. e stands for external, i for internal, mc for microclimate. The number represents the zone.*

inter-comparison of sensors having different response times. In doing so, the measurement equipment needed to be moved to the next measurement location. Critical area or risk zones were determined by this method. However, a remark must be made that the micromaps are presented as snapshots on a specific time. With the moving of equipment and response time of instruments into account using a time-average would be more accurate to present indoor climate.

Evaluation indices

Several evaluation indices are briefly introduced in this section. The time-weighted preservation index (TWPI) was introduced by the Image Permanence Institute in 1995 [119]. The calculation is performed with the Permanence Index that links temperature and relative humidity to the chemical degradation rate of materials. The TWPI takes into account the time effect of variable ambient conditions as well. A drawback of this index is the use for only organic materials.

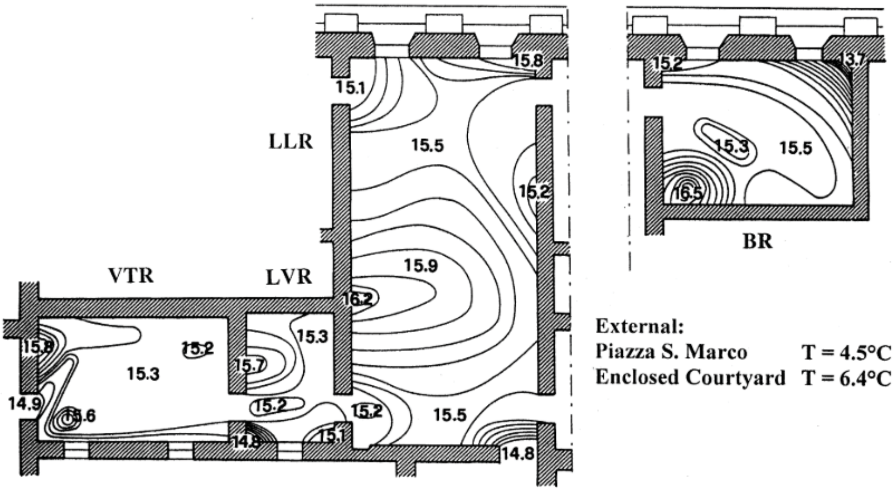


Figure 2.2: *Horizontal cross-section of the temperature distributions in the Correr Museum, 13 February 1996 at 09.00 h (exerpt from Camuffo et al. [88]).*

Corgnati et al. introduced the Preservation Index (PI) which can be defined as *'the percentage of time in which the measured parameter lies within the required (tolerance) range'* [120]. This index is dependent on the requirements determined by either standards and guidelines or experience of museum staff which requires interpretation of the standards and guidelines.

Schito et al. provide the Spatial Homogeneity Index (SHI) that evaluated the amount of time the indoor climate is within allowed spatial variations in a defined volume. The evaluation of the SHI was based on measurements around the perimeter (at h=1.5m) of a gallery and the corresponding maximum span of temperature and relative humidity. Using measurements near the walls of the gallery could miss out deviating climates in the center of the room or near objects [86].

A recent published study introduces an index that supports curators to properly evaluate planned interruptions for maintenance operations of HVAC systems and to establish the maximum time of acceptable discontinuity in service [121]. This index uses the integral of monitoring data of being over or under the T/RH requirements of a gallery. Based on this, the index tries to link system failure periods to possible damage occuring by incorrect indoor T and RH.

Evaluation scans

Martens used a quick scan to determine critical areas to include in an indoor climate monitoring campaign. This was based on the experience of a member of staff and infrared thermography (IRT). An inventory was set up to gather necessary information. Measurements were used to monitor the indoor climate, measurement locations were mainly out of reach for visitors [1]. Evaluation of the data was done with a climate evaluation chart in which for temperature and relative humidity the amount of time within specified boundaries was illustrated for a yearly period. Seasonal proofed short-term fluctuations were visually plotted in histograms for more insight. Martens also expressed concern in using risk assessment methods for evaluating object risk while data collected may not be representative for the objects location.

Lucchi used a simplified evaluation method for assessing and comparing the environmental and energy quality of a museum building [109]. This goes with the trend of providing guidance in case the owner of a historic building wants to pursue sustainability measures. With this evaluation method possible risk areas can be determined. An elaborate overview of the assessment procedure was made in the study (see figure 2.3). Three parts were evaluated; environmental, energy and policy. During the environmental assessment both conservation as comfort are included as criteria. The energy assessment is performed through an energy audit that includes energy consumption and losses and energy modeling. From these assessments, a total score is derived to show the buildings performance. Areas scoring low can analyzed in-depth. This evaluation overview is elaborate and holistic, however, it requires in-dept knowledge to execute this assessment.

Webb [122] created an overview of criteria used to assess energy measurement on historic

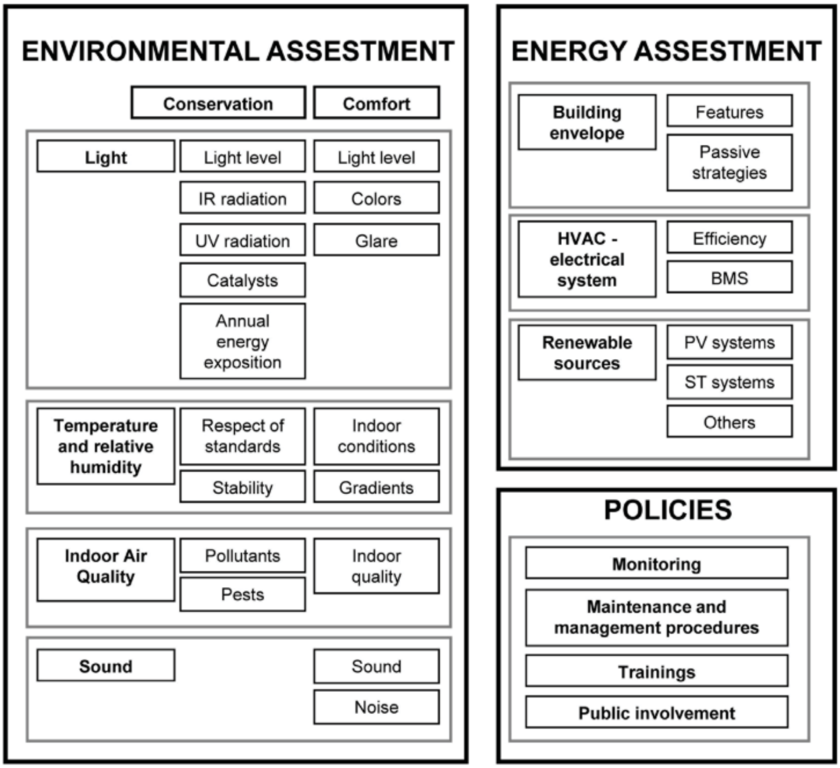


Figure 2.3: *Environmental assessment procedure (exerpt from Lucchi [109]).*

retrofits. Four categories were used, (i) global environment, (ii) building fabric, (iii) indoor environment and (iv) economics. The first is used to assess energy consumption through production and supply and climate resilience. The second category describes criteria for conservation (i.a. compatibility, reversibility and impact on heritage value) and hygrothermal behavior in terms of performance and durability. The indoor environment is assessed through occupants and collection criteria (e.g. comfort, pollutants and incorrect T/RH). The latter category describes necessary costs involved in retrofit. This criteria overview is mainly brought together for historic buildings in general and not necessarily used for museum buildings, or archives and libraries for that matter.

2.1.4 Problem statement and objective

The mentioned methods for the assessment of the indoor climate in a (museum) building are distinctive in terms of target auditor. For instance, micromapping requires an understanding of measurement instruments, the evaluation assessments require in-depth knowledge to acquire information or interpretation of the assessment results (in case of the climate evaluation chart [1]). For micromapping, monitoring data needs to be on a spatial level, the other methods are used with temporal data (time series).

It is however, important to not only evaluate the room-averaged environment (*bulk environment*; where the indoor climate is averaged) or investigate degradation risks to objects in laboratory studies. It is important to gain more insight into spatial distributions of environmental parameters and their effect on heritage objects or building components. Several studies mention the drawbacks in only using room-averaged climate conditions [1, 86]. Many climate scans focus on the effect of retrofit measures on historic buildings [109, 122]. The link between energy measures or retrofit measures and their effect on possible critical areas and the object environment is often not considered during the existing evaluations.

Based on research as performed by Martens ([1]), museums with imposed (stringent) climate control specifications do not meet the requirements when assessing indoor climate parameters within the galleries and especially near objects. In order to gain better insight into the cause and effect of these deviating indoor climates the objective of this study is to develop a climate scan which includes both spatial and temporal distribution for T and RH climate conditions. This scan is able to localize critical areas within a museum, archive or library.

2.2 Development of an indoor climate scan

The climate scan developed in this study targets (academic) researchers, facility managers, and conservation staff. Collaboration between these parties is a must in order to gain insight in the building, indoor climate and heritage objects on display. The main goal of the climate scan is to make use of spatial and temporal T/RH information to detect deviating local indoor climates. By identifying these critical areas, long-term measurements can be installed to monitor fluctuations to evaluate possible risks to objects.

Figure 2.4 provides the flow chart of the key elements involved for the climate scan to be performed. In the upcoming paragraphs these steps are described in more detail and where the origin of certain sub-processes lie. The appendix of this chapter provides several case studies in which this climate scan is used to promote sustainable use of the buildings based on different specific objectives per case study.

2.2.1 Step 1. Inventory

In order to assess a building on a general scale, it is necessary to collect information related to the building structure, systems and use. An inventory is a method to quickly gather information and provides a good first step in understanding the building and organization it houses. Appendix A provides a checklist that can be used during the inventory visit and information gathering. This step is largely based on both Martens and Lucchi [1, 109]. Martens introduced an inventory which was more oriented towards the monitoring period (e.g. visitor amounts and exhibition type during a monitoring campaign). Lucchi introduced parameters to be assessed such as maintenance procedures for building systems and exhibitions and energy management, in which energy consumption can be linked to certain events or building use in general.
Four categories have been defined in the check list to complete the inventory (see appendix, table A.1).

- The *Building* category defines the building fabric and spatial set-up of the building. Floor plans and sections are used to get an overview of different zones in the building and technical plans are used to gain insight in the building structure and to perform a preliminary assessment of the building envelope.
- *Building systems* are addressed in a separate category. The climate control system lay-out is used to gain insight in possible climate zoning and important information on the building management system is used to see how the system reaches its requirements such as hygrothermal setpoints.
- The category *Building use* is important to understand how the museum is used by the exhibitions, occupants and visitors. Locations of valuable (climate susceptible) heritage, special events, visitor presence or activities such as malfunctioning of systems should be documented and used in an assessment. This information can explain deviating outliers found in the building management system or during the measurement done in this scan.
- Last but not least, *energy management* is often documented by means of electric and gas bills. If possible, annual energy generation and consumption divided per system provide information on the energy efficiency of the different systems or creates input for energy related measures for sustainable use of the building.

The information gathered from the inventory is used to categorize areas of interest. Visiting the site provides additional information that might not be documented but provides valuable information. A walk-through with building users provides further insight in the use of the buildings and what is considered important from their perspective. Certain elements are temporary and might not be documented in the information gathered.

With this information a first categorization can be made based on Quality of Envelope (QoE) and Level of Control (LoC) for building systems typology. The description for the different categories of QoE is as follows (taken from [1]):

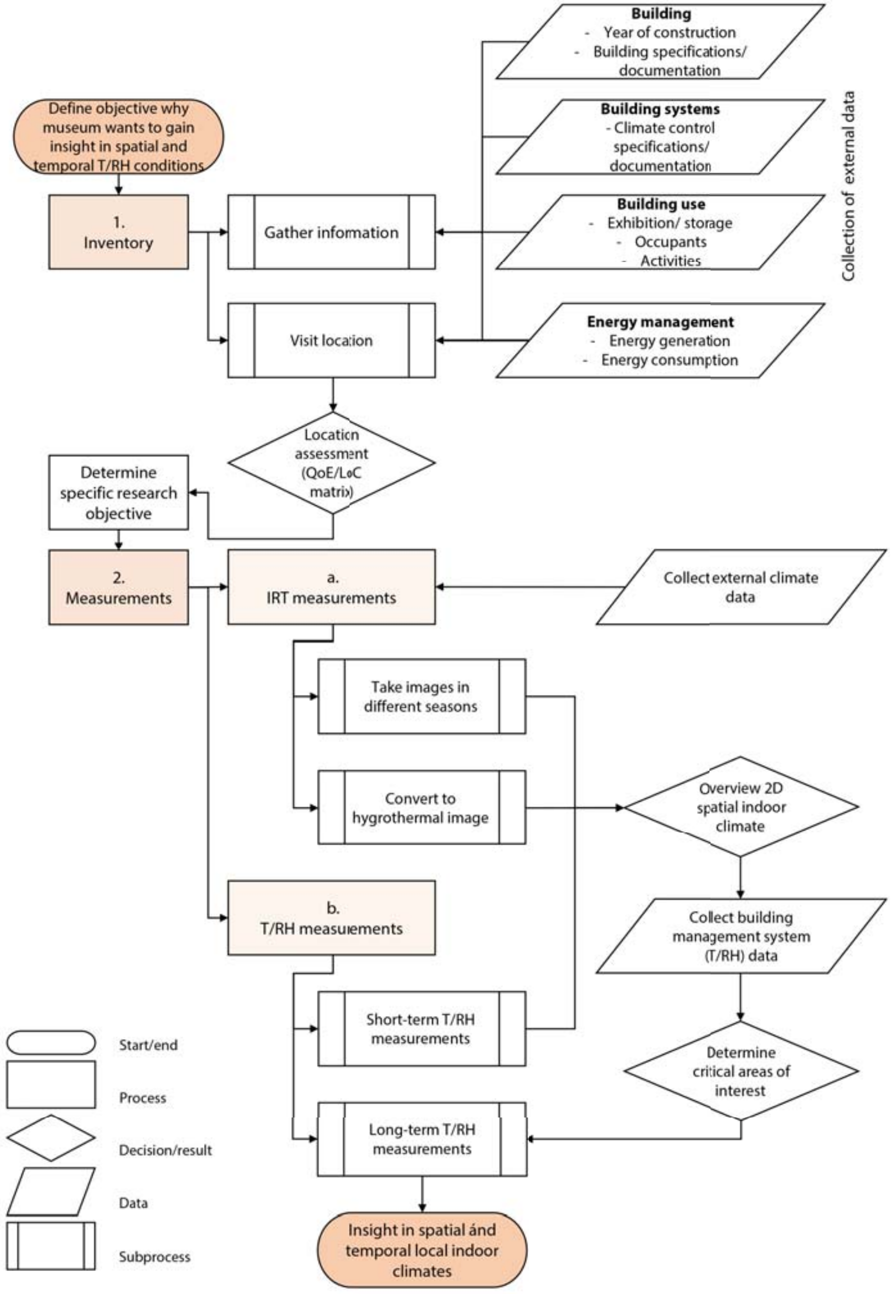


Figure 2.4: *Flow chart of key elements of the Indoor Climate Monitoring Scan. Collection of external data complemented by [122, 109], criteria used to assess retrofits in historic buildings. QoE stands for Quality of Envelope and LoC stands for Level of Control, both terms are used to classify (museum) buildings based on basic information [1]. Infrared thermography is used to enhance insight in the building envelope [123, 87] and spatial distributions T and RH are largely based on the method of Camuffo [58]*

- QoE 1: Old monumental building envelope: The envelope consists of an original construction made of stone or brick. The thickness is in most cases 300 mm or more, sometimes with a cavity. No insulation is applied and window frames are simple, in most cases wooden frames. Glazing is single sheet glazing.

- QoE 2: Slightly modified monumental building envelope: This envelope is based on QoE 1. The window frames are modified or replaced to contain double glazing or an extra sheet of glazing is added either on the inside or the outside of the original window frame. The amount of air leaks in the envelope is reduced, especially around window frames.

- QoE 3: Completely modified building envelope: This envelope is based on QoE 1. Changes are not limited to windows only, but the entire wall is modified. Insulation is added on the outside or on the inside, or an extra wall is placed next to the original wall. The air tightness increased, also the thermal resistance increased. Window frames are modified and glazing is replaced by modern low-e glazing or triple glazing. Still this façade is not as good as a newly built façade; problems might be caused by wooden beam ends in the outer part of the wall and thermal bridges in corners and due to joist anchors or window sills.

- QoE 4: Purpose built modern museum or storage building envelope: This type of façade was built after 1970 and matches or outperforms the building code at the time it was constructed. Insulation is applied and also air tightness is improved by using foils. Window frames are also airtight.

For Level of Control the following categorization is determined [1]:

- LoC 1: No control: Rooms with LoC 1 generally do not have any heating systems. An old fire place sometimes is present, but it is not used frequently.

- LoC 2: Temperature control: This type of control consists of temperature control only. This can be a simple heating system that uses radiators or convective heaters, but also air handling systems without (de)humidification are encountered in this type.

- LoC 3: Temperature and simple RH control: In LoC 3 temperature control is as described in LoC 2, but also some form of humidification and/or dehumidification is present. Usually these systems consist of simple, portable equipment that needs a lot of maintenance by the museum staff (filling or emptying reservoirs).

- LoC 4: Advanced temperature and RH control: LoC 4 stands for advanced control on temperature and humidity. Heating, cooling, humidification and dehumidification are present, usually combined in an all-air system.

A matrix with QoE and LoC on both axes gives a quick categorization of heritage buildings. Furthermore, a first distinction in important areas can be made based on a research objective. For instance, if valuable susceptible objects are located in critical galleries or galleries with no climate control, or whether the building is part of the heritage collection (e.g. non-movable collection).

2.2.2 Step 2. Measurements

In a short amount of time information on the hygrothermal state of a building indoor environment can be gained. Ideally, these measurements are done during the extremer seasons (i.e. winter and summer) to locate deviating local indoor microclimates during more severe circumstances. These short-term measurements locate critical areas to monitor for a longer period of time. Both infrared thermography (IRT) as well as hygrothermal (RH/T) measurements can help clarify indoor climate behavior on a more detailed scale with help of assessing performance metrics such as thermal transmittance, thermal bridges and moisture buffering (see figure 2.1).

Step 2a. Infrared thermography

IRT is used to gain insight in the hygrothermal performance of the building fabric and with a specific focus for spatial representation. IRT can be useful for building audits in terms of thermal characterization of walls, thermal bridges, thermal insulation examination, thermal characterization of glazing and windows, thermal transmittance measurements, air leakage inspection, and moisture detection [93, 87]. IRT images were taken by use of a thermal camera. This thermal camera records the intensity of infrared radiation (radiant exitance) and creates a digital full color image displaying different temperatures in a range of colors. Via an electronic signal, each pixel is converted into a surface temperature according to equation 2.1. Because each surface temperature pixel has its own color, warm and cool areas can be traced easily.

$$M = \epsilon \cdot \sigma \cdot T_s^4 \tag{2.1}$$

where M is the radiant exitance [W/m^2], ϵ is the emissivity [-], σ is the Stefan-Boltzmann constant [5.67·10^{-8} W/m^{2}K^4] and T$_s$ is the surface temperature [K]. The emissivity for most non-metal building materials is about 0.9. The radiant exitance is the sum of the emitted and reflected radiation. Therefore, highly reflective surfaces and differences in emissivity will influence the results. Reflecting surfaces show lower or higher temperatures depending on temperatures of the reflecting element. Equation 2.1 shows that a lower set emissivity results in higher calculated surface temperatures and vice versa. Emissivity is a material-dependent surface property, which defines the material's capacity to emit energy ranging from an ideal reflector (0) and a black body (1). Common building materials (excluding metals) have an emissivity value of 0.8 or higher.

Hygric imaging
The thermographic camera only measures surface temperatures, while the relative humidity is of great importance for the preservation of objects and building envelope. Therefore, Schellen [124] developed a tool in which measured surface temperatures are converted to near surface RH levels. To apply this tool, the indoor air temperature and relative humidity have to be measured near the investigated area. By using these measured indoor conditions, the surface temperature of each pixel of the thermal image is converted into a relative humidity as can be seen in figure 2.5.

At first, the vapour saturation pressure of the measured indoor temperature p$_{sat}(\theta)$ [Pa] is calculated. Thereafter, the vapour pressure of the indoor air is calculated from the measured indoor relative humidity ϕ_i [-] and the vapour saturation pressure of the indoor temperature according to:

$$\phi_i = \frac{p_\nu}{p_{sat}(\theta_i)} \tag{2.2}$$

$$\phi_s = \frac{p_\nu}{p_{sat}(\theta_s)} \tag{2.3}$$

$$p_{sat}(\theta) = \begin{cases} 611e^{\frac{17.08\theta}{234.18+\theta}}, & if \theta \geq 0°C \\ 611e^{\frac{22.44\theta}{272.44+\theta}}, & if \theta < 0°C \end{cases} \tag{2.4}$$

Merging the converted RH levels for all pixels results in a hygric image with near wall RH levels. Note that the hygric image is a result for assuming a well-mixed and homogeneous indoor climate. The conversion through calculation of the equation can be done by common data-analysis tools (i.a. MS Excel or Matlab). IRT should be used in multiple seasons to account for seasonal influences. Where to take thermal images can be derived from Martens who has categorized them into three divisions (i) building envelope (thermal bridging), (ii) building systems (temperature distribution), and (iii) object environment [1].

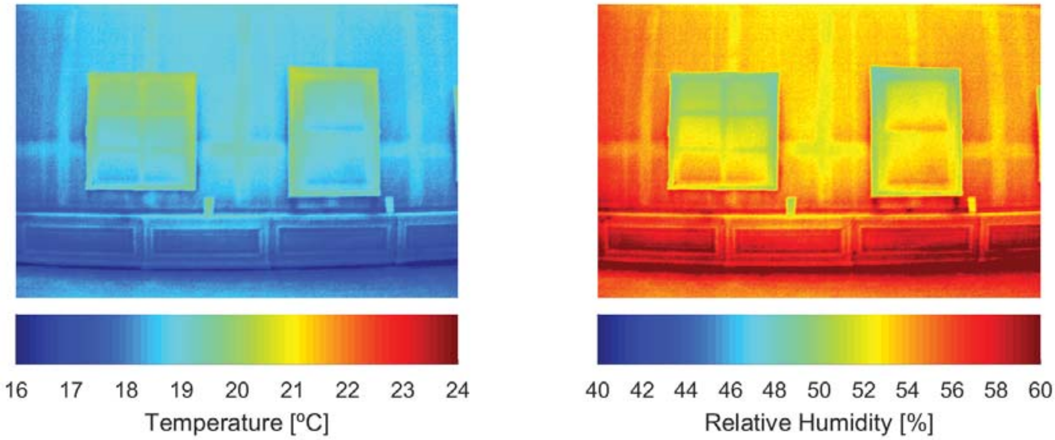


Figure 2.5: *Thermal image from FLIR camera system with calculated hygrograph of near surface RH.*

The output from the inventory and IRT imaging of the climate scan is used to determine a first long-list of critical areas. These areas can help define important locations for time-dependent measurements. The approach depends on the rationale of what to investigate. For instance, if conservation is leading, critical areas near objects need perhaps deeper investigation.

Step 2b. Hygrothermal measurements

Short-term hygrothermal measurements
By means of air temperature and relative humidity short-term measurements the

hygrothermal indoor climate behavior can be investigated. Based on the inventory and building visit, ambient and deviating locations can be identified. Two-dimensional, horizontal or vertical temperature and relative humidity distributions provide insight in the distribution of the air inside a room [58].

Micromapping was used to determine spatial differences within an area [58]. Air temperature and relative humidity measurements were taken in a horizontal (and vertical) grid where both near-wall measurements and locations in the center of the room are used. These measurements were performed in a back-and-forth way to find a mean value in time on each grid point. If the change in time is linear this mean value represents the results at the same time, namely the time of direction. To clarify, a gallery with a 12 measurement location grid is measured from location 1 to location 12. After the last measurement in location 12, the route is reversed (hence, back-and-forth), see figure 2.6. The grid-size and number of measurement locations depends on the detail and question underlying the climate scan. If, for instance, the influence of external walls on the indoor climate is investigated, a denser grid could be used near the wall region.

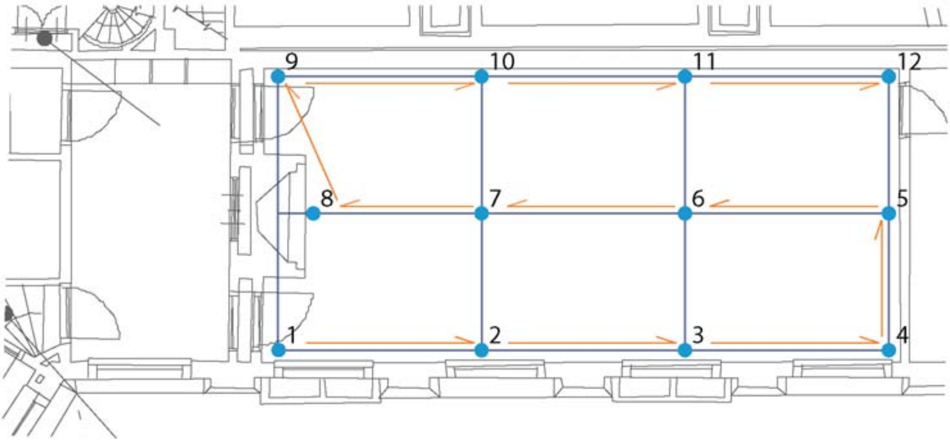


Figure 2.6: *Example of horizontal measurement grid with back-and-forth measurement process indicated by orange arrows.*

This short-term average results in a horizontal plane or vertical cross-section of T and RH where spatial deviations are shown. This measurement can be done during several seasons or during the day. The temperature gradient provides information on heat transport in the investigated area.

The response time of measurement equipment is important for the hygrothermal measurements. Ideally, measurement equipment of both temperature and relative humidity have similar response times to avoid interpretation of deviations as microclimatic anomalies [58]. It is important that no major disruptions occur (e.g. entering visitors, opening of a window, et cetera) during the measurements. Therefore, it is recommended to execute this measurement when no visitors are present and museum staff were noticed. The response time of the measurement equipment needs to be considered while performing these measurements. Preferably, a tripod construction is used to move the equipment along the grid and measuring an average over a short time interval of 2 minutes to avoid any small short-term disruptions skewing the data. An example of a disruption is the researcher walking away from the setup. This would results in a disruption in airflow which however, will have limited effect on temperatures [58].

The short-term measurements result in the micromapping of studied galleries and other areas. A first distinction of spatial differences between the indoor climate of different rooms can be made. Furthermore, a first insight can be gained into local indoor climates per gallery. This can be used to create a risk profile for long-term hygrothermal measurements.

Long-term hygrothermal measurements
Placement of long-term hygrothermal measurements at important spatial locations are used to complement existing building management system measurements. It might turn out that sufficient logging instruments are placed throughout the building, it could be of benefit to increase the data monitoring in certain critical areas, depending on the climate scan objective.

Indoor climate monitoring is preferably done over a full year to include all seasons and show time-dependent fluctuations. External climate data for temperature and relative humidity are of importance to collect, either through the building management system or by including it in the long-term measurement campaign. Collecting data from the building management system is preferred to compare the different time series and measurement location influence. Hygrothermal data from the building management system is a bare minimum to collect, if possible, insight in CO_2 measurements, ventilation rates and flow rates increase understanding of the indoor climate of a specific building, gallery or object environment.

These time series are frequently assessed with different evaluation tools and indices like the climate evaluation chart, performance index, spatial homogeneity index [1, 120, 86]. With the exception of the spatial homogeneity index developed by Schito et al., spatial deviations are often not considered in preventive conservation studies. Therefore, including long-term monitoring measurements at deviating indoor climate locations can increase knowledge on deviating local indoor climates influencing the object environment and. Identified local indoor microclimates can be thoroughly assessed by the specific risk assessment tool (object risk) and the climate evaluation chart (climate analysis) developed by Martens in [1].

2.2.3 From quantitative insight to qualitative assessment

The last step of the climate scan is to transfer from quantitative insight through gathered data to be able to form a qualitative assessment; can the collected data show whether an ideal indoor climate is present for object preservation? This qualitative assessment could differentiate depending on the aim defined early in the climate scan. For three pilot studies the climate scan was used to evaluate its suitability in practice. Resulting from data collection an assessment was made on the indoor climate and the objective of the pilot studies.

Appendixes B, C and D elaborate on three pilot studies (M1, M2 and M3) that have been used to evaluate the developed scan. Appendix B provides information on the participating pilot sites, appendix C elaborates on the climate scan being used for short-term measurements and appendix D shows the results for the long-term measurements in a historic room belonging to one of the pilot sites. The discussion will elaborate on how the results of these pilot studies affect the climate scan and how the climate scan is used in upcoming chapters.

2.3 Discussion and conclusions

This study aimed to develop an indoor climate monitoring scan to gain better insight into the cause and effect of deviating indoor microclimates and includes both spatial and temporal distribution for T and RH climate conditions. This scan is able to localize critical areas within a museum, archive or library.

2.3.1 Discussion of pilot case studies

While previously developed climate scans focus mainly on time series [1, 109], this climate scan also adopts methods to monitor spatial differences. With help of the developed climate scan critical areas with local microclimates were mapped out spatially based on the performed inventory, IRT measurements and short-term hygrothermal measurements (Appendix C, figures C.7, C.10 and C.13). In one glance, critical areas are determined to monitor for a longer period of time. These critical areas are determined by looking at the influence of (in)correct indoor climate, susceptibility and value of objects on display and physics related influences (i.e. low thermal resistance of the building envelope).

What was learned during this pilot study in terms of objectives defined by the participating museums? With the climate scan, the authors of this study were able reach the aims set out by the case studies.

- Placement of a climate control system within an historic gallery requires concessions that might not benefit the indoor climate it needs to maintain. The climate control system influences the local microclimate surrounding an object if the object placement is influenced by the airflow from either the supply or extract of the climate system. Gaining insight on the cause of an aberrant indoor climate provides opportunity to find the appropriate solution (M1).

- When the capacity of a climate system is sufficient, galleries with open connection to other zones might not experience major influences in terms of incorrect T and RH. Air supply to ensure a homogeneous climate creates a paradox. While ensuring -on average- a stable climate, supplied air often seeks out extremes. If objects are placed within this airflow additional measures should be taken to avoid unproofed fluctuations (M2).

- The indoor climate experienced in a building with both historic and purpose built parts can differ depending on the quality of envelope and general building concept. Even if the climate control system is equal to both building blocks, the building physics

> play an important role, especially during an extreme season like summer. Insufficient cooling capacity results in indoor local climates that create an increased risk to objects. Relying solely on building management system measurements does not consider critical areas with deviant T and RH induced by the building envelope (M3).

It was possible during this study to include spatial differences and therefore, fresh insights for the case studies in possible risk for susceptible objects. Ideally, this climate scan would provide specific local indoor microclimates that can be found in every gallery or (museum) building. However, every building is different and has undergone different conversions throughout its lifetime. This results in using this climate scan not as exhaustive and definitive but as guidance in identifying local indoor microclimates. Three main causes were identified as to increased chance of developing local indoor microclimates, (i) building envelope, (ii) building system, and (iii) building use (Appendix C, figures C.6, C.9 and C.12). A limitation that occurred during the use of the climate scan in the current case studies was the lack of controlled interventions in the climate system. The hypothesis of using energy conserving climate control to reduce indoor microclimates was not tested. It did provide an indication on the influence of climate control on indoor microclimates and the object environment (Appendix F, figure F.19).

2.3.2 Discussion of the climate scan

The long-term measurements based on the short-term evaluation of critical areas is an advantage of the climate scan compared to existing scans such as micromapping [88] or the assessment of Lucchi [109]. The long-term measurements will increase monitoring effort and the necessary knowledge base to interpret the results to benefit preventive conservation and risk management decisions. However, this will provide a more holistic understanding of the museum indoor environment. Solely short-term measurements will show the cause and location of critical areas, the long-term measurements will provide insight in seasonal and short-term fluctuations in these critical areas.

In practice, the first step is to determine the aim, what issue needs to be resolved. For this, multiple disciplines need to be gathered. These different perspectives might help define new insights and other objectives to be reached for. Not all steps can be handled by one discipline or person. The use of IRT proved useful for the climate scan. However, deriving a hygric image from the thermal image results, assumed a well-mixed homogeneous indoor climate. Near inlets of the HVAC system it is expected not to be well-mixed. Air is supplied to mix or disperse already present air within the gallery and result eventually in a sufficient well-mixed indoor climate. Research into the effect of air distribution in museum or depot areas would enhance the accuracy of assumptions made for infrared imaging and its translation to hygric images [123]. Besides this limitation, the use of infrared imaging needs to be executed correctly. The difference between indoor and outdoor climate conditions needs to be sufficient to gain accurate images. Interpreting these images requires a certain knowledge base. This makes the climate scan unsuitable for museum staff to perform independently, contrary to that, a valuable aspect of the climate scan was the necessity to involve experts with different expertise. Knowledge transfer between expert fields will result in a higher quality of the project outcome. Learning *why* an object is of high value or susceptible to incorrect T and RH or placed in a certain location provides a framework for the evaluation of the indoor climate. This applies to technical experts as well, while collecting plans of the building is necessary, most valuable is discussing why specific measures were taken in terms of building envelope or application of a climate control system.

The following conclusions can be drawn:

- This study introduced a climate scan based on temporal insights with the addition of spatial evaluation of indoor climate parameters T and RH. The method shows that lumped parameter approach for T and RH is not sufficient for preventive conservation and the building envelope, building system and building use have a significant part in creating or reducing local indoor microclimates.
- Based on the results of the presented case studies, deviating local indoor microclimates occur in both museum buildings where stringent setpoint requirements are established and museums where less stringent conditions are adopted.

2.3.3 Further work

This holistic approach to determining temporal and spatial indoor climate influences in museum buildings provides a new insight in the use of climate control. Current building management system measurements rely on room averaged feedback to control the indoor climate of a building. By raising awareness of possible causes for deviating indoor local climates and critical areas, appropriate (air and surface) measurement locations near susceptible object might offer improved preventive conservation.

Further work was performed on the need of climate control in a library archive (Chapter 3). The climate scan was used to determine critical areas that were monitored during this intervention study in both a temporal and spatial way.

Chapter 4 elaborates on measurements performed by using a lumped parameter approach as well as a spatial insight and measurements in the object environment, an archival box.

In order to research a novel display case design, several (air and surface) measurement locations near the object and in (possible) microclimate locations were used to investigate the effectiveness of the display case (Chapter 5).

3 Temporal and spatial analysis of library archives

This chapter is largely based on: K. Kompatscher, B. Ankersmit, R.P. Kramer, H.L. Schellen. *'Intermittent conditioning of library archives: microclimate analysis and energy impact'. Building and Environment* **147** (2019), pp. 50-66

Abstract

Libraries and archives house a majority of cultural heritage objects. The main purpose of libraries and archives is to provide suitable indoor climate conditions for preservation of their collection. In general, a large bulk of hygroscopic material is present which aids stable indoor climate conditions. Limited disturbances due to visitor presence occur in repositories and excludes to a large extent thermal comfort requirements. Library archives show potential of more tolerant setpoint control with permissible fluctuations. Little research is present into dynamic setpoint control and intermittent conditioning in libraries and archives. The aim of this chapter is to explore the possibility for intermittent conditioning and dynamic setpoint control on the energy impact and microclimate behavior in a library case study in The Netherlands. By means of a hygrothermal monitoring campaign from August 2016 to August 2017 the current indoor climate has been assessed under regular conditions and intervention periods (summer and winter) where the air handling unit was turned off. Both temporal and spatial measurements provided important information on microclimate behavior of the investigated repositories. A validated multi-zone model was used to investigate multiple setpoint strategies. Results show the potential of intermittent conditioning depending on whether dynamic setpoint conditions are used during operational hours (e.g. ASHRAE climate classes). If static conditions are applied, energy demand increases significantly, however, under dynamic setpoint control significant energy savings are possible. The lifetime multiplier is used to assess the chemical risks. The majority of investigated setpoint strategies show increased chemical risk.

3.1 Introduction

The indoor environment of museums, libraries and archives should provide an adequate indoor climate for the preservation of objects [21]. During the 20th century the notion evolved that a stable indoor climate decreased the risk for object degradation. Incorrect Temperature (T) and Relative Humidity (RH) were identified to be major causes of increased degradation to objects. The rise of Heating Ventilation and Air Conditioning (HVAC) technology resulted in the idea that if a fluctuation in indoor RH of ±5 % was good, a fluctuation of ±3% would be better [9]. The general notion for the need of a rather strict indoor climate in museums, libraries and archives is still present today. In order to provide an appropriate indoor environment for a variance of building types and building use, several indoor climate guidelines have been developed in the past decades, e.g. [33, 35, 7, 34]. Taking ASHRAE as an example, the chapter on Museums, Galleries, Archives, and Libraries presents design specifications for different indoor climate classes. These climate classes include specifications for short-term fluctuations, seasonal adjustments and levels for T and RH. The climate classes range from class AA (precision control) to class D (limited control) and serve as a guideline [4]. Though enough opportunities are presented in various indoor climate guidelines with respect to permissible fluctuations, the notion of a stable indoor climate being the optimum for artifact preservation resulted in many cultural institutions applying a stringent indoor climate class, e.g. ASHRAE class AA. Besides undesired consequences (e.g. condensation risks) in historic buildings [57], it also results in large energy consumption and frequent maintenance of technical components, and hence, high costs [125]. Besides the financial impact, the environmental impact has become an important performance criterion, i.e. becoming more sustainable and reducing the carbon footprint have also become important aspects for heritage institutions. This situation urges for a paradigm shift from the ideal climate to the appropriate climate in order to balance collection preservation, building preservation (in the case of historic buildings), energy performance, and thermal comfort (in the case of museums) [36].

Many studies have focused on the museum environment addressing various aspects such as energy efficiency [95, 42, 96, 75, 91], current museum indoor climate [110, 87, 126, 127], evaluation of indoor climate on collection preservation [1, 120, 97], and thermal comfort of museum visitors [127]. Libraries and archives are less frequently addressed in conservation research combined with indoor climate requirements. The main differences compared to the museum environment are the infrequently accessed repositories by visitors or employees and the often vast amount of hygroscopic materials present. A myriad of studies relate to the moisture buffering of building materials and interior materials, e.g. [46, 128, 129]. This resulted in more detailed studies on the moisture buffer capacity of specific collection types which can be found in archives and libraries [130, 131].

The combination of little disturbances and a naturally stable indoor climate limits the need for active climate control systems. Improved energy efficiency and less technology dependency may be provided by (i) passive measures, (ii) intermittent conditioning. Passive climate control in archives shows potential, however, ventilation or recirculation is needed to control internally generated pollutants [132]. In Denmark, several passive archives or storage buildings are constructed with external walls with high thermal and hygroscopic capacity and good insulation capacity. These buildings show the potential of passive measures [47, 51]. Less technology dependency is investigated by turning off the air handling unit (AHU) creating intermittent conditioning, and provides generally positive results according to the study of [41].

Though many guidelines include different conservation purposes such as museums, galleries, archives and libraries, the number of guidelines providing specific specifications for archives and library repositories is limited. Velios [35] mentions their proposed specifications as suitable for both storage and display conditions. ASHRAE [7] provides a table with different climate classes including classes for cold and cool storage, however, only related to chemically unstable objects. National regulations describing indoor environment specifications for national archives stem often from the idea of stringent indoor climate conditions, e.g. the Dutch Archival Legislation with T is 18±2°C and 50±5% RH [133]. Research showed the potential of archives and libraries to maintain a stable climate though striving for improved energy efficiency and less technology dependency. The aim of this study is to explore the effects of intermittent conditioning and dynamic setpoint control on the energy demand in a Dutch library case study. The resulting indoor environment will be analyzed to assess possible risks to the present archival collection.

Section 3.2 explains the used methods including a description of the case study, data acquisition of the experimental and computational study, and the used climate control scenarios. Sections 3.3 and 3.4 present the results of the measurement campaign, the microclimate analysis, and the results of the computational modeling. The energy impact of the indoor climate scenarios and the evaluation of the indoor climate with respect to object preservation is illustrated to propose a suitable climate control strategy for library archives. Section 3.5 provides a discussion and concluding remarks.

3.2 Methodology

In order to gain insight into current practices and improved climate control practices a Dutch case study was used in an experimental and a numerical study.

3.2.1 Case description

The building under investigation is anonymized and necessary details are described in this section. The building is located in The Hague, the third largest city of The Netherlands and part of a heavily urbanized area called the Randstad. Besides a public function, the case study library has primarily the task to preserve a copy of every book that has been published in or about The Netherlands. This results in a building largely existing of a repository to preserve over seven million books, newspapers, magazines and micro materials covering a time span from the Middle Ages until today. The collection is partly housed below ground level and partly in a four floor building. This study focuses on four floors above ground level which are constructed in such a way that this tower is situated above a tram line. The investigated repository is constructed with steel columns penetrating the different floors acting as thermal bridge on the fourth floor. Further structure materials for the repositories can be found in table 3.1 and an exploded view of the floor plans in figure 3.1.

The repositories have a very small heat and moisture load due to people. They are visited three times a day by employees, with varying dwelling times. In order to keep the indoor T and RH as stable as possible and eliminate sudden fluctuations, an all-air HVAC system is used. The AHU consists of a cooling coil, heating coil, humidifier and fan. The four floors have individual reheating and recooling coils to adjust the air temperature to meet the setpoint at every floor. In the reference case, the setpoints were 18°C for T and 55% for RH all year round.

3.2.2 Experimental campaign

An experimental campaign was set-up to assess the present indoor environment. From august 2016 to august 2017, continuous measurements of T and RH have been performed on floors 4 to 7, each floor consisting of two in-use repository zones. Outdoor measurements consisted of air temperature, relative air humidity, and solar irradiance. Eltek measuring equipment has been used with combined T and RH sensors providing a measurement accuracy of ±0.4°C and ±2% RH. The sensors have been calibrated by the Building Physics and Systems Laboratory of the Eindhoven University of Technology. Calibration of temperature and humidity sensors is performed to check the accuracy of the equipment. The data of the sensors will be compared to a very precise reference sensor (calibrated by the NMi; Nederlands Meetinstituut). The sensors are placed in a special climate chamber in which a temperature and humidity trajectory is imposed. A polynomial function containing calibration constants is the result of the relation between the sensor and reference sensor. This function is used to convert the measurement data in the database to be as accurate as possible. After calibration the overall accuracy of the sensors is slightly better than the accuracy provided by the manufacturer. An Eltek RX250AL data logger was used to collect, store and send data to a server at Eindhoven University of Technology. The sampling interval was 10 minutes. On floor 6, an extensive measurement grid has been set up, see figure 3.1. Spatial differences of T and RH have been measured both horizontally and vertically. This was done to investigate the homogeneity of the investigated areas. The horizontal grid was situated in such a manner that near the building envelope, near the bookshelves, and in between the shelves at a height of 1.60 m measurement equipment was located. The figures presented in section 3.3 are constructed with a Matlab script in which the sensor data is used as output to create a contour plot (see Appendix G). The vertical stratification measurement was performed at positions 13 and 14 at heights of 0.12 m, 1.60 m and 2.60 m.

Everyday operation of the library's repository was monitored and considered to be a reference. Two intervention experiments were conducted: (i) During the summer period from August 29 to September 2, 2016; (ii) during the winter period from December 12 to December 16, 2016. During these intervention periods the AHU of the repository was turned off and the indoor climate was closely monitored during this free floating situation. As soon as the indoor climate in the repository reached the maximum or minimum permissible T or RH, the AHU was activated to maintain climate conditions that fit the original boundary conditions.

3.2.3 Numerical modeling

Numerical modeling was used to study the effect of different climate control strategies and keep risks for the collection to a minimum. The Heat, Air and Moisture modeling tool, HAMBASE, was used to develop a multi-zone model of the library environment [98, 134]. HAMBASE is developed in the MATLAB environment where indoor T, RH and energy consumption have been simulated in the model. Energy consumption has been simulated

Figure 3.1: *Floorplan with measurement positions and zonal distribution.*

for heating, cooling, humidification and dehumidification. More extensive information on HAMBASE modeling is given in the appendix of [97].

The HAMBASE model consists of three zones representing the 6th floor. Zones B and C are used as filled repositories and have been extensively monitored in the experimental campaign. Zone A is empty and reserved for possible expansion of the current collection. Employee presence was determined by visual observation. Moisture gains from these employees were set to 270 g/h as their work mostly consists of walking with a certain weight. Since there are no employees continuously working in the repositories, moisture gains were limited to 10 min/h to create an intermitted pattern in employee presence [135]. Casual thermal gains including heat from lighting fixtures and gains by employee presence also were created with an intermittent pattern resulting in 10 W/m^2 and 80 W per present employee per full hour. On average the percentage of fresh outdoor air is 10% of the total ventilation air (21820 m^3/h averaged per floor), 90% is recirculated air. Since there are so few people present in the zones it is not needed to increase the ventilation rate and it is therefore kept low during the operational hours of the library. Table 3.1 shows the used building data for the model.

The collection forms a substantial part of the heat and moisture capacity which stores and releases heat and moisture. Internal walls are used to model the collection. The material properties of paper have been assigned to these internal walls. Properties such as thermal conductivity (W/mK), density (kg/m^3), specific heat capacity (J/kgK), and emissivity (-) are based on literature studies [130, 80]. The moisture properties of paper, like the diffusion resistance factor μ (-), specific moisture capacity related to relative humidity ξ (kg/m^3) and water vapour effusivity b_v ($s^3/2/m$) were calculated (see appendix H).

Energy weather data for Amsterdam, The Netherlands have been retrieved from the EnergyPlus Weather Database [136]. The typical weather data is specifically used for the energy simulations of the different scenarios and consist of IWEC data. IWEC comprise multiple years of climate data to represent typical weather conditions of a location. The database weather files were converted to the correct file format for HAMBASE. Global radiation was split to direct and diffuse radiation using the Perez model. The file format uses the following data: diffuse solar radiation, air temperature, direct solar radiation, wind speed, wind direction, relative humidity outside, duration rainfall, summation hourly rainfall, cloud cover.

3.2.4 Model validation

Validation of the building simulation model was performed using data collected with the experimental measurements. Figure 3.2 compares measurements to simulation results of the indoor T, RH and specific humidity (SH) for zone B. The measured data is based on an average of all the present sensors in zone B, because HAMBase calculates an average temperature and RH for each zone. The histograms on the right side of figure 3.2 show the frequency of deviations between measurements and simulation. It shows that the model overestimates RH and SH values while the T deviations are small. The graphs on the left side show that, during the simulation of the entire year, the model slightly overpredicts T and RH in Summer and underpredicts T in Winter. The peaks that can be observed in figure 3.3 during August, December and March are related to intervention periods. The March intervention period used active cooling and was omitted from this study due to different study objectives. The numerical model used to validate these periods is shown in Figure 3.3.

The intervention periods have been separately simulated with different control settings than the regular operational use of the HVAC system. Figure 3.3 compares measurements and simulation results of the intervention. The intervention simulations show that during the free-floating period both T and RH show the same trend as the measurements. Both during summer and winter intervention it is shown that T increases, RH remains unchanged, and specific humidity increases.

Table 3.1: Building data of the library used for the model.

Dimensions	**Zones**	**Area (m^2)**	**Volume (m^3)**	**Height (m)**	
Floor 4	3	1961	6667.4	3.4	
Floor 5	4	2667	9067.8	3.4	
Floor 6	3	800	2720	3.4	
Floor 7	3	1489	5062.6	3.4	
Construction	d **(m)**	λ **(W/mK)**	ρ **(kg/m^3)**	c **(J/kgK)**	R **(m^{2}K/W)**
Roof $U=0.24$ W/m^2K					
Outside					0.04
PVC roofing	0.005	0.17	1300	1470	0.03
EPS insulation	0.14	0.036	35 1470	3.89	
Hollow core concrete slab	0.2	1.4	2500	840	0.14
Inside					0.13
Floor $U=0.22$ W/m^2K					
Finishing	0.01	0.8	1900	840	0.01
EPS Insulation	0.14	0.036	35	1470	3.89
Light concrete	0.05	0.12	400	840	0.42
Hollow core concrete slab	0.2	1.4	2500	840	0.14
Inside					0.13
Exterior walls $U=0.18$ W/m^2K					
Outside					0.04
Sandwich panel	0.004	200	2800	505	0.00
PUR insulation	0.14	0.026	33	1470	5.38
Reinforced concrete	0.2	1.7	2400	840	0.12
Inside					0.13
Internal walls					
Light concrete slabs	0.1	0.12	400	840	0.83
Books	no. racks $\cdot 0.25 \cdot 2.8$	0.06	840	750	

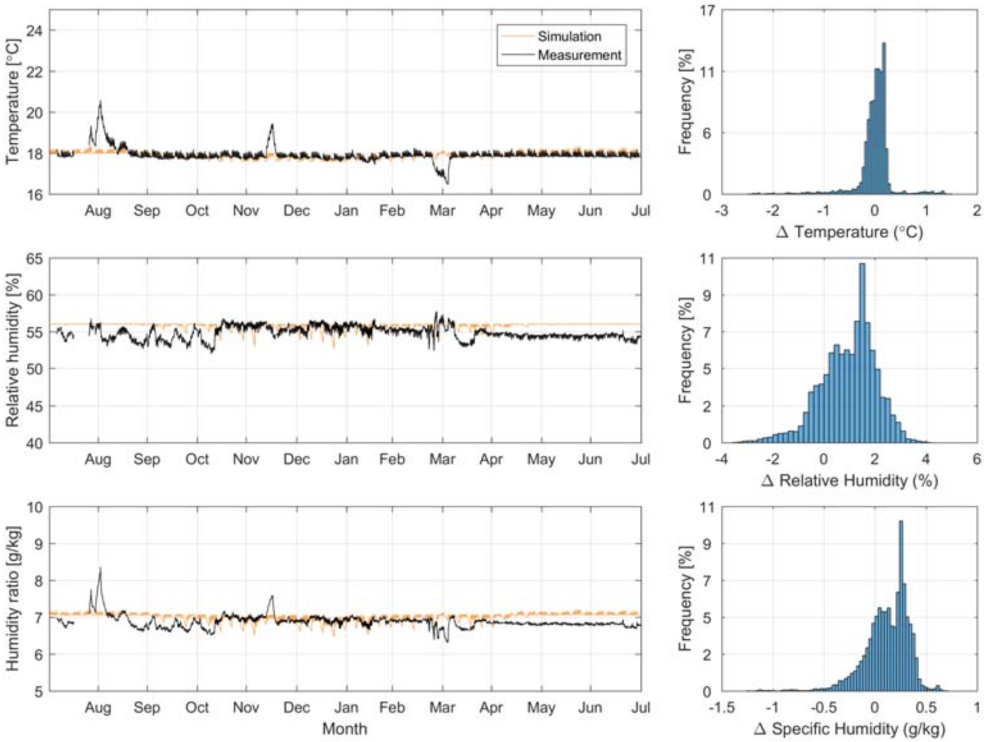


Figure 3.2: *Comparison between measurement (black) and simulation (orange) in zone B over one year under normal operating conditions (left) and the frequencies of the variations between measurement and simulation (right).*

Table 3.2 provides model calibration results based on the statistical indices cumulative variation of the root mean squared error (CV RMSE) and the mean bias error (MBE) (see equations 3.1-3.2). These indices are used for model accuracy of the building simulation compared to measurement data [137].

$$MBE(\%) = \frac{\Sigma_{i=1}^{N_p}(m_i - s_i)}{\Sigma_{i=1}^{N_p}(m_i)} \tag{3.1}$$

$$CVRMSE(\%) = \frac{\sqrt{\Sigma_{i=1}^{N_p}(m_i - s_i)^2/N_p}}{\bar{m}} \tag{3.2}$$

Where m_i are the measured data points for each model instance i, s_i are the simulated data points for each model instance i, N_p is the number of data points at interval p and m is the mean of the measured data points. Models are considered calibrated if they comply with criteria set out by ASHRAE guidelines 14 [138]. Attaining a 10% MBE and a 30% CV RMSE using hourly data is considered a calibrated model. Though the ASHRAE guideline

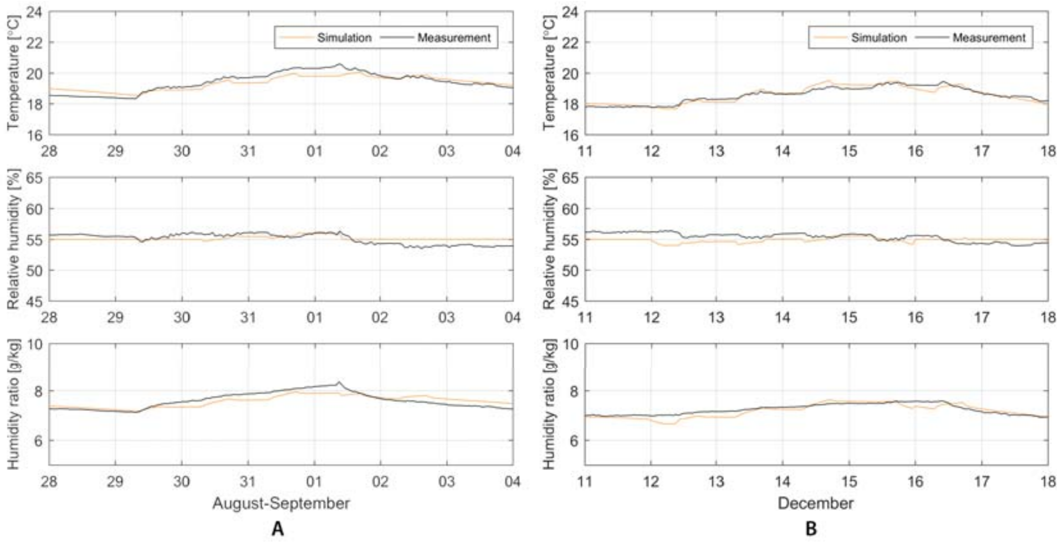


Figure 3.3: *Measurements compared to simulation results of the indoor climate conditions during two interventions: (a) Summer, (b) Winter.*

14 is mainly used to evaluate energy models, an agreed upon standard for hygrothermal performance simulations is not present yet. The model used in this study is considered calibrated (see Table 3.2).

3.2.5 Scenarios

In order to model intermittent conditioning and dynamic setpoint control, several scenarios have been developed. With the validated model these scenarios were simulated to gain insight in the potential energy impact and indoor climate behavior.

- The first modelled scenario is the reference scenario. The environmental specifications of the case study were used: 18°C for T and 55% for RH.
- The second scenario uses permissible short-term fluctuations for T and RH according to the Dutch Archival Legislation [133]. This bill was first defined and approved in 1995 and has since then not changed. The legislation uses the setpoints 18±2°C/ 55±5% for the preservation of specific materials like paper, parchment, wax, leather, textile, wood, paper black and white photo material, and optical discs. Certain other materials have defined indoor climate specifications but are not considered in this study.
- Multiple setpoint strategies are made for modeling intermittent conditioning. Intermittent conditioning implies that for periods of time the AHU is turned down resulting in a free floating indoor climate. This study considers closing hours in the weekends as an appropriate period to turn down the AHU when no disruptions from employees are present. From Friday 06:00PM till Monday 00:00AM the AHU is turned

Table 3.2: Model calibration based on statistical indices CVRMSE and MBE.

	T (°C)		RH (%)		x (g/kg)	
	CV RMSE (%)	MBE (%)	CV RMSE (%)	MBE (%)	CV RMSE (%)	MBE (%)
Zone A	0.99	-1.04	0.74	0.78	0.36	-0.38
summer intervention	0.40	-0.40	1.13	1.13	0.85	0.85
winter intervention	5.47	-5.50	5.45	5.48	0.66	-0.66
Zone B	0.01	0.01	2.24	-2.34	2.25	-2.35
summer intervention	0.40	-0.40	0.36	-0.36	0.81	-0.81
winter intervention	5.45	-5.48	6.79	6.83	0.87	0.88
Zone C	2.85	2.89	0.15	0.16	3.29	3.44
summer intervention	5.94	5.59	7.67	-7.97	0.44	-0.44
winter intervention	2.61	-2.61	6.90	6.91	4.10	4.12

down. This decision is based on the experimental results of the intervention period which were performed during Monday till Friday when disruptions (e.g. employees) were present. The simulation scenario models the operational hours of the HVAC system upon the strict reference and ASHRAE climate classes (AA, As, A, B) requirements, during non-operational hours of the AHU, no T and RH setpoints are imposed.

- The last scenario is based on the dynamic setpoint control algorithm developed in [42]. This algorithm consists of several steps to determine suitable indoor climate specifications for T and RH introducing the concept of controlled fluctuations. Temperature is mainly based on visitor thermal comfort and RH is regulated by collection requirements. The algorithm starts with determining when visitor thermal comfort in museums [127] overrules the T limits for collection requirements [7] and vice versa. RH limits are determined by the collection requirements based on the ASHRAE climate classes. Since the current study does not take visitor or employee presence into account, collection requirements is considered leading. Dynamic setpoint control results in an upper and lower limit with no predefined static setpoint. This allows the indoor climate parameters to vary freely in between these limits resulting in a T and RH range. Since ASHRAE provides two archive climate classes, i.e. cool and cold storage, which do not apply to the case study preservation environment, the indoor climate specifications were determined by ASHRAE climate class AA. With the allowed fluctuations of ±2°C and ±5% RH, climate class AA is in line with the Dutch archival legislation fluctuations.

Table 3.3 provides the T and RH setpoints of the different scenarios including short-term fluctuations and seasonal adjustments. Figure 3.4 provides a visual overview of the used

Table 3.3: Overview of used *T* and *RH* setpoints and allowed short-term fluctuations and seasonal adjustments.

			T (°C)			*RH* (%)	
			fluctuations			fluctuations	
		T$_{sp}$	short term	seasonal	RH$_{sp}$	short term	seasonal
Scenario 1	Reference	18	-		55	-	
Scenario 2	Dutch archival legislation	18	±2		50	±5	
Scenario 3	Intermittent strict	FF*	-		FF	-	
A		18	-		55	-	
B	AA		±2	±5		±5	-
C	As		±2	+5/-10		±5	±10
D	A		±2	+5/-10		±10	-
E	B		±5	+10		±10	±10
Scenario 4	Dynamic control	-	±2	±5	-	±5	-

*Where FF stands for Free Floating and the climate classes are based on [7]

scenarios. The intermittent scenario is represented by the use of strict climate specifications during operational hours.

3.3 Experimental results

The climate data that are measured were analyzed both in the temporal and spatial domain. The degradation risk of the collection were evaluated based on object analysis.

3.3.1 Microclimate analysis

Figure 3.5 depicts the outdoor climate conditions during the summer and winter intervention periods for *T*, *RH* and specific humidity. Summer outdoor conditions included warm days with temperatures of 25°C and high peaks in solar irradiance. Winter conditions show temperatures below 10°C and limited solar irradiation. *RH* during summer showed a strong day/night cycle between 50% and 95%. During winter *RH* was constantly above 75%. Figure 3.6 shows the results of the indoor climate measurement campaign during the summer and winter interventions. It shows a significant difference between the lower three floors and the upper floor. This phenomenon was not only present during the interventions but throughout the entire measurement period. Internal heat sources such as an adjacent technical room, and the large roof area exposed to solar radiation could be of influence on the indoor climate during the measurements of floor 7.

During the summer intervention, indoor temperature increased steadily over the measurement period. This is expected during a summer period. During the intervention it was expected that the relative humidity would decrease over time. However, *RH* remained

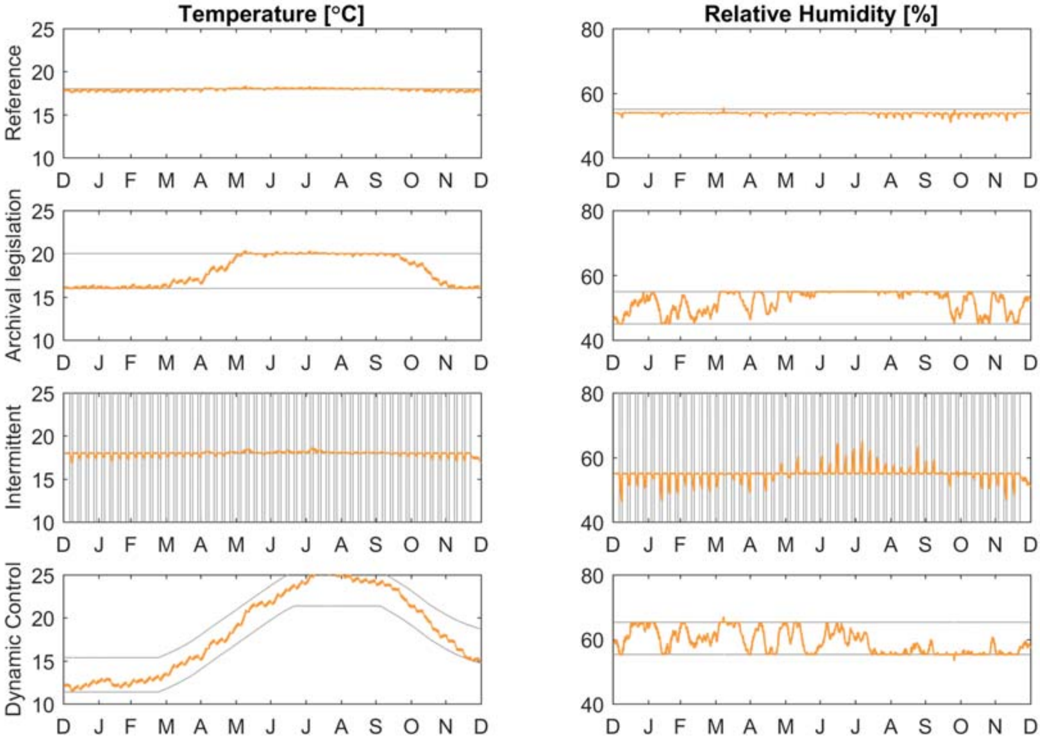


Figure 3.4: *Overview of different setpoint strategies for temperature and relative humidity. The indoor climate conditions (orange curve) and setpoints, minimum and maximum, (grey curves) are depicted for different scenarios.*

stable, presumably due to the presence of large hygroscopic mass provided by the paper collection. The collection desorbed moisture which can be seen by an increase of the humidity ratio, see Figure 3.6 bottom. The absolute moisture in the air increased together with the temperature which means moisture is released from the collection to the indoor air. Both in Summer and in Winter interventions, the collection presence is responsible for a stable indoor RH. It took around 3-4 days before the temperature to increase with 2 K.

3.3.2 Spatial measurements in the vertical plane

Near the building envelope and near the bookracks, vertical stratification measurements were performed. Figure 3.7 shows the measurement results. Summer intervention (Figure 3.7a, c) and winter (Figure 3.7b, d) intervention show an increase in temperature and specific humidity throughout the intervention periods. RH remains fairly stable throughout both interventions.

Stratification measurement 13 near the external wall (Figure 3.7A, B) shows a larger vertical gradient for T and RH than measurement 14 which is located near the bookshelves (Figure

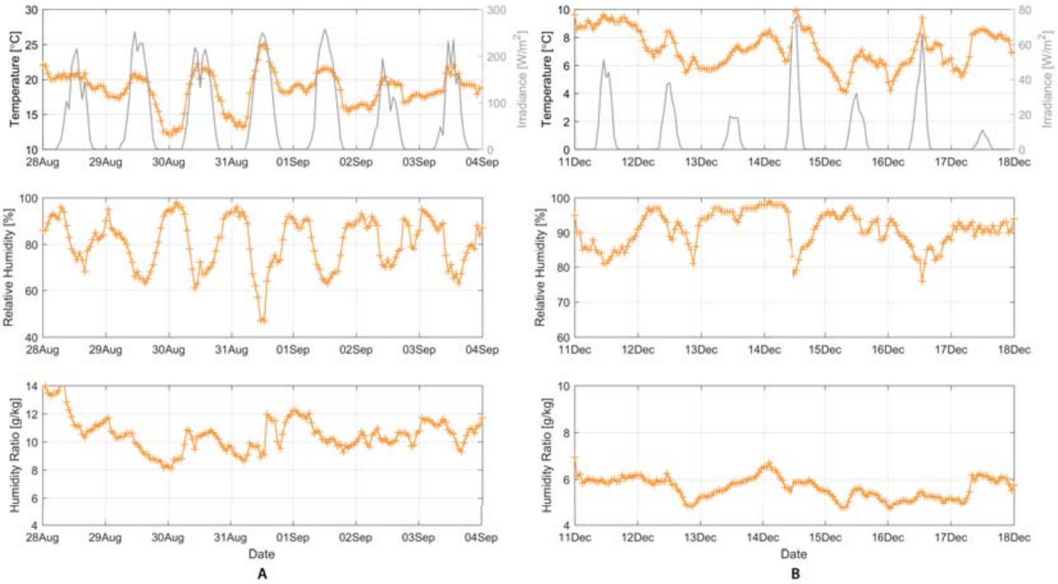


Figure 3.5: *Outdoor climate conditions during summer (a) and winter (b) intervention periods.*

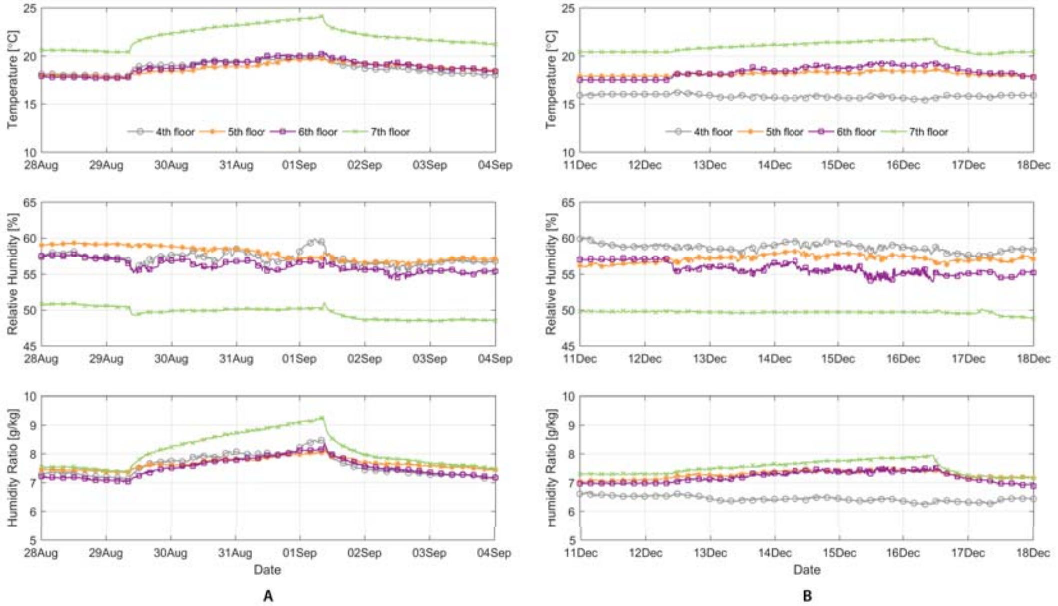


Figure 3.6: *Outdoor climate conditions during summer (a) and winter (b) intervention periods.*

3.7C, D). This occurs when the AHU is turned off. This shows that thermal convection due to buoyancy is the driving force for mixing the air near the building envelope. The indoor climate conditions near the collection show less spatial differences during the interventions.

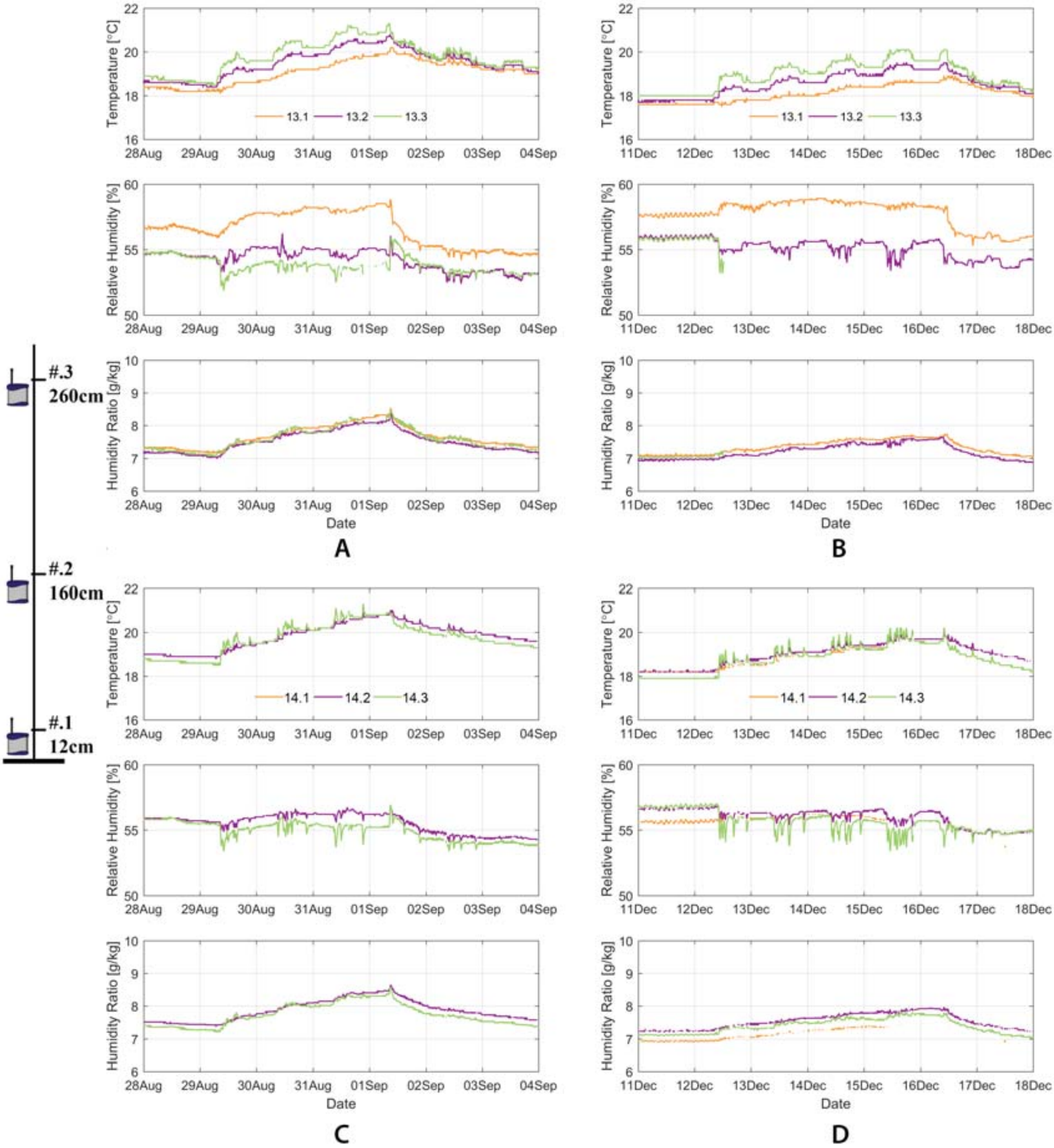


Figure 3.7: *Spatial stratification results for summer and winter intervention periods. Both near the building envelope (a-b) and near the book shelves (c-d) measurements were performed.*

3.3.3 Spatial measurements in the horizontal plane

T and RH data were collected with a 10 minutes time-interval over the period of a year. This gives insight in the temporal behavior over different seasons and intervention periods. The vertical stratification provides insight in the behavior near the building envelope and near the collection in the vertical plane. Moreover, during the experimental study a horizontal measurement grid was also installed on floor six zone B and C, which consists of twenty combined T/RH sensors and provides spatial information on the distribution of the indoor climate conditions that were measured. The measurement grid is indicated in figure 3.1, and provides 52560 data points per location per variable. Figure 3.8 presents the results of the day that intermittent conditioning started during the summer intervention. The AHU was turned down at approximately 09:00h. The difference between each isoline is 0.5 K for temperature, 2% for RH, and 0.2 g/kg for specific humidity. In figure 3.9 the plots are presented for every six hours. The schematic floorplan at the top shows the two zones and the external walls (orange) and internal walls (blue). It shows the trend of T slightly increasing during the day and the gradient present in the upper image decreases over time from ΔT=2°C to ΔT=1°C in the lower left image. RH remains stable and a slight increase in specific humidity is shown in the middle and right columns. On an hourly bases very slow changes are visible. Figure 3.9 and figure 3.10 show the spatial distribution during the summer and the winter intervention. On Monday the AHU was turned off and on Thursday at approximately 10:00h the AHUs were set to normal operational use. These figures provide insight in critical areas in the storage spaces during intermittent conditioning and during normal operational HVAC use. Zone C, which has a few large exterior walls facing South-West (see Figure 3.8, schematic floorplan for wall definition), shows a larger increase in temperature during the summer intervention mainly caused by solar irradiation on the external walls. Overall, T increases at every location while RH stabilizes over time. Specific humidity shows an increase in gradient near the North-East wall of Zone B. During Winter intervention both T and specific humidity increase when the AHU is turned off. Compared to Summer intervention the T gradient is lower during Winter intervention. RH remains stable in both situations.

3.4 Numerical results

Building simulation allows analysis of the energy impact of the modeled scenarios. Climate risks to the collection are analyzed using the specific risk assessment [1] and the measured T and RH data.

3.4.1 Energy impact

Figure 3.11 shows the results of the scenarios simulated with the computational model on the energy impact during a reference year. Table 3.4 provides the absolute numbers of the energy consumption for each scenario. The AHU is constantly correcting small deviations from the rigid setpoints of T and RH specifications of 18°C and 55%. This results in a large energy demand for cooling and dehumidification. Using the Dutch Archival Legislation effectively by allowing permissible ranges for T and RH fluctuations the energy consumption for climate conditioning would be reduced by 40% for Zone B. The first intermittent conditioning strategy shows an increase of approximately 60% in energy consumption compared to the

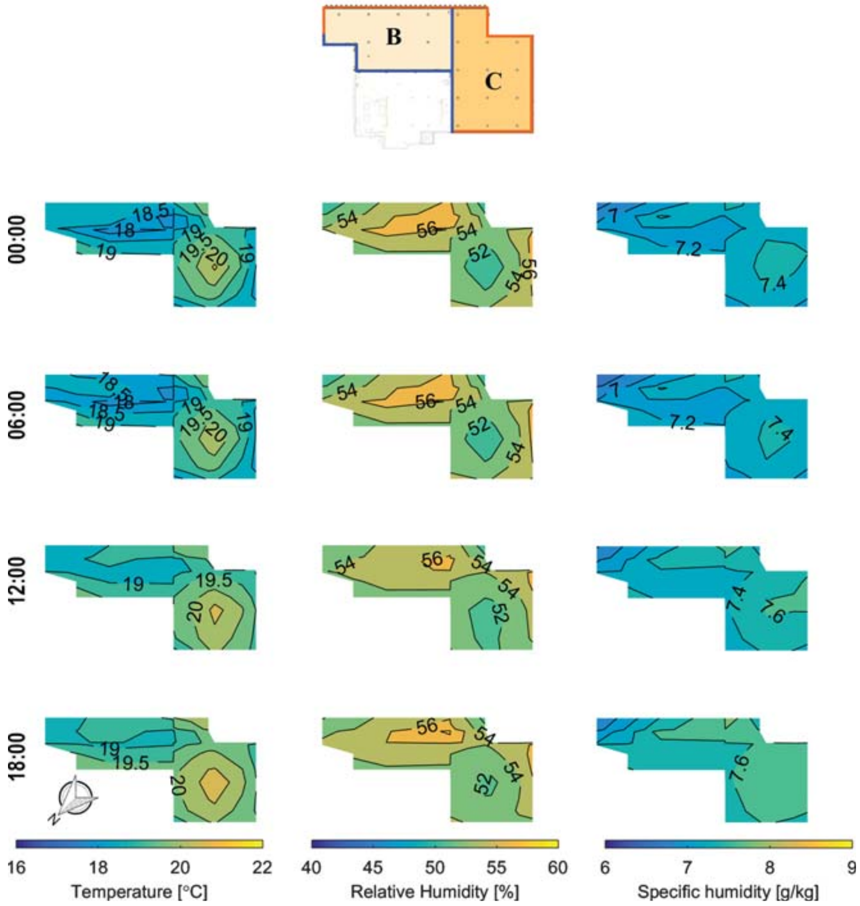


Figure 3.8: *Top; schematic view of important areas and walls. Spatial distribution of indoor temperature (left), relative humidity (middle), and specific humidity (right) during the first day of turning AHU off at 9.00h. Date Monday 29-08-2016.*

reference case. The T and RH requirements during operational use are based upon the strict setpoints of the reference used in the case study (T=18°C and RH=55%). During the period the AHU is off, the free floating condition start to fluctuate from these strict setpoints. This results in constantly cooling or heating back the free floating conditions at full capacity to these strict specifications when the AHU is turned on. When a more tolerant setpoint strategy can be realized during the operational hours, this could lead to large energy reductions. Applying ASHRAE climate classes (AA-B) during operational hours show a significant reduction in cooling, heating and dehumidification energy demand (see table 3.4). Climate class AA shows that humidification has the largest share in energy demand. This is due to the relatively small bandwidth compared to climate classes A and B. Class As has a seasonal adjustment which reduces this humidification energy demand to a certain extent, however, class A shows that a wider range in relative humidity setpoint decreases

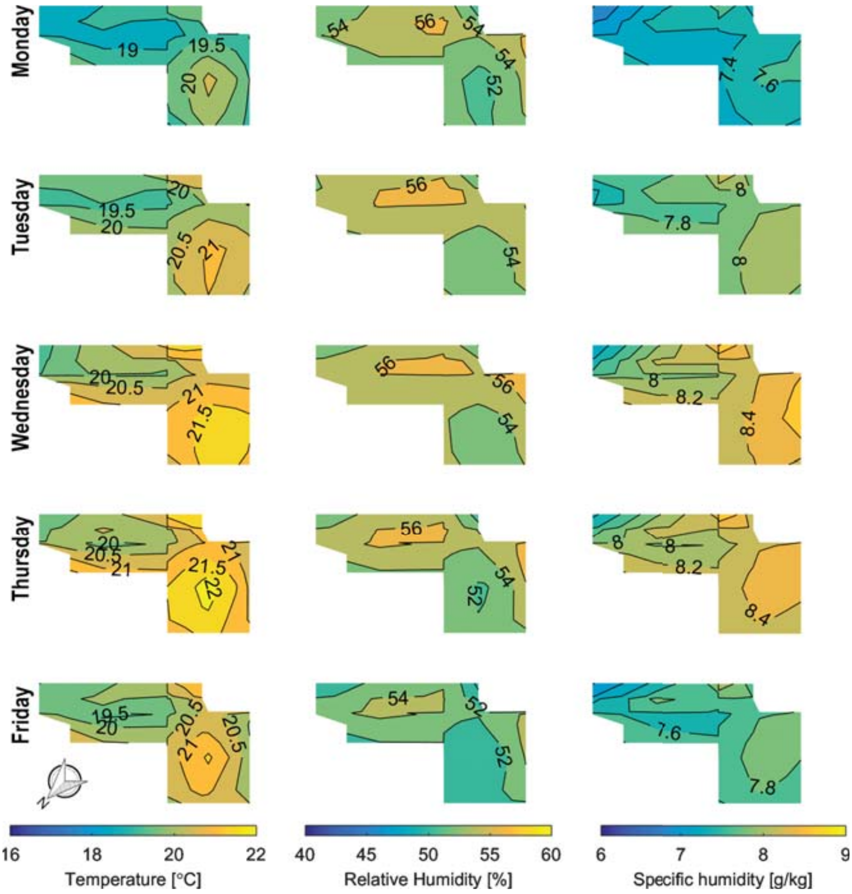


Figure 3.9: *Spatial distribution of indoor temperature (left), relative humidity (middle), and specific humidity (right) during the summer intervention week.*

energy demand more. Dynamic setpoint control is based upon the ASHRAE climate classes and a reduction in energy demand is expected. Figure 3.11 shows an energy reduction of 93%. A wider bandwidth for T and RH setpoints provides possibility to introduce permissible fluctuations. The AHU needs to condition less which results in high energy reduction compared to the tight bandwidth the case study currently allows.

3.4.2 Indoor climate evaluation

Energy consumption results look promising for strategies based on climate which allows a larger bandwidth. However, it is important to relate the simulated indoor climates to possible risks for object degradation. With the climate evaluation chart (CEC), which has been introduced by Martens [1], an evaluation has been made for both the reference setpoint control and dynamic setpoint control. The CEC plot, see Figure 3.12, shows the indoor climates plotted in a so-called psychometric chart. The thick green line represents the mold curve developed by Adan [139]. Figure 3.12 shows the results of four scenarios. The reference

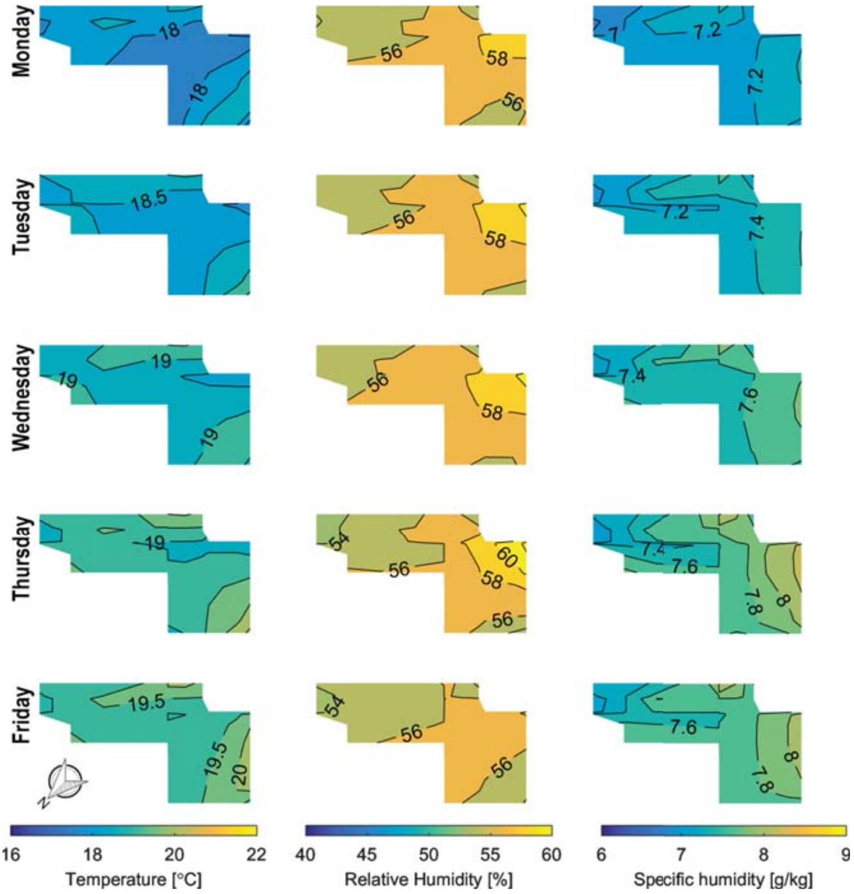


Figure 3.10: *Spatial distribution of indoor temperature (left), relative humidity (middle), and specific humidity (right) during the winter intervention week.*

case (grey) is concentrated around the strict setpoints. The archival legislation scenario (magenta) shows a wider spread for T and limited spread for RH. Both intermittent conditioning (green) and dynamic control (orange) show a wide spread for both T and RH. All other scenarios are within these limits. Figure 3.13 shows the histogram plots for all investigated scenarios. They represent the mean values with standard deviation σ plotted as error bar of the hourly and daily fluctuations of indoor temperature and relative humidity.

The reference illustrates that fluctuations of the indoor climate were very small. The fluctuations of T per hour or per day are 0.2°C or smaller. RH hourly and daily fluctuations are 1% or smaller.

Intermittent conditioning scenarios AA – B and dynamic control show similar trends concerning the daily and hourly fluctuations per season. This means that for temperature the values are increasing with seasonal adjustment in a stable manner and not exceeding short-term fluctuation limits. Hourly and daily fluctuations of RH, although slightly larger

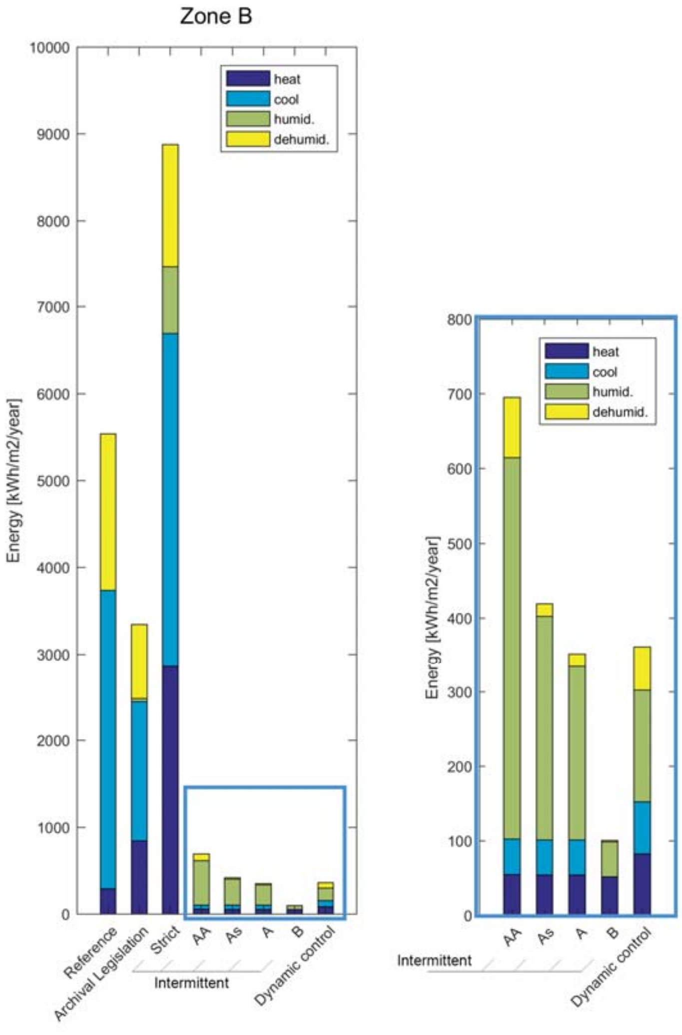


Figure 3.11: *Energy impact for eight different scenarios for Zone B.*

deviations than the reference study, did not exceed short-term fluctuation limits.

3.4.3 Object damage risks evaluation

An object evaluation has been carried out with the specific risk assessment developed by Martens [1]. Though the specific risk assessment is available for four typical museum objects, the library collection consists mainly of paper and books. Figure 3.14 provides the results of the assessment for paper based objects. It shows that the indoor climate does not increase the risk for mold degradation. Measurements for all scenarios are not exceeding the germination

Table 3.4: Detailed energy demand of different setpoint strategies for Zone B.

	E (kWh/m^2)			
	Heating	Cooling	Humidification	Dehumidification
Reference	290	3448	0	1802
Archival legislation	841	1602	37	867
Intermittent				
Strict	2856	3833	785	1404
AA	55	47	512	80
As	54	47	301	17
A	54	47	234	17
B	52	0	234	17
Dynamic control	83	70	150	59

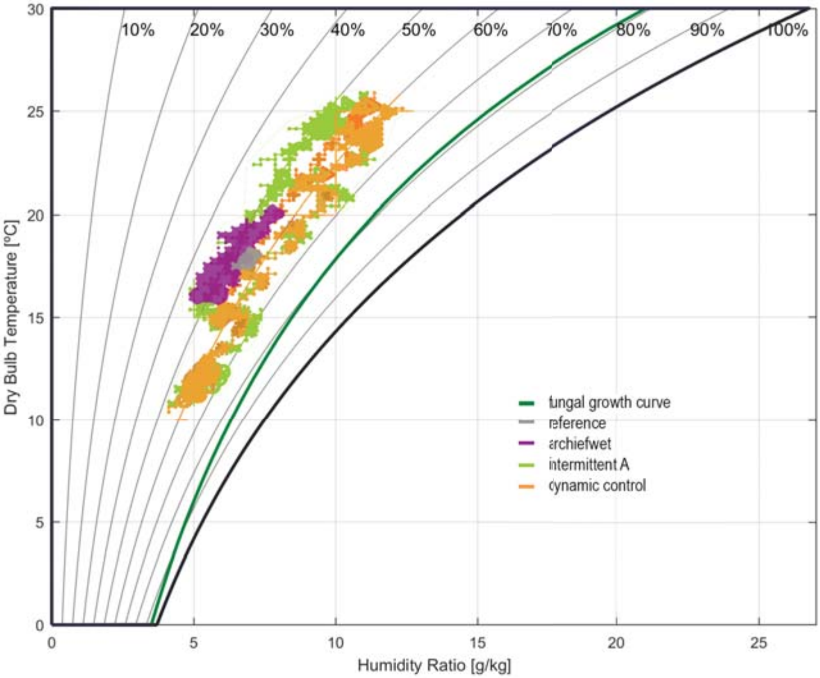


Figure 3.12: *CEC plot with the indoor climate parameters simulated for the reference, archival legislation, intermittent A and dynamic setpoint strategy.*

limits.

The lifetime expectancy is based on the isoperm method developed by Sebera [140]. This method quantifies the effect of T and RH on the lifetime of a paper based collection compared to a reference condition of 20°C and 50% RH. Michalski used this method to define

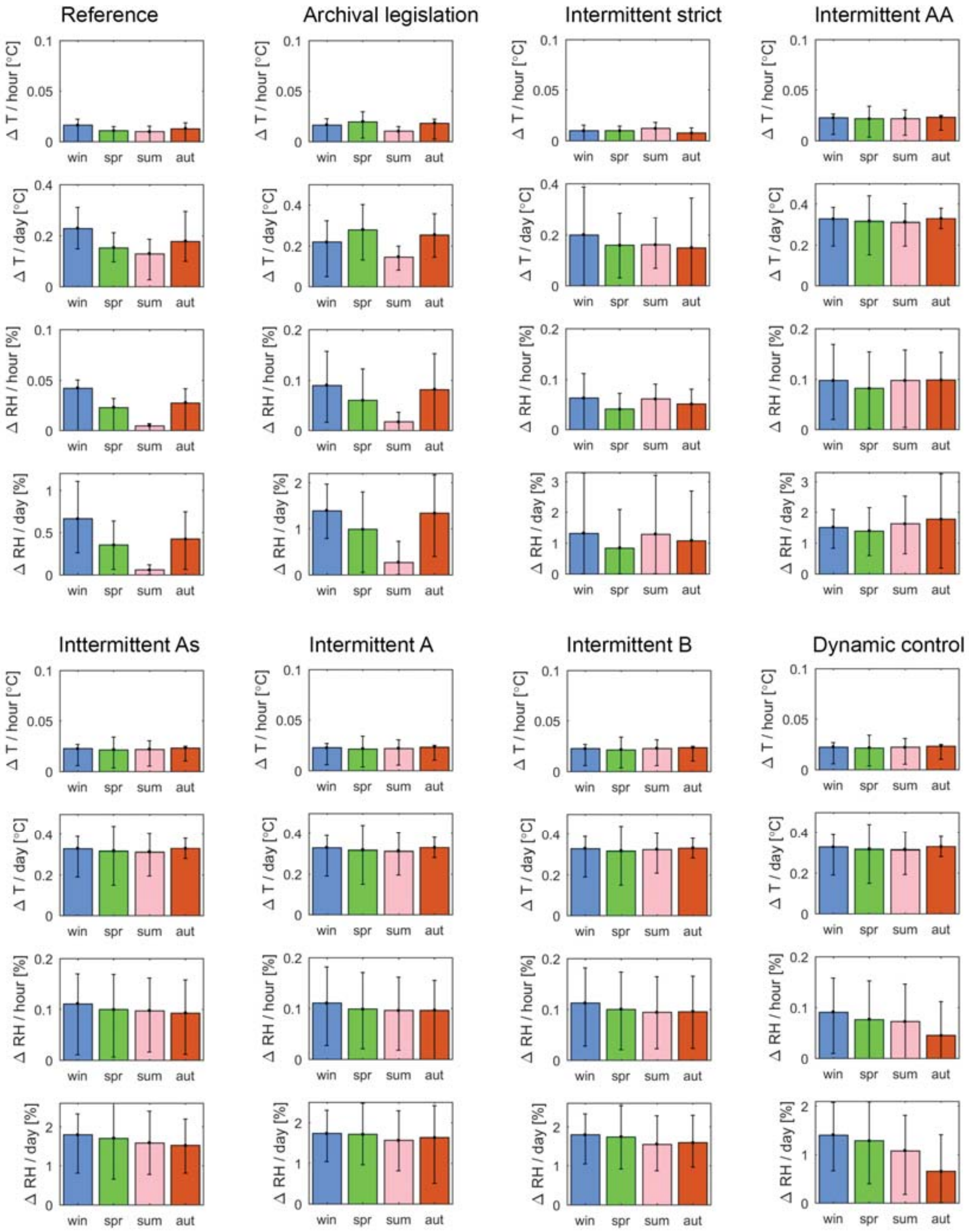


Figure 3.13: *Histogram plots with the indoor climate parameters per season simulated for all scenarios.*

the lifetime multiplier (LM) [141]. Since ASHRAE climate class A is based on collection requirements in museum exhibition rooms, it is expected that the dynamic control scenario will have a lower LM since T and RH are higher than the reference case. Currently, the ASHRAE climate classes for archives and libraries are limited to cold and cool storage classes. Figure 3.14 shows that the LM for the reference case stays over 1 the entire year, resulting in environmental conditions for T and RH where the collection exceed its lifetime compared to the reference conditions of 20°C and 50% RH. The LM for the archival legislation case drops below LM = 1 during the summer months. During winter the LM increases and the equivalent LM (LM_e) is 1.19 for this scenario. The intermittent conditioning and dynamic control scenarios show similar trends. Summer months, during which the temperatures rise, show low LM values. Winter provides a significant rise in LM. The LM_ee for these scenarios is within 0.79-0.89.

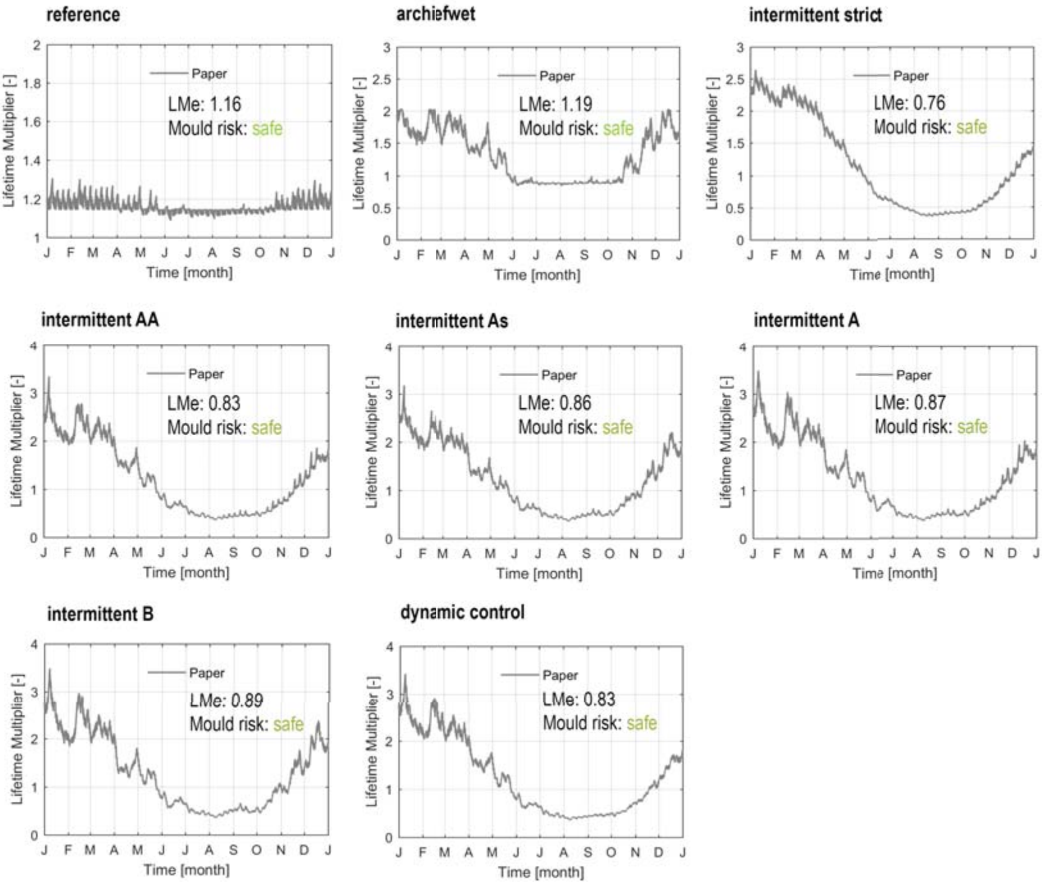


Figure 3.14: *Mold growth and Lifetime Multiplier for simulated scenarios.*

3.5 Discussion and conclusions

With an AHU in operational use, the investigated repository shows small gradients in T and RH. The injected air seems well-mixed and results in homogeneous air conditions for the present collection. Per investigated floor the air conditions are different, the upper floor shows a significant higher indoor T during the measurement campaign. An increase in indoor T was not expected during the winter intervention period. The external climate conditions with lower T cannot explain this observation. Simulating the winter intervention also showed this increase of indoor T. Internal heat exchange between different zones might be causing this since offices are kept at higher T to ensure employee thermal comfort.

Fluctuations in T and RH during the interventions are small and acceptable during both intervention periods. Indoor T slowly increases and indoor RH remains stable, indicating the moisture buffering effect of the collection. This is endorsed by the specific humidity which increased during the intervention periods.

Vertical stratification measurements show the indoor climate behavior near external walls and near the collection during the intervention periods. The latter results in limited to no gradients in indoor parameters while the indoor climate near external walls show an increase in temperature, and hence, in relative humidity gradients.

Horizontal stratification measurements show the effect of wall orientation and indoor climate behavior during the interventions. This results in small gradients for both temperature and relative humidity in different zones. Considering the building to be relatively airtight and no active air exchange being present, the indoor climate conditions for T and RH are expected to come to equilibrium after a certain amount of time. HAMBASE proves to be a suitable tool for simulating multi-zone indoor climates and accompanying energy demand. During this study, the energy demand was calculated based on building needs only. The building and its use is modeled into detail. However, more elaborate results might be obtained in combination with an accurate HVAC model. The dehumidification process by deep cooling and reheating could be more accurate. The inclusion of fan energy in the modeled scenarios may influence the current outcome. Previous research showed the impact of fan energy inclusion on the energy demand [42]. An advantage of simulating only building needs is the low computational effort needed for these calculations. With the inclusion of a coupled HVAC model this could result into large computational effort.

HAMBASE calculations result in averaged conditions for each zone. The averaged measurement results show a good agreement with the averaged simulation results, however, it misses some information such as vertical stratification or the effect near (external) walls or collection. This information is presented in temporal and spatial measurement results sections.

The numerical model developed in this study proves to be suitable to determine the effect of different (intermittent or dynamic) setpoint strategies on energy impact and object preservation. Intermittent conditioning and therefore, the needed energy demand, is highly depending on the control strategy during operational hours of the AHU. Dynamic setpoint control provides a set of minimum and maximum requirements based on a sophisticated algorithm developed in [42]. This algorithm has been adapted in the current study to exclude thermal comfort requirements which are less stringent in archival functions. A future perspective might include intermittent conditioning during dynamic setpoint control when no active conditioning is needed within the setpoint limits. Instead of using recirculation within the T and RH setpoint limits, the AHU could be turned down to yield energy reduction. During this investigation it became clear that archival requirements are often combined with requirements for exhibited artifacts [35] or are applicable for very specific types of archival collections [7]. Relating T and RH requirements to risk assessment of an archival collection needs further research, e.g. book collections are stored more likely in bulk than single paper sheets. It is of importance to be aware of the difference in possible risk that belongs to the different types of storage solutions. The present study used the lifetime multiplier based upon material properties of a single object.

The main conclusions of this chapter are as follows:

- The impact of moisture buffering of the collection should be considered in designing climate control strategies for archives and libraries. In this study RH remained stable due to desorption and absorption of moisture under variable T conditions. It is possible to use computational modeling to model the influence of library collection to include moisture buffering of the objects.
- Conditioning in between two limits, i.e. applying a range of permissible T and RH, instead of one strict setpoint, significantly saves energy: In this study, conditioning according to the Dutch Archival Legislation saved 40% compared to the strict reference case.
- Intermittent conditioning proved to be a viable way to improve energy efficiency if combined with ranges for T and RH during operational use such as the ASHRAE climate classes used in this study.
- Dynamic setpoint control shows promising results concerning the energy efficiency of a library environment. Permissible T and RH ranges based on collection requirements provide more security for library management.
- Reduction in energy consumption is possible for the majority of the tested setpoint strategies. However, collection requirements in terms of object lifetime multiplier should be investigated further. The current lifetime multiplier is based on a single object and might not represent book archival collections as a bulk.

4 | Indoor airflow distribution in repository design

This chapter is largely based on: K. Kompatscher, R.P. Kramer, B. Ankersmit, H.L. Schellen. *'Indoor airflow distribution in repository design: Experimental and numerical microclimate analysis of an archive'. Buildings* **11** (2021).

Abstract

The majority of cultural heritage is stored in archives, libraries and museum storage spaces. To reduce degradation risks many archives adopt the use of among others archival boxes and provide the necessary climate control to comply with strict legislation requirements regarding temperature and relative air humidity. A strict ambient indoor climate is assumed to provide adequate environmental conditions near the objects. Guidelines and legislation provide requirements for ambient indoor climate parameters, but do often not consider other factors that influence the near-object environment such as the use of archival boxes, airflow distribution and archival rack placement. This chapter aims to provide more insight in the relation between the ambient indoor conditions in repositories and the hygrothermal conditions surrounding the collection. Comprehensive measurements were performed in a case study archive to collect ambient, local and near-object conditions. Both measurements and Computational Fluid Dynamics (CFD) modeling were used to research temperature/ relative humidity gradients and airflow distribution with changing rack orientation, climate control strategy, and supply and exhaust set-up in a repository. The following conclusions are presented: (i) supplying air from one air handling unit to multiple repositories on different floors leads to small temperature differences between them. Differences in ambient and local climates are noticed; (i) archival boxes mute and delay variations in ambient conditions as expected, however, thermal radiation from the building envelope may have a large influence on the climate conditions in a box; (iii) adopting night reduction for energy conservation in mind results in increased influence of the external climate, with adequate insulation this effect should be mitigated; and (iv) specific locations of supply air and extraction of air resulted in a vertical gradient of temperature and insufficient mixing of air, adequate ventilation strategies should enhance sufficient air mixing and in combination with insulation of external walls gradient forming should be reduced.

4.1 Introduction

Archives, libraries and museum storages preserve the majority of cultural heritage: for a typical museum around 90% of the collection is placed in storage and 10% is on display[1]. The indoor climate conditions in these buildings are important to ensure longevity of objects and reduce degradation risks such as biological, chemical and mechanical degradation. Besides many other factors, indoor temperature and relative air humidity play a vital role in collection conservation. Compared to archival buildings, indoor climates in museum galleries with objects on display are frequently researched. In exhibition galleries the indoor climate parameters can be disturbed by visitor presence acting as a heat and moisture source [62] and in archives, thermal and hygric inertia of the stored objects could be of influence [46]. The current paradigm on environmental conditions in archives includes the preference for a low temperature (T) and a relative humidity (RH) that is more or less stable around the midrange [21, 58, 93]. A high incorrect T can accelerate chemical degradation of organic material (e.g. cracking of leather bindings, yellowing of paper). Fluctuations in T result in fluctuations in RH which might, in case of continuous high RH, accelerate mold growth, warping and curling of susceptible paper materials [41, 142, 143]. In a recent study the effect of cleaning procedures in a museum building on the variability of RH was found. The use of water in the cleaning procedure should be minimized to avoid fluctuations [144].

Guidelines and legislation often provide ideal values for ambient indoor climate parameters to ensure low degradation risks, i.e. strict prescriptive values resulting in a strictly controlled indoor climate. Meeting the requirements often meant that archives needed to implement a Heating, Ventilation and Air-Conditioning (HVAC) unit to compensate incorrect indoor T and RH conditions caused by, among other factors, poor quality of the building envelope.

British legislation adjusted their storage requirements over the past decades from strict setpoints for T and RH [31] towards more tolerant setpoints [32]. Dutch Archival Legislation is, compared to the current British legislation, very prescriptive and strict about the permissible indoor climate [133]. In recent years, two types of storages have been distinguished in the Dutch Archival Legislation: long-term, i.e. for over twenty years, and short-term, i.e. up to twenty years. The specifications for T and RH are less strict for short-term storage spaces. Instead of an 18°C setpoint with allowed fluctuation ±2°C for long-term preservation, a bandwidth is allowed for short-term preservation as long as temperature stays within the range of 16-20°C and the permissible fluctuations for RH have been doubled from ±5% to ±10%. Long-term specifications require more energy to maintain than the short-term specifications even though the minimum and maximum values for T are similar.

Archives and libraries house a bulk of hygroscopic materials (i.e. large paper collections). Limited occupancy of staff and visitors results in less need for ventilation and thermal comfort. This has resulted in a new way of thinking about ventilation purposes in archives and opened opportunities for possible energy savings. Several studies investigated possibilities such as intermittent conditioning [42, 145], increasing building envelope quality

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[1] https://www.bbc.com/news/uk-england-london-12214145

[146] and seasonal setpoint adjustment [80, 41].

Besides adjustment of the climate control in archives, multiple building physics related measures have been investigated in literature. Limiting external factors such as external climate is required for a storage environment. Passive measures are pursued such as reducing air infiltration by sealing cracks, and increasing thermal insulation of walls. Optimizing ways to limit the impact of the outdoor climate has resulted in a plethora of studies on passive and low-energy museum storage and archive buildings [44, 147, 52, 51, 48, 23, 53]. The underlying thought is that the storage facility needs a large hygrothermal storage capacity and an airtight building envelope to reach a stable T and RH for preservation purposes. Thermal buffering is also a result of the ground and building envelopes thermal capacity. External seasonal fluctuations are delayed and mitigated through buffering. Besides a stable (and low) T, RH buffering is mainly caused by the collection materials end the building walls. Small HVAC systems with limited capacity may be needed to provide (de)humidification and pollutant filtering. The limited energy demand may be provided by renewable energy sources such as solar panels. Holl et al. [27] suggested that a new-built depot building should consider passive measures to reduce energy demand, ideally, with so-called archival concrete which has high water retention properties and low initial moisture levels. Another study advocates passive measures as well with the note that infiltration needs to be kept low. This would keep daily fluctuations low and may reduce investments in air-conditioning systems [148]. Smedemark et al. compared spatial distributions for T/RH between a semi-passive repository without mechanical ventilation present compared to a repository with an HVAC system [53]. The study showed with data collected from an extensive grid measurement that both repositories upheld an acceptable climate performance. The study was performed in a purpose-built building for safekeeping heritage. The investigated repositories have no external walls but are connected to service areas [53].

Deterioration mechanisms of unstable objects highly depend on environmental conditions [104]. In order to increase the longevity of archival collections, enclosures such as archival boxes or envelopes have been largely adopted in this field. These enclosures form an extra layer that mitigates disruptive ambient climate variations. Studies based on laboratory experiments exist and a number of in-situ measurements in operational archives have been performed. Wilson et al. [149] showed the effect of objects in enclosures in open shelves based on risk mitigation and on dust transfer. Limited research has been found on in-situ hygrothermal measurements in archival boxes. The National Archives in the UK showed that relative humidity in an archival enclosure such as an archival box or envelope can have different values compared to ambient conditions in the used environmental test chamber [150]. Clare et al. describe that under certain circumstances the RH in a box increases beyond the ambient RH conditions. Such a circumstance is, for example, a quick drop in ambient RH conditions. Humidity is being delayed in the archival box even if the levels are higher than ambient conditions. The microclimate shows fluctuations even when it has not reached the ambient level. The study shows that it would take approximately over a week to reach an equilibrium inside the box when ambient conditions have changed significantly [150]. In a white paper the Image Permanence Institute disclosed several conclusions drawn from a large study where photographs, paper, books and the use of different enclosures were tested in laboratory setting [151]. Intentional temperature set-backs, based on energy saving potential, showed that temperature change distributed quite fast through the used samples. Only hours passed for the core of the test sample to reach thermal equilibrium. Moisture variations seemed to be mitigated due to used enclosures. The test samples showed a distinct difference between surface and core. One of the major conclusions was that RH fluctuations in the test samples in the box are less dependent on change in ambient RH, but more on temperature change.

Given the current trends in designing and developing low-energy storage facilities and the more traditional required climate specifications in Dutch Archives, the question is to what extent the dependence on technology (i.e. HVAC) can be reduced while still maintaining appropriate conditions for collection preservation. Smedemark et al. [53] showed that semi-passive climate control is promising, however, the conclusions are valid for repositories in purpose-built storage facilities with limited external walls present. External temperatures of below 0°C during wintertime and above 25°C during summer were present. Indoor conditions of archival or library facilities housed in existing or even historic buildings are more likely to be affected by conditions in adjacent rooms or external climate conditions [145]. Storage spaces are often packed with archival collection in special archival racks. The large amount of hygroscopic material is able stabilizing RH when ventilation flows are reduced [71, 46]. The archival racks form bluff bodies meaning they separate airflow and stagnant air zones might occur resulting in microclimates. Stable and homogeneous conditions are largely dependent on the airflow distribution in a room. In repositories, an air handling unit (AHU) is to a large extent responsible for distribution and well-mixing of air. It is therefore important to understand to what extent airflow is influenced by the repository design. Guidelines and legislation provide requirements for ambient indoor climate parameters, but do often not consider other factors that influence the near-object environment such as the use of archival boxes, airflow distribution and archival rack placement.

This study aims to provide more insight in the relation between the ambient indoor conditions in repositories and the hygrothermal conditions surrounding the collection. Through an experimental campaign hygrothermal indoor conditions provides insight in the use of archival boxes to create a favorable preservation microclimate. A numerical study is conducted to help investigate whether HVAC air supply and extraction and archival rack placement have influence on indoor airflow distribution. Without increasing risk to the archival collection, computational modeling provided quantitative means to investigate the results from the measurements and whether reducing the air supply during a limited amount of time has influence on stable indoor conditions suitable for preservation of heritage collection.
The following research questions have been formulated to structure the current study:

- How do the ambient hygrothermal conditions of the repository affect archival box hygrothermal conditions?

- In what way does the orientation of archival racks influence the air distribution of supplied air and therefore the homogeneity of ambient air conditions?

- what is the effect of a reduction of ventilation at night on the hygrothermal conditions and air distribution throughout the repository?

4.2 Methodology

Case study description

The case study investigated in this research is an archival institution situated in Leiden, the Netherlands. The collection present in the repositories comprises archival collection (i.e. books, newspapers, building plans etc.) and archaeological collection of Leiden and surroundings. The majority of the archival collection is housed in storage racks and is placed in some type of enclosure such as archival boxes and envelopes to protect it from external risks (figure 4.1, a building plan can be found in figure I.20).

Several functions are housed in the building; (i) public accessible areas such as an auditorium and research facilities and (ii) internal areas such as the repositories and offices. These areas are divided over multiple, interconnected buildings. Part of the building is an enlisted building. Most repositories with a ground surface of 836 m^2 are located in a five-story high tower (see Appendix figure I.20). The other part of the archival collection (652 m^2) can be found in a two story building connected to the general, public rooms such as a reading room and auditorium. This study focused on the repository tower. Per floor the repository takes up approximately 170 m^2 and with a height of 2.3 m the repository volume is 391 m^3 (figure 4.2 shows one repository floor of the tower). This part of the building is an extension with a brick cavity wall with low thermal resistance (U-value $>$ 2 W/m^{2}K). On all floors small repetitive windows are present on both the east and west side of the building. The windows are internally blinded by a layer of dark paint to prevent internal solar irradiation.

Figure 4.1: *External impression (image from www.visitleiden.nl).*

The climate control system of the repository is an older Heating, Ventilations and Air-Conditionsing (HVAC) system (>25 years old) which is able to control both temperature and relative humidity in the repositories by means of heating, cooling, humidification and dehumidification. It also has an F9 filter to collect fine dust and particles (1-10 μm) The AHU makes use of recirculation (90%) and fresh air (10%) mixing. The AHU supplies conditioned air to all floors. Combined T/RH sensors in the return ducts of each floor are averaged and determine the control action. Figure 4.2 shows the floor plan of repository number 6 (located on the 4th level of the tower), moreover, a schematic representation is given for the supply ducts (orange) and extraction ducts (blue). Figure and figure 4.3 shows the section of the repository tower including depots 3 through 7. Over the entire width of the room ducts were placed at the top of the walls. Inlet grids (75mm x 225mm) were placed every other meter to provide an even inlet profile. Climate control adopted a temperature setpoint of 16.5°C with a permissible fluctuation of ±1°C. During summer, inlet conditions could be even lower to reach the adopted room setpoint. Due to the low inlet T conditions it is difficult to dehumidify the supply air. This resulted in an adopted RH specification of 55% with a permissible fluctuation of ±5% RH by the institution. Visitors are incidentally allowed in the repositories for special tours. The conservation specialist retrieves items to a special restoration area to work on the preservation of the objects. Visits to the repositories are limited.

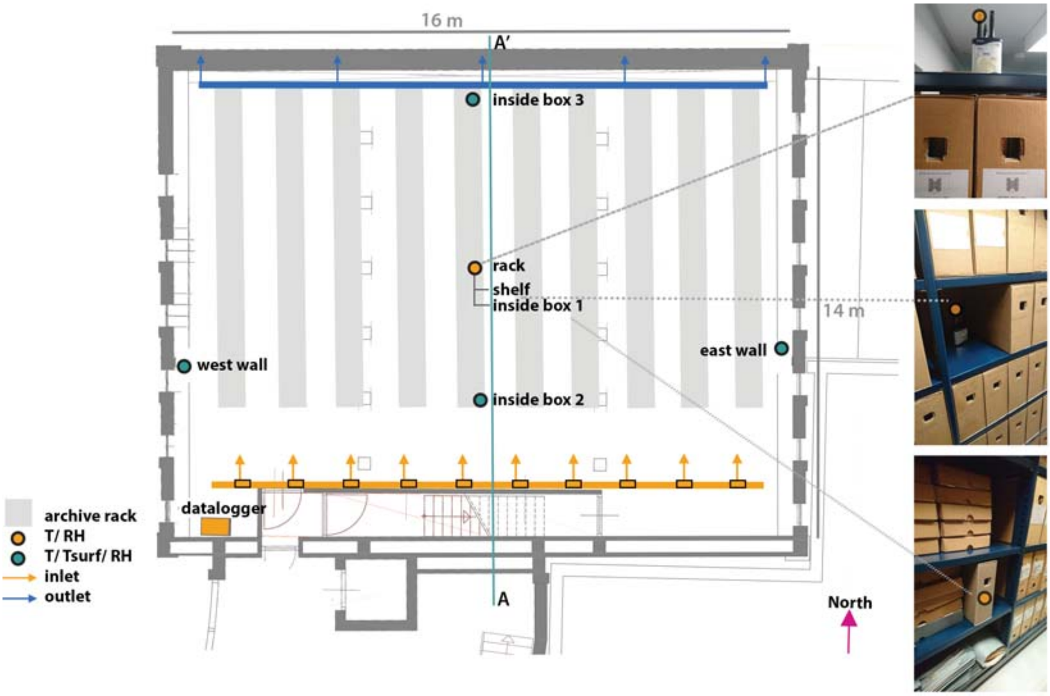


Figure 4.2: *Floor plan of depot 6 with locations of experimental measurement campaign.*

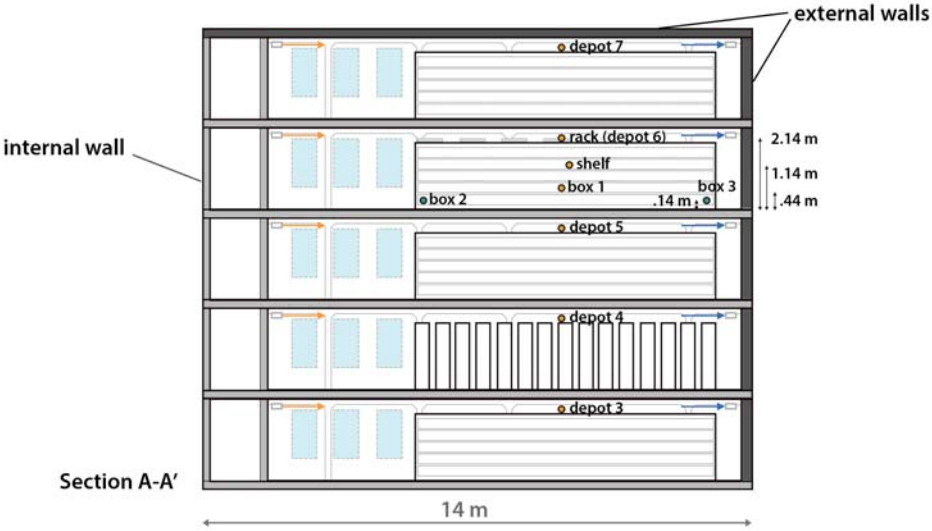


Figure 4.3: *Vertical section A-A' shows a schematic of the repository tower (floors 3 to 7) with the locations of the T/RH sensors.*

4.2.1 Environmental monitoring

To gain insight in the indoor climate conditions of a specific archive and the effect of archival boxes, T and RH measurements were performed using combined T/RH Eltek sensors [152] with a time interval of 10 minutes and a measurement accuracy of ±0.4°C and ±3% RH. An Eltek RX250AL data logger was used to collect, store and send data to a server at Eindhoven University of Technology. This campaign started in September 2017 and lasted until June 2019. The measurement positions were determined by using a climate scan that determines deviating local indoor microclimates.

External climate conditions

External climate conditions were retrieved from the Royal Netherlands Meteorological Institute. This data was collected from a location approximately 5.5km from the repository location in the city of Leiden. External climate conditions where measured on an hourly basis. Table 4.1 shows seasonal statistical parameters for the year 2018.

Measurement locations

The area of interest comprises five floors of archival storage space in the *repository tower* of the building. Per repository floor the ambient hygrothermal conditions were measured with a combined T/RH sensor placed in the center of the room (the sensor location is called *rack shelf* in figure 4.2). On the fourth level of the repository tower (room name: *depot 6*), extra sensors were added to gain insight in possible vertical and horizontal stratification of the indoor climate conditions. The vertical measurement positions are (i) on top of an

Table 4.1: Overview external climate conditions using statistical parameters

	$T_{average}$ [°C]	T_{std} [°C]	T_{max} [°C]	T_{min} [°C]	$RH_{average}$ [%]	RH_{std} [%]	RH_{max} [%]	RH_{min} [%]
winter	3.9	3.9	14.3	-8.3	81	13	100	35
spring	14.7	4.8	28.8	1.2	79	16	100	24
summer	17.3	4.7	34.6	2.5	78	16	100	24
autumn	8.4	4.7	25.1	-3.1	86	10	100	48

archival rack; (ii) in the center of the rack on a shelf; (iii) on the bottom part of the rack in an archival box (figure 4.2, photographs on the right). The repository tower has three external walls (east, north and west) and one internal wall (south) which is adjacent to a hallway connecting the tower to the listed building. In depot 6 two sensors were placed near the east and the west wall and a connected surface temperature sensor was placed on the surface of the walls. At the beginning of the year 2019, two extra sensors were placed inside boxes 2 and 3. This was done to investigate the influence of microclimates on the climate conditions in the archival box.

Data processing and analysis

The measurements were used to gain insight in the present indoor climate behavior of the repositories. Ambient climate conditions in the different repositories were compared with the cumulative distribution function (CDF) per floor level for the entire measurement period. The slope of the curve gives information on the stability of the climate. The steeper the curve (slope is large) the more constant the variable is (in this case either T or RH is plotted). If the curve is relatively flat (slope is small), there is a large spread in measured values. The weekly, daily and hourly short-term fluctuations are plotted for both parameters. Biological risk based on high temperatures and/or high relative humidities are depicted through the fungal growth curve [139]. Biological deterioration could severely damage archival collection objects [142]. Chemical risk is presented by the lifetime multiplier (LM) (equation 4.1).

$$LM_x = (\frac{50\%}{RH_x})^{1.3^{e^{\frac{E_a}{R}(\frac{1}{T_x}-\frac{1}{293})}}} \tag{4.1}$$

Where RH_x [%] is the measured relative humidity at time point x, E_a is the activation energy in [J/mol] dependent on the type of material of the object, R is the gas constant 8.314 [J/mol], T_x [K] is the temperature in point x, and x is a data point in the data series. The lifetime multiplier is dependent on a reference T and RH of 20°C and 50% respectively [141]. The percentage of time the measurement data are within a certain criteria range (in this case Dutch Legislation for long-term preservation) is used to provide information on the preservation conditions for different measurement locations. Object environment measurements were used to assess the preservation conditions in an archival box.

4.2.2 Numerical study

The finite element modeling software COMSOL Multiphysics version 5.2a [99] was used to investigate the hygrothermal distribution in the repositories and explain the measurement results. With a simplified model, representing the geometry of the fourth floor of the case study, both air velocity and temperature profiles were calculated. Inlet conditions supplied by the current climate system were used as inlet boundary conditions. The simplification of the model was mainly due to simplification of the geometry to reduce computational complexity (i.e. computational time). The simulations serve as qualitative means to explain the obtained results from the T and RH measurements. The case study repository was set-up in such a way that the AHU inlet ducts were situated along the south wall. Several inlet grids supplied air at a height just above the archive racks. Air was extracted from the other side of the room at the north wall (see figure 4.4).

The numerical model consists of a heat transfer with surface-to-surface radiation model to account for radiation influences. The model combines convective heat transfer and radiant heat transfer. Assuming a well-mixed air zonal model is insufficient, and therefore, CFD was included to predict temperature distributions in the indoor air and heat transfer near the walls [153]. The heat transfer and fluid flow (CFD) modules of COMSOL were coupled through a multiphysics node. For this study the k-ϵ turbulence model was used to provide insight for this general-purpose case.

Figure 4.4A shows the model geometry setup for the numerical study. The repository, where fixed storage racks were placed parallel to the inlet ducts supply direction (red arrows), is shown in figure 4.4A. The red inlet grid has a height of 75mm. On the other side of the room a similar opening was assigned as outlet (dark blue). Measurement values of the external temperature - gained from the experimental campaign - were placed as boundary condition on the external wall. The floor, ceiling and internal wall had boundary conditions based on measurements from these surfaces. A 3D-section of one meter width was used to research the distribution of supplied air around the storage racks in the 3D model (figure 4.4A, orange segment). The 2D plane of analysis is marked as a blue plane in figures 4.4B and 4.4C. The *symmetry* boundary condition was used to reduce computational time and included all necessary elements surrounding the investigated 3D section. Figure 4.4C shows the model with racks perpendicular to the air supply direction.

Hygrothermal distribution was investigated by means of different scenarios where rack configuration, extract position and collection filling ratio were varied. Changes in the model were based on geometry differences (rack orientation, extract position and collection filling ratio) and by altering the inlet boundary conditions (night reduction). Table 4.2 provides an overview of the investigated scenarios.

Table 4.3 provides an overview of the boundary conditions of the numerical model. The four geometry scenarios as described in table 4.2 were used for multiple simulations. The time step interval was set to 30 minutes for all simulations to maintain good convergence.

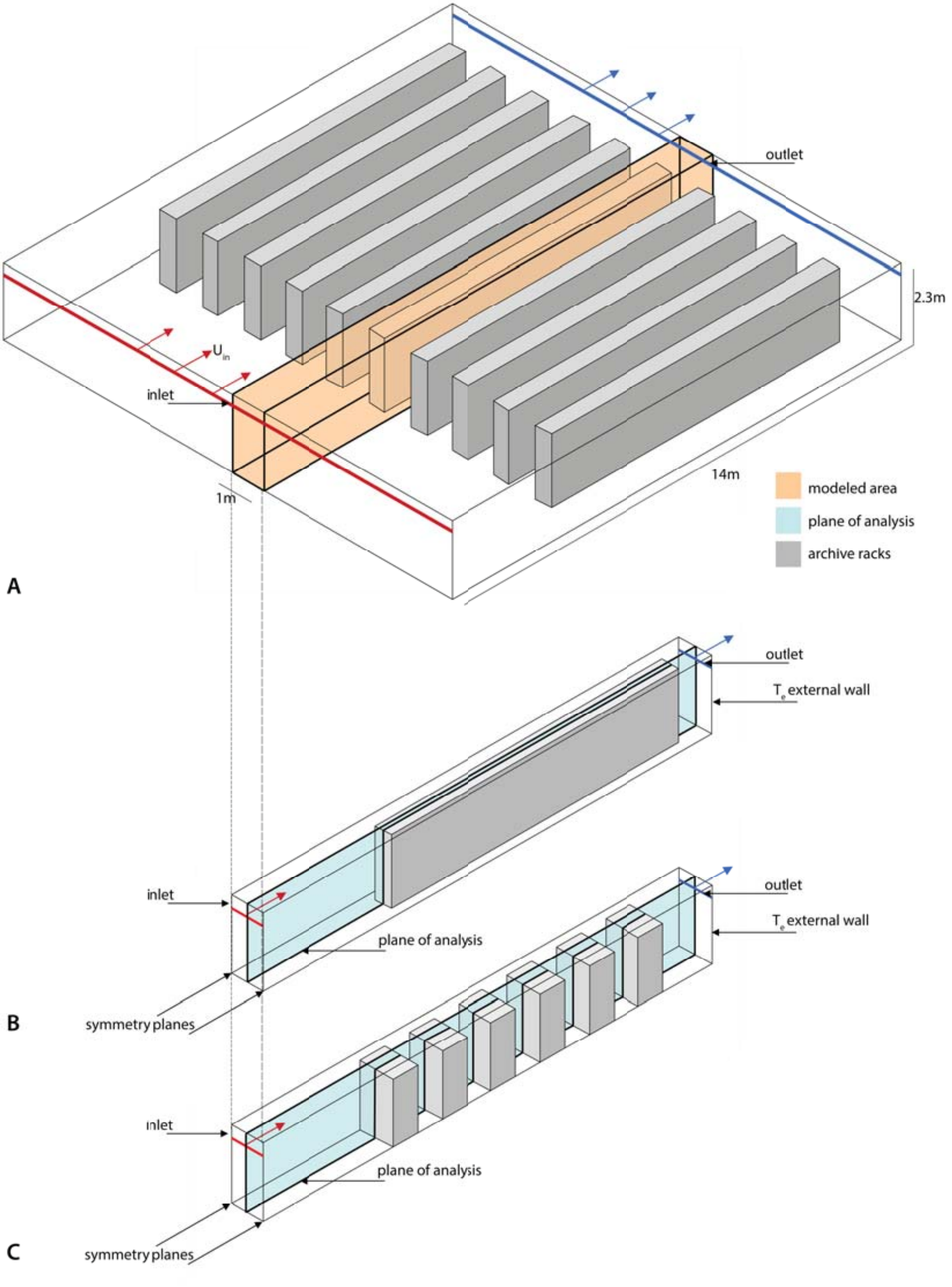


Figure 4.4: *Schematic geometry and boundary conditions for the 3D model for the archival racks parallel to the inlet direction scenario (A) and 3D representation of the perpendicular scenario (B) with open shelves.*

Table 4.2: Overview and description of different scenarios.

Scenario	Geometry	Description
A	Parallel racks	This configuration is commonly found in the repository. The archival racks are considered bluff bodies and represent collection filling up the racks (filling rate = 100%).
B	Perpendicular racks	This configuration is also commonly found in the repository. The archival racks are considered bluff bodies and represent collection filling up the racks (filling rate = 100%).
C	Perpendicular open shelves	This configuration has open shelves to investigate airflow through the different racks and shelves.
D	Night reduction	This configuration represents a change in climate control. The AHU can be turned off during closing hours (18:00h – 06:00h) by reducing the inlet conditions to no ventilation. During these hours no employees are present in the repositories and no disruptions are expected. The building envelope of the archive has low thermal insulating properties. The external climate boundary conditions are based on a climate file from the Royal Netherlands Meteorological Institute (KNMI). Using night reduction as control strategy would benefit energy savings [145].
E1	Parallel racks low extract	This configuration investigates whether placing the outlet near the floor would increase mixing of air and as a result promote more stable indoor climate conditions.
E2	Perpendicular racks low extract	This configuration investigates whether placing the outlet near the floor would increase mixing of air and as a result promote more stable indoor climate conditions.

Multiple statistical operators were used to quantify whether the model is considered accurate. Measurement data and simulated outcome were compared with the fractional bias (FB), fraction of data (FAC), normalized mean bias error (NMBE) and coefficient of variation of root mean square error (CV RMSE). The latter two are more commonly used in building simulation [137, 154, 155]. The FB and FAC1.05 are commonly used for CFD studies and are leading in the current CFD study [156].

$$FB = \frac{\bar{O} - \bar{P}}{0.5 \cdot (\bar{O} + \bar{P})} \tag{4.2}$$

Where O are the observed (measured) data points and P are the predicted (simulated) data

Table 4.3: Boundary conditions and settings of the numerical model

Physics modules	Conjugate heat transfer with surface-to-surface radiation; Non-isothermal flow
Radiation settings	Wavelength dependence of emissivity: constant
Surface emissivity factor	0.9 (colored paint – estimated value)
Inlet	$U_{in} = 1$ m/s, T_{in} = interpolation from on-site measurements
Outlet	$P = 0$ Pa
T_e	KNMI measurements
Internal walls	Heat flux based on on-site measurements from adjacent rooms
Turbulence model type	RANS
Turbulence model	k-ϵ
Reynolds number at inlet	1166
Include gravity	yes

points.

$$FAC1.05 = \frac{1}{N}\sum_{i=1}^{N} n_i \tag{4.3}$$

Where:

$$n_i = \begin{cases} 1 \text{ for } 0.95 \leq \frac{P_i}{O_i} \leq 1.05 \\ 0 \text{ for else} \end{cases}$$

The factor 1.05 is commonly used for temperature comparisons. Where N is the number of data points, P_i are the predicted values and O_i are the observed values.

$$\text{MBE } (\%) = \frac{\sum_{i=1}^{N}(O_i - P_i)}{O_i} \tag{4.4}$$

$$\text{CV RMSE } (\%) = \frac{\sqrt{\sum_{i=1}^{N}(O_i - P_i)/N_p}}{\bar{O}_i} \tag{4.5}$$

4.3 Results

This section describes the results gained from the measurement campaign. The section starts with results from the ambient indoor climate conditions in the repository tower. The next section explains the results found in depot 6 where more sensors were placed and different local microclimates were investigated during summer and winter seasons.

4.3.1 Ambient indoor climate conditions

Figure 4.5 (top) shows the Cumulative Distribution Function (CDF) per floor level for the entire measurement period. The majority of measured values was similar and this is reflected in the steep slopes for depot 3, 4 and 7. In general, average temperature values were between 16°C and 18°C and average relative humidity between 55% and 60%. Multiple statistical operators have been calculated and are presented in appendix I. The subfigures show the CDF plots for weekly, daily and hourly fluctuations in temperature and relative humidity. These were calculated by taking the difference between minimum and maximum values within the specified time. Temperature changes were small and were limited to 2°C for daily and weekly fluctuations. No obvious differences between floors stood out for temperature changes. It showed that temperature values can be considered rather constant.

The largest fluctuations in relative humidity were found in repository 7. Both daily and weekly relative humidity fluctuations show a large spread for all floors. This means that the relative humidity fluctuations that occur throughout the year were not as stable as the measured temperature values. The majority of hourly RH changes was below 3%/h (figure 4.5, D-right graph).

For all depots, an assessment was performed to see the percentage of time whether the T/RH requirements for Dutch Archival Legislation *long-term conservation* were met. The measurement locations evaluated in table 4.4, represent the average conditions of the different depots and were placed in the center of each depot. As soon as either T or RH is not met, the criteria is marked as not OK.

The Lifetime Multiplier was used to assess possible chemical degradation for paper objects. Table 4.4 provides the results of these calculations. Though the Dutch Archival Legislation criteria in most depots was not met, the Lifetime Multiplier showed values over 1.0, meaning the objects would last over 1 lifetime. This can be ascribed to the low temperatures present in the depot areas and the reference conditions the LM equation uses of $20°C/50\%$ (see equation 4.1).

Table 4.4: Assessment parameters for the different repository levels. The assessment criteria are based on the Dutch Archival Legislation [133]. The Lifetime Multiplier is calculated for paper material.

	Criteria OK - 18±2$°C$ and 50±5% [%]	LM [-]
depot 3	13	1.27
depot 4	10	1.5
depot 5	5	1.32
depot 6	7	1.31
depot 7	31	1.28

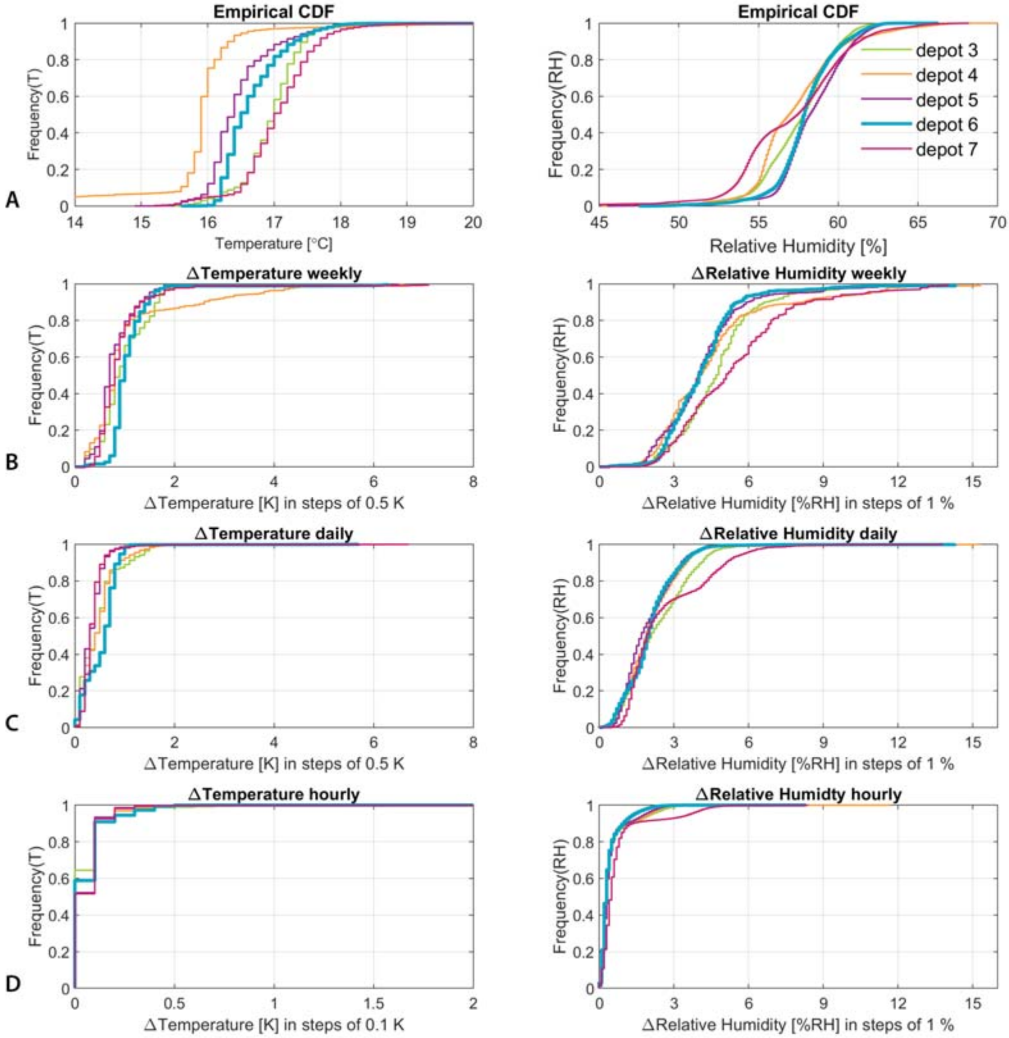


Figure 4.5: *Cumulative Distribution Function plots for all floors (A) over the year 2018. Going from top to bottom are the average short fluctuations for weekly (B), daily (C) and hourly (D) values presented in graphs for temperature (left) and relative humidity (right).*

4.3.2 Local microclimate (archival box)

To evaluate the local indoor microclimates found in repository 6, figure 4.6 shows the yearly results of the different sensors placed in repository 6. Figure 4.6A shows the measured data of T/RH in color and the dashed lines are the predicted spore germination time (starting from 75% RH as limit for biologically recyclable materials) [157]. This quickly shows the possibility of increased risk for biological degradation.

Figure 4.6 also shows the allowed fluctuation according to the Dutch Archive Legislation represented by the dark gray square. The amount of dots plotted in this square is the amount of measurements complying with the legislation requirements. As can be seen, the number of measurement points within this square was very little. Overall, the temperature was somewhat lower than the required specifications as defined by the archival legislation. The lower temperature was not resulting in an increased risk to the archival collection and even increased the Lifetime Multiplier (archival box 1 LM = 1.35 while 0% of the time the legislation criteria were met). The relative humidity is rather high. High relative humidity near the external wall shows increased risk for mold growth when it exceeds the limit. During the measurement period the climate conditions were not increasing the overall risk of biological degradation.

The cumulative distribution function shows that the spread in T and RH over a year of measurements in the archival box (orange) was 14-18°C and about 10% RH. Short-term daily fluctuation of T and RH were small inside the box. Again, near the external wall large daily fluctuations for T/RH were found. Objects placed near these walls might experience increased degradation risks from these short-term fluctuations such as mold risk.

Seasonal influences

Repository 6 has been investigated in depth by adding extra T/RH sensors. Figures 4.7A and 4.7B provide the results of T, RH and HR measurements in a typical summer and winter week. The sensor placed on top of the archive rack (blue line) showed larger fluctuations in T and RH compared to the other two locations. The shelf sensor (magenta line) showed a muted and more stable indoor climate. As expected the archival box showed muting and delay in both T and RH.

The typical winter week showed temperature declining inside the archival box of about 1°C. A cooling effect was noticed (3-5 December). While RH remained relatively stable, the humidity ratio also showed decreasing dips similar to the temperature curve. After noticing this cooling effect happening twice more during colder external periods in April and May of 2019 (figure 4.7C), additional sensors were placed in three archival boxes. One at the external north wall (box 3) and one near the internal south wall (box 2), (see figure 4.2 for exact sensor positions). Extra temperature sensors were also positioned just outside the archival box. The results of the sensors showed that box 3, near the external wall, experienced low temperatures while box 2, near the internal wall, showed no decrease in temperature in the period of 10-17 April (4.7B). The temperature sensors just outside the archival boxes showed similar trends as the sensors inside the archival boxes. Results showed that the climate inside the archival boxes was influenced by the local temperature which was a result of the thermal quality of the external wall.

A vertical stratification with high RH near the floor and low RH near the ceiling and vice versa for temperature was noted (figure 4.8A). The differences between preservation microclimate inside the archive boxes are shown in figure 4.8B. Differences in microclimate can reach 2°C and 4%RH with low external air temperatures. As the external air

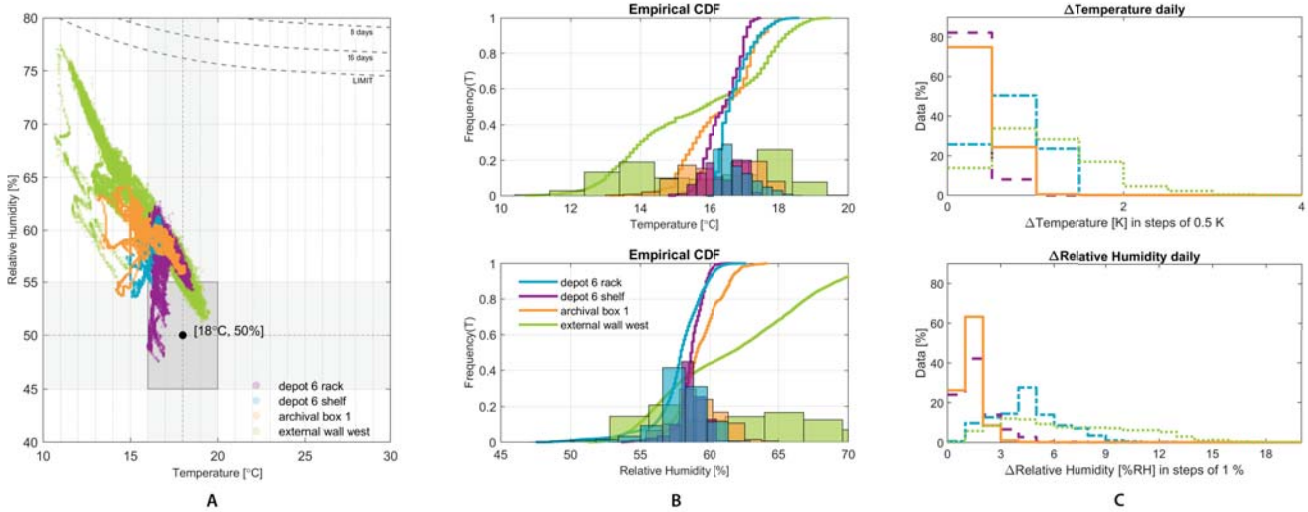


Figure 4.6: *Collected data of a year compared to Dutch archival legislation (A), empirical cumulative distribution function for T (B, upper) and RH (B, lower). The remaining graphs shows the average short daily fluctuations for temperature (C, upper) and relative humidity (C, lower)*

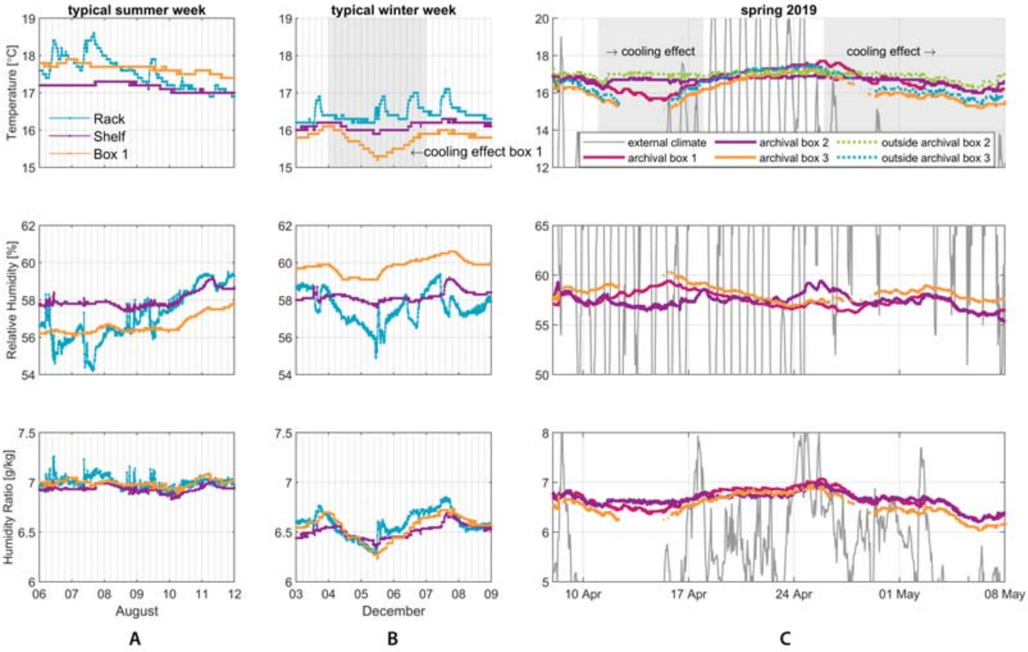


Figure 4.7: *T (up), RH (center) and HR (down) results for two typical seasonal weeks in 2018 (left, center). The typical summer and winter week show results of three measurement locations, rack (cyan), shelf (purple) and archival box (yellow). T, RH and HR for sensors in archival boxes (continuous line) and T measurements just outside archival boxes (dashed line) for April/May 2019 (right)*

temperature will be much lower in winter and higher in summer it was expected that these differences become larger. When external air temperature reached values of about 10°C the airflow circulation was not sufficient to eliminate the cooling effect near the external north wall. Thermal transmittance through the external wall in combination with surface radiation resulted in a local microclimate near the external wall with influence on the preservation conditions inside archival box 3. A difference in T of approximately 2°C was noticeable compared with the ambient temperature condition in depot 6. Decrease in thermal transmittance (lower U-value) of the external wall would be required to mitigate this effect.

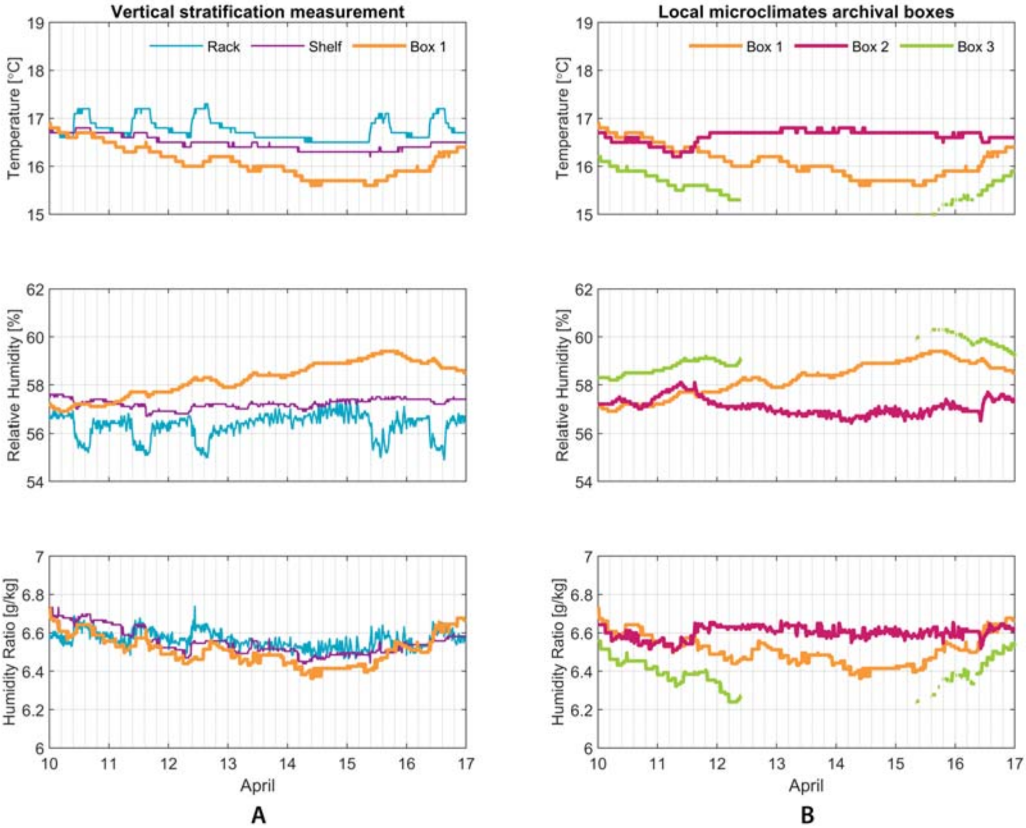


Figure 4.8: *Results for vertical stratification measurements and local microclimate conditions found in archival boxes for the period 10-17 April.*

4.4 Numerical results

This section shows the results of the validation of the computational model by comparing the data gained from the experimental campaign in repository 6, with the data gained from the numerical study of reference scenario A, archival racks parallel to the air supply direction. The results from modeling scenario's A-D are given in later paragraphs.

4.4.1 Calibration

A period of 7 days (10-16 April 2019) was modeled during the numerical study. This timeframe represented a critical period for the indoor climate preservation conditions due to low external temperature conditions (see figures 4.7C and 4.8) and as a result, a dip in T was observed in the archival box. External temperature of below 0°C during this period. These external conditions were used in all scenario's to see whether the dip in T through thermal radiation could be reproduced for different scenario's.

After performing a sensitivity analysis on the mesh size, the computational mesh consisted of a physics-controlled mesh with a COMSOL pre-calculated "normal" element size, the number of elements in the plane of analysis is 4,560 for scenario A, 9,280 for scenario B, 26.608 for scenario C, and 158,278 elements for the entire model (Figure 4.4 – orange segment).

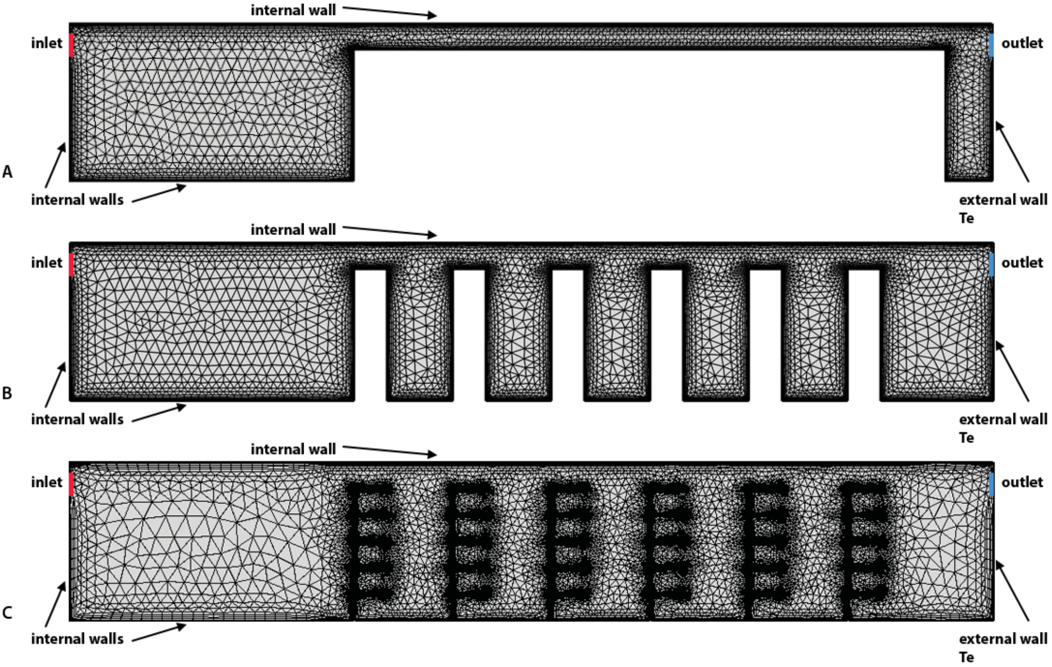


Figure 4.9: *Computational mesh in the plane of analysis for the geometry with parallel racks (A), perpendicular racks (B), and the geometry of perpendicular racks with open shelves (C).*

Figure 4.10A shows the evaluation grid set up to compare the numerical outcome with the measurement locations of the experimental campaign. The grid provided evaluation positions every 1m for a horizontal stratification evaluation and every 40cm for a vertical stratification evaluation, both coinciding with measurement locations.

Figure 4.10B shows the comparison between measurement positions and calculated evaluation locations. Good agreement between measurements and calculated values was reached between $T_i$rack and location 9f (figure 4.10C) as is shown in the statistical parameters of table 4.5. Comparison between $T_i$shelf and location 9d shows good agreement according to the statistical operators in table 4.5, however, figure 4.10 shows that the measurements show more muting of the T and RH fluctuations between the shelved. $T_i$shelf was placed in an occupied rack (see figure 4.2) whereas the numerical model does not take buffering from the collection into account.

Table 4.5 provides the full overview of the comparison between the numerical model and the measurement data. The model was evaluated in locations 9b, 9d, and 9f. The RMSE for location 9b, which is compared with measurement data inside archival box 1 is not in agreement which can be clarified by the box not being modeled as a separate entity.

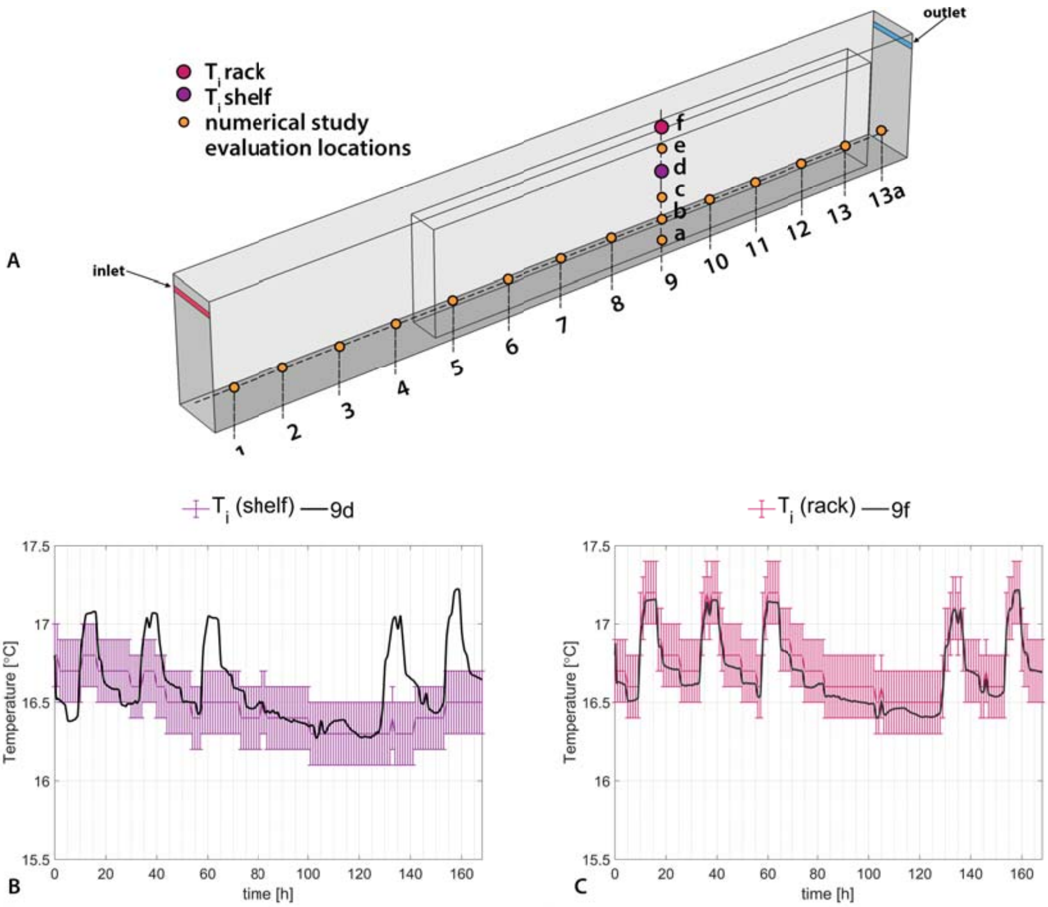


Figure 4.10: *Evaluation grid locations presented in the 3D model (A). Comparison between simulated temperature results and measurements performed in depot 6. The measured indoor temperatures for $T_i$rack (pink) and $T_i$shelf (magenta), including equipment accuracy error bars, compared to the calculated locations 9d (B) and 9f (C).*

Indoor climate behavior

The results in figure 4.11A show a typical colder night based on the coldest values modeled in evaluation point 9b (see figure 4.10B). External air temperature dropped below 0°C during that night. Figure 4.11B also shows the results of an average spring day during which the highest external air temperature during the measurement campaign was approximately 17°C and used during the calculations as boundary condition on the external wall. This simulation was performed to understand the cooling effect in the archival box that was discovered during the measurements. Figure 4.11 shows that, as expected, a large difference between outdoor and indoor air temperatures caused vertical temperature stratification. The air distribution

Table 4.5: Results of statistical operators for comparison between measurements data and 3D simulation results based on configuration scenario A. The criteria range for MBE and CV RMSE is based on ASHRAE guideline [138]

	FB [-]	FAC 1.05 [-]	MBE [%]	CV RMSE [%]
Aim	0	1	0	0
Range	(-0.3, 0.3)	>0,5	<10%	<30%
Rack (9f)	0.004	1	0.40	12.7
Shelf (9d)	-0.008	1	0.79	25.2
Box 1 (9b)	-0.022	1	2.23	70.8

mixing was not efficient due to the blockage by the archival racks. Maximum temperature difference throughout the zone was approximately 4°C (figure 4.11A). When external air temperature and internal supply air temperatures were similar to each other this resulted in a much more homogeneous temperature distribution (figure 4.11B). Temperature differences were within 0.5°C.

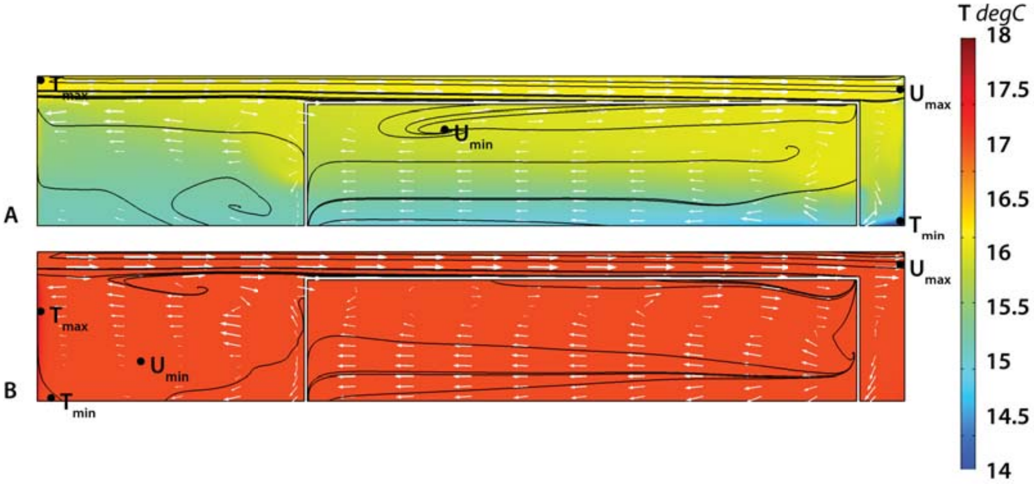


Figure 4.11: *Temperature distribution and velocity streamlines inside repository evaluated in the plane of analysis of scenario A for a cold night (April 14th 2019) and a regular spring day (April 16th 2019).* $T_{max,A}$ *is 16.8° C,* $T_{min,A}$ *is 12.5° C,* $U_{max,A}$ *is 1.0m/s.* $T_{max,B}$ *is 17.8° C,* $T_{min,B}$ *is 17.2° C,* $U_{max,B}$ *is 1.0m/s.* U_{min}*<0.0001 m/s and represents stagnant air in both cases.*

4.4.2 Scenario study results

In the next section the results of the different scenario's are discussed. An overview of the scenario's can be found in table 4.2. Figure 4.12 provides insight in the transient behavior of temperature in different evaluation points for all scenarios. The evaluation point locations are provided in vertical cross section A-A' of figure 4.12.

Appendix figures I.22 and I.23 shows the temperature and velocity distribution on April 14$^{\text{th}}$ 2019 at 04:00h. During this time the most extreme boundary conditions on the external wall applied. These figures will, besides figure 4.12, be discussed per investigated scenario in the following subsections.

Archival rack orientation; scenario A-C

In figure 4.12, scenario's A, B and C describe the rack orientation configurations where racks are oriented parallel (A), perpendicular (B) and perpendicular with open shelves (C) to the air supply are investigated. The temperature values found in evaluation points 13 and 13a for scenario's A-C were influenced by the external wall temperature reaching minimum temperatures during the night. A day-night cycle for T of about 2°C was established, which is similar to found daily fluctuations in T during the measurements (figure 4.6C). The remaining evaluation points were similar in temperature values which might indicate sufficient distribution of supply air (see figure 4.12 scenario's A-C).

Figure 4.11 shows that the spatial temperature distribution in between the parallel racks is fairly homogeneous. Comparing the different rack orientations (parallel, perpendicular and perpendicular with open shelves) in appendix I figure I.23 showed a temperature difference of 0.8°C in between archival racks between scenario B and C. Both the parallel as the perpendicular rack orientation form an obstacle and interrupted the forced airflow. This occurred especially behind the last rack near the outlet which was also observed during the measurements regarding archival box 3 (figure 4.7C).

Near the external wall lower temperatures were present in all three scenario's. In between the perpendicular placed racks stagnant air pockets were present (appendix I figure I.23B and appendix I figure I.23C). Modeling with open shelves provided better temperature distribution in between the racks. In most repositories however, the shelves were filled with archival boxes which would be more accurately represented by scenario B. Scenario C provides insight for repositories with lower filling ratio's and open areas near collection (as was the case with the measurements as shown in figure 4.2).

Night Reduction; scenario D

Scenario D uses night reduction to reduce ventilation and therefore reduce energy consumption. This scenario had the lowest wall temperature of 12.5°C during the night. A fluctuation towards the setpoint of 16.5°C was visible during the day considering the high fluctuation peaks in figure 4.12. It took approximately 12 hours to reach the setpoint at these locations before night reduction set in again. Location 9f showed interesting behavior. Increasing temperatures throughout the night due to heat transmission through the internal wall were noticeable.

In appendix I the temperature distribution plots with both AHU on and off are shown in figure I.22D$_{off}$ and I.22D$_{on}$. During nighttime the negative influence of the low thermal resistance of the external wall was visible with near wall temperatures of 12.5°C. With low temperature a higher relative humidity will be expected near the wall surface. A gradual spreading horizontal temperature stratification was noticed in between the racks.

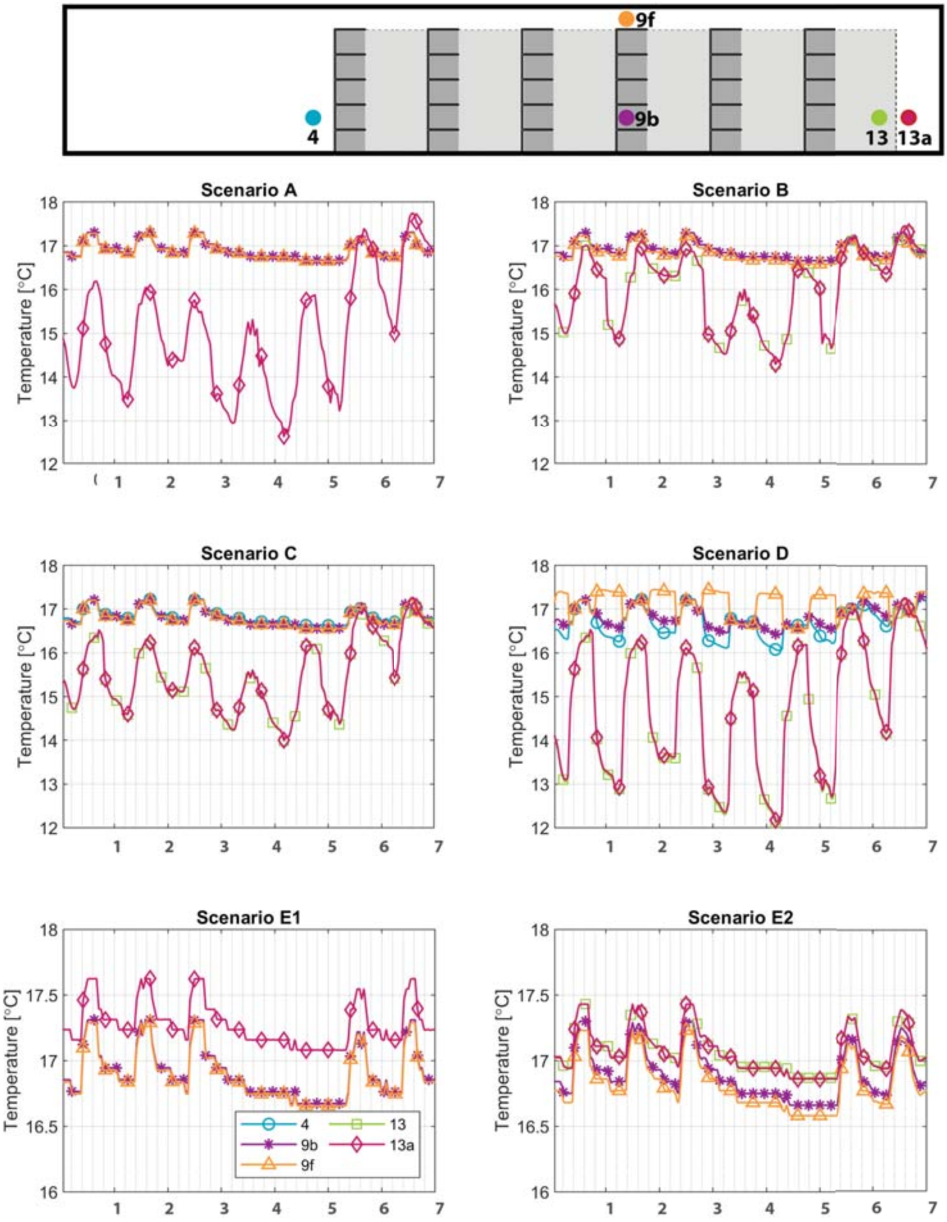


Figure 4.12: *Results for temperature evaluation in different evaluation points for the investigated scenarios. Vertical section A-A' shows the locations of the different evaluation points. Green and red (13 and 13a) are located near the external wall. Magenta (9b) is located on the center shelf, orange (9f) is located as ambient condition position on top of a rack and blue (4) is located in front of the racks. Scenario A positioned the racks parallel to the inlet direction. Scenario B positioned the rack perpendicular to the inlet direction and Scenario C has perpendicular positioned open shelves. Scenarios E1 and E2 have a low extract compared to scenarios A-D. Scenario D has no AHU influence during closing hours.*

During daytime, when the AHU is operational, a homogeneous temperature distribution was calculated.

Air supply and extraction placement; scenario E1-E2

In terms of stable indoor climate conditions, scenarios E1 and E2 provide the least air temperature fluctuations in this study (mind the difference in x-axis of figure 4.12). Placing the outlet grid near the floor provided improved mixing behind the archival racks and resulted in a more homogeneous temperature distribution. Scenario E is recommended to increase air mixing for both rack configurations.

4.5 Discussion

While legislation provides normative indoor climate requirements, achieving these proves difficult. The influence of the building envelope design and building systems design on indoor climate parameters is significant. It is recommended that collection placed near external walls is monitored closely. This is mainly the case when low thermal quality walls are present in the building. While Dutch Archival Legislation mentions to be careful of placing objects near floor and ceiling, no mention of adjacent areas with different climate conditions is mentioned [133]. A solution to overcome this would be to increase thermal insulation of the building envelope, for passive buildings a U-value of 0,10-0,15 W/m^{2}K is recommended. Increasing thermal insulation would create a buffer between external climate and indoor climate in which a low T would be maintained. Another option would be to look into sufficient airflow distribution in the repository, however, this seems the less energy conserving road to take and without innovative solutions would result in an increase in dependency on (climate control) systems. This research could be of help for arranging the archival racks to optimize airflow mixing of inlet conditions. The research provides interesting information for ‘closed’ archive systems (i.e. rolling rack storage) where the racks are placed against each other with limited form of airflow in between and the investigated fixed archival racks. Dutch Archival Legislation provides requirements per type of rack set-up and how much air-circulation needs to be present [133]. Further research could be performed in optimizing the filling ratio of shelves in different rack configurations for increased buffering capacity.

Measurements and numerical modeling provide insight in the climate conditions in repositories. While it is common to monitor the ambient indoor air conditions of a space or in the HVAC return duct, the experimental part of the research shows that locally deviating indoor climates are present and the ambient indoor conditions do not represent the hygrothermal conditions of the repository inside archival boxes. While stable T and RH are required by legislation, this study shows that even though an HVAC system is present, stable conditions might not be maintained and near the external wall daily T fluctuations occur. T/RH cycling seems not to be of influence on chemical degradation and avoiding fluctuations from a chemical decay point of view is not necessary [158]. This would underscore the idea of using passive ways to maintain preservation conditions (specifically low, stable T which results in a stable RH) archival facilities where daily fluctuations are almost canceled out but seasonal fluctuations do gradually occur [44]. With passive or semi-passive measures the effect on accumulation of volatile organic compounds (VOCs) needs to be considered [53, 159].

A limitation of the current study is the lack of extensive validation based on wind speed distribution measurements. The numerical study was used as a means to understand the hygrothermal measurement results. For this, the inlet velocity was measured short-term and compared with the building management system velocity. The building management system inlet velocity was used as imposed boundary condition. To gain more accuracy in the numerical model, the calculated air distribution needs to be compared with measurements.

The microclimate measured during the experimental campaign is influenced by thermal radiance of the external wall. Both boxes 3 (closest to external wall) and 1 (in the center of the repository) show influence with a dropped $T_archivalbox$. This complies with results mentioned in studies such as Wilson et al., Clare et al. and Bigourdan et al. where the microclimate monitored in archival boxes showed a time delay of a few days [149, 150, 151]. Comparing both the microclimate in the archival box and just outside of the archival box, the trend shown in the two results is similar (see figure 4.7). Therefore, the degradation risks for objects placed in or out of an archival box would most likely be similar when it comes to incorrect T and RH. In the currect case, there was a cooling effect which did not increase risk to archival objects that prefer preservation specifications with low T. Further research could account for thermal and hygric buffering of the archival box and to what extent this reduces degradation risk during long periods of warm external temperatures.

Based on the research questions described in the introduction, the following conclusions can be drawn from this chapter:

- Measurements show that the microclimate in an archival box has a small daily span for T and RH. A stable daily climate surrounds the archival collection inside the box. The seasonal span for T and RH of the archival box near an external wall shows larger fluctuations compared to other positions in the archival rack. This is mainly due to the influence of the external wall radiation which is also experienced by objects outside archival boxes placed near the external wall. Since relative humidity does not exceed 65% for a long period to form biological risk issues and short-term (hourly) fluctuations in temperature do not exceed 1°C, preservation conditions are considered good inside the archive box even when the conditions do not meet the criteria set by Dutch Archival Legislation. T is on average lower than legislation prescribes. During summer this increases cooling energy consumption significantly.

- The simulated scenario's with archival racks perpendicular to the inlet direction show low velocities in between the racks. Placing the racks in a parallel orientation ensures air-movement and therefore air-mixing in between the racks. Fixed archival racks with a low fill rate create local indoor microclimates in between objects or shelves. Completely filled archival racks have the convenience of high thermal and hygric buffering by the objects, short-term fluctuations will have limited effect on the core of the objects due to this buffering capacity.

- According to the numerical model, scenario D (night reduction in which the AHU is turned off) provides the largest temperature fluctuation near the external wall with 4°C. The fluctuation occurs gradually over a time period of 12 hours (≈0.35°C/h).

Turning off the AHU in a repository indicates more influence of indoor temperature towards the building envelope quality. In the case of a low thermal quality this results in temporal gradients near the external walls. If the thermal quality of an external wall is good, very limited influence of the external climate is expected and energy conservation increases. A small amount of ventilation might be needed to remove volatile organic compounds emitted by objects or building materials.

- The duct placement of an HVAC system assists in creating vertical stratification when both supply and extract are located near the ceiling. It results in limited airflow. Low external wall quality contributes to a horizontal stratification when air-mixing is blocked by objects such as archival racks. Improving airflow for better air-mixing near an external wall is done by placing the outlet grid near the floor near the external wall.

5 | Analysis of a novel display case design

This chapter is largely based on: K. Kompatscher, B. Ankersmit, E. Neuhaus, M.A.P. van Aarle, A.W.M. van Schijndel and H.L. Schellen. *'Experimental and numerical analysis of a novel display case design: Case study of the renovated Anne Frank House'. Studies in Conservation* **65** (2019), pp. 262-284

Abstract

Many museums are housed in historic buildings, sometimes the building itself is part of the museum collection. Creating a stable environment by providing a nearly constant temperature and relative humidity at correct levels decreases the risk of object degradation. Maintaining this steady indoor environment, however, increases energy consumption and risks to the historic building. Museum display cases offer a solution to the mitigation of risks to which valuable objects may be subjected by providing an extra layer of protection to indoor climate fluctuations. The Anne Frank House is a historic house museum located in Amsterdam. The museum has undergone several renovations in the last years to deal with an increase in the number of visitors to over 1.2 million a year. The original diaries and other documents of Anne Frank are permanently on display in the Anne Frank House. With the recent refurbishment the possibility arose to design a new state-of-the-art display case. This study presents the results of the experimental research related to the design, performed in-situ. The temperature and relative humidity in the new exhibition space and inside the new display cases were monitored to gain insight into the hygrothermal behavior of these controlled environments. A complementary numerical study was performed to investigate effects of dynamic climate control of the exhibition gallery and climate conditions in the display case under various circumstances. Four main conclusions are presented in this paper. The investigated display case design is able to provide a stable relative humidity environment by means of silica gel, while using an active box-in-box climate control system to create stable temperature conditions. The inner case temperature depends on the temperature supplied by the display case air handling unit. Protocols must be in place in case of malfunction or failure of the climate control system of the display case. The air handling unit of the case needs to be shut off to create a passive environment for the objects on display until necessary actions are taken. Exhibition gallery setpoints can be less stringent when susceptible museum objects are on display in the display case. The environments are separated and provide opportunity for energy saving set point strategies. The last conclusion drawn is that the numerical study

provides valuable insight into imposing dynamic control of setpoints for temperature and relative humidity in the exhibition gallery and the effect on the display case environment.

5.1 Introduction

Museums are often located in historic buildings. Many historic buildings have been adapted to house museum collections. Often, a Heating, Ventilation and Air-Conditioning (HVAC) system is installed to provide indoor climate control. This climate control is needed to provide suitable indoor climate conditions for object preservation. Based on limited research in the past and development of precise technical equipment, a constant temperature (T) and relative humidity (RH) were strived for to reduce risks to objects [9]. Maintaining this strict indoor climate can result in high energy costs, possible damage to the building itself, and in the case of historic buildings, the desired setpoints are often not reached [1, 36, 57].

The use of museum display cases make it possible to maintain less stringent climate conditions in the exhibition area while providing climate control for objects in the display case. Museum display cases provide an extra layer of protection against (i) physical damage (ii) theft and (iii) inappropriate climate variations [160]. Shiner 2007 described different trends in display case designs throughout the years [161]. In order to buffer T and RH fluctuations, passive systems make use of thermal and hygroscopic inertia. Certain finishing materials or the use of silica gel can create an environment where vapor adsorption capacity is high and RH can be regulated [49]. Active display case systems rely on equipment to control the internal conditions [162, 163]. Although the display case creates a well-controlled microclimate, it provides some risks as well. Air tightness of the display case may trap internally generated pollutants. Examples are organic acids emitted from certain types of wood, reduced sulfur compounds from wool, or even fatty acids from the oil medium found in paintings. Internally generated pollutants from the object itself can build up or be trapped if the display case is well sealed. Ventilating the case requires filters to prevent external pollutants from entering, and increases exchange with external unconditioned air [50].

This study focuses on the Anne Frank House located in Amsterdam. The museum is housed in buildings surrounding the World War II hiding place of Anne Frank. These buildings are part of the museum collection. Because of its societal value, one of the primary tasks of the Anne Frank House is to preserve the diaries and other writings by Anne Frank. The museum strives to educate and spread awareness on the WWII period in Amsterdam based on Anne Frank's life story. The collection of the museum is comprised of the building, and interior furnishings. Major collection items are the documents of Anne Frank, including her diaries, which have been since listed since 2009 by UNESCO as "Memory of the World". The majority of collection items on display are placed in display cases to provide protection from the impact of high visitor numbers.

Before the renovation, the Anne Frank diary and other documents were exposed to wide daily temperature fluctuations where the room temperature (T_{room}) could reach 24°C during opening hours while it cooled down to 19°C during the night (δT = 5°C). These fluctuations could be ascribed to the quality of the building envelope, the number of visitors present, and an HVAC system unable to compensate. RH was maintained stable by means of silica gel in the display case. The temperature fluctuations in the display cases were especially of great concern to the museum management for conservation purposes.

Museum management decided that display case renovations were necessary to keep welcoming the high number of visitors to the site without increasing risk to the displayed objects. Since the display cases were not providing the microclimate the museum management desired, a new design was aimed at maintaining the established T setpoint of 17°C with no permissible fluctuations. Another requirement was to reduce the vibration risks caused by visitors. After careful consideration and discussion with external consultants, a box-in-box principle was adopted for the new display case design. Separating structures into an inner display case and an outer display case provided less risks to the diary in terms of vibration. The air cavity that was created by this box-in-box principle lent itself to T control. The cavity separating the inner display case from the outer one, can be cooled to provide stable internal T conditions. Silica gel in the inner airtight case provides a stable RH. The objects, such as the diary, are placed in this inner compartment. In-depth details and description are provided in section 5.2.

Though a plethora of research can be found on both active [162, 163] and passive [49, 50, 164, 165, 166] display cases, an active box-in-box principle used for a display case is novel. In the current study, active T control has led the box-in-box design while RH is controlled passively. This in contrast to most literature where RH control is primary in the design and evaluation of collection care. However, varying T can lead to RH fluctuations in a display case and this influence should not be underestimated [49]. Stabilizing T results not only in a more stable RH, it also reduces the risk of chemical degradation of paper objects.

The goal of this study was to obtain insight into the following objectives:

- Evaluate the performance of the novel display case design using experiments and modeling simulations.

- Evaluate display case design with active T control as a measure of preventive conservation for paper objects.

- Gain insight into the relation between the established exhibition room and display case inlet conditions on the T and RH distribution of the display case.

- Gain insight into performance behavior by evaluation of predicted performance for one year of exhibition room conditions.

The outline of this paper is as follows. Sections 5.2 and 3 provide a description of the research methods that have been used in this study. First, the display case is described in detail. Then, both experimental and numerical methods are described. Section 5.3 elaborates on the results of the experiments and performed simulations. The results are discussed and conclusions drawn in Section 5.4. An Appendix is added to provide additional T and RH calibration information of the experimental campaign (Appendix K).

5.2 Methodology

To structure the research the following methods were used during this study. First, a description of the museum, the novel display case design and all systems involved in climate control is given. Second, the measurement setup and experiments performed are described in detail. Lastly, the numerical model is explained that was used for predictive performance simulations.

5.2.1 Site description

Figure 5.1 illustrates the museum exterior and interior. The museum is located in the city center of Amsterdam in two 17^{th} century canal houses. The museum has undergone several renovations to deal with the increase in the number of visitors to over 1 million a year. Over the years, additional buildings were annexed to use for museum facilities such as entrance, café and offices. The galleries can be divided in the main house, the secret annex, the diary gallery and the general exhibitions. The general exhibitions are housed in a refurbished addition. The canal houses have an original brick masonry exterior wall, internal separation walls finished with drywall sheets, and wooden floors covered with linoleum. Adaptations to the building have been made to fit a hybrid climate control system. Conditioned air is supplied by AHUs and in certain museum galleries only radiators are present for heating purposes. The AHUs are located on the roof of the buildings. Once the air is conditioned through either heating, cooling, dehumidification, humidification and filtering it is supplied to the museum galleries. Certain galleries make use of an extra heater in the supply duct to reheat the air just before being delivered to the gallery. The galleries are all in open connection with each other. This means the air is distributed based on pressure, concentration and temperature differences.

Gallery

An important gallery in the museum is the exhibition gallery where manuscripts of Anne Frank are on display. The exhibition gallery is rectangular in shape, 13.1 m deep and 4.8 m wide. Windows are located on the northwest wall facing the canal (see figure 5.2). Visitors enter through a hallway and descend a three-step staircase into the exhibition gallery. A red-colored wall is located in the center of the room as a backdrop for the display case containing one of the diaries of Anne Frank (DC1). Behind the red wall, near the exterior façade, two other display cases show other writings by Anne Frank (DC2 and DC3). The exhibition gallery climate is controlled by one Air Handling Unit (AHU_{room}). The supply and return ducts of AHU_{room} are located at the canal side of the building and additional supply grilles are placed in the three-step staircase and near the entrance area of the gallery. These extra supply grilles create enough mixing ventilation for a homogeneous indoor climate. Figure 5.3 shows the HVAC system placed in the technical area below the exhibition gallery. The upper elevation shows the AHU_{room} while the lower elevation shows the AHU assigned to the display cases (AHU_{case}). AHU_{room} preconditions the air by means of humidity control and temperature control. The return duct of the exhibition gallery is connected to AHU_{room} for recirculation purposes. By means of a bifurcation the return duct of AHU_{room} is also connected to AHU_{case}. AHU_{case} conditions only for air temperature. The use of display cases makes it possible to relax previously adopted strict

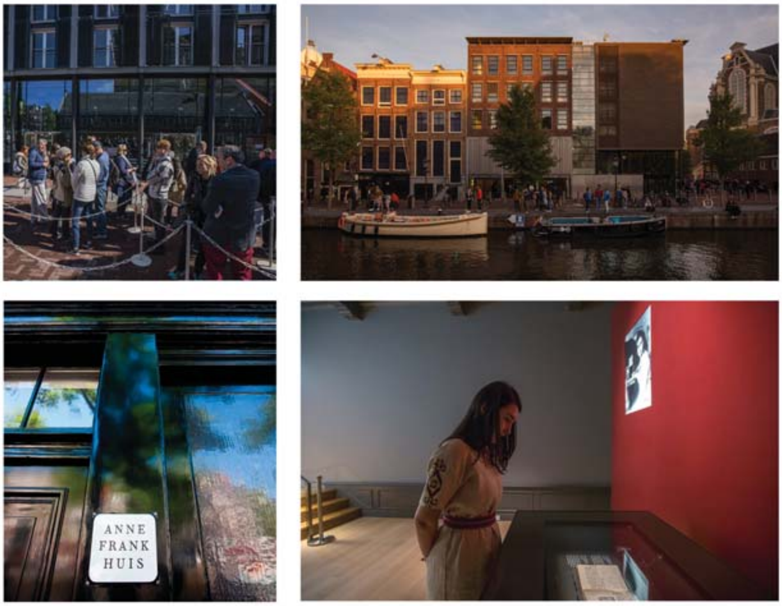


Figure 5.1: *Impression of Anne Frank House exterior (left images and top right) and the interior of the new Diary room (bottom right) with display case 1. Images ©Anne Frank House / Photographer: Cris Toala Olivares.*

room setpoints of 50±5% RH and 20±1°C. Museum management adopted the idea for less stringent RH setpoints. RH is allowed to fluctuate within lower and upper limits of 45-60%. The exhibition gallery T set point was kept at 20±1°C.

Display cases

With the refurbishment it became possible to improve the display case design. Past measurements showed that the display cases could stabilize RH, however, T fluctuated according to gallery conditions. The newly developed display cases had the objective of stabilizing both T and RH throughout the year, reducing risks caused by vibrations, increasing safety, decreasing possible risks by internal and external pollutants and decreasing risks caused by illumination. It took a number of years to develop the concept and finalize the design by the Anne Frank House, Getty Conservation Institute, multiple companies, the Cultural Heritage Agency of the Netherlands and the Eindhoven University of Technology.

The result was a state-of-the-art display case design consisting of a larger outer display case and an inner display case (i.e. a box-in-box design). Figure 5.4 provides a schematic view of the cross-section of the display case. The larger case was used to create space for air ducts that supply preconditioned air into the air cavity that separates the outer from the inner display case. The outer display case was placed on the new raised floor which leads directly to the technical area below. The inner case was attached to steel beams fixed directly to the walls of the outer case. Injected air overflowed partly into the technical room and partly to

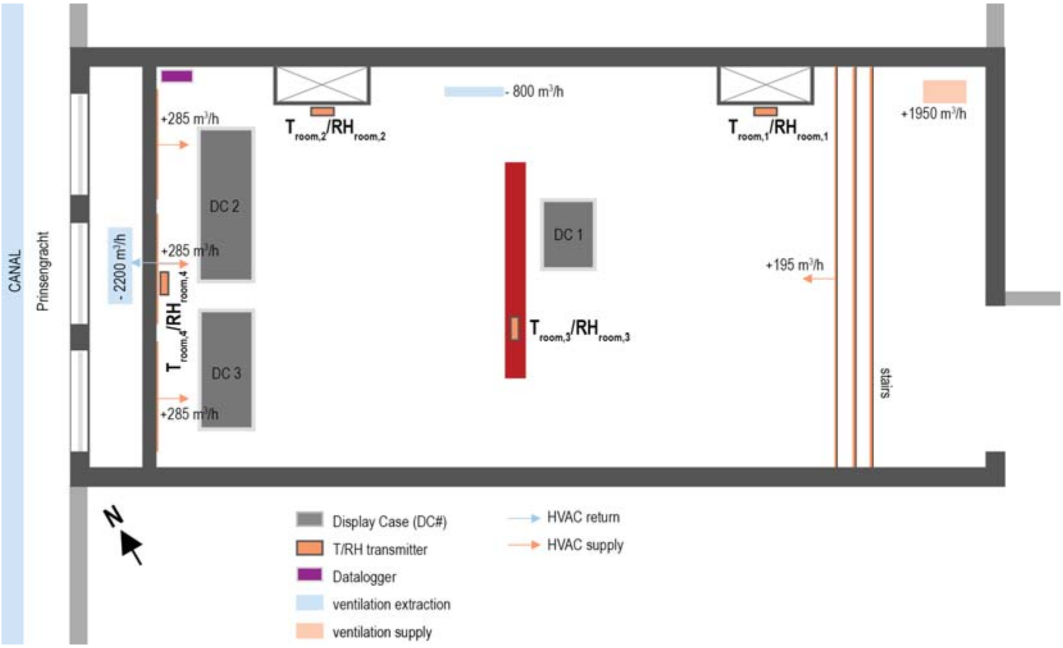


Figure 5.2: *Floorplan of exhibition gallery with T/RH sensor locations and positions of the air in- and outlets with the air volumes involved.*

the exhibition gallery by exfiltration. The inner display case air temperature ($T_{a,case}$) has a set point of 17.5°C without permissible fluctuations. The inner display case was separated into two compartments. The lower compartment houses two drawers for preconditioned silica gel for RH management. The upper compartment displays the museum objects. A gap of 17 mm between the object compartment and silica gel compartment provides sufficient moisture exchange to create a stable environment. By means of diffusion principles RH should stabilize in both compartments at 45% RH. The result should be a constant RH of 45% in the inner display case due to the preconditioned silica gel. The inner case was sealed to limit air exchange between the cavity area and object area. Air exchange rates (AER) were calculated from experimental testing by the manufacturer after constructing the cases (AER DC1 = 0.1335/d; AER DC2 = 0.0943/d; AER DC3 = 0.0802/d. These AER experiments were performed based on Thickett et al.[167]. The display case was constructed with steel, glass and finished with the nonporous, surfacing material Corian (acrylic resin mixed with natural minerals). Figure 5.5 shows impressions of the display case design while opened.

5.2.2 Experimental campaign

During the experimental campaign the indoor climate of the exhibition gallery and the environment within the display cases were monitored. This campaign was used to gain insight into the box-in-box concept and the influence of the room conditions on the inner display case. A preliminary experimental campaign was carried out at the manufacturer as soon as one of the cases was finalized. This preliminary campaign was used to pinpoint

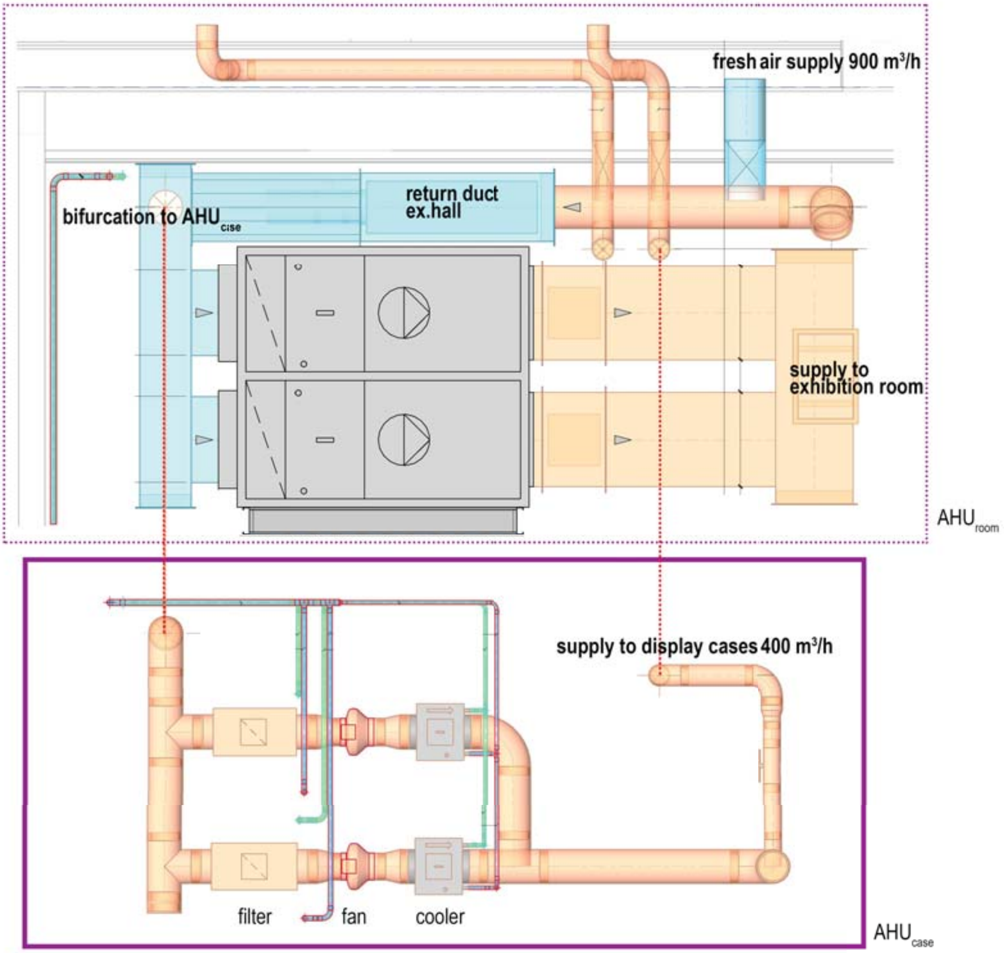


Figure 5.3: *Sections of AHU_{room} and AHU_{case}. Image adapted from Breman.*

the airstream behavior in the cavity. Several inlet air velocities were investigated and temperature fluctuations were imposed by means of an external heat source. This provided initial insight into the potential of this novel display case design. The measurement campaign held at the refurbished exhibition gallery ran from May 7th until June 29th 2018. This provided limited time for experiments from the installation of the display cases in the gallery to the actual opening to the public.

Measurement setup

Figure 5.2 illustrates the floorplan of the exhibition area. Two T/RH sensors are mounted near the wall at a height of 1.50 m. These are placed near the Building Managements System (BMS) sensors that monitor the indoor environment of the area. A third sensor is placed on top of the red wall at a height of 2.20 m to create insight in possible vertical

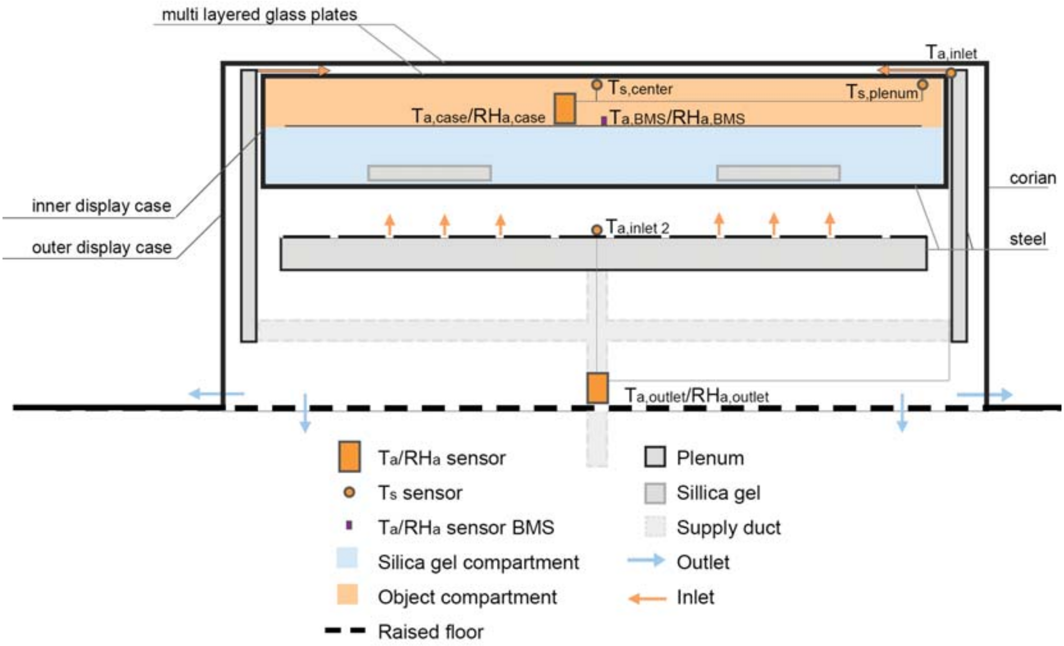


Figure 5.4: *Simplified cross-section of display case with locations of combined* T/RH *sensors and surface* T *sensors. Where BMS stands for Building Management System.*

Figure 5.5: *Photographs of display case design while opened. Combined* T/RH *sensors were placed in the center of the inner display case and surface temperature sensors mounted to the inside of the glass plate.*

stratification. Another sensor monitors the inlet T/RH of the exhibition gallery near the Prinsengracht wall façade.

Figure 5.4 shows the locations of the combined T/RH sensors and the surface temperature sensors (T_s). The remaining display cases were equipped with the same number of sensors and at similar locations inside the cases. Two T/RH sensors were used. One to measure T and RH of the inner display case near the objects on display ($T_{a,case}/RH_{a,case}$) and one to measure the outlet conditions ($T_{a,outlet}/RH_{a,outlet}$). Two surface negative temperature coefficient sensors (NTC) were additionally attached per transmitter to measure T_s. The surface temperature at the inside of the inner display case was measured at the center ($T_{s,center}$) and near the edge ($T_{s,plenum}$) of the glass plate. This was done to locate non-uniformity in Ts caused by the $T_{a,inlet}$. The two NTCs in the outer display case were used to measure inlet T_a. One is located in the lower plenum ($T_{a,inlet2}$) and one in the right side plenum ($T_{a,inlet}$). The sampling interval was 1 minute. A small interval was chosen to be able to observe sudden changes in the $T_{a,inlet}$. Eltek measuring equipment was used with combined T and RH Sensirion sensors providing a measurement accuracy of ±0.4°C and ±3% RH provided by the manufacturer [152]. An Eltek RX250AL data logger was used to collect, store and send data to a server at Eindhoven University of Technology.

Before the measurements took place, the measurement equipment (specifically the T/RH sensors) were calibrated. This was done by comparing the Eltek sensors to a reference sensor of which the uncertainty is known. After calibration the overall accuracy of the sensors was better than the accuracy provided by the manufacturer. A precise calibration was necessary since the museum required that no fluctuations should occur near the objects in the new display case design.

Experiments

Nine experiments were performed to investigate the influence of T_{room} on the $T_{a,case}$. The experiments were mainly focused on the behavior of T. RH around the object was controlled by silica gel in the inner display case. In the first 7 experiments no silica gel was present and the inner display case had no RH control to eliminate influence on RH stabilization by T control of the case. Table 5.1 provides an overview of all the experiments conducted. The first experiment set strict boundary conditions for T_{room} and $T_{a,inlet}$ for approximately 5 days. $T_{a,case}$ could vary and provided insight in the response time of the cases. Experiment 2 was performed over 8 days to analyze what would occur in an extreme situation where the AHU$_{case}$ would malfunction for a longer period. Experiment 3 was executed to test the control setting that could be used in emergencies. This was a requested setting to last-minute turn the pages of Anne Frank's documents before visitors would arrive if necessary. After manually selecting this setting, T_{room} would cool back from 20°C to 18°C within one hour. In experiment 4 the display case could be opened to take out the object or turn the pages. The opening of the case would normally take less than a few minutes, for the experiment the case was opened for one hour. In experiment 5 the effect of high gallery temperatures was examined over the course of five days. Experiment 6 used the standard control setting for a period of seven days. T_{room} was set to 20°C and the T_{case} setpoint was leading for a fluctuating $T_{a,inlet}$ to keep a constant 18°C in the inner display case. This setting was the regular operational mode of AHU$_{case}$ and was not described in the results section. Results of experiment 6 can be found in Appendix J. Experiment 7 was used when museum staff wanted to turn a page. T_{room} would cool during the night to match $T_{a,case}$ in avoidance of a temperature shock when the display case was opened. This setting was for planned work related to the display cases. The final experiments were in preparation of the opening of the exhibition gallery to the public. The silica gel was added to the inner display compartment and $RH_{a,case}$,case was monitored (experiment 8). The last experiment had boundary conditions for T_{room} and $T_{a,case}$ being in operational use and allowed visitors to be present in the exhibition gallery.

Table 5.1: Overview of all experiments performed during this study.

Exp.	T_{room} [°C]	$T_{a,case}$ [°C]	$T_{a,inlet}$ [°C]	Control setting	Duration [h]	Objective
1	20		16	T_{inlet} control	121.5	T control performance
2	20	-	-	AHU_{case} off	193	Malfunction test
3	20-18	18		control setting 1	1	Emergency setting (1h) test
4	18				1	Opening of display case
5	24		16	T_{room}/T_{inlet} control	122.5	Extreme boundary conditions test
6	20	18		Operational control	165.5	Operational use setting test
7	20-18	18		Control setting 2	18	Overnight setting (12h) test
8	20	18		*RH* control present	Continuous	*RH* control performance by placement of silica gel
9	20	18		*RH* control present	Continuous	Visitor influence

5.2.3 Numerical model

A coupled multiphysics model was built with the COMSOL software to perform simulations in a complex 2D and 3D geometry [99].

Model domain and grid

The model was set up in both 2D and 3D. The 2D model was built using the geometry of display case 1 to establish whether the multiphysics settings were computable for this type of model set-up (figure 5.12). Symmetry is applied to decrease computational time while simulating. $T_{s,center}$, $T_{s,plenum}$, and T_{outlet} are used as locations to compare experimental data with the simulated data. These locations are used to validate and compare the model over a timeframe whereas H_{line} and V_{line} are used to compare different model behavior in certain areas of the geometry. After establishing that the 2D model converged, a 3D model was developed (figure 5.7). This model better resembled reality. Certain simplifications were made to the geometry to reduce computational time. Inlet and outlet edges and planes were kept similar to the display case design.

Grid independence

In order to check whether results are influenced by the grid size, a grid sensitivity study was performed. Figure 5.8a shows the coarse, medium and fine grids that were made with the COMSOL physics controlled grid builder. The number of cells is 5,791, 8,837, and 46,738

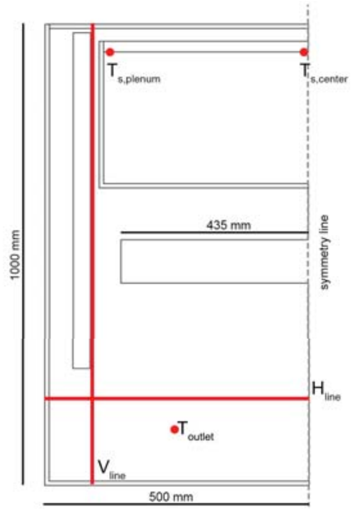


Figure 5.6: *2D model geometry of display case 1. Data point locations and dimensions in mm (right) and boundary division (right).*

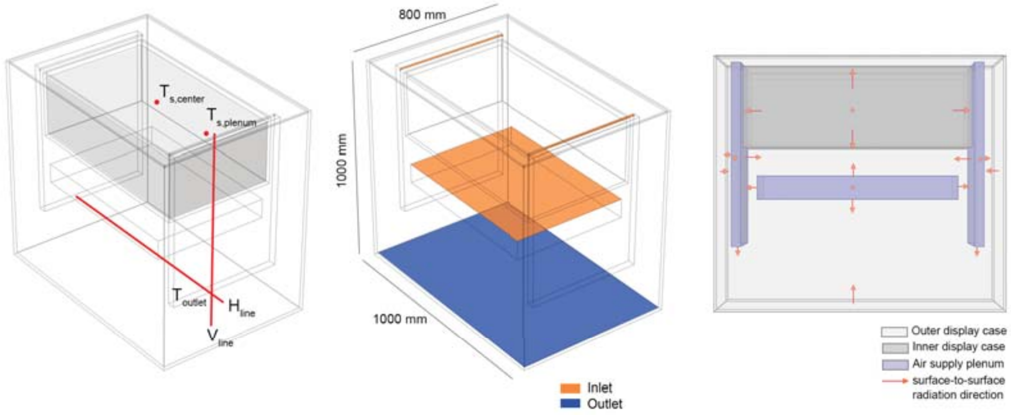
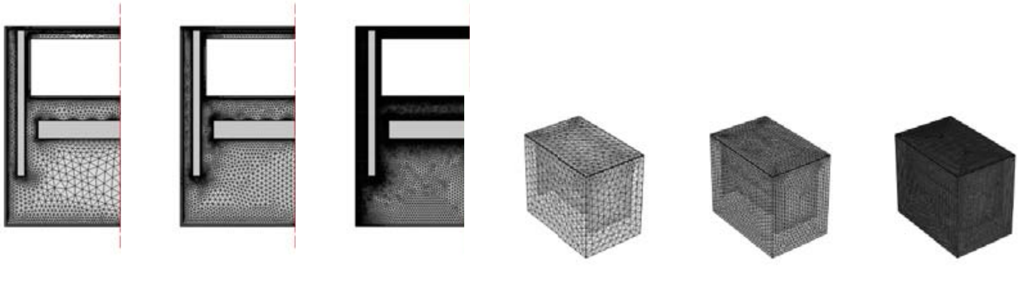


Figure 5.7: *3D model geometry of display case 1. Data point and data line locations (left) and dimensions in mm with boundary division (center) and surface-to-surface radiation planes (right).*

respectively. Computational time and effort increases when the number of cells increase, however, accuracy might increase as well.

Boundary conditions and solver settings

The model built in the current study used the physics modules for heat transfer and turbulent flow. Radiative heat transfer between wall surfaces was included with the surface-to-surface radiation module and conductive heat transfer was modeled with the non-isothermal flow multiphysics coupling. The model combined conductive heat transfer through the display



(a) (b)

Figure 5.8: *Coarse (left), medium (center), and fine (right) grid used for grid sensitivity analysis for the 2D and 3D cases.*

case envelope, convective heat transfer through the supplied air and radiant heat transfer. The model was able to perform transient simulations. Figure 5.7 (center) shows the inlet and outflow planes of the 3D model. Figure 5.7 (right) shows the diffuse surfaces included for radiative heat transfer. The material properties were taken from the manufacturer where possible. Due to some simplification in the geometry, not all structure elements were modeled. The inlet boundary conditions were set based on the measurements for validation. T_{inlet} for the validation simulation was based on the dynamic experimental measurements performed in this study. A heat flux was imposed to represent T_{room}. Air velocity was set to a uniform 1.5 m/s for all the three inlets. The turbulent flow module used turbulence model k-ε. Different adaptations of this model are more widely used in indoor airflow studies [168]. Turbulence model k-ω was used to see if this turbulence model gains better agreement with the experimental data obtained from the experimental campaign [169].

5.3 Results

5.3.1 Experimental results

In the following paragraphs, the results of the experiments described in Table 5.1 are provided. The results are described for display case 1 since they are similar for all display cases and were performed simultaneously.

Outdoor conditions

Figure 5.9 provides results of outdoor measurements collected by the Royal Dutch Meteorology Institute. These measurements were done at Schiphol Airport, located 12 km from the Anne Frank House. During several weeks the $T_{outdoor}$ was above 25°C. $RH_{outdoor}$ was between 40-95%. Specific humidity went from 5 g/kg during early May to peaks of 15 g/kg at the end of May, early June. During this period the Diary Room investigated in this study was able to condition T and RH towards the wanted setpoints. Figure 5.10 shows comparison between Eltek data with those provided by the BMS system for the three display cases studied. The BMS sensors direct the air handling unit that conditions all

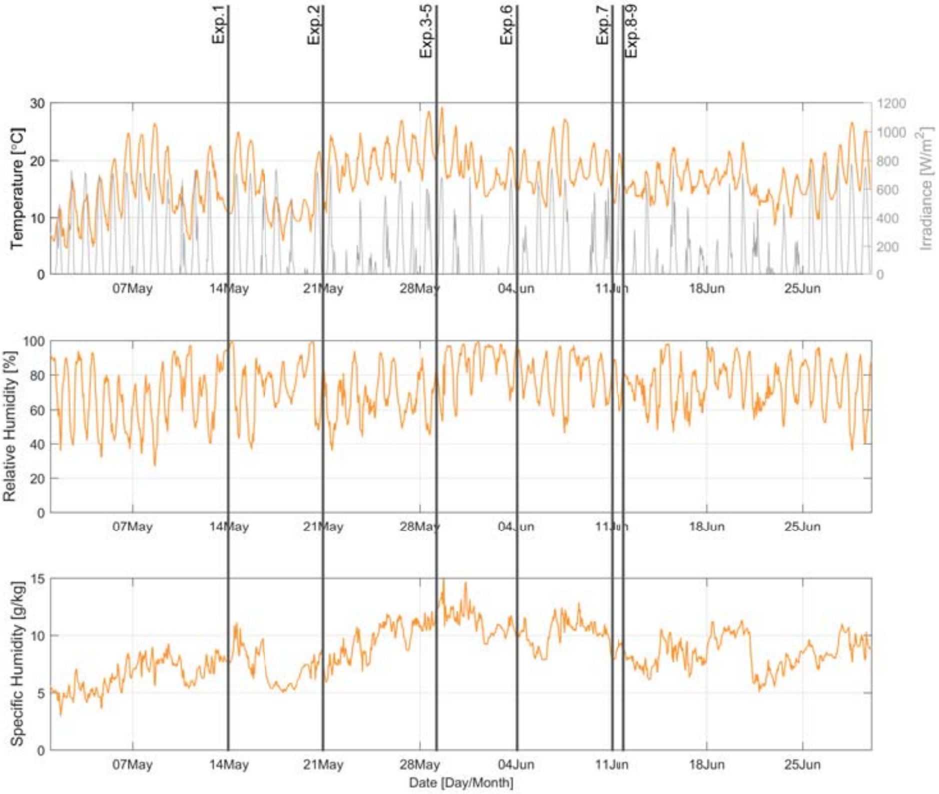


Figure 5.9: *Outdoor Temperature, Relative Humidity, Specific Humidity and irradiance of the Amsterdam location (Schiphol) during the measurement period. Starting dates of experiments are expressed by the vertical lines.*

display cases. Overall, DC1 showed very limited variations between the BMS and Eltek measurements. ΔT showed two peaks of -0.1°C and -0.2°C. Display cases 2 and 3 had limited ΔT variations, -0.1°C and -0.15°C respectively. Both the BMS and Eltek sensors were calibrated and showed no variations.

Regular and malfunction experiments

For sake of conciseness the results discussed are measurements from DC1. This display case displayed the red checkered diary of Anne Frank. Figure 5.11 shows the results of the first two experiments for the display case design. The first experiment started at May 16$^{\text{th}}$ at 08:00h. The dark grey line represents the room conditions. The magenta line shows the air conditions in the inner display case. The orange line shows the conditions of the return air in the outer display case and the green line provides information on the inlet conditions of the display case. Peak A and drop B are discussed in the description of figure 5.11. Under

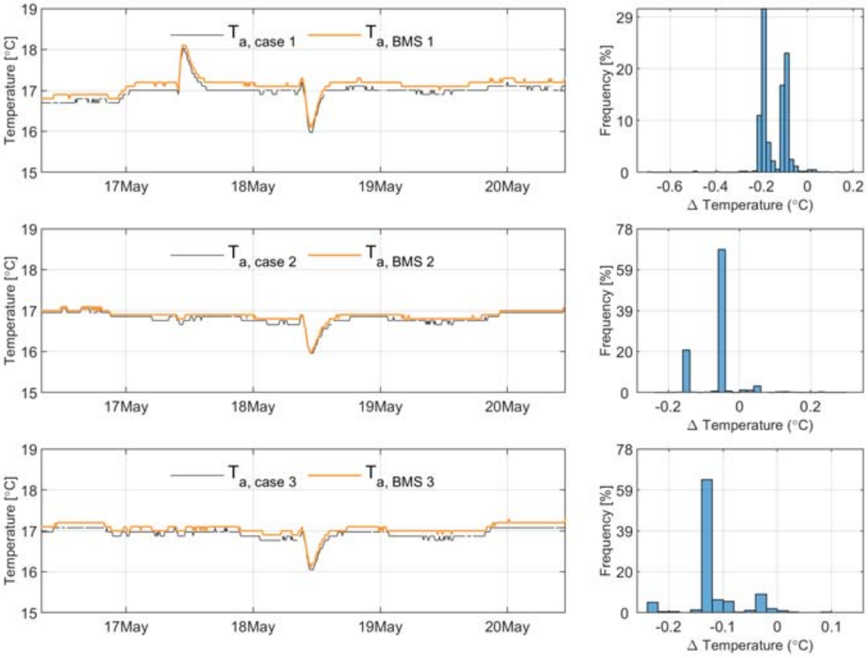


Figure 5.10: *Comparison between $T_{a,case}$ of the Eltek sensors (grey) and BMS sensors (orange) in display case 1 (upper), 2 (middle) and 3 (lower) during the first experiment.*

stable boundary conditions of T_{room} and T_{inlet}, the inner display conditions were stable as well. Under fluctuating RH_{room} and RH_{outlet}, the RH_a, case in the inner display case remained stable even though it was an empty case and no RH regulation was present.

The second experiment in which the AHU of the display cases was turned off, started at 9:30h on May 21st. This graph shows that as soon as the T_{inlet} alters, $T_{a,case}$ responds almost immediately. The response time of the system in this test was 34h and 45 minutes, given that the step change of $T_{a,case}$ was from 17.2 to 19.8°C. $RH_{a,case}$ remained stable during this experiment.

Opening of case with control setting 1 and extreme T_{room} experiments

Figure 5.12 illustrates the results of three experiments. In experiment 3 T_{room} was set to drop from 20°C to 18°C within an hour. This is shown in the drop of the grey line and the sudden rise in $RH_{a,case}$ (magenta line). As soon as the emergency setting was operated T_{room} dropped, however, AHU$_{room}$ was not able to dehumidify the cold air before being supplied to the exhibition gallery. This resulted in a high RH_{room} nearing 70% RH.

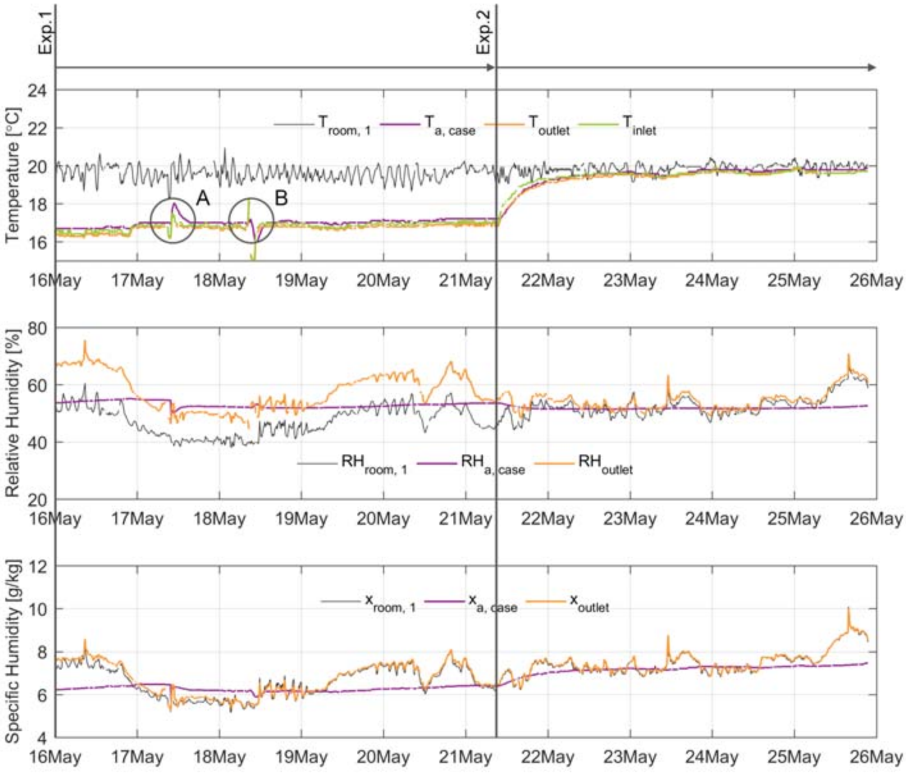


Figure 5.11: *Indoor climate conditions of the exhibition gallery and display case 1 during experiment 1 and 2. Peak A shows a malfunction of the cooling machine and dip B shows an extra cooling capacity tests performed by the technicians.*

In experiment 4 the display case was opened (May 29th at 11:30h) and closed after one hour. An increase of $RH_{a,case}$ and $x_{a,case}$ can be seen (magenta line). Due to the opening of the case $RH_{a,case}$ increased to RH_{room} conditions which turned out to be high since the system was not able to dehumidify the air before it entered the exhibition gallery. After closing the display case the sealed case created a stable $RH_{a,case}$, however, at an inappropriate RH for preservation needs.

In experiment 5, the T_{room} setpoint was increased to 24°C. This experiment started on May 29th at 12:30h. Figure 5.12 shows the increase in T_{room} which lasted several days. Four hours after increasing T_{room}, a peak was visible in $T_{a,case}$ (purple arrow figure 5.12), caused by a sudden rise of the supply air temperature. The peak of T_{room} started at 18:00h and T_{inlet} rose from 17°C to 20.5°C, the display case $T_{a,case}$ peak started with a delay at 19:00h and rose to 19°C in an hour. At the moment, the authors cannot fully explain why the peak occurred during this experiment. $T_{a,case}$ and $x_{a,case}$ were less affected by the change in room conditions. RH_{outlet} (orange line) showed high relative humidity while RH_{room}

decreased significantly from 70% to 50% RH. The high value for RH_{outlet} might result in increased condensation risk on the cold surfaces of the display case. However, air velocity at the outlet location was high which resulted in limited stagnant air present [170].

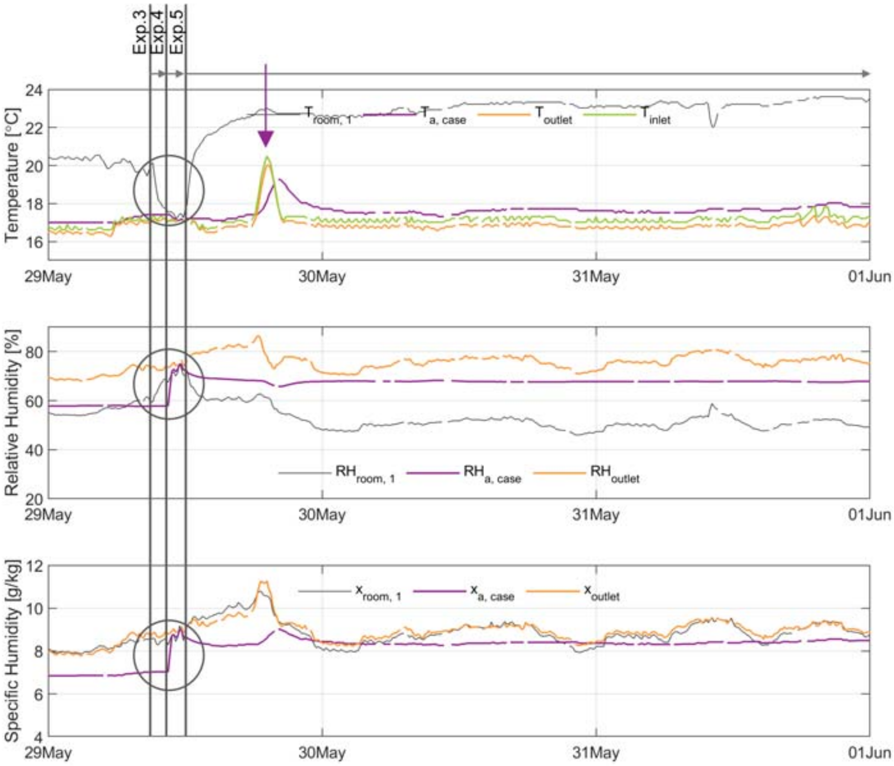


Figure 5.12: *Indoor climate conditions of the exhibition gallery and display case 1 during experiments 3, 4 and 5. Emergency setting was tested and T_{room} decreased to 18° C within an hour, after which and extreme situation was imposed and T_{room} increased to 24° C. T_{inlet} was kept as close to 16° C throughout the experiment.*

Opening of case with control setting 2 and RH control experiments

Figure 5.13 shows the results for experiment 7, 8 and 9. Before these experiments took place the figure shows a rise in $T_{a,case}$ conditions starting from 09:00h. During the morning, light fixtures were installed at the ceiling of the the gallery and the display cases were frequently opened to position a mockup of the diary to adjust the light beams.

In experiment 7 T_{room} was cooled to 18°C overnight. This experiment started at 15:00h on June 11th. Figure 5.13 shows that the exhibition gallery reached the set point of 18°C at approximately 18:30h. Considering that the display cases would be opened the next day between 08:00 and 09:00h. At 16:00h on June 11th silica gel was added (experiment 8) to the inner display case to create a stable 45% RH environment. The figure shows that in a gradual manner $RH_{a,case}$ decreases towards 55%. The next day at 08:00h the case was opened and the museum items were placed in their new display. T_{room} was set to operational mode, 20°C. After placement of the objects a spike in $RH_{a,case}$ can be found which indicated opening the display case. The silica gel managed to lower $RH_{a,case}$ towards 48%. Figure 5.14 shows the climate in and around the display case during experiment 9. In experiment 9 every system was set to operational mode for both AHU$_{room}$ and AHU$_{case}$. Visitors were able to enter the exhibition gallery and view the manuscripts of Anne Frank on display. The figure shows T_{room} to constantly fluctuate around a set point of 20°C with ΔT of 1.8°C. The inlet conditions of the display case showed a steady profile resulting in a stable $T_{a,case}$ (17.4±0.5°C). $RH_{a,case}$ around the manuscripts was very stable. Though RH_{room} was kept between the setpoints of 45-60%, RH_{outlet} shows values up to 80% RH, mainly due to the low T_{inlet} and not being able to control RH in AHU$_{case}$. The small dips during the week of June 15th were caused by tweaking the control settings of AHU$_{case}$. The dip around June 28th in T_{inlet}, $T_{a,case}$ and T_{outlet} was caused by a change in control setting bringing the T setpoint of the display case down to 17°C upon museum management request. In

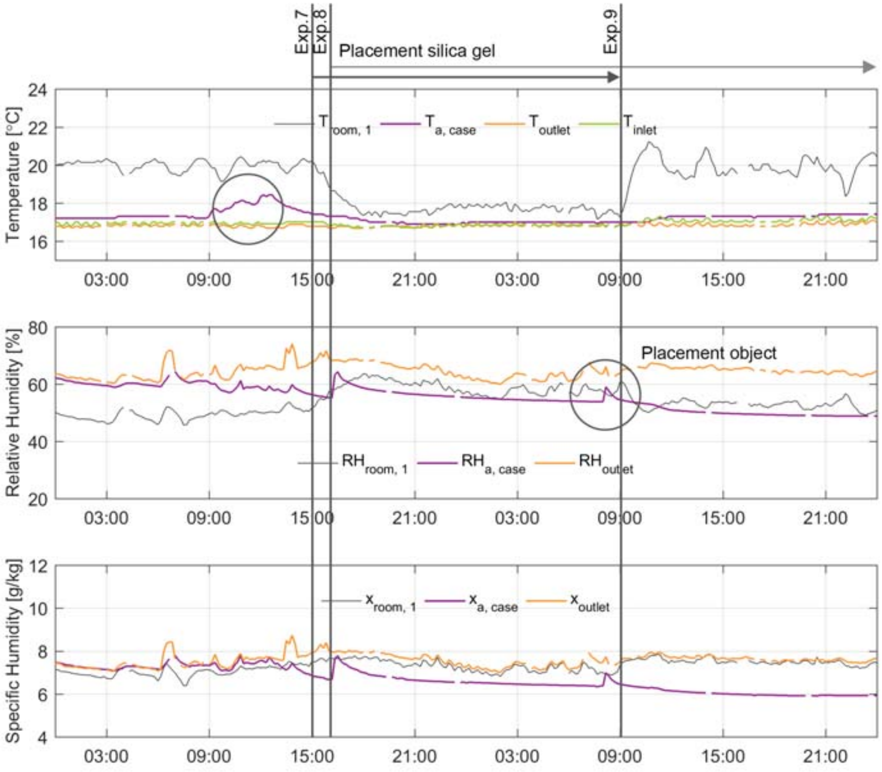


Figure 5.13: *Indoor climate conditions of the exhibition gallery and display case 1 during experiments 7-9.*

the days preceding June 21st, RH_{room} exceeded the upper limit of 60%. With some slight adaptations to the cooling system RH_{room} remained within the set point limits during the following days. RH_{outlet} remained high due to the low T_{inlet} and the fact that this air stream has no RH control in AHU$_{case}$. Part of the outlet air entered the exhibition by means of infiltration. The remainder overflowed to the technical room below the exhibition gallery. This might have caused some locally deviating RH_{room} levels. Since the objects were located in buffered airtight display cases these deviating RH_{room} levels were not a preservation risk for these objects.

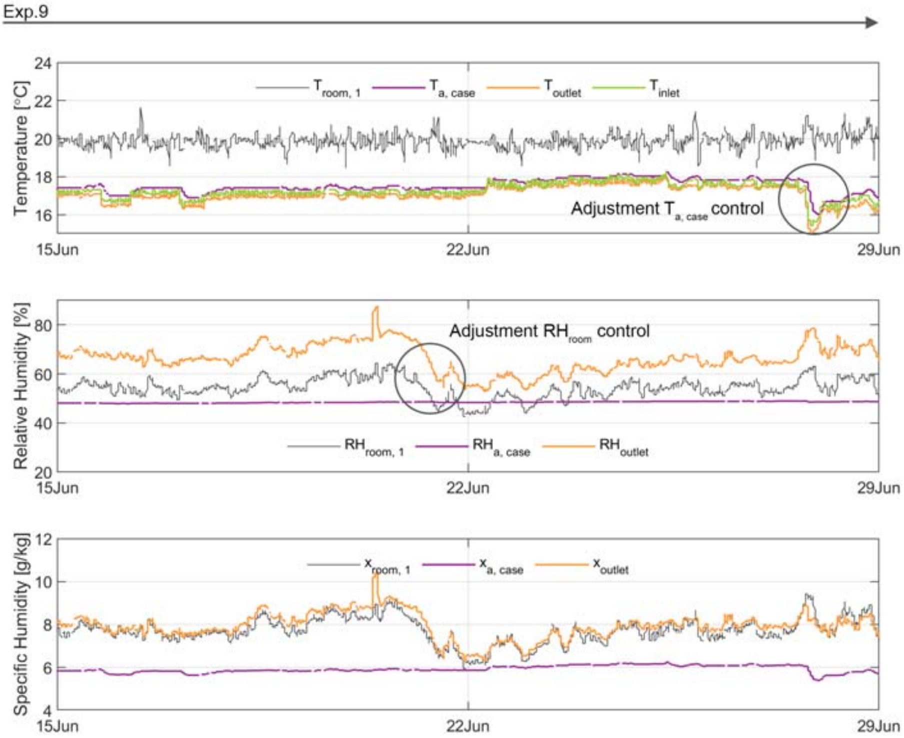


Figure 5.14: *Indoor climate conditions of the exhibition gallery (grey) and display case (colored) during experiment 9. The exhibition gallery was opened to public during this experiment and silica gel controls* $RH_{a,case}$.

5.3.2 Modeling results

Figure 5.15 shows the results for the 2D grid sensitivity analysis performed for the k-ε turbulence model. This model is commonly used in CFD and uses a two-equation mathematical model to provide a general description of turbulence flow. The coarse and medium grid show similar results for three locations. The measurement locations can be found in Figure 5.6. The boundary condition in the numerical model for T_{inlet} (grey line) was taken during experiment 5. T_{room} at that moment was constant at 24°C and T_{inlet} showed a peak of 4K that resulted in a peak in $T_{a,case}$ as well (see 5.12). For the grid sensitivity analysis the coarse and medium grid were almost overlapping indicating grid independency. The fine grid shows no significant improvement compared to the medium and coarse grid. The coarse grid was sufficient to predict surface temperatures of the inner display case influenced by the imposed room conditions without a significant increase in computational time.

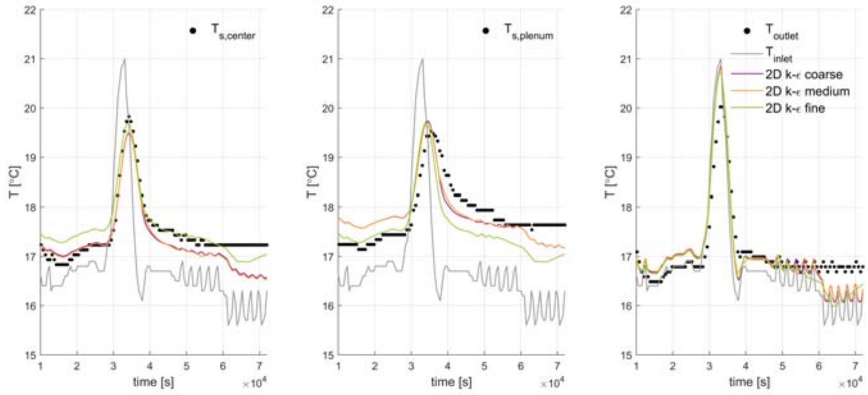


Figure 5.15: *Grid sensitivity analysis for 2D model for $T_{s,center}$ (left), $T_{s,plenum}$ (center) and T_{outlet} (right). Measurement locations can be found in figure 5.6 where $T_{s,center}$, $T_{s,plenum}$ and T_{outlet} are pictured.*

Figure 5.16 shows the grid sensitivity analysis over a horizontal line and a vertical line in the 2D case. The k-ω turbulence model was added to investigate if it would perform more accurate near the wall-region. No significant deviations are shown and the coarse grid in combination with the k-ε turbulence model seemed sufficient for the remainder of simulations.

Validation

Figure 5.17 shows the comparison between simulation outcomes and experimental data during experiment 5 for different turbulence models and both 2D and 3D case. Exact compared measurement locations can be found in figure 5.12 and figure 5.13. The results show that the amplitude of the peak imposed by T_{inlet} were buffered partially and delayed in time. Looking at the agreement between measurements and simulations, the 3D case underestimated the Ts,center peak (figure 5.17 left). There might be a 3D flow component which caused this deviation compared with the 2D case results. The results near the inlet plenum shown in the middle figure of figure 5.17, show that for the 3D case both turbulence models underestimated T_s. The 2D case shows good agreement with the measurement results. For the outlet location the simulation results follow the T_{inlet} line and buffer some oscillation (figure 5.17 right). Comparing different turbulence models only shows significant deviations for the T_{outlet} data for k-ω turbulence model where it agrees slightly better than the k-ε turbulence model. To quantify whether the computational model was representing

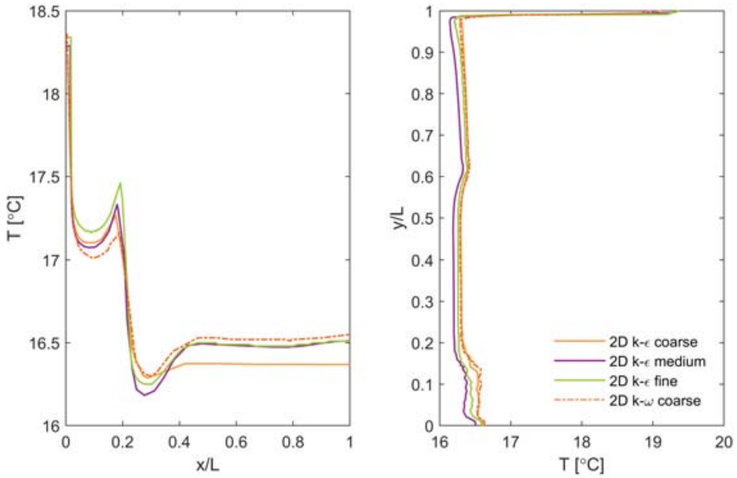


Figure 5.16: *Grid sensitivity analysis through horizontal (left) and vertical (right) plane for 2D model. Locations of the lines can be found in figure 5.6.*

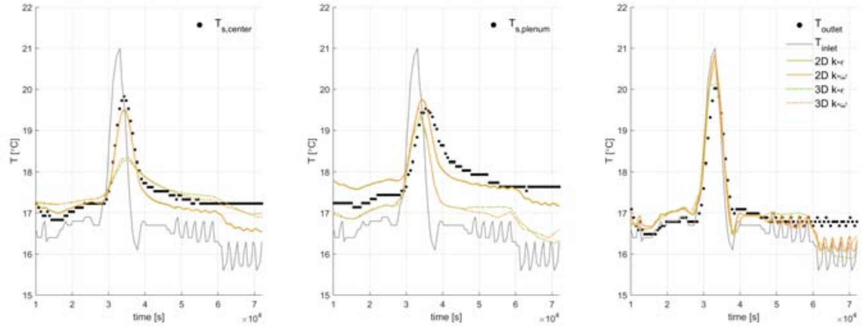


Figure 5.17: *Comparison between experimental results and simulation results for $T_{s,center}$, (left), $T_{s,plenum}$, (center) and T_{outlet} (right) in the 2D and 3D case for several turbulence models.*

reality and to check which turbulence model performed more accurate, the measurement data and simulated outcome were compared by means of validation metrics. The fractional bias (FB) can be used to quantitatively compare simulated output with measured data with the note that parameters with both negative and positive values were not suitable for this metric [156, 171].

$$FB = \frac{\bar{O} - \bar{P}}{0.5 \cdot (\bar{O} + \bar{P})} \tag{5.1}$$

Where O are the measured (observed) data points and P are simulated (predicted) data points. The overbar shows that the average over all data points need to be taken as input in the equation.

Another method for model comparison between model and experimental results is the fraction of data within a factor. The factor 1.05 is used for temperature comparisons [156].

$$FAC1.05 = \frac{1}{N}\sum_{i=1}^{N} n_i \tag{5.2}$$

Where:

$$n_i = \begin{cases} 1 \text{ for } 0.95 \leq \frac{P_i}{O_i} \leq 1.05 \\ 0 \text{ for else} \end{cases}$$

Where N is the number of data points, P_i are the predicted values and O_i are the observed values.

Two other validation metrics that are often used in building simulation are the mean bias error (MBE) and root mean square error (RMSE). These indices are used for model accuracy of the simulation model compared to measurement data [137].

$$\text{MBE (\%)} = \frac{\sum_{i=1}^{N}(O_i - P_i)}{O_i} \tag{5.3}$$

$$\text{CV RMSE (\%)} = \frac{\sqrt{\sum_{i=1}^{N}(O_i - P_i)/N_p}}{\bar{O_i}} \tag{5.4}$$

Table 5.2 shows the results for all validation metrics. The FB metric shows good agreement with the 2D model in all locations. The center location of the 3D k-ε comparison shows exceedance of the range for the fractional bias. FAC 1.05 was still in agreement for both the 2D and 3D cases. In general, a good agreement was shown for the reviewed measurement locations. The 3D k-ε case under predicted the peak in the center of the display case (0.620). This can be ascribed to the two flows merging in the center of the air cavity creating an area with overpressure where lower velocities were present. The current 3D k-ε model under predicted temperature at this location while still being in compliance with the majority of validation metrics. The MBE and CV RMSE both showed disagreement for the 2D fine grid case with the k-ε turbulence model. The CV RMSE also showed disagreement for the 3D case for both k-ε and k-ω turbulence models for $T_{s,center}$.

Results simulations

After model validation, a study was performed to see the effect of imposed room boundary conditions on T_{case}. Museum management already approved regulating RH within an upper and lower limit, performing a simulation in which T_{room} was able to fluctuate within a controlled upper and lower limit provided insight into the performance of the museum display case. Since collection environmental requirements were addressed by the museum display case, the T and RH setpoints for the exhibition gallery were determined by visitor thermal comfort. The elaborate study of Kramer et al. [42] used a dynamic

Table 5.2: Validation metrics for the 2D medium grid display case.

		FAC 1.05			FB			MBE			CV RMSE		
		T$_{s,plenum}$	T$_{s,center}$	T$_{outlet}$	T$_{s,plenum}$	T$_{s,center}$	T$_{outlet}$	T$_{s,plenum}$	T$_{s,center}$	T$_{outlet}$	T$_{s,plenum}$	T$_{s,center}$	T$_{outlet}$
Aim			1			0			0			0	
Range			>0,5			(-0,3;0,3)			<10%			<30%	
k-ε													
	coarse	1.000	1.000	1.000	0.006	-0.004	0.001	0.64	0.44	0.10	7.06	4.80	1.13
	medium	1.000	1.000	1.000	0.007	-0.005	0.000	0.71	0.47	0.02	7.77	5.18	0.22
	fine	1.000	1.000	0.992	-0.008	-0.149	0.003	0.78	16.07	0.32	8.60	176.72	3.50
k-ω		1.000	1.000	1.000	0.007	-0.005	0.001	0.70	0.50	0.12	7.70	5.55	1.35
Spalart Allmaras		1.000	1.000	1.000	0.008	-0.011	0.000	2.61	5.13	0.00	8.72	12.31	0.12
3D k-ε		0.942	0.694	0.950	0.001	0.033	0.004	0.10	3.26	0.45	1.12	35.87	4.90
3D k-ω		0.950	0.620	1.000	0.001	0.033	0.004	0.13	3.27	0.37	1.41	35.93	4.12

control algorithm to dynamically determine the setpoints for T_{room} and RH_{room}. The collection requirements were based upon the ASHRAE climate classes [7]. The visitor thermal comfort requirements were based upon adaptive temperature limits for museums [172].

In the current study the dynamic control algorithm was used to calculate the upper and lower limit for T and RH while complying with ASHRAE climate class AA. Class AA is the most strict climate class with proofed short-term and seasonal fluctuations to decrease mechanical risk to fragile and susceptible objects.

Figure 5.18 shows the results for imposing a simulated indoor temperature as T_{room} (light gray). This indoor temperature was based on the study of Kramer et al. [42]. The dark grey line provides the 30 day moving average to see the seasonal fluctuations. The colored dash-dotted lines show the results of an actively controlled case temperature. $T_{s,center}$ (orange) and $T_{s,plenum}$ (blue) show a stable line throughout the year indicating AHU$_{case}$ being able to maintain a set point of 17°C. Another simulation has been performed where AHU$_{case}$ was turned down and the display case could be seen as a passive system. The results for this simulation in figure 5.18 show an increase in surface temperature of the case for the passive case compared to the fully active T controlled system. Besides a seasonal fluctuation, shorter fluctuations are also present and not thermally buffered by the system.

The results of this study show that though T_{room} varies throughout the year, $T_{s,case}$ is able to be conditioned in a stable manner in the active situation with imposed boundaries for T_{room}. Ts,case is complying with the museum requirements of 17.5°C without permissible fluctuations.

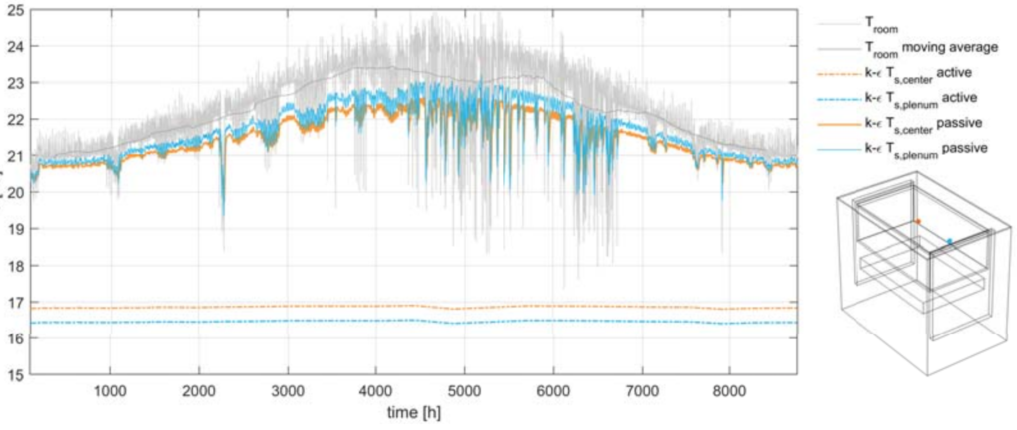


Figure 5.18: *Simulation results of yearly imposed dynamic conditioning with ASHRAE climate class AA as T_{room}.*

5.4 Discussion and conclusions

The display case was developed and designed to create a stable environment around culturally important manuscripts. The use of silica gel in the inner airtight display case and flushing the air gap between the outer and inner vase with conditioned air proves to be effective.

In case of malfunctioning of the climate control system or AHU components, $\mathrm{T}_{a,case}$ will follow imposed T_{inlet} conditions. Protocols need to be in place for museum staff to reduce risk impact when T_{inlet} conditions are not appropriate. In those situations it is best to turn off the AHU_{case} and use the display case in a passive mode until the issues are resolved.

The display case climate conditions were also dependent on the exhibition gallery T_{room} and RH_{room} conditions. During handling of the museum items and opening the display cases the room conditions need to be as close to the display case conditions as possible to avoid sudden fluctuations. In practice, the gallery can be cooled down to $T_{a,case}$. Since the objects were placed in their own microclimates, RH_{room} was allowed to fluctuate between the limits of 45-60%. Lowering RH_{room} to 45% was more difficult to achieve in combination with the low T_{room}, resulting in a peak fluctuation in RH when the display case was opened (illustrated in figure 5.9). These sudden fluctuations in RH_a,case should be investigated further. Literature showed that due to the time it takes for an object to reach moisture equilibrium, the risk of degradation caused by fast fluctuations was limited. A timeframe for these fast fluctuations was often not given [158]. However, from previous literature it was known that the response time for paper objects or an opened book was in the range from hours to three days and a single sheet of paper responded within minutes. Books in tightly sealed cases had a response time of around 2-3 months. As a worst case, a response time of minutes was often used for paper objects [36, 30].

During experiment 5, T_{room} was increased to 24°C. The peak in T_{inlet} and $T_{a,case}$ a few hours afterwards cannot be explained satisfactorily. The building management system did not account for an error or malfunction alarm but showed a temporary rise in cooling temperature which can be contributed to a short malfunction of the cooling system.

Experiment 7 involved cooling T_{room} back to 18°C in a time span of 18 hours. The test showed that it was possible to cool back T_{room} to 18°C, however, it takes less than 2 hours for the system to reach this set point. Maintaining the set point of 18°C consumed a significant amount of energy.

During the experiments it was noted that due to a low T_{inlet}, the RH of the airflow in the cavity is high (>60%). Though this airflow does not have direct contact with the displayed objects it might cause other types of inconvenience like condensation on the cold display case surfaces. During the experimental campaign attention was paid towards condensation issues although no cause for increased concern was noted based on measured values of temperature and relative humidity. However, it is recommended to keep monitoring the outlet conditions of the display case as well.

The main conclusions of this chapter are:

- From the experiments it can be concluded that $T_{a,case}$ follows T_{inlet} closely. $RH_{a,case}$ remains stable due to the almost airtight inner display case. This results in stable climate conditions where museum climate requirements are met in the inner display case.

- The novel display case design is able to generate a stable RH environment by means of silica gel, while using an active box-in-box climate control system to create stable and relative T conditions to increase collection lifetime.

- $T_{a,case}$ depends on the AHU$_{case}$ system. Protocols need to be in place in case of malfunction or failure of the climate control system. AHU$_{case}$ needs to be shut off to create a passive environment for the objects on display. Experiment 5 shows that a sudden, unplanned rise in T_{inlet} provides unnecessary increased risks to the objects on display.

- Placing climate sensitive objects in display cases allows exhibition gallery control set points to be relaxed. Numerical modeling provides insight into the effect of dynamic simulation of T_{room} on the display case performance. It shows that relaxation of T_{room} setpoint does not influence T_{case}.

6 General conclusion and perspectives

“Il piacere più nobile è la gioia di comprendere”
The noblest pleasure is the joy of understanding
— Leonardo Da Vinci

6.1 Discussion and limitations

Guidelines in practice

Evolved with the introduction of climate guidelines and standards, preventive conservation for indoor climate conditions frequently resulted in an increase in presence of mechanical climate control systems in (historic) museum buildings. With the evolution and development of more precise climate control systems, the possibility to adopt more stringent indoor climate conditions arose. This resulted in (irreversibly) adapting historic buildings, high energy consumption and increased energy costs. With more detailed climate control, the option to choose the most stringent requirements to realize an ideal indoor climate is often picked, after all: *"if close control (+2%RH) provided no benefit for the objects than wider control (±5%RH), then at least it did no harm"* [9]. The consequences of such decisions in terms of sustainable use of climate control is often not considered.

The ASHRAE guidelines are well known in the field of climate control and describe *"best practices and advice on planning, designing, and implementing environmental strategies for long-term preservation of cultural heritage"*. The guidelines provide a table for several climate classes (AA, A, As, B, C and D) with corresponding short-term and long-term setpoint values for T and RH suggesting an ideal indoor climate for preservation of objects by accepting a certain level of risk. The table with its contents is, however, often differently interpreted. In practice, the most stringent climate class (AA) is frequently chosen and considered to provide the 'best' indoor climate rather than an appropriate or optimal indoor climate. The difference between short-term and long-term fluctuations are also unfamiliar terms for most users of the guidelines, resulting in incorrect use of the given climate class setpoints in climate control [118].

To account for energy efficiency, robust (proofed) fluctuations and securing in-house knowledge requires a shift from striving for an *ideal* indoor climate towards an *appropriate* indoor climate for preventive conservation. The shift from blindly picking the ideal indoor climate with stringent setpoint conditions towards an appropriate indoor climate requires a change in decision making. First, a qualitative statement must be made what a museum, archive or library wants in terms of indoor climate and (risk-accepting) preservation conditions for their collection. For this, a clear insight in their collection, building and climate control must be present (chapter 2, this thesis). After this, a climate class can be matched with this aim. To execute the climate classes to their optimal use, the ASHRAE guidelines need to be clear in how to be interpreted and used in practice. The latest version of the ASHRAE has made an effort to clarify the climate classes and their intent [173]. To provide users of the climate classes more insight in the consequences of their decisions, the guidelines should be extended with insights in energy consumption (chapter 3, this thesis) and costs when deciding upon a specific climate class.

Temporal and spatial monitoring

In the 21^{st} century, reducing the carbon footprint of buildings and moving towards energy transition are high on the agenda. With HVAC systems contributing approximately 50% to the energy consumption of a building many research moved towards the field of energy conservation. Climate control was mainly based on building management system measurements that would average the indoor climate of several galleries or based on measurements of air temperature and relative (or absolute) humidity in the return duct of the climate system. Research thus far focused mainly on sustainable climate control solutions in relation to lumped parameter (e.g. room-averaged) evaluation for indoor climate parameters like air temperature and relative humidity. The indoor climate parameters are mainly monitored in the return duct of the climate control system to be able to adjust settings in case of deviating from selected setpoint requirements. Critical indoor climate areas, where the indoor climate parameters deviate from the requirements, are not monitored unless known.

Chapter 2 of this thesis described the adopted climate scan to identify these critical areas and chapters 3 and 4 showed the application of this scan in practice. The investigated case studies were located in an archive and storage building of a library. This entailed that no visitors were present and less limitations were present on the location of monitoring equipment. In exhibition galleries this method results in location restrictions. Visitors should not be able to influence monitoring results. This would result in removing equipment from the reach of visitors, which are often locations near objects and therefore, points of interest. In chapter 2 the short-term monitoring campaign provides a quick solution to this issue. In a short amount of time, the critical areas can be identified and long-term monitoring equipment can be positioned in critical areas. This reduces a large experimental long-term equipment effort by positioning a monitoring grid and prevents interference with visitors' experience.

Limitation of the climate scan as presented is the knowledge base necessary to interpret results stemming from temporal and spatial monitoring results as well as the required increase in monitoring effort compared to current indoor climate monitoring. However, this will also provide a more holistic understanding of the museum indoor environment for everyone involved in the decision making process surrounding appropriate indoor climate requirements. The evaluation of critical areas is an advantage of the climate scan compared to existing scans such as micromapping [88] or the assessment of Lucchi [109]. Solely short-term measurements will show the cause and location of critical areas, the long-term measurements will provide insight in seasonal and short-term fluctuations in these critical areas.

One can argue whether spatial monitoring is necessary when objects are placed in separated climate zones such as a museum display case or archival boxes. Archival boxes often have small infiltration openings to prevent particle (VOC) built-up in the box. This indicates that the surrounding indoor climate could influence the T and RH inside the box and near the object. Chapter 4 shows the necessity to monitor inside the archival boxes, especially near external walls. Near an HVAC inlet such deviations could also be expected. This research did not look into the effect of deviating microclimate inside the archival boxes on the stored paper objects, however, comparison of monitoring data from inside and close outside the archival boxes resulted in the notion that similar indoor climate parameter values were present. Therefore, degradation risks for objects placed inside or outside an archival box are most likely similar considering incorrect T and RH (see figure 4.7).
In chapter 5, an airtight display case was investigated. Data collection on indoor climate parameters inside the display case would suit monitoring the active control of active climate control. The remainder of the exhibition gallery does not have susceptible objects outside display cases. Monitoring of spatial distribution would therefore only result in increased effort and not necessarily appropriate indoor climate variables for preservation conditions.

Numerical modeling

Numerical modeling is often a trade-off between computational effort and representing reality as detailed as possible during calculations. The numerical models developed and used in this thesis prove to be suitable to determine the effect of different (intermittent or dynamic) setpoint strategies for energy conservation impact (chapter 3) and object preservation (chapters 4 and 5). In the case studies used in this research, thermal comfort of visitors and employees was neglected during opening hours of the library and archive repositories and varies from the original research to combine both visitor comfort during opening hours of an exhibition gallery and collection requirements during closing hours [42]. It does provide insight in how seasonal fluctuations can influence the indoor climate in storage rooms and impact energy consumption by releasing stringent setpoint requirements.

The COMSOL computational models made use of a simplified geometry. An advantage of such a simplified geometry is the decrease in computational effort, the drawback however, is accuracy during the numerical calculations. Therefore, the comparison between the simulations and experimental data was checked with statistical parameters (chapters 3-5). More detailed models would increase accuracy. This also applies to the choice of grid, the finer the grid, the more accurate the model calculates. However, this results in increased computational effort. A grid comparison was made for all used models resulting in a suitable grid size for the calculations without compromising accuracy. A limitation during chapter 4 is the lack of extensive validation based on wind speed distribution measurements. The numerical study was used as a means to understand the hygrothermal measurement results obtained from the experimental campaign. For this, the inlet velocity was measured short-term and compared with the building management system velocity. The building management system inlet velocity was used as imposed boundary condition. To gain more accuracy in the numerical model, the calculated air distribution needs to be compared with measurements. Increasing accuracy in this area would result in more insight in how stagnant air zones contribute to an increase or decrease in (biological) risk for specific archival rack set-ups and storage methods such as archival boxes. In-depth research into mold germination under inappropriate indoor T and RH conditions in stagnant air pockets is needed.

In chapter 3, HAMBASE proves to be a suitable tool for simulating multi-zone indoor climates and accompanying energy demand. The energy demand was calculated based on building needs only. The building and its use is modeled into detail. However, more elaborate results might be obtained in combination with an accurate HVAC model. The dehumidification process by deep cooling and reheating could be more accurate than the current model provides. The inclusion of fan energy in the modeled scenarios may influence the current outcome. Previous research showed the impact of fan energy inclusion on the energy demand [42]. An advantage of simulating only building needs is the low computational effort needed for these calculations. With the inclusion of a coupled HVAC model this could result into large computational effort. This would limit the use of such a model in practice.

Object risk

This research showed that storage requirements are often combined with requirements used for exhibited objects [35] or are applicable for very specific types of archival collections [7]. Relating requirements for T and RH to risk assessment of archival collections needs further research. For example, book collections are more likely stored in bulk than as single paper sheets, as presented in both chapter 3 and 4. It is of importance to be aware of the difference in possible risk that belongs to the different types of storage solutions. A limitation of chapters 3 and 4 is that risk is related to the lifetime multiplier which is based upon material properties of a single (paper) object.

Measurements and numerical modeling provide insight in the climate conditions in repositories. While it is common to monitor the ambient indoor air conditions of a space or in the HVAC return duct, the experimental part in chapters 3 and 4 of this thesis show that locally deviating indoor climates are present and the ambient indoor conditions do not represent the hygrothermal conditions of the repository inside for instance, archival boxes (chapter 4) or archival racks (chapter 3). While stable T and RH are required by legislation, this thesis shows that even though an HVAC system is present, stable indoor conditions might not be maintained and near external walls daily T fluctuations occur. T/RH cycling seems not to be of influence on chemical degradation and avoiding fluctuations from a chemical decay point of view is not necessary according to Bigourdan et al. [158]. This would underscore the idea of using passive ways to maintain preservation conditions (specifically low, stable T which results in a stable RH) archival facilities where daily fluctuations are almost canceled out but seasonal fluctuations do gradually occur [44]. A limitation of this thesis is that with passive or semi-passive measures the effect on accumulation of volatile organic compounds (VOCs) needs to be considered, this has not been studied during this research [53, 159].

6.2 Conclusions

This thesis revolves around the hypothesis that *operating existing HVAC systems can be used in a more sustainable way - via temperature and humidity requirements to establish an appropriate indoor climate for preventive conservation - and will therefore improve local microclimates by reducing spatial gradients and consequently benefit object preservation.*

Overall conclusion

The presented approaches and resulting knowledge gathered in this thesis are valuable to continue research in the fields of energy conserving indoor climate strategies and preventive conservation of susceptible objects. Using climate control based on accepting descriptive requirements over stringent normative requirements will not increase spatial and temporal gradients for temperature and relative humidity. In other words, the hypothesis can be answered with yes, with the proviso that adopting a more risk-accepting approach in terms of climate control (i.e. dynamic control or intermittent conditioning) will not automatically result in the *ideal* indoor climate for conservation or storage purposes. This does however, show a preference for doing less: i.e. as little as possible heating in winter (resulting in little humidification) and as little as possible cooling in summer (resulting in little dehumidification). This would reduce thermally driven air flows resulting in deviations. Important is to adopt passive measures such as archival boxes in storage facilities, the use of museum display cases for exhibition purposes, installment of solar blinds to avoid direct solar gains, and improving building envelope thermal quality as a more invasive measure.

This overall conclusion is based on the four studies (chapters 2-5) that were performed during this research with objectives related to the hypothesis of this thesis:

- To develop an environmental scan to investigate and represent critical areas with deviating indoor climate conditions compared to ambient climate conditions in buildings with climate control systems present. This gains insight in which different indoor climate and local microclimates (see figure 1.3) are commonly present in different heritage institutions such as museums, archives and libraries in order to better understand how they impact the object environment.
- To gain insight into climate control strategies, air distribution and the presence of (hygroscopic) collection on indoor climate parameter behavior. This to better understand temporal and spatial distributions in buildings with storage functions and therefore, large thermal and hygric buffer present.
- To investigate the influence of less stringent ambient (risk-accepting) climate control requirements on local microclimates.
- To investigate the possibility to (thermally) separate gallery indoor climate conditions and object environment. A distinction was made between exhibition purposes by means of a box-in-box museum display case design and for storage purposes the use of archival boxes.

In the upcoming sections the conclusions from these studies are listed.

Objective 1: Scanning for critical areas

Research and practice have been focused on control of average ambient climate conditions of a conservation environment. When evaluating indoor climate conditions, a lumped parameter approach was often adopted. For instance, the building management system used (averaged) data from sensors either placed on a gallery wall, or in the return duct. These measured ambient climate conditions did not represent object environmental conditions well. Temporal gradients are considered important in preventive conservation. Among others, short-term fluctuations, seasonal variations and incorrect temperature and relative humidity could impact preservation of objects by increased risks for mechanical, chemical and biological degradation depending on objects susceptibility. Besides temporal gradients, spatial distribution and homogeneous distribution of indoor climate conditions were often not considered in most evaluation indices. These evaluation indices focus on whether indoor temperature and indoor relative humidity remained within the required bandwidth to be considered an appropriate climate for object conservation.

Inhomogeneous climate conditions resulting in spatial and temporal gradients were investigated in chapter 2. A climate scan was developed to pinpoint critical indoor (micro)climate areas and their possible causes within historic buildings. The use of experience and expertise of participating case studies during the inventory steps provided different perspectives when it came to technical installations, (historic) building use and collection requirements.
The climate scan as presented in this thesis is of substance when historic buildings (and their building physics) are used for conservation purposes. These purposes are related to exposition, restoration and conservation of objects. This can be achieved in museum, archive or library functions. Historic buildings often have a monumental status which makes modifications such as improving thermal insulation necessary but also undesirable for conservation purposes. Internal insulation could, for instance, impact immovable heritage (e.g. floors, walls and ceilings of great value). Therefore, galleries maintaining original immovable heritage could benefit from this climate scan to locate local critical areas and implement specific measures. While the building envelope cannot be altered to a great extent, climate systems were also not always installed in the most optimal way by using existing ducts and supply openings to avoid depreciation, this influenced available capacity and caused local deviating climates. Investigating the effect of these measures to sustain a homogeneous indoor climate for conservation purposes can be done with the climate scan (Figure 2.4).

By determining not only temporal fluctuations but also spatial distribution of indoor conditions the climate scan showed that building envelope (thermal bridges, condensation issues due to air-tightness), building use (uninsulated temporal retention walls for exhibition purposes) and the climate system (overshooting of temperature and relative humidity near the supply to compensate for the large amount of air volume) were main causes of deviating local indoor microclimates (Appendix C and D). These local indoor microclimates caused spatial gradients that were of importance when a temperature or humidity gradient runs over susceptible collection items (e.g. Figure C.6b), and objects within one zone experienced different indoor climates (e.g. Figure D.15 and D.16). Susceptible objects placed on external walls with low thermal resistance (e.g. Figures C.12b and c), placed on retention walls in front of a single glazed window (e.g. Figure C.6a), and placed within the airflow of the supply duct of the climate system (e.g. Figure C.9b) were not uncommon findings during the climate scan. In order to avoid this, it was recommended to (a) retrofit the building envelope if possible, (b) change the location of susceptible objects that showed degradation signs due to the presence of these local indoor microclimates and (c) adjust the existing indoor climate control setpoint strategy. Certain measures are considered low hanging fruit while other measures impose quite the retrofit of the building, such as improving the quality of the building envelope.

Heritage institutions shift in a slow pace towards accepting fluctuations for indoor temperature and humidity conditions, for instance, M1 in appendix C allows for relative humidity short-term fluctuations of ±10%. The use of passive conservation measures (e.g. silica gel, airtight buildings with limited external influence) and energy conservation measures become interesting. The climate scan proved to be helpful for buildings that want to monitor the effect of energy conservation measures on the indoor climate and in specific, spatial distribution. Energy conservation measures consist of energy saving control strategies with use of existing HVAC system configurations, i.e. adjusting control by intermittent conditioning (switching it off or turning it down when possible), dynamic control (using an allowed bandwidth during climate control), and separation of object and gallery local climates (separated systems for different climate control objectives).

Objectives 2 and 3: The influence of buildings physics and active energy conservation measures on local microclimates and the object environment

The second and third objectives of this thesis elaborated on important factors influencing object environment and local indoor microclimates. In chapters 3 and 4 of this thesis, research on energy saving control strategies with existing HVAC systems and their impact on spatial gradients was performed.

Intermittent conditioning strategies and dynamic setpoint control are promising energy conservation strategies in existing buildings that consider thermal comfort of people and collection preservation (Figure 3.4). Dynamic climate control showed already promising results for museum buildings [42]. Dynamic conditioning employs controlled variations of temperature and RH setpoints within collection requirements, and if applicable, comfort requirements. The controlled variations ensure optimal seasonal adjustments and permissible short term fluctuations. Intermittent conditioning meant that climate control was turned off for a period (free-floating climate), and during opening hours, the climate system was in operational state. During operational state the air handling unit took long to reach the required setpoints, depending on their upper and lower boundary. When the setpoint had a boundary condition close to the temperature or relative humidity conditions that were maintained during free-floating, the time it took to meet the setpoint requirement was small. Intermittent conditioning and dynamic setpoint control in libraries and archives showed the potential for possible energy savings with need of simple adjustment in mechanical control and minimal impact on environmental conditions when monitored precisely (Figure 3.11).

The results of chapter 3 show that in a library storage, the presence of hygroscopic collection in bulk had impact on the hygrothermal conditions measured near the collection and ensured equilibrium in changing conditions by adsorption and desorption processes of the paper collection material. The impact of moisture buffering should therefore be considered in designing climate control strategies for libraries and archives.

During the research in an existing archival building adjacent rooms were of influence on the hygrothermal indoor conditions of the investigated area. Conduction through and radiation from internally shared walls needed to be considered. Especially areas controlled by two different climate control zones and different climate setpoints impacted each other. For instance, office spaces, which tend to be controlled based on thermal comfort of office workers, adjacent to storage rooms resulted in a temperature gradient over the shared internal wall if insufficiently insulated and airtightness is low. The shared wall then acted as a radiant heater creating hot spots for nearby placed susceptible objects that needed conservation conditions with lower temperatures for better preservation. In practice, zoning of air handling units and different building use (i.e. functions) should be attuned to each other and areas thermally separated with sufficient insulation.

Air distribution induced by a climate system was one of the main factors in reduction or increasing spatial gradients. In open exhibition galleries better mixing of air can take place compared to storage, libraries or archives. These buildings pursued a high collection/air ratio by filling racks with collection. Obstacles such as archival racks resulted in turbulent behavior of supplied air and pockets of stagnant air might be present within the archival racks (Figure I.23). The climate scan was adopted to investigate whether critical areas occurred where indoor climate conditions deviated, and inappropriate preservation conditions dominated. During this research, the combination of low (insufficient) air mixing and poorly insulated external walls caused collection to experience seasonal fluctuations. This was not expected since the collection was placed in archival boxes as an extra buffering layer. Fluctuations were muted and delayed, nevertheless, present (Figure 4.8). Intermittent conditioning might not have the same beneficial effect on energy conservation in the case study of chapter 4 compared to the case study of chapter 5, due to its low thermal quality of the envelope.

In an archival box, measurements showed that only a small daily span for temperature and relative humidity occured (Figure 4.6C, chapter 4). Therefore, it was assumed that a stable daily climate surrounded the archival collection inside the box. The seasonal span of the archival box showed larger fluctuations compared to other positions in the archival rack, this was mainly due to the influence of the external wall temperature radiation, one of the main findings of this study (Figure 4.6A). The temperature radiation of the external wall influenced the microclimate conditions inside the archival box in such a way that the influence of the climate control system during winter period was neglectable.
In the performed research, relative humidity did not exceed 65% for an extended period to form biological risk issues and short-term (hourly) fluctuations in temperature did not exceed 1°C, preservation conditions (temperature $<17.5°$C) were considered good inside the archive box for paper collection preservation.

Objective 4: Separation of preservation climates

The last objective of this thesis, resulting in chapter 5, provided the results of a case study where object environment was decoupled from the indoor environment (and therefore separation of thermal comfort) by means of a novel museum display case design. Application of this novel museum display case was based on, among others, incorrect temperature conditions and vibrations in the previous display case for preservation of paper collection. A low temperature condition was wanted without providing discomfort to visitors and without directly supplying cold air to the object on display.

Separating preservation climates created opportunities for climate control strategies to focus on preservation conditions in the display case and reduce energy consumption by specifically conditioning a smaller volume. When susceptible objects were not present in the gallery, focus could be on thermal comfort for people in determining the setpoint strategy for the gallery volume during opening hours.

The investigated box-in-box display case design generated an appropriate object environment by means of active stable low temperature control that met museum climate requirements set by museum staff (Figure 5.14). Experiments provided insight in the impact of malfunctioning active climate control on the object environment (Figure 5.11). Sudden unplanned rises in inlet temperature provided unnecessary increased risk to a susceptible object (Figure 5.11, green peak). Protocol needs to be defined to turn off the active system and let the display case act as a passive display case until either the control system was operational, or the object was secured. Due to the airtightness of the display case, gallery indoor climate conditions had a delayed impact and the display case could serve as a passive display case.

6.3 Further research

In this thesis, topics such as preventive conservation, incorrect indoor climate parameters temperature and relative humidity, and energy conservation have been investigated. During this research some gaps and interesting directions have been identified that could not be addressed during this research trajectory. These gaps will be discussed in the upcoming paragraphs with recommendations for further research.

A current trend in preventive conservation that is mainly seen in storage and collection centers, is passive measures and passive design. Passive buildings are used to create a stable indoor climate mainly focused on indoor temperature, and minimize the use of, amongst others, climate control installations. The use of passive building concept lends itself for purpose-built buildings and storage purposes where interventions by visitors are limited and the bulk material provides extra hygrothermal mass. Adapting historic buildings with passive measures requires a significant investment and might not always be possible or even allowed depending on the building its monumental status. Active measures such as climate control are in place to level out the presence of visitors that act as thermal and moisture sources. Further research towards passive renovation or retrofit measures for historic buildings should continue.

The influence of air distribution on indoor climate parameter fluctuations has been investigated in chapters 3 and 4 and has shown that the building envelope quality has a major effect on these fluctuations. The impact of these fluctuations in the object environment and its effect on (in this case) books would benefit from further research into this topic. For instance, specific risk assessment models currently available often use a single sheet of paper to predict risks in the worst-case scenario with the smallest response time. Information on hygrothermal impact on degradation risks for stacks of books (especially the impact near the surface region) or the in-depth effect on leather spines is limited and would provide important information for a large sector within preventive conservation, the paper archives and libraries.

While temperature is actively controlled in the novel display case, relative humidity is controlled by means of preconditioned silica gel. By placing an object in an airtight volume an equilibrium moisture content will be reached by absorption or desorption of moisture. Within the display case a separation of silica gel and the object is made by placing these in different compartments. Through the diffusion principle the moisture levels in the display case level at the preconditioned setpoint of the silica gel. Diffusion is the movement of something (in this case moisture) from a region of higher concentration to a region with lower concentration until an equilibrium is reached. This diffusion needs to take place through a small opening between the display case compartments. Object behavior (e.g. absorption and desorption of moisture) might be affected by the large moisture uptake of silica gel. Therefore, it is recommended to research the effect of silica gel used in enclosed areas with susceptible objects present.

In chapter 5, the inner display box was considered the object environment. The partition between silica gel and the object, and specifically the opening between the compartments, is of influence on diffusion (speed). To what extent and which configuration (e.g. perforated plate, open on each side, or permeable material [174]) stimulates optimal moisture exchange and moisture equilibrium is limitedly researched. Diffusion speed between two compartments can be increased by increasing air exchange and therefore creating more or larger surface openings. The application of silica gel is very popular as moisture control in preventive conservation. However, research is limited to what extent silica gel influences the moisture content of a susceptible object and how silica gel can be used to its full potential in display cases by controlling diffusion speed between two compartments. It would be important for future research to focus on this topic.

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Appendices

A Inventory list for ICMS

Table A.1: Inventory check list to gather information on four topics [1, 109, 122].

Building	Yes/No
year of construction	
building fabric specifications/documentation	
floor plans	
sections	
elevations	
structure plans	
Building systems	Yes/No
climate control system	
climate control system technical drawings	
climate control system specifications	
building management software	
T/RH setpoints	
monitored parameters and data	
Air handling unit zoning	
sensor positions	
sensor types	
lighting fixtures	
future plans for renovation	
Building use	Yes/No
exhibition/ storage	
object types and values	
object locations	
temporary/permanent	
special events	
activities	
extra opening hours	
exhibition technical preparation	
system malfunctions logbook	
visitors annual/day	
average length visit	
guided tours	
extra preventive measures	
Energy management	Yes/No
energy consumption	
per zone	
per type (illumination, ventilation etc.)	
power generation	

B Case study descriptions

Three case studies were used to perform the ICMS on. The first case study in this research is the Amsterdam Museum (M1) located in Amsterdam, the Netherlands. Since 1975, the museum is housed in a former orphanage located in the historical city center of Amsterdam. Over four centuries the orphanage was located in this 15th-century historical building. From this period, important rooms were preserved like the *Historic Room*. Other buildings were annexed over the years and refurbished to expand museum functions into them. To avoid damaging the original brick walls, retention walls are mainly used when needing wall surfaces for objects to be displayed. Most single-glazed windows were covered with an extra layer of glass to create better thermal properties. Indoor screens were placed to prevent direct sunlight to cause damage.

The museum installed an all-air HVAC system to maintain a favorable indoor climate for museum objects. Since the building consists of nearly 17 merged buildings, installment of the climate control system was complex. Certain rooms like the *Historic Room* are conditioned by their own air handling unit (AHU) which was only installed in 2007. Use was made of already present heating and ventilation inlet ducts. The ventilation strategy is not CO_2-based; a fixed amount of 10% fresh air is conditioned and added to recirculated air during opening hours. Full recirculation is used as ventilation strategy during closing hours, no fresh air is needed since no visitors are present and energy savings are higher. Humidification was done with an ultrasound humidifier with pre-processed reverse osmosis water to reduce micro-organisms being added to the supply air. The objects housed in the *Historic Room* – paintings, wooden ceiling and furniture – are (at the time of writing) considered most valuable to the museum. Most objects in this room can be displayed in other areas, the wooden ceiling and mantelpiece are part of the interior.

Figure B.1: Exterior and interior (Historic Room) impressions of M1.

The second museum is the Kröller Müller Museum (M2) located in National Park De Hoge Veluwe. The area surrounding the museum consists of various impressive nature areas and makes the building one of a few in the National Park. The purpose-built museum opened in 1938 for public and is called the *Gallery Wing*. The collection was comprised from works bought by the Dutch government of the private collection. In 1971 and 1977 extensions were realized by Quist to increase the exhibition galleries for public. The extension consisted of an auditorium, exposition areas, offices, restaurant, and depot. The original museum building dating from 1938 is a National monument. The original building consists of a more closed off exhibition room where daylight can enter through transparent patches in the ceiling. The addition during the 70s had wide hallways with large areas of glass and made the connection with the surroundings. A sculpture garden was realized surrounding the museum buildings.

Climate control was updated at the time the extensions were realized and air was supplied through mainly ceiling panels for the Gallery Wing. The new built made use of an integrated floor framework. The system is CO_2-controlled and supplies more fresh conditioned air when the CO_2 levels are exceeded due to high visitor numbers. A rotary heat exchanger is present in the air handling unit to extract heat and moisture from the exhaust air to be added to the supply air. Humidification is done by an ultrasonic humidifier. The collection exhibited in the Gallery Wing presents a large collection of Van Gogh paintings. The large majority of these paintings are displayed in a microclimate frame.

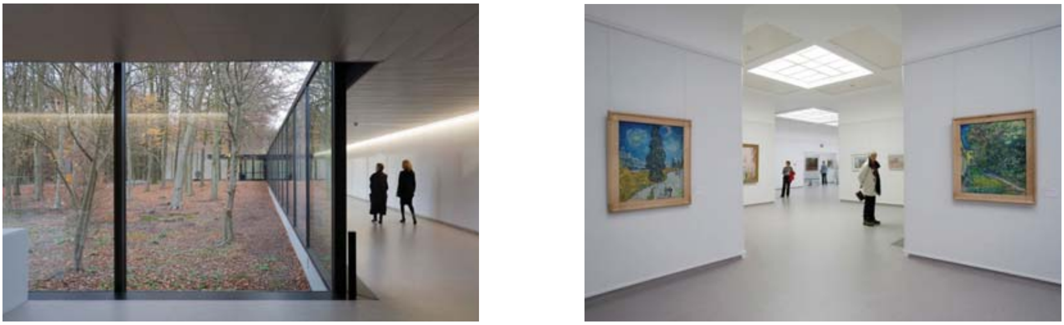

Figure B.2: Interior impressions of M2. (image from: https://www.qwa.nl/projecten/cultuurenonderwijs/krollermuller.html)

The last museum investigated in this paper is the Van Abbemuseum (M3) located in the city center of Eindhoven. This museum opened in 1936 to exhibit a private collection of modernist painters collected by Henri van Abbe. The brick building with recognizable tower is a National monument. The roof is comprised of large glass areas that, through the transparent ceiling of the gallery rooms, lets in daylight.

In 2003 the original brick building was renovated by updating it to most recent building code where possible. The glass roofs functioned as a greenhouse to the attic, where temperatures of over 50°C were measured. However, the steel structure was not designed to replace the glass. An extension was built behind the original building to increase exhibition gallery floor plans and add square meters for a restaurant, depot, and workshop areas. The principle of light entering the galleries was copied, in a more modern way, in the new building. A double ceiling was still used, however, LED lighting replaced the daylight entering the rooms.

The museum uses two air handling units to control the ventilation, air temperature and relative humidity. One controls the old building, one the new building section. A by-pass for recirculation was added to reduce energy consumption to the air handling units.

Nowadays, the collection is comprised of the original, privately-collected, collection and extended with more modern installations and materials. The original building part is frequently used for temporary exhibits and activities.

Figure B.3: Exterior and interior impressions of M3.

C Climate scan (whole building)

The case studies each had an objective when executing the climate scan. M1 wanted to gain more insight in the influence of climate control systems on the indoor climate in historic buildings, in specific in the Historic Room where an air handling unit was installed in 2007 by making use of existing floor ventilation ducts.
M2 wanted to gain more insight into the influence of the climate control system on the indoor climate in a gallery space that has been divided into smaller areas, however, all in connection with each other. Would a more tolerant setpoint strategy create less differences, especially since the majority of objects on display were placed in microclimate frames?
The objective of M3 was to investigate where the difference in indoor climate parameters came from when comparing the old and new building part, a similar climate control system was installed at the same time per building part. However, building management system monitoring measured high exceedances in terms of temperature and relative humidity during summer months.

The climate scan as described in the methodology section was used to describe and define the present indoor climate in the case studies. The case studies served as pilots to see where the climate scan was incomplete and to enhance the methodology.

Visits, short-term and long-term measurements were scheduled for each case study. After gathering the necessary documents and information through the inventory and walk-through (mostly guided) visit, the information was processed and evaluated.

Table C.2: Scheduled visits, short-term and long-term measurement periods.

	Short-term		**Long-term**
	Winter	Summer	
M1	January 13, 2016	July 2, 2015	November 2015-2016
M2	February 16, 2016		May 2016-2017
M3	February 17, 2017	July 20, 2016	August 2018-2017

Classification of case studies

The museum buildings were classified after the first visit and study of the documents gathered by the inventory. Based on their quality of envelope (QoE) and level of control (LoC) they were sorted in a matrix (see Figure C.4). This matrix represents the spread in QoE for the investigated buildings based on the information gathered by inventory and visit. The first step of the climate scan looked in-depth to the quality of the building envelope and level of control present. The LoC was similar in all museums, LoC4. A full HVAC system was present to control the indoor climate of the different galleries and other areas. Though the climate control for both T and RH was present, the setpoints differentiated per case study (see Table C.3). M1 was built in the 15th-century which makes it the oldest building envelope. Though some adjustments were made, the climate control requirements were adapted to suit the feasibility of the building envelope. The installed HVAC had been

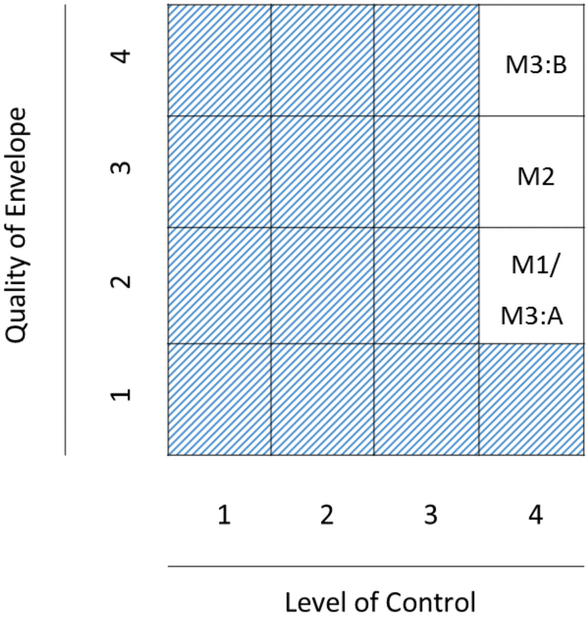

Figure C.4: *First classification of museum buildings by quality of envelope and level of control present. M3:A stands for the original building part of M3; M3:B stands for the modern addition built in 2003.*

added in 2007. Before this time, no control was present in the *Historic room* and a large part of the museum. The combination of an historic building envelope and a long period of no climate control resulted in the decision by facility staff to use more tolerant setpoints for *RH* (50% ±10). M2 kept their setpoint specifications conform the most stringent ASHRAE climate class: AA [7]. According to ASHRAE, no increased risk profiles are present when adopting this climate class the investigated building part was renovated in the early 1970s resulting in QoE 3. M3 had adopted the Dutch recommended setpoints as suggested in 1994 [3]. This publication suggested more strict short-term *RH* fluctuation control than compared with the ASHRAE Climate Class AA. The building envelope of M3 is divided in two classifications. One is a slightly adapted old monumental building envelope (part A) with a QoE2, and the other part (B) is classified as QoE4, being purpose-built as a museum.

Table C.3: Temperature and relative humidity specifications (setpoints and allowed short-term fluctuations) as adopted by the museum.

	Temperature [°C]		**Relative Humidity [%]**	
	Setpoint	Short-term	Setpoint	Short-term
M1	20	±1.5	50	±10
M2	20	±1	50	±5
M3	20	±1	52	±3

Investigation of a 15$^{\text{th}}$ century museum (M1)

It was important to gain insight in how the building was used to locate critical areas. The short-term measurements provided information on the *T* and *RH* in that specific short period of time. It quickly showed deviating galleries that needed further investigation. The measurements were taken with a handheld device on a grid. Near-wall and center measurements were taken and an average was derived for this. The measurements were taken twice to average for the time spent performing all the measurements. Though already differences were noticeable between different grid locations, averaging provided information on the whole building and if climate control zones were visible or whether other influences predominated the indoor climate.

Figure C.5 provides the short-term results of the *T* and *RH* measurements performed throughout the ground floor of M1. The used handheld hygrothermal measurement equipment (HygroPalm 21 used in this study) specifications can be found in Table C.4.

Measurements were taken over a 2-minute interval per grid point. Several non-exhibition areas were measured as well but not considered during this study. Those rooms showed to be on the excessive side of the museum requirements (*T* = 18.5-21.5°C; *RH* = 40-60%), however, not obliged to apply to these requirements. In general, both figures show that the requirements were met for the majority of exhibition rooms. It shows that despite being considered a building with low envelope quality (figure C.4) the galleries are kept within the museum requirements based on these measurements.

Table C.4: Specifications for short-term measurements with handheld indoor air quality instruments (as used in the case studies).

		Temperature [°C]	**Relative Humidity [%]**
Hygropalm 21	Accuracy	±0.2	±1
	Resolution	0.01	0.02
	Response time	<5s	<10s
IAQ-CALC, Model 7545	Accuracy	±0.6	±3
	Resolution	0.1	0.1
	Response time	<30s	<20s

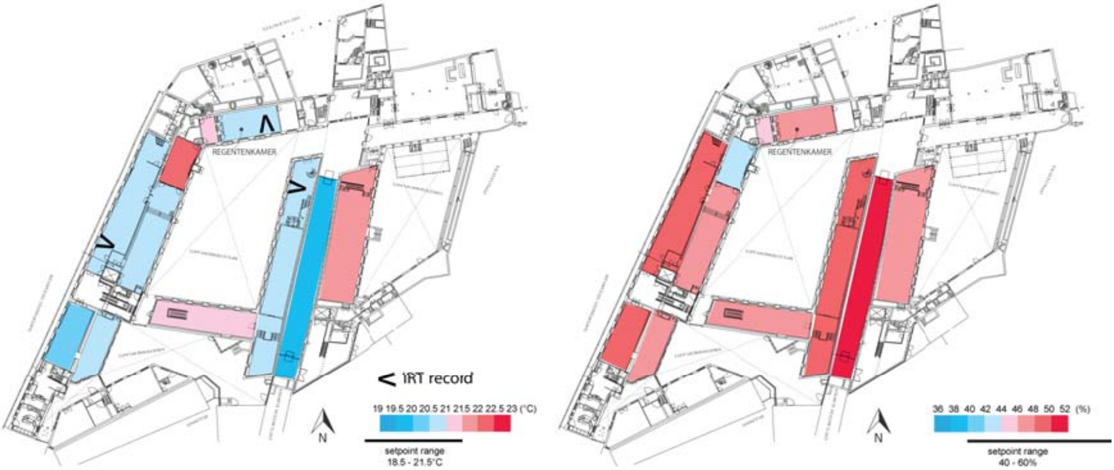

Figure C.5: *Averaged short-term measurements for T (left) and RH (right) for the ground floor of M1. Measurements were performed on January 13, 2016. External climate data:* $T_{average}$ *was 8.3° C (*T_{max} *= 10.0° C,* T_{min} *= 5.2° C),* $RH_{average}$ *was 90%.*

Infrared imaging was used to study spatial gradients in more detail. The infrared thermographs and hygrographs displayed in figure C.6 are subdivided in critical areas originating from either building envelope, building system or building use. This does not exclude that in certain instances a combination of multiple divisions occurred. Figure C.6a shows the use of a retention wall placed in front of a window. Even the details of the window frame were visible. The deviating surface temperature and near-surface relative humidity could result in a gradient over the object if the air surrounding the object is conditioned to different values. Figure C.6b shows the influence of heat emitting light fixtures. In many cultural institutions it is common to use a spot to illuminate an object. With the IRT method the influence of such spots on T and RH gradients has been investigated. A T gradient of 4K was visible over the painting and approximately 10%RH. Switching the lights on and off during opening and closing hours creates periodical fluctuations. Figure C.6c shows an HVAC inlet placed in an existing convector system. The image shows a direct influence of the supply air conditions on the furniture object. The object was exposed to a microclimate with unevenly distributed climate conditions. In addition, the object was exposed to cool and dry air in the winter, and warm and humid air in the summer. The continuously changing supply conditions caused increased risks for mechanical degradation of the object placed in the vicinity.

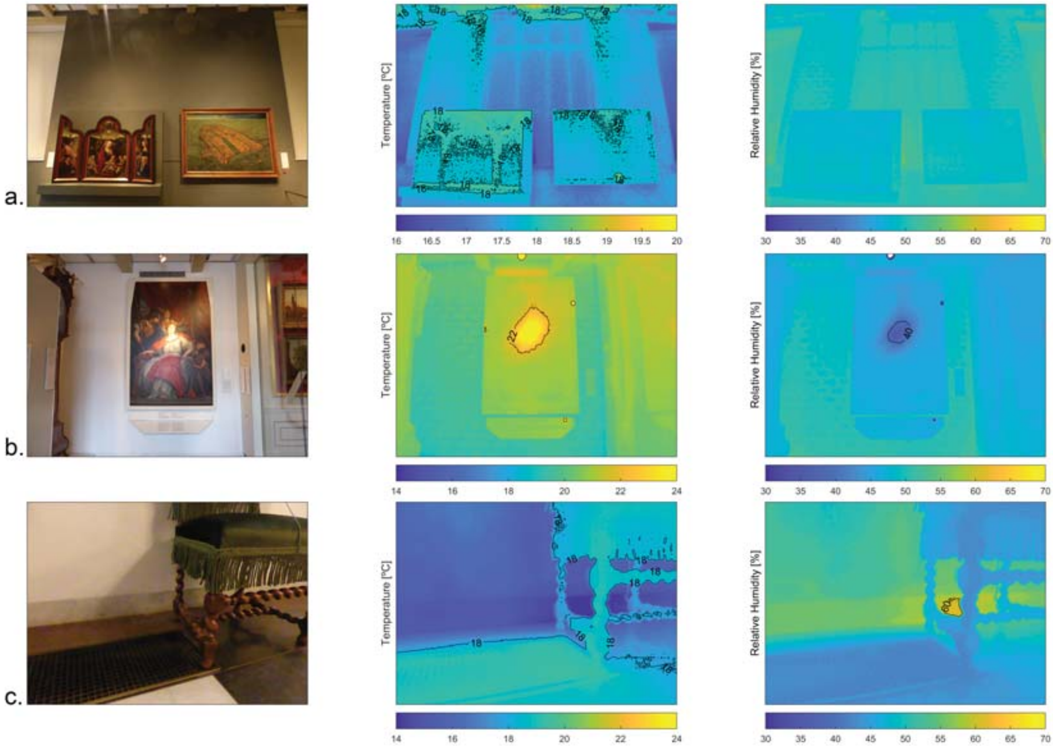

Figure C.6: *Visual image (left), thermograph (center) and hygrograph (right) for three location in M1. An non-insulated retention wall is shown in (a). The effect of using a light spot with high heat distribution (b). Influence of supply duct near a susceptible object (c).*

Deviating indoor climate is not necessarily a risk in traffic areas but might form a risk when objects are present. During the visit, a conservation specialist provided information on where the most valued objects and susceptible objects were located at that moment. The most valuable objects are part of the permanent collection of the museum and their placement in specific galleries are due to the link with the gallery or due to the size of the objects and possibilities to be exhibited. It is unlikely for these objects to be placed in a different gallery. The building is comprised of multiple buildings joint together. This resulted in galleries of various sizes scattered throughout the building. Several exhibition rooms have facades experience direct solar radiation. This means that during sunny days, solar gains can be high and objects placed on an external façade might be affected due to hygrothermal inconsistencies. These insights are gathered in figure C.7.

Figure C.7 also shows the building fabric in the floor plan of the ground floor for M1. The figure provides information for the exhibition rooms only. This can, depending on the researched area, be expanded. In this research solely the exhibition rooms were considered.

The blue walls were external walls. In certain instances the external walls were covered by a retention wall to make the surface suitable for object placement. The retention wall often covered windows. In cases where the windows were not hidden, a protective glass layer was added on the inside to increase thermal resistance and limit thermal losses and solar gains. To avoid direct solar radiation, shading was added. Based on these interventions, M1 could be categorized in QoE3 in certain areas of the building.

Combination of the hygrothermal measurements, IRT measurements and the inventory resulted in a combined evaluation of M1. Areas were identified where critical areas were registered and either building envelope, building system or the indoor climate in general increased risk for objects. For instance, the *Corridor Gallery*, the only room where large paintings were able to be placed was also considered a critical area. This gallery part is a closed of street with low quality of envelope resulting in an indoor climate resembling external climate conditions. The Historic Room was considered a critical area due to the building system and envelope inducing a possible risk to objects placed near or on the external wall. Considering this building stems from the 15th century, this was expected. In the *Historic Room* every type cause for a local deviating climate was registered. Therefore, this room was taken as example to pursue long-term hygrothermal measurements to verify the occuring LICs.

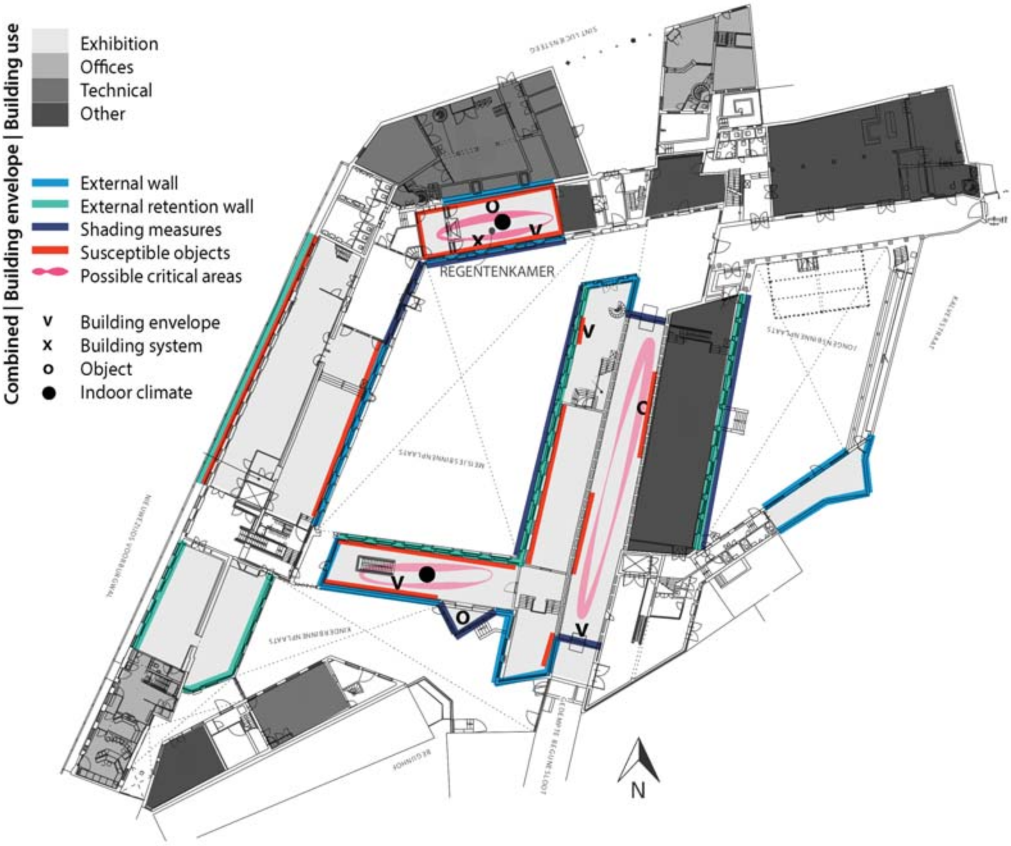

Figure C.7: *Overview of building use, building envelope and critical areas and location of the ground floor of M1.*

Investigation of a renovated museum (M2)

M2 has a large exhibition wing where the most valuable artifacts were located. The majority of the paintings displayed in this wing were placed in microclimate frames. The short-term measurements in M2 were performed during a winter day. The setpoints specifications of M2 were strict, however, figure C.8 shows that the gallery area is able to easily meet these requirements. There was a temperature spread of 1.6°C throughout the gallery and a *RH* spread of 2.6% during the short term measurements period of 1 hour and 50 minutes. The average external temperature and relative humidity were: T_{ex} was 11.8°C, and RH_{ex} was 84.4%. In general, a higher T results in a lower RH; however, some areas did not show this principle. This could be caused by a local moisture source or cold surface temperatures where moisture was able to condensate. However, the values measured during this study lie within small vicinity from each other and could also have been influenced by the accuracy of the measurement equipment.

In Figure C.9a, figure C.9b and figure C.9c several situations are presented where a local climate affects an object located in M2. As can be seen in Figures C.9a and C.9c, the

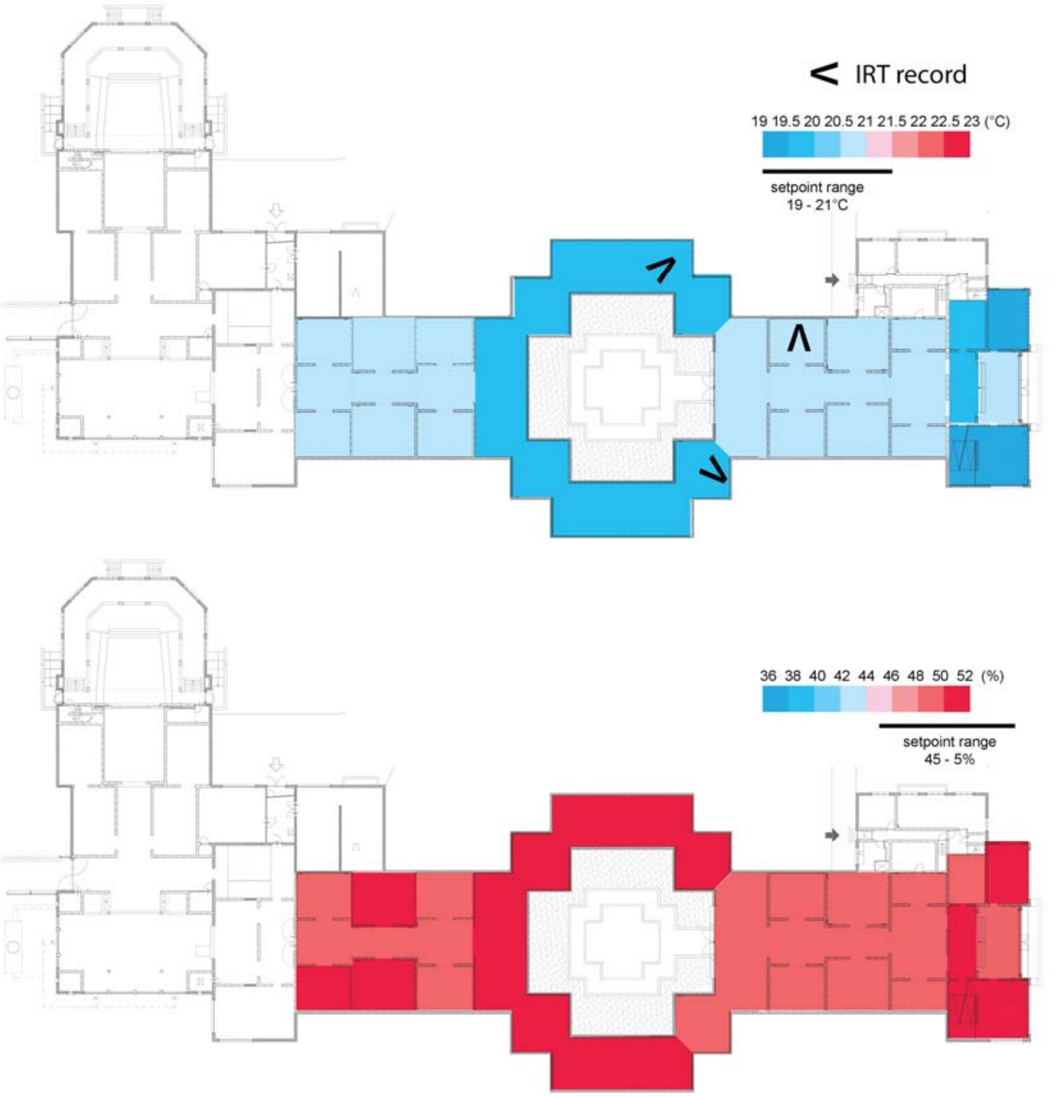

Figure C.8: *Averaged short-term measurements for T (upper) and RH (lower) for the ground floor of M2. Measurements were performed on February 16, 2016. External climate data:* $T_{average}$ *was -1.1°C (*T_{max} *= 5.4°C,* T_{min} *= -6.7°C),* $RH_{average}$ *was 76%.*

temperature close to the 3D connection between external walls and floor was around 16.5°C, which is lower considering the temperature requirements. This causes a gradient in surface temperature towards the object. The low surface temperature indicated a thermal bridge due to absence of insulation in the construction. This can be linked to the construction year of 1937. A convector radiator was placed in the floor just below the object in figure C.9a. Supplying air in an upward direction resulting in a temperature of more than 27°C has a significant influence on the object environment. The unintentional high local temperature of 27°C lies above recommended safe ranges and can cause object deterioration [175, 176]. Figure C.9b shows similar influences by a convector heating an object located above it. It should be noted that the paintings shown in the figures relating to M2 were positioned in a microclimate display frame with heat reflective glass. The actual object temperature may deviate from the infrared picture. The backside of the painting could have been affected by the surface temperatures of the wall.

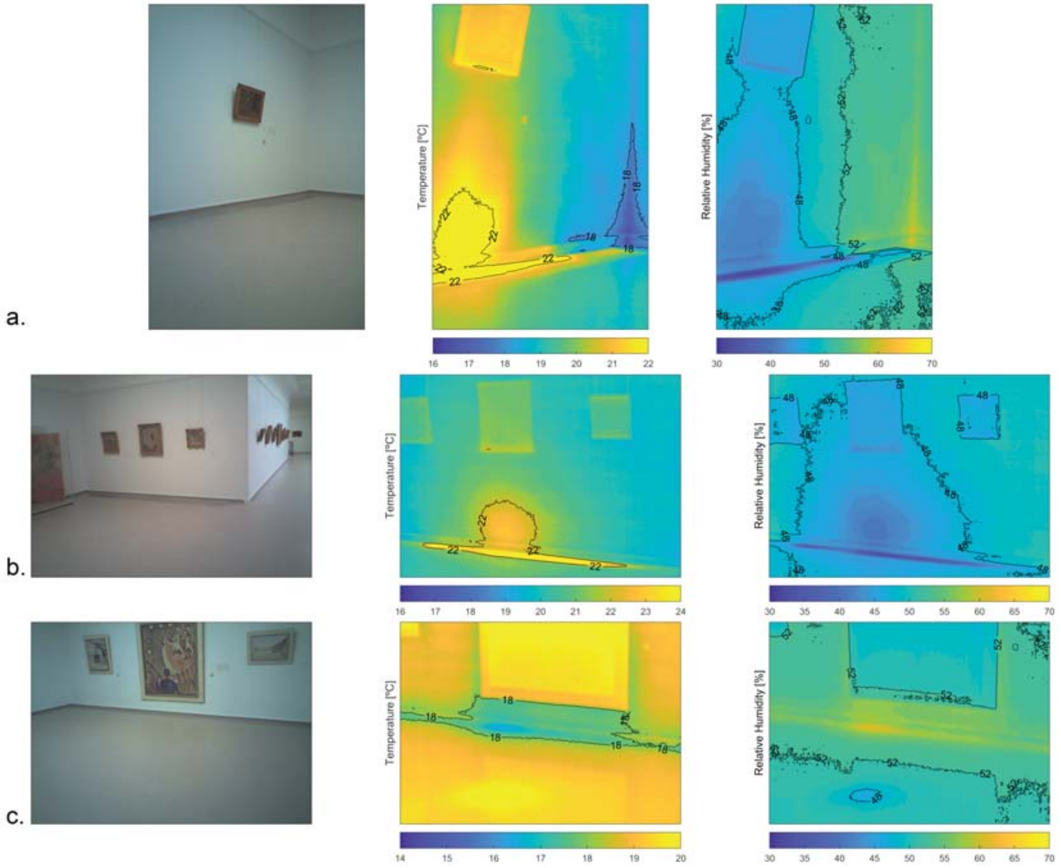

Figure C.9: *Visual image (left), thermograph (center) and hygrograph (right) for three locations in M2. A combined effect of a wall/floor joint and an HVAC system inlet (a, b). Building envelope thermal bridge with floor/wall joind (c).*

Figure C.10 provides an overview of all the input gathered through the hygrothermal measurements, IRT measurements and inventory. This image shows the exhibition wing with connected galleries. In the center a patio was created which increased surface to place objects, however, also increased the share of external walls on which objects were placed. Figure C.10 also shows the different building envelope types. This wing has surfaces of glass present. A protective foil was placed to limit solar gains in the gallery. However, direct solar radiation is able to enter the galleries and increase sudden fluctuations in T and RH. A patio placed in the center of the gallery increased the external wall surface significant.

The majority of museum collection in that wing was placed on the external walls which increases the influence of the external walls performance on object risk like cold surfaces during the winter period.

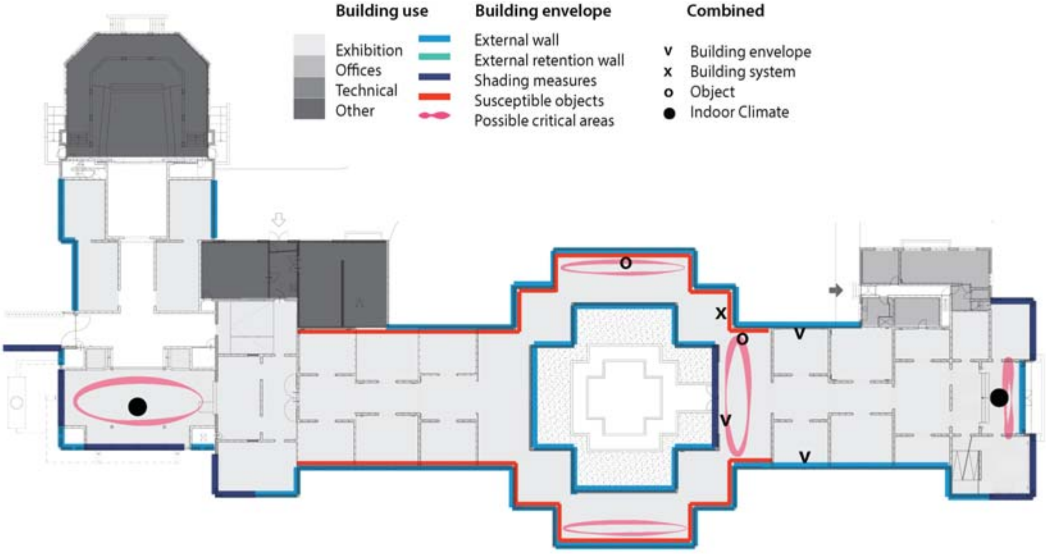

Figure C.10: *Overview of building use, building envelope and critical areas and location of the exhibition wing of M2.*

Investigation of a monumental and purpose-built museum (M3)

Figure C.11 depicts the results of the short-term measurements performed at M3 during summer. It was known with museum management that during the summer period, indoor climate paramteres were all over the place. In general, values of T were inconsistent in the original museum building while the T values in the addition were kept closer to the setpoint of 20°C. The higher temperatures resulted in lower relative humidity in the galleries in the new building, this is shown in the figure on the right side. The area above the galleries has a roof made of glass which functions as a greenhouse during summer for temperature. Measurements showed extreme temperatures of 50°C occurring in these spaces and in general, daily fluctuations of 20°C were common. This had the effect that the galleries below were influenced by the indoor climate of the plenum. The building system did not have a large enough capacity to cool this part of the museum. T varied from 19.5-26.5°C and RH from 41.6-54.4% resulting in exceeding the requirements set for the indoor climate setpoints by museum management. During winter, the spread was small between the exhibition galleries and two building types (see appendix E for the winter measurement results for M3).

Figure C.11: *Averaged short-term measurements for T (left) and RH (right) for the ground floor of M3. Measurements were performed on July 20, 2016. External climate data:* $T_{average}$ *was 26.4° C (*T_{max} *= 33.9° C,* T_{min} *= 20.2° C),* $RH_{average}$ *was 41.7%.*

Figure C.12 shows the IRT results for M3. Figure C.12a shows a corner of a gallery in the original built of M3. External climate showed temperatures well below 0°C in order to investigate the thermal transmittance through the external walls of the gallery. High thermal transmittance was expected in combination with the 1930s building envelope. However, the building had been renovated and insulation was added over time. Even with the refurbishment, low indoor surface temperatures were present. Figure C.12b shows the impact of an added glass house on the indoor surface temperatures adjacent to the glass-wall junction. The glass house was a small add-on where a few visitors could stand and admire the view. The influence on the external wall adjacent to the conservatory was visible and indoor surface temperature between 15-16°C were present. The temperature in the conservatory increased during the day and due to direct sunlight the temperature of the walls connected with the glass increased. It would be an important area to research surface temperatures near objects placed on these walls. Figure C.12c shows thermal bridges due to old construction columns where surface temperatures lower than 18°C were reached. These figures show that it is important to research, besides indoor T and RH, the indoor surface temperatures since they were influenced by external climate conditions and could result in diurnal and seasonal fluctuations near objects placed on walls. It is common to place sensors on internal walls to control the indoor climate by means of the climate system. During these measurements it showed that placement of sensors near objects in possible risk-areas would benefit decision making for exhibition installment. Compared to the short-term hygrothermal measurements the IRT measurements showed that there are some critical areas present. Figure C.12a is the result of obscuring a window by adding a pack of insulation material. However, the thermal insulation was low and external temperature influences were found. The derived RH did not provide a reassuring image.

Figure C.13a shows the ground levels of the new built and old built of M3. The old building exhibited a temporary exhibition during the investigated period. The new built ground level is used to exhibit the original collection of modernist painters with addition of modern installations. Most of the highly valued objects on these levels were placed on internal walls. With that, the influence of building systems and the building use would be of more influence than for instance the building envelope quality. The original building has two small glass surfaces of which one was sealed with a board to limit daylight from that specific direction. All galleries were in connection with each other or with traffic areas (Figure C.13). The new addition has two glass add-ons which were in open connection with a gallery. It was expected that in combination with the orientation - one was placed on the west façade – solar gains increased during sunny days and it was therefore important to investigate surface temperatures near objects placed on walls near these conservatories.

From the inventory and visits the climate scan has seen three important effects on the process to determine indoor climate. The building envelope, which was different in the three cases investigated, showed to be deviating within a single gallery based on the inventory and visit. The main reason for the spatial deviations within a single gallery was due to retention walls to increase thermal resistance and create surface for objects to be placed in older buildings. With the IRT measurements more detailed information could be extruded on the building envelope quality in relation to possible object placement.

IRT provided a 2D overview of spatial deviations in surface T and, after calculation, near-surface RH. These deviations were ascribed to (i) the building envelope quality, (ii) the influence of the building systems, and (iii) the building use. IRT showed that the QoE could be deviating for one surface or within a single area due to addition of (non-insulated) retention walls or the presence of thermal bridges. In the case of M1, a seasonal difference is noted in the impact of a lower envelope quality when assessing the IRT images (appendix F). Therefore, continuous hygrothermal measurements would provide insight in temporal gradients occuring due to diurnal cycles and seasonal cycles to research the increase (or decrease) of biological, chemical and mechanical degradation of objects. Since IRT was used as an instantaneous measurement it was important to complement them with hygrothermal measurements as well. A quick insight was gained in indoor climate behavior by these short-term measurements.

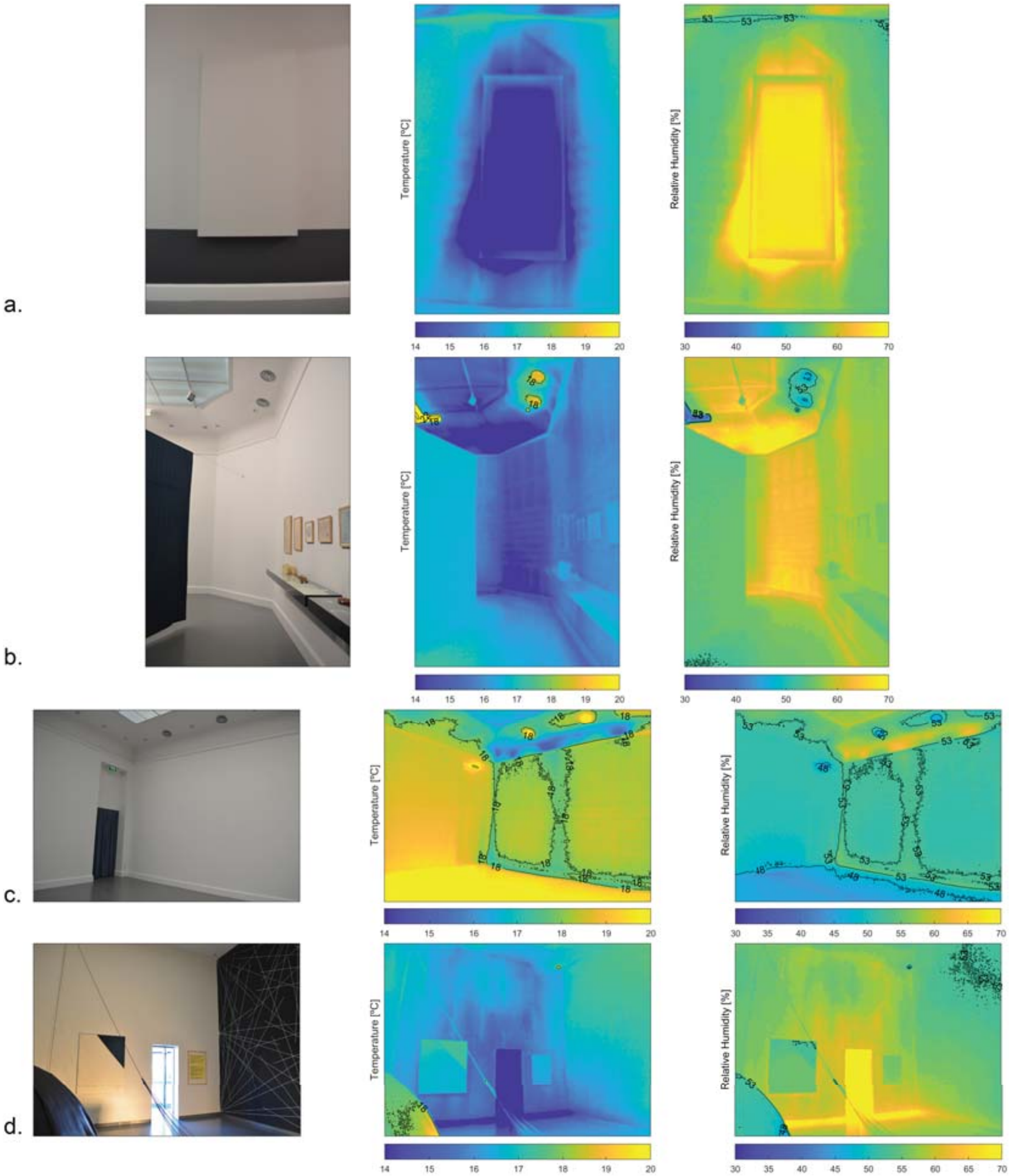

Figure C.12: *Visual image (left), thermograph (center) and hygrograph (right) for four locations in M3. Obscuring a window with the addition of a slab of non-insulating material is seen in (a). Three instances of building envelope with low thermal quality and thermal bridges (b, c, and d).*

The short-term measurements provided quick insight in indoor climate behavior. Though the information plotted was based on room-averaged conditions, the measurements were

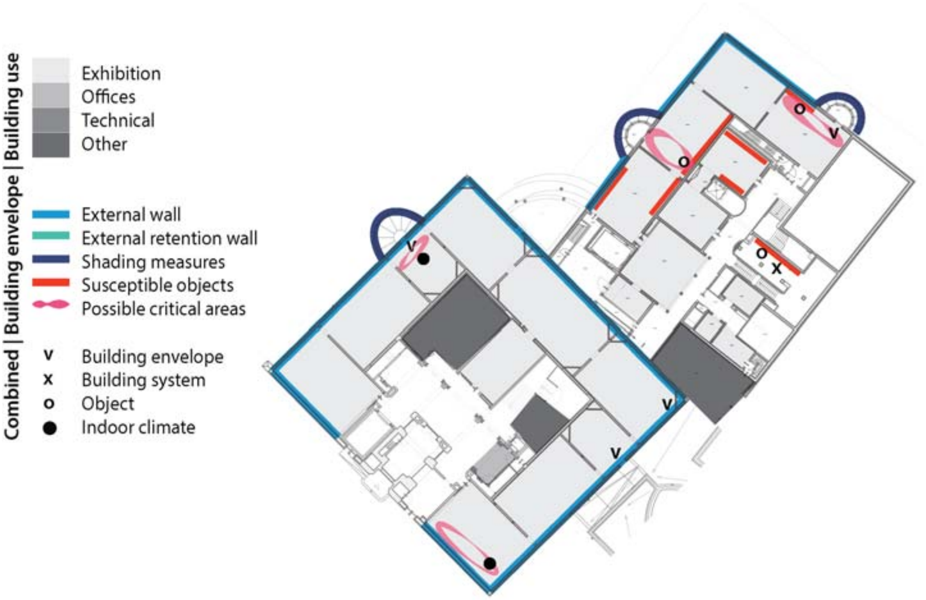

Figure C.13: *Overview of building use, building envelope and critical areas and location of the exhibition wing of M3.*

based on a number of grid-measurements which resulted in taking spatial differences into consideration. Combining the results from the hygrothermal measurements, IRT measurements and inventory provided a starting point for long-term measurements of T/RH in which insights in spatial gradients were complemented by temporal measurements.

An overview of the following causes for deviating indoor local climates were found in the case studies.

Table C.5: Overview of found causes for deviating indoor microclimates

Cause	M1	M2	M3
Building envelope			
Thermal bridge	x	x	x
Envelope	x	x	x
Building systems			
Climate control	x	x	
Light fixtures	x		
Building use			
Retention walls	x		x

D Long-term measurements

The previous sections provided a classification of common local indoor microclimates in museum buildings. Using these classifications on a more detailed level the ICMS was deployed in a single gallery as well. The *Historic Room* of M1 shows a multitude of causes for deviating indoor climate. This gallery was used to illustrate short-term measurements in Figure D.14. For T and RH the short-term measurements showed a slight spatial gradient for this gallery. Whereas the spatial air gradient for T and RH seemed negligible, the IRT showed significant deviating climates due to the external wall and influences of the climate system inlet. Appendix F provides images for a comparison between winter and summer season of the external wall and near the inlet. In this study long-term measurements were executed by means of a datalogger and Eltek transmitters (for instrument accuracy see Table D.6). The datalogger temporarily stores data with a preset interval of 10 minutes.

Table D.6: Eltek combined T/RH transmitter specifications for long-term measurements.

	Temperature [°C]	**Relative Humidity [%]**
Accuracy	±0.2	±2
Resolution	0.1	0.1

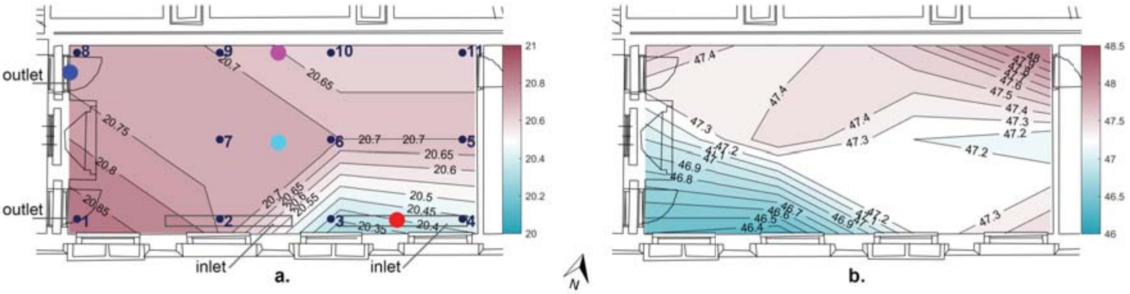

Figure D.14: *Interpolated air temperature in a horizontal cross-section of the Histori Room (M1) (a) and relative humidity in a horizontal cross-section at 1.50m (b). The measurement locations are shown in (a) at a height of 1.50m measurements were taken on June 10th 2015. The long-term measurement locations are also provided for supply (red), extract (blue), object (magenta), and room average (cyan).*

Based on the climate scan, long-term measurements were set-up. A selection of location results of the *Historic Room* located in M1 was used. Measurements were taken at the following locations (see figure D.14):

- the supply duct of the climate system,
- the extract of the climate system,
- on a cupboard near a hanged painting,
- the room average taken at the center of the gallery placed near a valuable table.

Near the supply duct of the climate system, artifacts were placed. Near the extract of the climate system, panel paintings were located. So, the majority of these monitoring locations were in the vicinity of valuable artifacts. Figure D.15 shows a time-series of the measurement locations in this gallery. The inlet location showed the largest gradient during the month February, this was a typical winter period. Temperature is kept within the museum requirements for all locations. However, the inlet measurements showed drops below 18°C and peaks just above 21°C that can occur within the time frame of one hour. This is regular behavior of a climate system, however, not beneficial for the objects placed near this supply duct.

For relative humidity, the spread across the room was larger (approximately 10%RH during frequent periods and on average 5%RH) and dips of 32%RH were seen near susceptible wooden objects (magenta line). The measurements have been carried out for a year and the results are shown in a climate evaluation chart for the four measurement locations (figure D.16). The climate evaluation chart was developed by Martens and provided the measurement results for T and RH in a psychrometric chart [1]. This visualized the spread throughout the year and in this case, showed the differences between the measurement positions. The blue square shows the museum setpoint criteria. The column on the right side provides the percentage of time these measurements met the requirements. The location near the internal wall and the objects (magenta) showed the highest temperatures and lowest

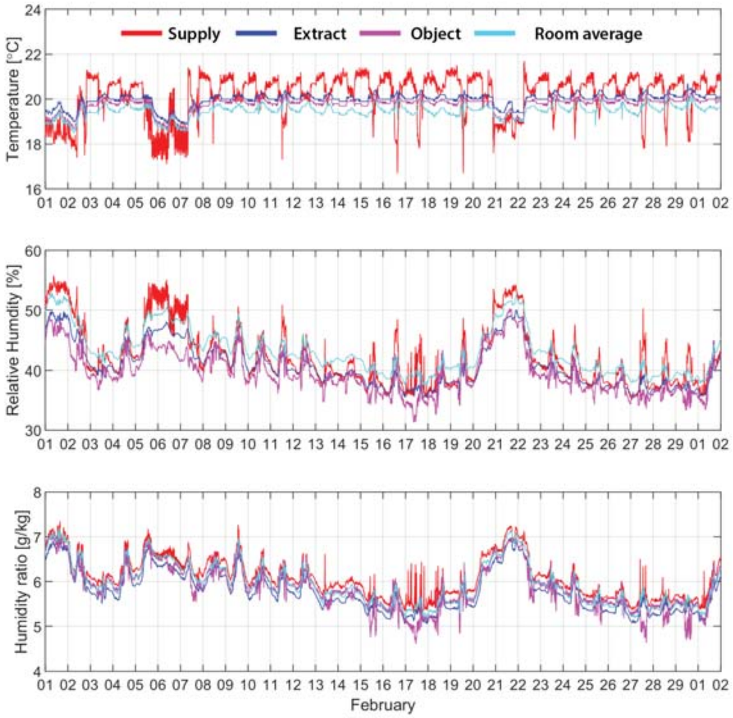

Figure D.15: *Temperature, relative humidity and humidity ratio measured in the Historic Room inlet (red), outlet (blue), near an object (magenta) and the room average (cyan) during February 2016.*

relative humidity.

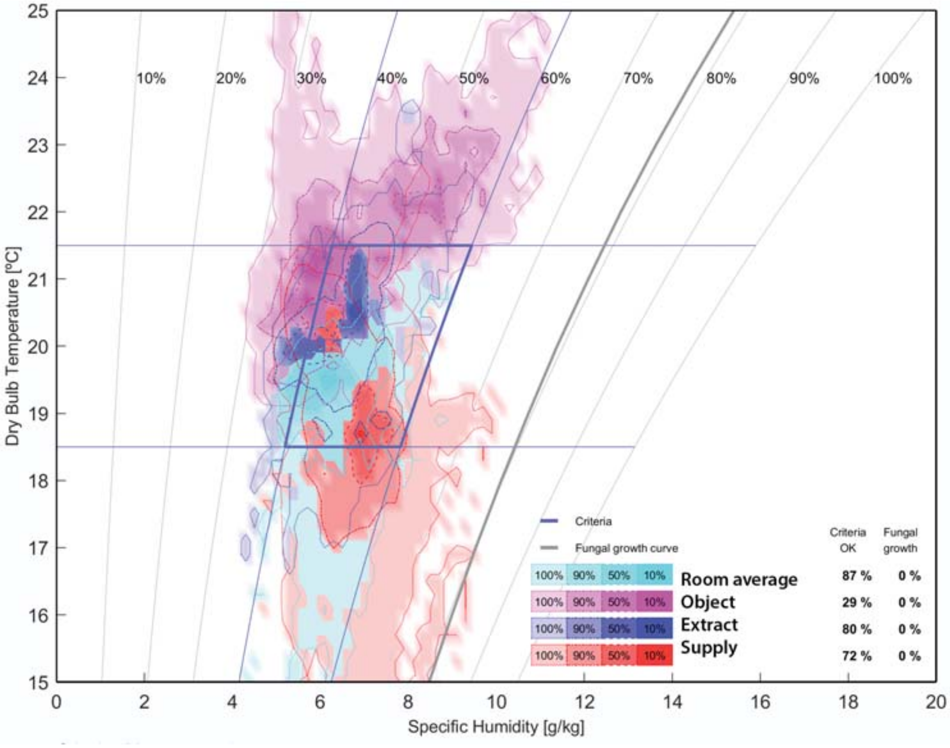

Figure D.16: *Climate Evaluation Chart of four locations over an entire year where temperature, relative humidity and specific humidity are set out on the axes. The criteria (blue square) is equal to the museum setpoint specifications for T and RH (b).*

Conclusions from the case studies

The following conclusions can be drawn based on the pilot studies:

- The building envelope serves as a boundary between the external climate and indoor climate. When this boundary provides insufficient thermal resistance or air tightness, the external climate influences indoor climate parameters T and RH. I.e. thermal bridges result in cold surfaces and deviating local microclimates during cold external climate condition. If a susceptible object is placed near or in such a local microclimate diurnal or seasonal fluctuation in T and RH might cause biological, chemical or mechanical degradation.

- Susceptible objects placed near supply ducts of the climate system, radiators or local humidifiers experience more extreme conditions in terms of heating or humidification. Spatial differences within an object could turn into mechanical strain and result in irreversible damage.

- Building use has to do with how a gallery is used, this could be by blocking off windows or creating more wall surface to place objects. Result is that if done on external walls, differences in thermal resistance occur. Certain areas become colder and more susceptible for vapor condensation during winter periods causing increased biological risk (mold). During summer increased heat loads caused by solar radiation increase risks for spatial differences resulting in mechanical strains in objects.

E Winter situation for M3 ICMS short-term measurements

Figure E.17 shows the short-term measurements in M3 during the winter season. The original building is comprised of the gallery level and a plenum level where shutters were placed in the dividing floor/ceiling with the galleries to let daylight enter if wanted. During winter low temperatures are present in the space above the gallery which results in maintaining the indoor climate conditions within the proposed museum requirements.

Figure E.17: *Averaged short-term measurements for T (left) and RH (right) for the ground levels of M3. The measurements are performed on February 17^{th} 2016*

F IRT seasonal differences

Figure F.18 and Figure F.19 show the IRT figures made for two areas of the *Historic Room*. The first shows part of the external wall where a plaque is placed in between to shaded windows. Figure F.18a shows the situation during summer (July 2nd 2015), F.18b provides the results for winter (January 13th 2015). Both situations show the influence of the building envelope. The thermal bridges at the window frames and the joint between walls and floor.

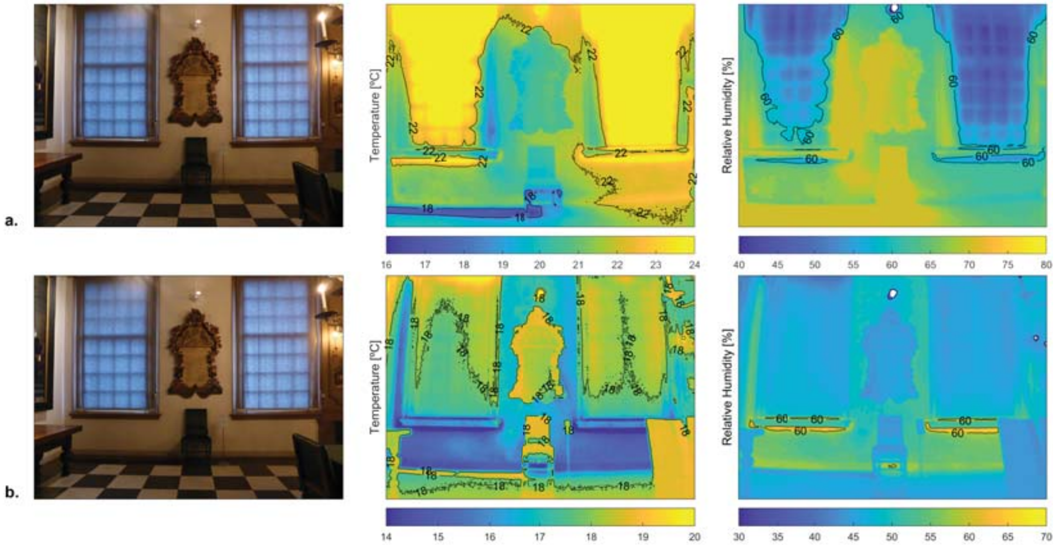

Figure F.18: *Visual image (left), thermal image (center) and hygric image (right) for a summer situation (a) and winter situation (b).*

Figure F.19 shows the influence of building equipment on object preventive conservation. The object was placed on top of the supply grille where conditioned are was supplied into the gallery. During summer the gallery is cooled with inlet temperatures of 16°C. During winter the supplied are can reach temperatures of 22°C. The derived relative humidity during the summer hygric images can reach up to 90%RH. This poses a high risk for object preservation.

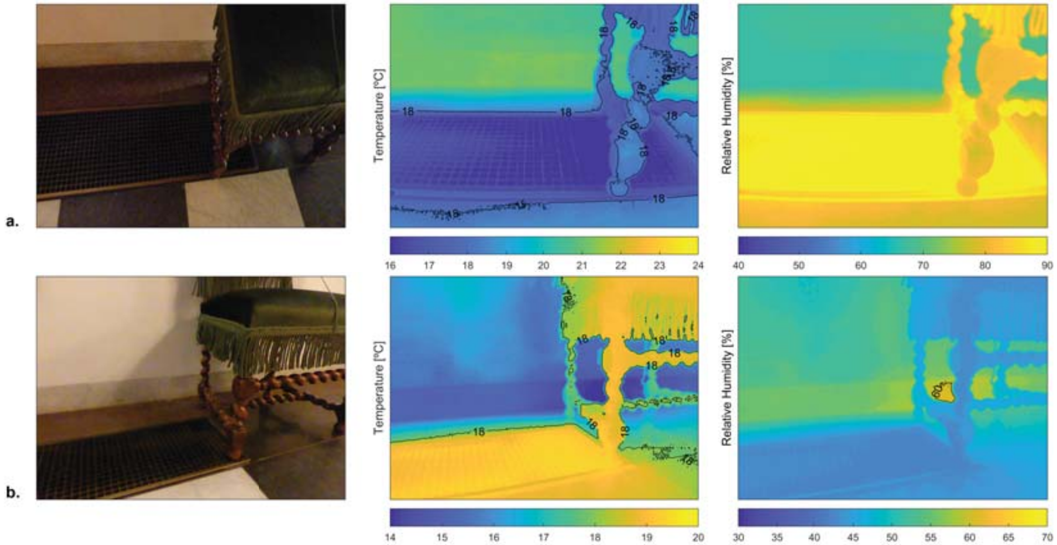

Figure F.19: *Visual image (left), thermal image (center) and hygric image (right) for a summer situation (a) and winter situation (b).*

G Script to plot spatial gradient distribution

The following Matlab script was used to plot spatial gradient distribution per interval measurement.

```
%Load files
load ('x1.csv');
load ('y1.csv');
filename = 'Data.mat';
l = who('*','-file',filename);
load(filename);
loc = length(l);
classes={'Monday','Tuesday','Wednesday','Thursday','Friday','Saturday'};
%%
for i = 12
    eval(['ye =' l{i} '.ye']);
    eval(['mo =' l{i} '.mo']);
    eval(['da =' l{i} '.da']);
    eval(['ho =' l{i} '.ho']);
    eval(['mi =' l{i} '.mi']);
    eval(['time =' l{i} '.time']);
    ticktime = datenum(ye,mo,1,0,0,0);
    tick = unique(ticktime);
    ticktime2 = datenum(ye,mo,da,ho,mi,0);
    tick2 = unique(ticktime2);
end

%%
for j = 12:38
    eval(['T =' l{j} '.T']);
    eval(['RH =' l{j} '.RH']);
    minT = floor(nanmin(T));
    maxT = ceil(nanmax(T));
    minRH = floor(nanmin(RH));
    maxRH = ceil(nanmax(RH));

    for k = 0:5 %startDate 00 04 08 12 16 20 hours
        startDate = datenum(2016,08,29,(24*k)+12,00,00);
        [row,col] = find(ticktime2==startDate);
        Tmag(j-11,k+1)=T(row,1);
        RHmag(j-11,k+1)=RH(row,1);
    end
end
%%
%Converse data to matrix location
Tmagmatrix=cell(1,6);
RHmagmatrix=cell(1,6);
x2=cell(1,6);
z1=cell(1,6);
w1=cell(1,6)
for m = 1:6
    Tmagmatrix{1,m}(8,10) = Tmag(1,m);
    Tmagmatrix{1,m}(1,5) = Tmag(2,m);
    Tmagmatrix{1,m}(7,4) = Tmag(3,m);
    Tmagmatrix{1,m}(9,4) = Tmag(4,m);
    Tmagmatrix{1,m}(11,3) = Tmag(6,m);
    Tmagmatrix{1,m}(9,3) = Tmag(9,m);
    Tmagmatrix{1,m}(6,3) = Tmag(11,m);
    Tmagmatrix{1,m}(11,1) = Tmag(12,m);
    Tmagmatrix{1,m}(9,2) = Tmag(13,m);
```

```
    Tmagmatrix{1,m}(6,1) = Tmag(14,m);
    Tmagmatrix{1,m}(4,2) = Tmag(15,m);
    Tmagmatrix{1,m}(4,2) = Tmag(16,m);
    Tmagmatrix{1,m}(5,9) = Tmag(21,m);
    Tmagmatrix{1,m}(1,10) = Tmag(22,m);
    Tmagmatrix{1,m}(2,9) = Tmag(23,m);
    Tmagmatrix{1,m}(3,8) = Tmag(24,m);
    Tmagmatrix{1,m}(11,7) = Tmag(25,m);
    Tmagmatrix{1,m}(10,7) = Tmag(26,m);
    Tmagmatrix{1,m}(11,5) = Tmag(27,m);

    RHmagmatrix{1,m}(8,10) = RHmag(1,m);
    RHmagmatrix{1,m}(1,5) = RHmag(2,m);
    RHmagmatrix{1,m}(7,4) = RHmag(3,m);
    RHmagmatrix{1,m}(9,4) = RHmag(4,m);
    RHmagmatrix{1,m}(11,3) = RHmag(6,m);
    RHmagmatrix{1,m}(9,3) = RHmag(9,m);
    RHmagmatrix{1,m}(6,3) = RHmag(11,m);
    RHmagmatrix{1,m}(11,1) = RHmag(12,m);
    RHmagmatrix{1,m}(9,2) = RHmag(13,m);
    RHmagmatrix{1,m}(6,1) = RHmag(14,m);
    RHmagmatrix{1,m}(4,2) = RHmag(15,m);
    RHmagmatrix{1,m}(4,2) = RHmag(16,m);
    RHmagmatrix{1,m}(5,9) = RHmag(21,m);
    RHmagmatrix{1,m}(1,10) = RHmag(22,m);
    RHmagmatrix{1,m}(2,9) = RHmag(23,m);
    RHmagmatrix{1,m}(3,8) = RHmag(24,m);
    RHmagmatrix{1,m}(11,7) = RHmag(25,m);
    RHmagmatrix{1,m}(10,7) = RHmag(26,m);
    RHmagmatrix{1,m}(11,5) = RHmag(27,m);

    for n=1:6
        a=Tmagmatrix{1,n};
        ind=find(a<=1)
        a(ind)=NaN
        Tmagmatrix{1,n}=a;
            z1{1,n} =inpaint_nans(Tmagmatrix{1,n});
            z1{1,n}(9:11,8:10)=NaN;
            z1{1,n}(1:3,1:4)=NaN;
            z1{1,n}(4:5,1)=NaN;

        b=RHmagmatrix{1,n};
        ind=find(b<=1)
        b(ind)=NaN
        RHmagmatrix{1,n}=b;
            w1{1,n } =inpaint_nans(RHmagmatrix{1,n});
            w1{1,n}(9:11,8:10)=NaN;
            w1{1,n}(1:3,1:4)=NaN;
            w1{1,n}(4:5,1)=NaN;
   end
end
for ii=1:6
    x2{1,ii}=abv(z1{1,ii},w1{1,ii}); %humidity ratio calculation
end
%%
for p=1:6
        startDate = datenum(2016,08,29,(24*(p-1)),00,00);
        formatOut = 'HH:MM';
        formatOut2 = 'dd-mm-yyyy';
```

```
        str = datestr(startDate,formatOut);
        title1(1,p)= {[ str ]};
end
%%
      str2 = datestr(startDate,formatOut2)
      title2 = {[ 'V2_Repository_contour_' str2 ]};
x0=50;
y0=50;
width=500;
height=500;
set(gcf,'units','points','position',[x0,y0,width,height],'Color','w');
for p=1:5
%T
    subplot(5,3,p*3-2); % left to right reading order
    [C,h] = contourf(x1,y1,z1{1,p},'LevelStep',[0.5]);
%     title(classes{1,p});%(title1{1,p});%
    c=colorbar;
    c.Label.String = 'Temperature [\circC]';
    clabel(C,h);
    caxis([16 22]);
    axis([0 57100 0 33800]);
    hAxes = gca;
    hAxes.XRuler.Axle.LineStyle = 'none';
    set(c,'Location','southoutside','Position', [.1 .08 .25 .01])
    axis off
%RH
    subplot(5,3,p*3-1); % left to right reading order
    [C,h] = contourf(x1,y1,w1{1,p},'LevelStep',[2]);
%     title(classes{1,p});%(title1{1,p});
    c=colorbar;
    c.Label.String = 'Relative Humidity [%]';
    clabel(C,h);
    caxis([40 60]);
    axis([0 57100 0 33800]);
    hAxes = gca;
    hAxes.XRuler.Axle.LineStyle = 'none';
    set(c,'Location','southoutside','Position', [.4 .08 .25 .01])
    axis off
% x
    subplot(5,3,p*3); % left to right reading order
    [C,h] = contourf(x1,y1,x2{1,p},'LevelStep',[0.2]);
%     title(classes{1,p});%(title1{1,p});
    c=colorbar;
    c.Label.String = 'Specific humidity [g/kg]';
    clabel(C,h);
    caxis([6 9]);
    axis([0 57100 0 33800]);
    hAxes = gca;
    hAxes.XRuler.Axle.LineStyle = 'none';
    set(c,'Location','southoutside','Position', [.7 .08 .25 .01])
    axis off
end
```

H Material properties calculations for library books

Based on literature of [130, 80], calculations have been performed to receive needed material properties of books in order in HAMBASE to correctly model the impact of a large buffering capacity. The adsorption isotherm is described based on a Genuchten type curve.

$$w_p(\phi) = w_{sat}(1 + (a \cdot ln(\phi))^n)^m \tag{6.1}$$

In which w$_p(\phi)$ (kg/m^3) is the specific moisture content of paper related to $RH(\phi)$ (-), and w_{sat} is the maximum moisture content at $\phi = 1$. a, n and m are parameters defined in [130]. The parameter a = -5, n = 1.03 and m = 0.9709. The moisture capacity of paper (ξ_p) can be calculated as follows:

$$\xi_p = \frac{\partial w}{\partial \phi} \tag{6.2}$$

Another important property is the moisture diffusion resistance factor μ (-). This factor indicates the relation between the water vapor permeability δ (s) of the material and that of air.

$$\mu_p(\phi) = \frac{1}{a + b \cdot e^{c\phi}} \tag{6.3}$$

Where a = 0.00167, b = 7.57$\cdot$ 10^{-7} and c = 11, parameters mentioned in [130] for the paper used in this study.
The water vapor permeability of paper δ [s] can be calculated with the following equation:

$$\delta_p = \frac{\delta_a}{\mu_p} \tag{6.4}$$

Where δ_p is the water vapor permeability of paper, δ_a is the water vapor permeability of air ($2.0 \cdot 10^{-7}$ at T = 293K).

To translate the properties of paper to be valid for a book, [130] performed experiments that concluded books should be considered as a system of paper layers with air in between. The air layer increases effective vapor permeability. The ratio between paper and air is called the paper fraction ψ_p. A paper fraction of 75% yields good results for books standing in a book rack according to Derluyn. This is representative for the setup in the case study library.

The water vapor permeability of the book needs to be calculated by using water vapor permeability of paper and air and their weighted fractions.

$$\delta_b = \psi_p \cdot \delta_p + \psi_a \cdot \delta_a \tag{6.5}$$

From this, the diffusion resistance factor of the book is calculated.

$$\mu_b = \frac{\delta_a}{\delta_b} \tag{6.6}$$

The moisture capacity of a book can be calculated as follows:

$$\xi_b = \psi_p \cdot \xi_p \tag{6.7}$$

I Repository temperature and velocity distribution

Figure I.20 shows the building plan of the investigated building. Figure 4.3 in the main text shows the building from the perspective of the public entrance. The repository tower (orange) has been an addition to the back of the building comprised of 5 stories.

Figure I.20: *Building plan of the investigated buildings ground floor.*

In order to have a global insight in the hygrothermal indoor climate table I.7 provides multiple statistical properties of the used measurement data.

Though air velocity was not extensively validated with measurements, the CFD model provides an indication of the occuring flow field. Limited air mixing was present near the external wall as can be seen in figure I.21. Stagnant air might increase risk for mold growth in combination with T and RH conditions favorable for mold germination. Improving air-mixing by ventilation is mainly to avoid internally generated pollutants that could harm susceptible objects [44, 53].

Figure I.22 shows the numerical results of all scenario's. With the exception of I.22D$_{on}$, all temperature distribution plots were calculated for April 14th at 04:00h. During the night temperature stratification was largest, especially for scenario D$_{off}$. Table I.8 shows minimum and maximum temperatures and velocities. A horizontal temperature gradient of 0.57K/m was present for scenario D$_{off}$ while air speed was 0m/s (figure I.23D$_{off}$).

Figure I.23 provides the results of velocity calculations per scenario. Overall, the same airflow distribution is present. Influence of the position of the archival racks is of limited influence on the airflow. Increased velocity and circulation is visible near the external wall when the extract of the AHU is placed lower.

Table I.7: Results for ambient and surface conditions over the year 2018: statistical properties.

	$T_{y,av}$ (°C)	$T_{y,av,min}$ (°C)	$T_{y,av,max}$ (°C)	ΔT (K/h)	ΔT_{std} (K/h)	ΔT (K/d)	ΔT_{std} (K/d)	ΔT (K/w)	ΔT_{std} (K/w)	$RH_{y,av}$ (%)	$RH_{y,av,min}$ (%)	$RH_{y,av,max}$ (%)	ΔRH (%/h)	ΔRH_{std} (%/h)	ΔRH (%/d)	ΔRH_{std} (%/d)	ΔRH (%/w)	ΔRH_{std} (%/w)
depot 3	17.1	-0.2	0.2	0.1	0.1	0.5	0.4	1.0	0.3	57.1	-2.6	1.6	0.5	0.6	2.4	1.2	4.8	1.7
depot 4	16.0	-0.1	0.2	0.1	0.1	0.4	0.2	0.8	0.2	56.5	-2.2	1.6	0.5	0.6	2.1	1.0	4.1	1.5
depot 5	16.6	-0.5	0.7	0.1	0.1	0.3	0.2	0.8	0.3	58.0	-1.9	1.8	0.5	0.5	1.9	0.9	4.1	1.7
depot 6	16.7	-0.4	0.6	0.1	0.1	0.6	0.3	1.1	0.3	57.8	-1.3	1.4	0.4	0.4	2.1	1.0	4.2	1.4
depot 6 wall east	15.7	-1.3	1.0	0.0	0.1	0.3	0.1	0.8	0.4	59.8	-1.4	2.7	0.7	0.8	2.1	1.2	3.9	1.6
T_{surf}	16.1	-1.3	1.1	0.0	0.0	0.2	0.1	0.7	0.4									
depot 6 wall west	15.8	-2.5	2.3	0.1	0.1	1.1	0.5	2.3	0.8	61.7	-6.1	7.5	0.7	0.7	3.8	1.7	7.2	2.2
T_{surf}	15.8	-2.8	2.5	0.1	0.1	1.0	0.5	2.4	0.9									
depot 6 shelf	16.4	-0.7	0.6	0.0	0.0	0.1	0.1	0.5	0.2	58.6	-0.9	1.0	0.1	0.2	0.6	0.5	1.5	0.9
depot 6 box 1	16.3	-1.3	1.1	0.0	0.0	0.2	0.1	0.7	0.4	59.2	-1.8	2.7	0.0	0.1	0.4	0.4	1.5	1.0
depot 7	17.1	-0.3	0.4	0.1	0.1	0.4	0.2	0.8	0.3	56.6	-3.5	2.7	0.9	1.1	2.8	1.6	5.4	2.1

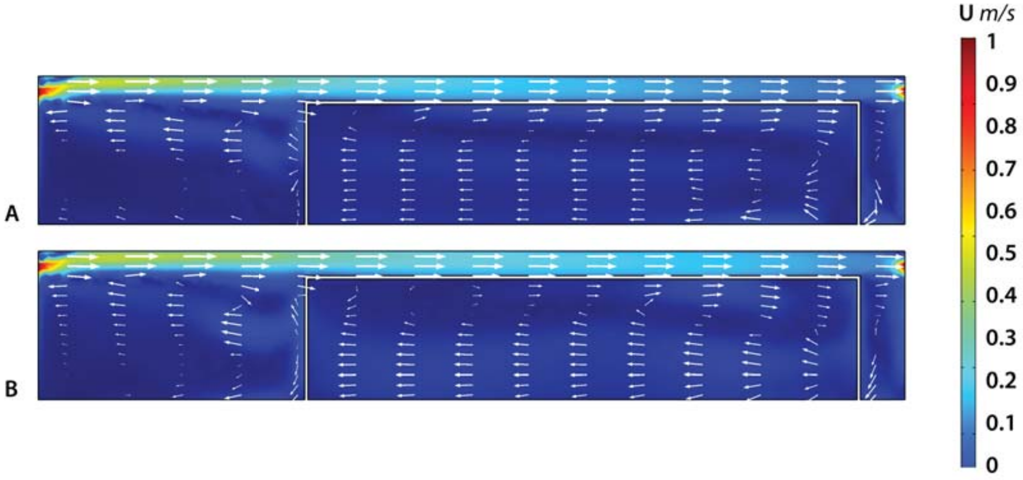

Figure I.21: *Time-averaged velocity distribution plot of scenario 1 with plane of analysis in between archive racks. Outdoor T was below 0° C on April 14th 2019 at 04:00h (A). figure B shows the results for April 16th when external T was 17° C at 14:00h. The white arrows represent the proportional velocity in a calculation grid.*

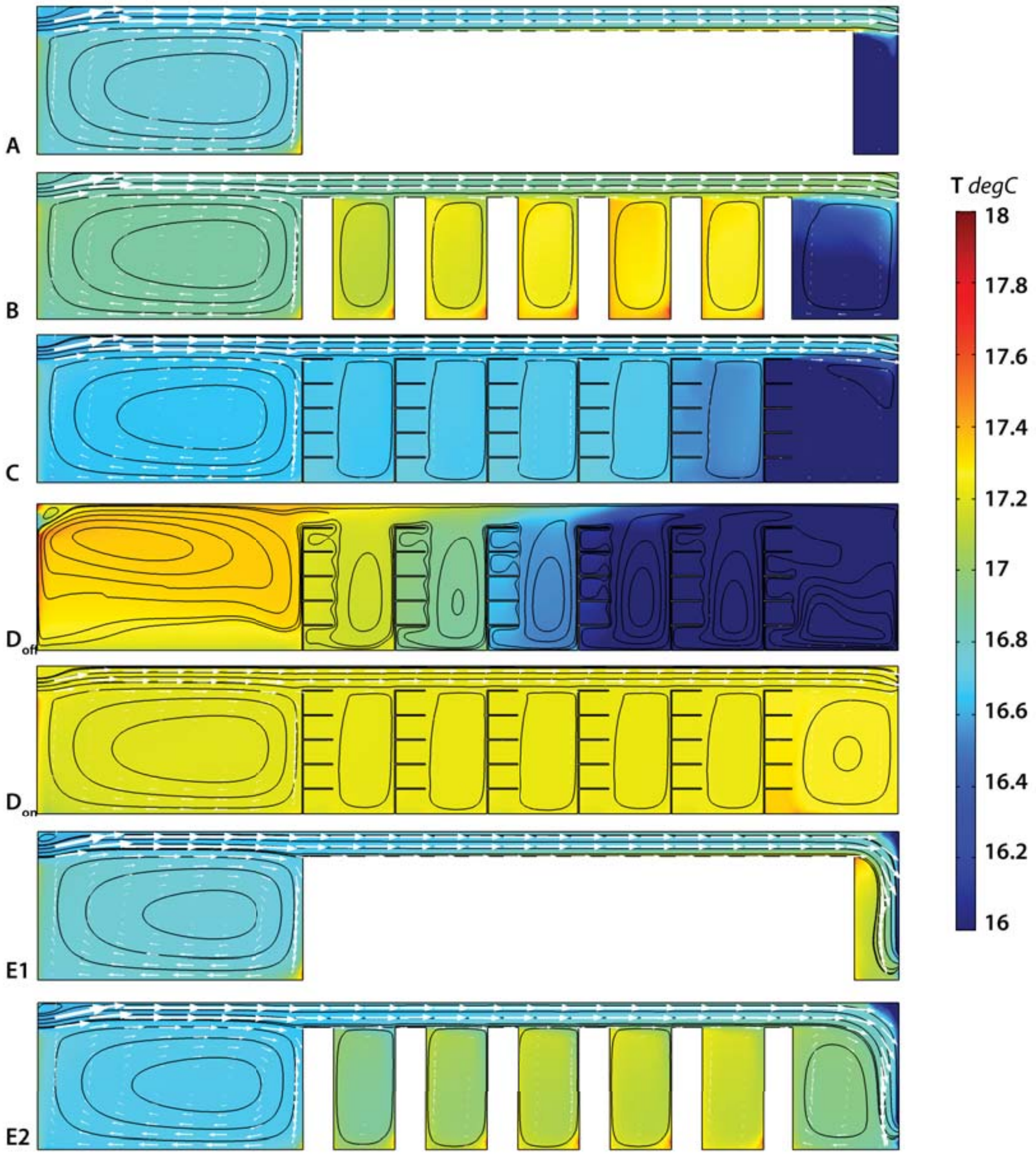

Figure I.22: *Time-averaged temperature distribution plot of all modeled scenario's when outdoor T was below 0° C on April 14th 2019 at 04:00h. The figures are time-averaged over 30 minutes of calculations. The figure for scenario D_{on} shows the results for April 16th when external T was 17° C at 14:00h. The velocity streamlines are shown in black and the white arrows represent the proportional velocity in a calculation grid.*

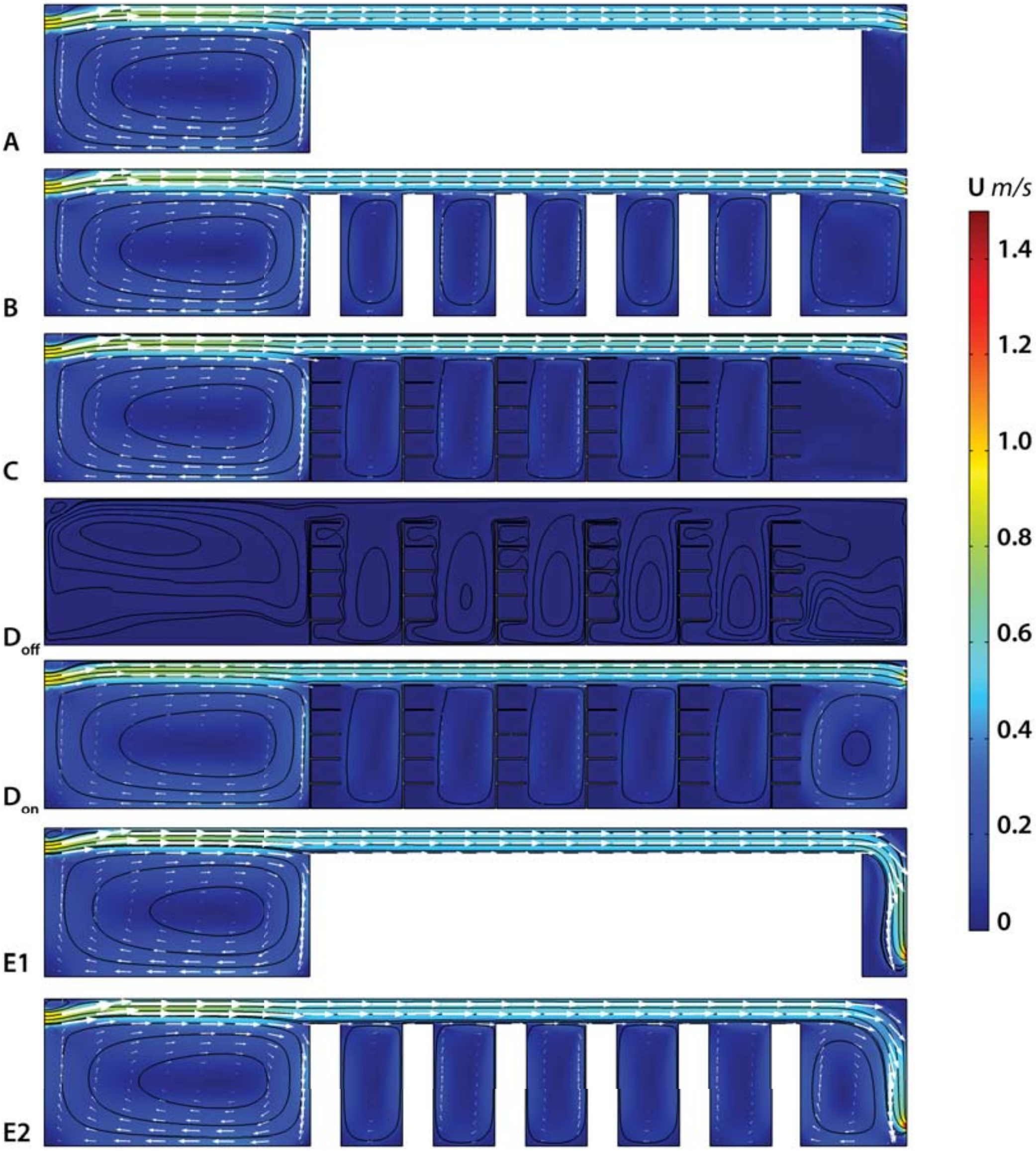

Figure I.23: *Time-averaged velocity distribution plot of all modeled scenario's when outdoor T was below 0° C on April 14th 2019 at 04:00h. The figures are time-averaged over 30 minutes of calculations. The figure for scenario D_{on} shows the velocity results for April 16th when external T was 17° C at 14:00h. The velocity streamlines are shown in black and the white arrows represent the proportional velocity in a calculation grid.*

Table I.8: Minimum and maximum values for temperature and velocity found for all modeled scenario's when outdoor T was below 0°C on April 14th 2019. The values found for scenario D_{on} show the results for April 16th when external T was 17°C.

	A	B	C	D_{off}	D_{on}	E1	E2
T_{min} [°C]	10.4	14.4	11.6	9.9	16.9	14.7	13.2
T_{max} [°C]	17.8	17.8	17.2	18.0	17.6	17.9	17.7
U_{min} [m/s]	2.6E-05	4.2E-05	4.8E-06	0	0	3.8E-05	2.9E-05
U_{max} [m/s]	1,4	1,5	1,5	0,16	1,5	1,6	1,6

J Regular control setting of a display case (experiment 6)

While the T_{room} conditions were set to 20 °C the T_{inlet} of the display case design should maintain a stable temperature of 17.5 °C in the inner display case. This was the regular control setting that should be maintained throughout the year. Figure J.24 provides the results of this experiment. As can be seen the $T_{a,case}$ is kept at a stable 17.5 °C throughout the experiment. While the $RH_{a,case}$ is too high, it shows stable behavior. To decrease the number of 65%RH towards the wanted 45%RH, silica gel is added in later experiments.

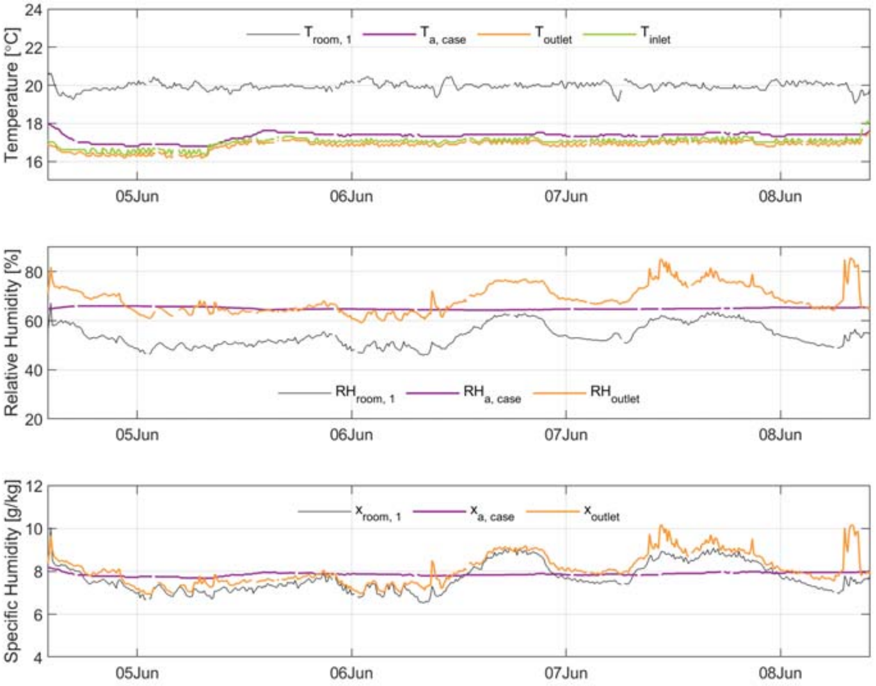

Figure J.24: *Indoor climate conditions of the exhibition gallery and display case 1 during experiment 6.*

K Calibration of combined T/RH measurement equipment

During the measurement campaign it became clear that the requirement of no permissible fluctuations in the inner display case was a challenge to monitor. The Eltek data transmitters all have an accuracy of ±0.4 °C and ±3%RH which, in this case, resulted in a large a spread. In order to decrease these numbers to be able to decrease the fluctuations noticed in this study, all transmitters were calibrated to such an extent that it removed the inaccuracy of the measurement equipment significantly. This appendix is divided in two parts. First, the temperature calibration is described, second, the relative humidity calibration is described.

Figure K.1a shows the results of the imposed T trajectory in the climate chamber. The results compared the Eltek data transmitter including a Sensirion temperature sensor (object) with the reference sensor (figure K.1b). When the difference between Eltek and reference fall within the accuracy of the manufacturer the device was suitable for use. When more accuracy is wanted it is possible to make a correction by fitting the Eltek sensor data for T and RH to the reference sensor T and RH of which the accuracy was more precise. The Eltek sensor has a working range between -40 – 120 °C. The investigated range for calibration lay between -10 – 40 °C and the needed range for measurements was within 15 – 30 °C.

In order to do this, the most constant period was determined by calculating in which window the two sensors showed the least amount of deviations. Figure K.1c shows the results in which the green markers provide the constant period of the reference sensor and the magenta markers show the constant period of the Eltek sensor. The period where these markers overlap can be compared to each other. Since it was important to know that all periods weigh in equally, the smallest overlap was chosen (Figure K.1d). In case of *T*, this resulted in a correction as presented in Table K.1.

Table K.1: Temperature calibration correction; average value of 44 measurements per imposed set point.

θref [°C]	θ_{object} [°C]	$\theta_{correction}$ [°C]
-9.92	-8.90	-1.02
0.10	0.84	-0.74
10.10	10.50	-0.4
20.22	20.31	-0.08
30.36	30.20	0.16
39.75	39.41	0.34

In order to fit the correction for values in between the tested calibration set points, a polynomial function is used (equation 6.8).

$$X_{fit} = B_2 \cdot {X_{object}}^2 + B_1 \cdot X_{object} + B_0 \tag{6.8}$$

X$_{object}$ is the variable *T* or *RH* of the sensor. X$_{fit}$ is the corrected value for *T* or *RH*. B$_2$, B$_1$, and B$_0$ are parameters used to fit the function. Figure K.2a shows the measured reference sensor data (magenta markers) set out against the measured Eltek data and the correction function (grey line). sX$_{fit}$ is the accuracy standard deviation due to fitting. The residuals were used to check if the correct polynomial function was used. The markers should be grouped around 0 to assume that the polynomial function was correct (figure K.2b). Table K.2 provides an overview of the parameters and statistical variables calculated for both *T* and *RH* correction. sB$_2$, sB$_1$, and sB$_0$ provide the standard deviation for the corrected variable. The uncertainty as result of the fitting was based on one times the standard deviation with a confidence interval of 68.3%.

Table K.2: Polynomial parameters for *T* and *RH* of the sensor used in inner display case 1.

	B$_2$	B$_1$	B$_0$	sB$_2$	sB$_1$	sB$_0$	1·sX$_{fit}$	R^2
T	-0.00016787	1.034	-0.7301	1.1e-005	0.00037	0.0035	0.036 °C	1.0
RH	0.00087202	1.0689	-11.67	6.2e-005	0.0082	0.25	0.47%	0.9995

Figure K.3, Table K.3, and figure K.4 provide the relative humidity calibration results. The steps correspond with the above described temperature calibration method.

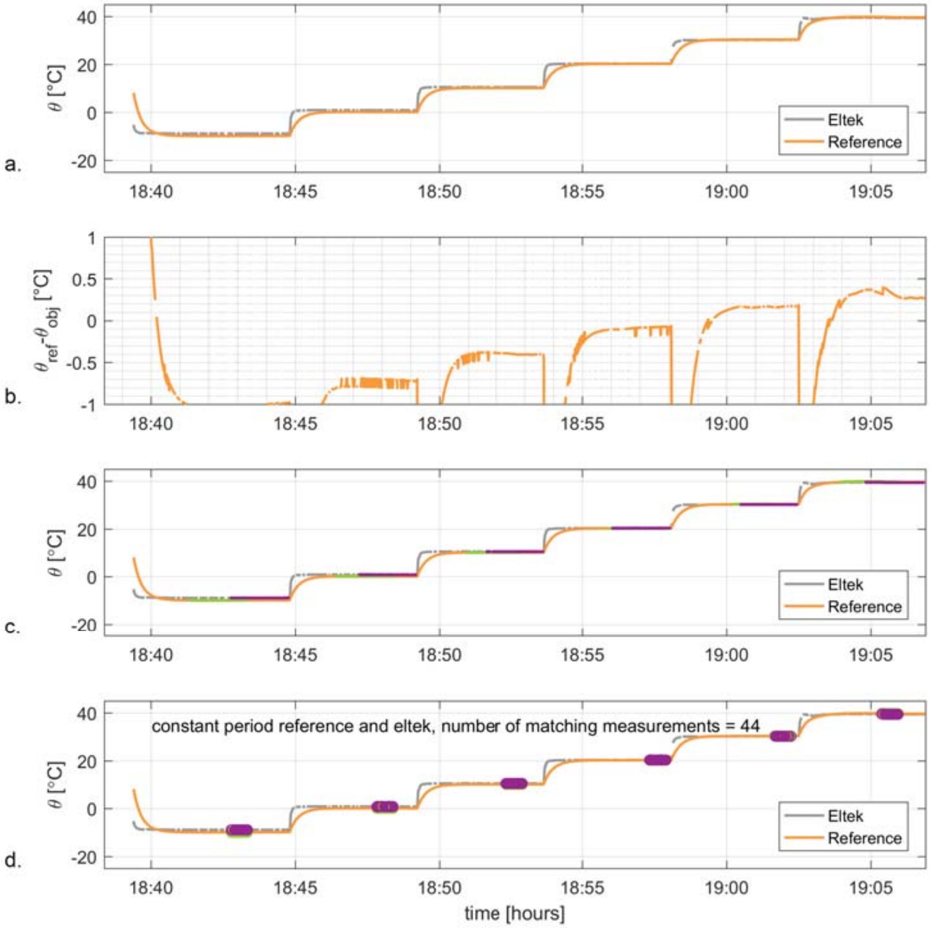

Figure K.1: *Imposed temperature trajectory with results (a) and comparison (b) between Eltek sensor (object) and reference sensor. The constant period is calculated (c) to provide a number of overlapping matching measurements (d).*

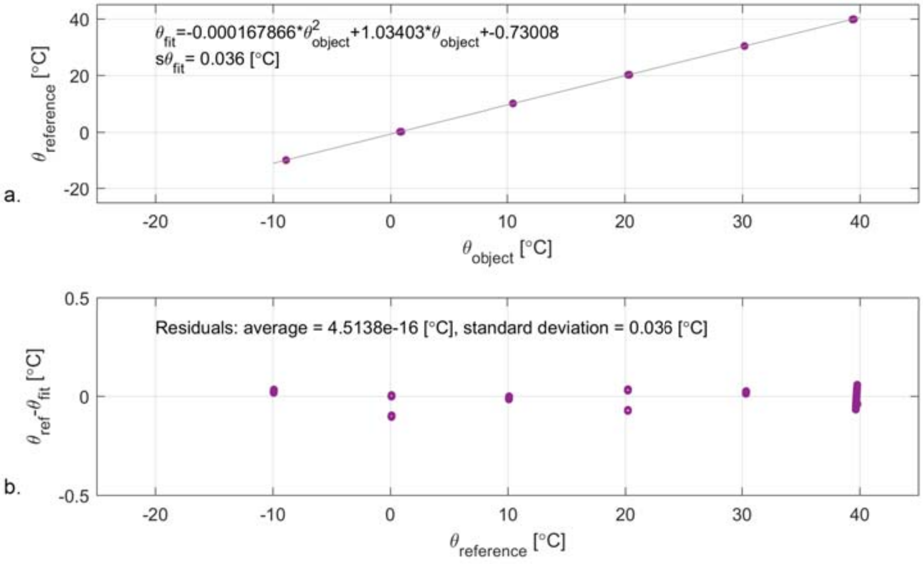

Figure K.2: *Eltek and reference fitting by using polynomial function (a) and the residuals to confirm the correct use of this function (b).*

Table K.3: Relative Humidity calibration correction; average value per set point.

RH$_{ref}$ [%]	RH$_{object}$ [%]	RH$_{correction}$ [%]
45.20	50.30	-5.1
66.97	69.11	-2.1
88.08	86.73	1.3
46.05	51.82	-5.8
67.40	69.89	-2.5
87.79	86.92	0.87
35.43	42.50	-7.1
45.73	51.64	-5.9
67.31	70.53	-3.2
90.44	88.85	1.6
30.26	38.33	-8.1
45.98	52.10	-6.1
70.60	72.98	-2.4
90.06	89.13	0.93

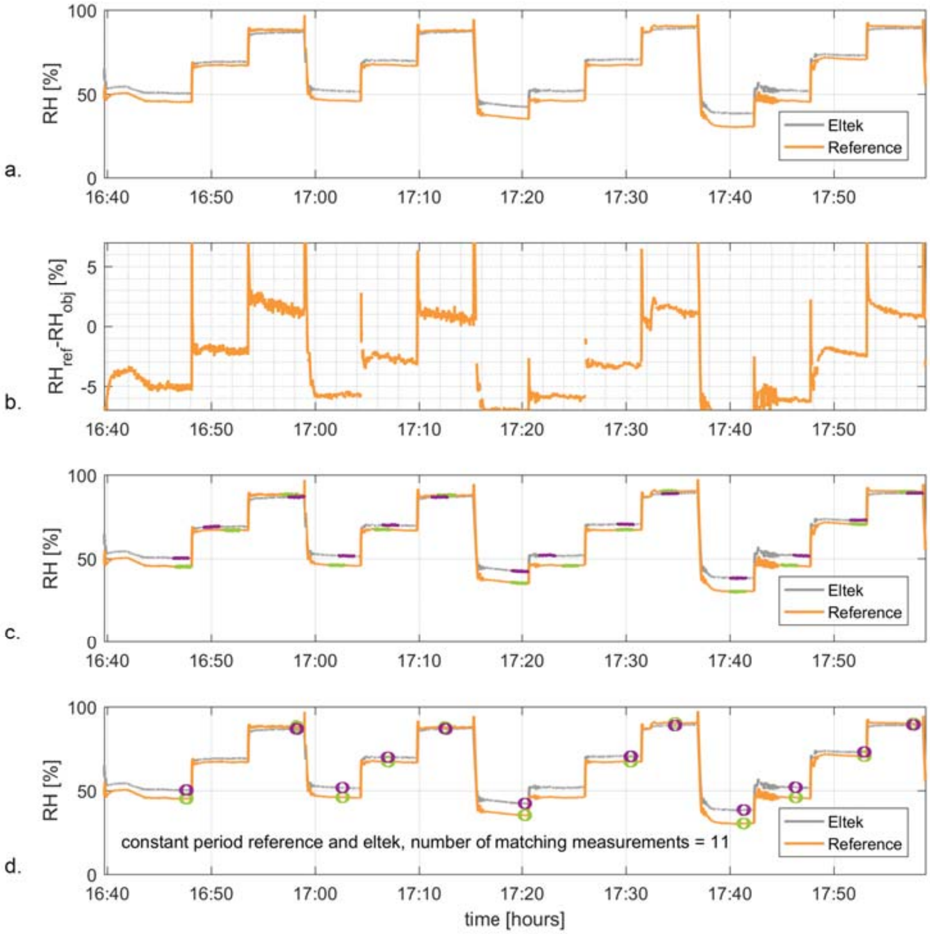

Figure K.3: *Imposed relative humidity trajectory with results (a) and comparison (b) between Eltek sensor and reference sensor. The constant period is calculated (c) to provide a number of overlapping matching measurements (d).*

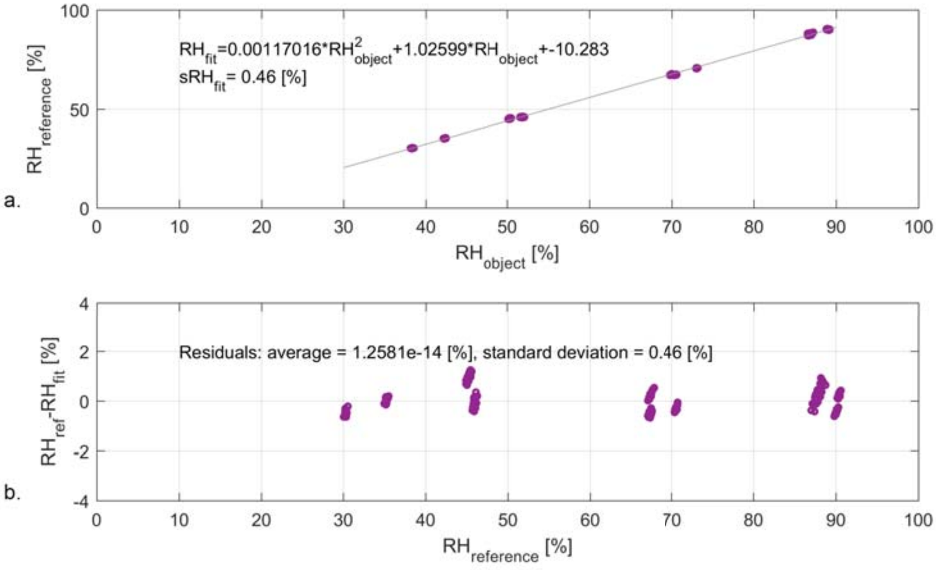

Figure K.4: *Eltek and reference fitting by using polynomial function (a) and the residuals to confirm the correct use of this function (b).*

Acknowledgements

"If you want to go fast, go alone.
If you want to go far, go together."
— African proverb

I have come full circle now and arrived at the final stage of this research project that started in 2015 for me. While having completed the master course on Heat, Air and Moisture transfer, I had no significant background in this area with relation to museums and monuments. I'm therefore still wondering what convinced my promoter Henk to take me on board! I'm glad that something did do the trick though. Since starting in the group of Building Physics for Cultural Heritage I've been guided, educated and inspired by a group of men that are passionate about this topic.

The first expression of gratitude needs to go to my promoter: dr.ir. Schellen; dear Henk. During these years I've been convinced that a great passion for this topic keeps you going. Education runs through your veins and I have been the subject of that many times. Thanks for the valuable lessons learned, not solely content-wise but more often the lessons of life. I will miss the meetings that started with discussing research but more often ended in office gossip. Enjoy your retirement!

Dr.ir. Rick Kramer, I am grateful you were willing to teach me how to think before speaking or writing. I have deep respect for your discipline in your work life, but more so in raising a big family next to it! Welcome back to research in Eindhoven and I hope our paths will cross again one day.

For the numerical modeling I have thankfully been able to fall back on dr.ir. Jos van Schijndel. His knowledge of multi-physics modeling elevated this research. Besides his valuable work ethics, Jos was the one who has traveled with me most. Relying on his meticulous research skills for being on time at airports and knowing which direction to go, I could use these trips to really relax and let Jos take control of the schedule. While being warned for his talent of finding a pizza restaurant in whatever country or city he'd travel to, I have had the pleasure to actually try local food with him each trip. Thank you for a great time!

I've been supported by the Dutch Cultural Heritage Agency in more then one way. The help of dr. Bart Ankersmit was priceless. With his knowledge on the practical side combined with the knowledge of everything and everyone involved in running a museum, I've gained insights in the field of museum management from top to bottom. Thank you for your critical questions and valuable feedback.

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I would like to express an immense gratitude to all the museums and archive institutions who have opened their doors and welcomed me in their work environment. There are too many names to list here for all the people I came in contact with during these years of research. I have been blessed to have stood among great masters in empty exhibition halls, seen the treasures hidden in storage rooms and gained knowledge on all that entails conservation of cultural heritage and managing a museum or archive. In many ways you have made me feel like part of your organization and gave me all-access to your buildings. For this strong trust I am indebted to you all.

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This research wouldn't have been possible if it weren't for the lab residents. Thanks to Jan, Wout and Harrie for all the ordering, preparing and fixing over the past years. Special thanks to Marcel who has made installing experimental set-ups a joy. Who'd have thought the most beautiful museums had damp cellars and dusty attics as well, and most of our time would be spent there .... Geert-Jan I want to thank for the social interactions on the lab floor or hallways, having such a positive outlook uplifted my spirits!

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I want to express deepest gratitude to my fellow corner PhDs (some already doctors now). I want to thank Shalika, Waqas and Julien, for introducing monday drinks! This tradition is hopefully carried on since I left! Magda I want to thank for the fun last few months in the office and doubling the number of PhD candidates in *our* group!

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To my floor 6 girls I'm greatly indebted for some really fun times both in the Netherlands and UK. It started by being office neighbours with some similar interests - proper coffee and too much talking - to a deep friendship that made the PhD process fun both inside and outside the office. Katarina Košútová (all the squiggly letters included), Wendy Janssen and Adelya Khayrullina, you are the best! We have already proven that this friendship lasts outside Vertigo and across borders.

Juliëtte, I'm glad I could convince you to do a PhD as well. It resulted in deepening our friendship for which I'm very grateful. I have the utmost respect for your discipline and hope some of it rubbed off on me over the years, though I think we both know the answer of this wishful thinking!

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Voor Joris en Otis heb ik slechts enkele woorden die alles omschrijven:
"Het leven wordt elke dag een stukje mooier met jullie erbij."

Curriculum Vitae

> *"I love deadlines. I like the whooshing sound they make as they fly by."*
> *— Douglas Adams*

Karin Kompatscher was born on August 4th 1989 in Bozen/Bolzano (South Tyrol), Italy. In 2012 she obtained a Bachelor of Science degree in Building Engineering from the department of Built Environment at the Eindhoven University of Technology (TU/e). She started the specialization track Building Physics and Services of the master track Architecture, Building and Planning and obtained her master's degree after successfully defending her master's thesis in 2015 titled: *Numerical study of wind energy harvesting by the Strata Tower: analysis of current performance and design improvements.* After completion she started as PhD candidate in the group Physics of Monuments in the department Built Environment (TU/e).

Her PhD research focused on experimental and numerical analysis of intermittent and dynamic climate control on (historic) buildings housing museums or archives to gain knowledge on its impact on the object environment.

Her main research areas are indoor climate monitoring in historic buildings with a museum, library or archive function, whole-building heat, air and moisture modeling, and modeling of the effect of air distribution on the object environment.

During her PhD research she was partly involved in the IEA Annex 68 project on Indoor Air Quality Design and Control in Low Energy Residential Buildings. During her PhD research she published in a number of international journals and attended and participated in several (inter-)national conferences.

As of 2019, Karin works as a *scientist innovator* for the Netherlands Organization for Applied Scientific Research (TNO) in Delft where she focuses on the energy transition in the built environment and in specific, healthcare buildings.

List of Publications

Karin Kompatscher has the following publications:

International Journal Papers: peer reviewed

K. Kompatscher, B. Ankersmit and H.L. Schellen. 'Indoor airflow distribution in repository design: Experimental and numerical microclimate analysis of an archive'. In: *Buildings* 11(4), (2021).

K. Kompatscher, B. Ankersmit, E. Neuhaus, M.A.P. van Aarle, A.W.M. van Schijndel and H.L. Schellen. 'Experimental and numerical analysis of a novel display case design: Case study of the renovated Anne Frank House'. In: *Studies in Conservation* 65 (2020), pp. 262-284.

K. Kompatscher, R.P. Kramer, B. Ankersmit and H.L. Schellen. 'Intermittent conditioning of library archives: Microclimate analysis and energy impact'. In: *Building and Environment* 147 (2019), pp. 50-66.

K. Kompatscher, S. Seuren, R.P. Kramer and H.L. Schellen. 'Energy efficient HVAC control in historical buildings: A case study for the Amsterdam Museum'. In: *Energy Procedia* 132. (2017), pp. 891-896.

Proceedings and Conference Contributions

M. Posani, M.R. Veiga, V.P. de Freitas, H.L. Schellen and **K. Kompatscher**. 'Dynamic hygrothermal models for historic buildings with indoor HVAC systems: complexity shown through a case study'. In: *12th Nordic Symposium on Building Physic*. Tallinn, Estonia, (2020).

K. Kompatscher, S. Kochen, A.W.M. van Schijndel and H.L. Schellen. 'Combined heat, moisture and CFD modelling to assess the impact of climate control on local climates near cultural objects in a museum exhibition room'. In: *2017 COMSOL Conference*. Rotterdam, The Netherlands, (2017).

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K. Kompatscher, S. Seuren, R.P. Kramer and H.L. Schellen. 'Energy efficient HVAC control in historical buildings: A case study for the Amsterdam Museum'. In: *11th Nordic Symposium on Building Physics; Energy Procedia* 132. Trondheim, Norway, (2017), pp. 891-896.

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Conservation of cultural heritage often poses a complex problem. To avoid risk for biological, chemical and mechanical degradation, a stable indoor climate is required for cultural objects sensitive to temperature and moisture. Depots and archives can provide stable conditions due to lack of external disturbances such as visitors entering. Often, museums are housed in historic buildings where objects are exposed to climate variations caused by either internal or external climate influence. Internal gains such as hygrothermal loads of visitors or thermal loads induced by a heating system causes locally deviating microclimates. External climate in combination with low thermal quality of the building envelope influences the indoor climate conditions. There is a clear conflict between the museum objective of exhibiting objects and the preservation needs to ensure the future of these objects.

The main aim of this thesis is to investigate that by operating existing HVAC systems in a more sustainabe way - via temperature and humidity requirements to establish an appropriate indoor climate for preventive conservation - this improves local microclimates by reducing spatial gradients and consequently benefit object preservation. In order to address this aim an environmental scan was developed to identify critical areas based on both temporal and spatial gradients. Furthermore, insight was gained into (risk accepting and energy conservation) climate control strategies, air distribution and the presence of (hygroscopic) collection on indoor climate parameter behavior. Lastly, seperation of gallery indoor climate conditions and object environment by means of a box-in-box museum display case design for exhibition purposes and archival boxes for preservation purposes.

The presented approaches and resulting knowledge gathered in this thesis are valuable to continue research in the fields of energy conservation indoor climate strategies and preventive conservation of susceptible objects. By not using climate control based on stringent normative requirements but by accepting descriptive requirements will not increase spatial and temporal gradients for temperature and relative humidity. Adopting a more risk-accepting approach in terms of climate control (i.e. dynamic control or intermittent conditioning) will not automatically result in the ideal indoor climate for conservation or storage purposes. This does however, show a preference for doing less: i.e. as little as possible heating in winter (resulting in little humidification) and as little as possible cooling in summer (resulting in little dehumidification). This would reduce thermally driven air flows resulting in deviations. Important is to adopt passive measures such as archival boxes in storage facilities, the use of museum display cases for exhibition purposes, installment of solar blinds to avoid direct solar gains, and improving building envelope thermal quality as a more invasive measure.

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